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Abstract

Lundgren, C. 2003. *Wood and fibre properties of fertilized Norway spruce*. Doctor's dissertation.
ISSN 1401-6230, ISBN 91-576-6522-2.

Very intensive forest management is relatively unexplored in Sweden, and while there is interest in pursuing *e.g.* the use of fertilizers on selected areas, there is concern about the quality of the wood when growth rate increases. This thesis summarises three studies on wood and fibre properties of Norway spruce grown in two nutrient optimisation experiments and one study from a Norway spruce provenance trial in Sweden. The nutrient optimisation trials were located at 57°08'N, 14°45'E and at 64°07'N, 19°27'E. Increment cores (12 mm) were sampled at breast height from three different treatments and a control. The treatments were irrigation, irrigation combined with liquid fertilization and solid fertilization. Density, microfibril angle, cell wall thickness and radial and tangential cell widths were measured on the wood samples and averages per annual rings and fibre property distributions were analysed. Density, microfibril angle, and cell wall thickness were clearly affected by fertilization. Density and cell wall thickness decreased due to fertilization and microfibril angle increased. Cell widths were moderately affected. Variables describing the inherent development from the pith, such as distance or ring number from pith and ring width, an expression of temporal growth rate and an indicator of varying amounts of earlywood and latewood, were the most important factors explaining differences in fibre properties. The provenance study was situated at 57°56'N, 5°39'E. The differences in density found between provenances were lower than differences caused by fertilization. The possible impact of intense commercial fertilization of Norway spruce for utilization in the pulp and paper industry is discussed.

Keywords: Picea abies, cell width distributions, cell wall thickness distributions, MoE, MFA, juvenile wood.

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Appendix

The present thesis is based on the following papers, which will be referred to by their roman numerals.

I. Lundgren, C. and Persson, B. 2002. Provenance variation in stem wood basic density and dry matter for *Picea abies* grown on farmland in Southern Sweden. Forest Genetics 9(2): 103-110.

II. Lundgren, C. Cell wall thickness and tangential and radial cell diameter of fertilized and irrigated *Picea abies.* (Submitted to Silva Fennica.)

III. Lundgren, C. Microfibril angle and density patterns of fertilized and irrigated Norway spruce. (Submitted to Silva Fennica.)

IV. Lundgren, C. Statistical distributions of tracheid diameter and wall thickness of fertilized Norway spruce. (Manuscript)

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Introduction

Background

In Sweden optimal wood production is more or less balanced against the target of environmental and biodiversity considerations for all forest land. However, interest in the application of more diverse forestry, in terms of silvicultural intensity, is increasing. This means that some areas would be managed more intensively while some areas with higher biodiversity values would be set aside from forest production (Vollbrecht, 1996). The bulk of forest land would however still be managed for a combination of interests. Very intense management is relatively unexplored in Sweden and there is concern about the quality of the wood when growth rate increases. There is also a trend to focus more forest research on wood properties, and efforts have been made to measure and model wood properties such as branching, density and latewood content, as well as properties of individual fibres (Lindström, 1997; Lindström *et al.*, 1998; Moberg, 1999; Lundqvist *et al.*, 2002; Wilhelmsson *et al.*, 2002). Wood ultrastructure has also been targeted via the initiation of a wood ultrastructure research centre, WURC, (http://www-wurc.slu.se; accessed 21-Jul-2003). The aim of the work presented in this thesis was to describe wood and fibre properties of trees subjected to optimal nutrient and/or water conditions in order to establish an expected upper limit if intensive forestry is to be applied in Sweden using the native species Norway spruce (*Picea abies* (L.) Karst.).

Species for intensive forest management

Norway spruce is a dominant species in Swedish forestry and comprises 43.6% of the growing stock (National Forest Survey, 2001) and 57% of seedlings used for regeneration by planting, which is the main regeneration method adopted in Sweden (National Board of Forestry, 2002). The fibres of Norway spruce are relatively long and slender (average length 3.4 mm (Trendelenburg & Mayer-Wegelin, 1955)) which makes them suitable for several pulp and paper products. The tracheids of softwoods are often referred to as fibres, especially in pulp and paper research. The term fibre was used in the present thesis when referring to utilization of the wood and the term tracheid was used when describing wood formation. The wood of Norway spruce contains smaller amount of extractives compared with *e.g.* Scots pine, the other main softwood alternative in Sweden, and Norway spruce is therefore more suitable for mechanical pulping (Varhimo & Tuovinen, 1999). Some hardwoods for which the wood properties may be more indifferent to faster growth rates, could be considered if the aim is to produce short fibres, which can enhance surface and optical properties of the paper (Varhimo & Tuovinen, 1999). Compared with other softwoods used for plantation-like forestry where growth rates are high, the wood properties of Norway spruce are often considered more sensitive to an increase in growth rate (Schmidtling, 1973; Zobel & van Buijtenen, 1989).

Effect of wood and fibre properties on utilization

Density and fibre dimensions

The properties of the wood and virgin fibres are important for the manufacturing process and the quality of the final product. Density is one of the most well researched wood properties and is correlated with solid wood performance as well as with pulp and paper quality. Stiffness and strength of solid wood is positively correlated with density (Cown *et al.*, 1999). Density is important from many aspects of pulping; a decrease in density reduces pulp yield by unit of volume for both chemical and mechanical pulping thus increasing costs (Sahlberg, 1998; Varhimo & Tuovinen, 1999). Variations in density can furthermore cause fluctuations in the energy requirements in the refining process (Brolin & Norén, 1993; Varhimo & Tuovinen, 1999). Earlywood, which has lower density *i.e.* thinner walls and fibres which are more elastic, has been shown to require more energy than latewood fibres for thermomechanical pulp (TMP) of *Pinus radiata* (Murton *et al.*, 2001; Dickson *et al.*, 2002). Density is a compound property that can be used to predict fibre properties and is positively correlated with cell wall thickness and covaries with fibre length (Zobel & van Buijtenen, 1989). Fibres in chemical pulp retain their dimension after delignification to a high degree whereas the relationship between virgin fibre properties and mechanical pulp is more complex as the refining process causes greater effects on the fibres. For TMP the correlation between virgin fibres and pulp is generally good which means that the properties of the virgin fibres are related to product performance (Kibblewhite & Evans, 2000). The relationship between different properties may however change throughout the process; tear and tensile strength can both be shown to depend on fibre length and intrinsic fibre strength, but do not necessarily covary as the process proceeds (McKenzie, 1989).

The fibres from high-density wood can be expected to be thick-walled and stiff which means they are more easily fractured in the refining process resulting in a pulp with shortened fibres (Sahlberg, 1998). High density has a negative correlation with optical properties and a positive correlation with tear strength but the effects diminish when the position in the tree is considered indicating that it is not the density in itself that is important but rather the properties of the fibres which are mirrored by density (Braaten, 1996).

Fibre length is one of the most important and well-researched individual fibre properties and is important for strength. Pulps from high-density wood with long fibres have the highest tear index and the lowest scattering coefficient when pulps are separated according to different combinations of virgin fibre length and basic density (Fuglem *et al.*, 2003). In the same study, fibre length and density were successfully combined to model tear index, light scattering and paper smoothness.

Cell wall thickness is an important morphological property for sulphate pulp as it determines fibre flexibility and collapsibility, factors important for the bonding ability and tensile strength of pulp and paper. Cell wall thickness is also related to fibre strength and is one of the factors determining tear strength (Paavilainen, 1993). Thin-walled narrow cells result in a paper with high tensile strength, burst strength and smoothness, sheet density and good optical properties (Jang & Seth, 1998). Cell wall thickness affects light scattering for TMP (Braaten, 1997) and positively influences tear strength (Dinwoodie, 1965). For high bulk sheets however, thicker cell walls are required (Seth *et al.*, 1997).

The microfibril angle is the angle between the cellulose fibrils and the fibre axis. Microfibril angle usually refers to the angle in the thickest cell wall layer (S2). As microfibrils can only shrink transversely, a large angle implies increased longitudinal shrinkage of the fibre and consequently increased longitudinal shrinkage of the wood. Wood stiffness and bending strength are negatively affected by large microfibril angles (Cave & Walker, 1994) as the tensile strength of the fibre decreases with increasing angle (Kellogg & Thykeson, 1975; Armstrong *et al.*, 1977; Page *et al.*, 1977). The tensile strength of paper depends on the bonding and strength of the fibre itself, which is negatively affected by high microfibril angles, a feature also linked to the low tear strength of paper (Uprichard *et al.*, 1994). Microfibril angle has furthermore been shown to negatively affect collapsibility (Jang *et al.*, 2002), which may lead to lower sheet densities. This may also explain why juvenile wood requires more energy to a given freeness than mature wood (Fuglem *et al.*, 2003; Persson *et al.*, 2003).

Other wood properties affecting pulp and paper

Apart from fibre dimensions there are other wood properties which influence pulp quality and which may be influenced by silviculture and growth rate. The chemical composition and the relative amounts of knot wood and incidence of compression wood are examples. Knots are undesirable in the pulp due to their compression wood-like characteristics: shorter fibres, higher microfibril angles, higher extractive content, more lignin and less cellulose (Varhimo & Tuovinen, 1999). Handsheets containing knot fibres were shown to have inferior strength, surface properties and light absorption, and even small amounts of knots degraded the pulp properties significantly (Sahlberg, 1995). Mäkinen *et al.* (2001) showed that fertilization leads to higher frequency and larger size of knots. The lignin content may increase due to fertilization (Shepard *et al.*, 1980; Anttonen *et al.*, 2002) and with increasing growth rates (Yngvesson, 1993).

The influence of wood assortments on pulp properties

The relationships between wood and fibre properties and pulp quality has primarily been utilised and controlled by separating wood types with different fibre properties. Norway spruce as well as *Pinus radiata* (Murton & Corson, 1992) have been sorted into classes of wood maturity by separating sawmill chips from top logs or logs from early thinnings. Analyses of separating wood according to site quality or growth rate have also been conducted (Tyrväinen, 1995; Braaten, 1996; Duchesne *et al.*, 1997; Spångberg, 1998; Persson *et al.*, 2003). Tyrväinen (1995) compared three assortments of pulpwood for TMP pulps: sawmill residues, first thinnings and a mature stand. The assortments differed with respect to fibre dimensions. Pulps from sawmill chips had highest tear and tensile strength and poorer optical properties, whereas pulp from thinnings had poor strength properties but superior brightness and light scattering. No differences in specific energy consumption when compared at the same freeness were found. Similar results where obtained by Braaten (1966) who found that wood from thinnings gave the best light scattering and brightness but the lowest tear strength. Sawmill chips represented the extreme at the other end while the top logs gave properties inbetween. The superior light scattering for the thinnings was explained by their thin cell walls; whereas fibre length was the factor which increased tear strength (Braaten, 1996). Differences between trees from young thinnings and top logs, *i.e.* differences between juvenile wood at different heights on the effects of pulp are harder to distinguish (Spångberg, 1998).

When comparing thinnings of different growth rates, Spångberg (1998) determined that the slow-grown (ring width ≤ 2 mm) trees have higher tear and lower burst index for kraft pulp. This is in line with Yngvesson (1993) who found that fast-grown kraft pulpwood has a lower yield and lower strength compared with slow-grown wood. For TMP pulps, Persson *et al.* (2003) found that first thinnings from fertile stands gave lower tear index and better optical properties than sawmill chips, and that the thinnings have a higher specific energy consumption. Sorting normal wood flow at the mill into two classes of ring width did not result in large differences in the pulp. Trees grown at very large spacings have lower tear index of produced sulphite pulp for spruce (Klem, 1942). Brolin *et al.* (1995) found that wood from a former agricultural stand had lower yield, higher tensile strength and lower tear strength than the average of a reference pulp, although Braaten (1996) found no impact of site quality on TMP-properties.

Factors affecting wood properties

The growth pattern of a tree is dependent on its genetic properties and on the environment in which it grows. In forestry the environment is manipulated via silvicultural measures mainly regulating competition for light, nutrients and water. The tree crown responds to increased or decreased resources and changes in tree growth are induced by hormones. Competition between trees can be regulated by manipulating the stocking, either initially by planting at different spacings or later in the rotation by removing trees during thinning. Fertilization provides an opportunity to decrease competition for nutrients without necessarily removing trees from the stand.

Genetics

The genetic component of tree growth can be exploited by molecular biology and through selection and breeding in which case the traits need to be hereditary and show sufficient genetic variance. For *Picea* wood density is a trait under genetic influence (Kennedy, 1966; Zhang & Morgenstern, 1995; Zobel & Jett, 1995). Density is more heritable than growth traits, but is sometimes unfavourably correlated with other traits. There is *e.g.* a strong negative correlation between ring width and density for Norway spruce (Blouin *et al.*, 1994; Rozenberg *et al.*, 2001).

The variation in density is larger within than between provenances (Nepveu, 1984; Blouin *et al.*, 1994). Inheritance, when assessed as heritability values for *Picea mariana* are reasonably high for tracheid diameter and length, but weak for wall thickness (Khalil, 1985). For Norway spruce high heritabilities for fibril angle, wood density and lignin content were reported whereas medium heritabilities were found for wall thickness, tracheid length, lumen diameter and microfibril angle (Hannrup *et al.*, 2003). Genotype-site interactions are generally small within normal ranges of site variations (Zobel & Jett, 1995). In the short term, the available choices for utilising genetic variation would be by provenance selection or selection of well adapted seed orchard seed sources rather than the use of molecular biology. Properties of individual trees could be utilised by the use of cuttings.

Inherent patterns of wood formation

As softwoods primarily consist of tracheid cells (ca 94% of the volume of Norway spruce wood (Petric & Scukanec, 1973)), the density is mainly dependent on the relation between tracheid wall thickness and width. Cell width and thickness differ between earlywood and latewood, which is why density is dependent on the latewood proportion on the annual ring level (Zobel & van Buijtenen, 1989). Latewood content, tracheid length, tracheid width and wall thickness increases within the juvenile wood core from the pith outwards (Zobel & Sprague, 1998). The density of Norway spruce is high near the pith, due to very small but numerous cells, decreases rapidly and then starts to increase again (Olesen, 1977). The increase is fast within the juvenile wood zone after which the increase is moderate. Microfibril angle decreases within the juvenile zone. Chemical composition also changes with distance from pith, with juvenile wood containing more lignin and less cellulose (Zobel & Sprague, 1998). Juvenile wood, particularly fast grown, has a higher incidence of compression wood (Bendtsen, 1978).

The characteristic development of properties within the juvenile wood core are retained, but modified, with increasing height in the tree. The gradual change in cell width from pith to bark becomes more pronounced with increasing height (Olesen, 1982), this affects the basic density level which decreases up the tree (Olesen, 1977). A greater increase of tracheid length, from pith to bark with increasing height has also been recorded (Atmer & Thörnqvist, 1982). However, Saranpää (1994) did not find particular differences in tracheid length development with height.

Effects of silviculture and site on wood properties

Changes in growth rate can modify the basic pattern of wood formation. In Norway spruce wood density is largely a function of growth rate and can therefore be controlled by controlling ring width (Lindström, 1996), a feature also shown by Johansson (1993) with juvenile wood. Density may also vary for the same annual ring width, which is part of the concept of basic density level. Basic density level changes with ring number from pith (Olesen, 1976). Pape (1999b), did not detect differences in basic density level between different thinning regimes, nor did Johansson (1993) find differences between different spacings. Fertilization decreased density, and density was more correlated with the amount of cell wall than with absolute cell wall thickness (Mäkinen *et al.*, 2002b).

The effects of fertilization on density are similar to the reduction achieved when growing trees on a naturally high quality site (Bevege, 1984), but there are studies indicating that some modification may occur. Madsen *et al.* (1985) found the density of Norway spruce fertilized with nitrogen to be unexpectedly low with regard to ring width. Fertilization of *Pinus pinaster* reduced maximum density leading to a more uniform density within the ring (Polge, 1969). Klem (1972) found no relationship between latewood ratio and density for fertilized Norway spruce. The density decrease that was observed was caused by a general shift in cell wall thickness. Both fertilization and irrigation prolonged the length of earlywood formation in Douglas-fir (Brix, 1972). For loblolly pine heavy fertilization on a wetter site gave a lower latewood ratio compared with heavy fertilization on a dry site (Kao Hsu & Walters, 1975), but no effect on growth rate or specific gravity was determined. Latewood proportion of Norway spruce has been shown to be positively correlated with high precipitation (Wimmer & Grabner, 2000).

Tangential tracheid widths and tracheid lengths are considered to largely mirror the size of the cambial initial and are therefore controlled by the rate of anticlinal divisions (Bannan, 1965). The rate increases when the growth increases, whereas the radial tracheid width may be a couple of times larger than the initial from which it is derived (Bannan, 1965). Tracheid length in relation to growth rate was addressed by Mäkinen *et al.* (2002a) who found that an increase in growth rate due to fertilization produced shorter cells. Sirviö and Kärenlampi (2001a) found that fibre length decreases with an increased growth rate index. Herman *et al.* (1998) however, found no significant effects of growth rate on tracheid length but the fast-grown trees in their study have longer tracheids before, and shorter tracheids after a first thinning when compared with slow-grown trees. When comparing fast-grown and slow-grown trees within the same stand other researchers have found the fast-grown category to have longer tracheids (Stairs *et al.*, 1966; Bergqvist *et al.*, 2000). Kyrkjeeide (1990) found a larger variation in the tracheid lengths of suppressed trees than in other tree classes. Tracheid widths were not affected by thinnings or changes in ring width due to thinnings (Pape, 1999a). Fertilization caused formation of larger tracheids at a given cambial age (Mäkinen *et al.*, 2002a) but differences diminished at a given distance from pith. Studying a Norway spruce fertilization trial, Lindström (1997) found that both radial and tangential cell widths were significantly affected by cambial age, ring width and site quality. Responses to silviculture in cell diameters are not usually comparable with the responses in growth increment, which is why the main effect is probably an increased cambial efficiency *i.e.* production of more cells (Pape, 1999a; Wodzicki, 2001). Trees grown on unfavourable sites tend to have smaller cells (Bannan, 1965) and water availability has been shown to have a positive influence on cell size (Kramer, 1962; Vysotskaya & Vaganov, 1989; Von Wilpert, 1991). Trees grown in drought have small cells with thick heavily lignified walls

(Kramer & Kozlowski, 1960). Water stress has a more adverse effect on diameter growth than on the rate of photosynthesis (Brix, 1972).

In a study on social position within the stand, Kyrkjeeide (1990) found that earlywood microfibril angle decreased with ring number from pith for suppressed trees but increased for dominant trees. Latewood microfibril angle stabilised on a somewhat higher level for the suppressed trees. Fertilization and irrigation of *Pinus taeda* adversely affected the modulus of rupture and elasticity (Kao Hsu & Walters, 1975) and higher growth rates causes higher average microfibril angles (Lindström *et al.*, 1998; Herman *et al.*, 1999; Saranpää *et al.*, 2000).

Some cell dimensions from various studies on Norway spruce are shown in Table 1. Cell size varies widely depending on where the sample is derived, particularly on whether it is juvenile or mature wood but also on height in the stem and site factors.

Table 1. *Cross-sectional dimensions of Norway spruce*

	Cell wall thickness, µm			Cell diameter, µm		
Author	Ew	Lw	All	Ew	Lw	All
Fengel (1969)	1.80	4.44		39.3[r], 32.7[t]	13.1[r], 32.1[t]	
Nylinder *et al.* (1954)						38.8
Atmer *et al.* (1982)						22[a], 38[b]
Pape (1999a) [c]	2.64	4.55	3.21	36.6[r], 34.6[t]	24.5[r], 29.8[t]	33.3[r], 33.3[t]
Norén (1996)	3.6[d]			36.6[d]		
Brolin *et al.* (1995)	5.0[e], 3.7[f]			36.3[e], 46.1[f]		
Tyrväinen (1995)			3.7[g], 1.8[h]			39.8[g], 22.7[h]
Persson *et al.* (2003)						34.1[i], 39.5[j]

a) at breast height, 2-3 rings from pith; b) breast height, 72-73 rings from pith; c) data from four rings approaching maturity on fertile land, unthinned latewood defined as cells where three times the common cell wall is equal to, or greater than, radial lumen width; d) mean at 0.1 m. height of four stands established on agricultural land; e) at 4 m. height suppressed trees from a forest stand; f) at 4 m, dominant trees from a stand established on agricultural land; g) sawmill chips; h), wood from first thinning; i) wood from first thinnings from very fertile sites; j) sawmill chips; t) tangential; r) radial.

Objective of the thesis

The main objective of this thesis was to analyse whether high growth rates caused by fertilization would significantly affect properties of the virgin fibres. Nutrient optimisation trials were used as their high growth rates were assumed to represent an upper limit that could be expected from fertilization at commercial rates. Wood density, microfibril angle, cell wall thickness and radial and tangential cell widths were analysed. In order to evaluate the possible effects on the wood by applying intensive management on stands established from other seed sources, a provenance trial was included to assess the genetic variation in density which can be found in Swedish spruce planted 20 to 40 years ago *i.e.* in stands which may be considered for fertilization.

Material and methods

Notation

The following notations are used:

Provenance study	The provenance trial at Östad; Paper I
Fibre property study	Data from the nutrient optimisation trials at Asa and Flakaliden; Papers II-IV
Tracheid width	The term width is used rather than diameter since cells are not circular and the tangential width differs from the radial
Latewood	Latewood is defined as cells where 3 × double cell wall thickness ≥ radial lumen width
Density	Basic density is used for the provenance data and density at appr. 8% moisture content is used for fibre property data
MFA	MFA refers to the microfibril angle measured by X-ray diffraction in Paper III, when references are made to other findings the term microfibril angle is written in full

The following abbreviations are used in figures, tables and models:

General	
C	untreated control
F	solid fertilization
I	irrigation
IL	liquid irrigation and fertilization
lw	latewood (see notations above for definition)
ew	earlywood

Abbreviations used in models	
I	irrigation dummy 1/0, used at Asa
F	fertilization dummy 1/0, used at Asa
T	treatment, C, F or IL, used at Flakaliden
d	distance from pith, mm
id	1/distance from pith
r	ring width, mm
n	ring number from pith

Wood properties

The initial objective of the fibre forestry initiative has been to produce pulpwood. This thesis has therefore mainly focused on the properties of the individual fibres. Density, which is a compound property dependent on cell dimensions, and MFA, which defines shrinkage and stiffness properties of the fibre, were also included.

Östad – the provenance study

In order to assess the possible variation due to seed source, a provenance trial at Östad was analysed. Background information on the Östad site and trial is given in Table 2. The trial comprised 16 provenances – six Swedish; three second generation Western continental, grown in southern Sweden; two Western continental; three Polish north-eastern continental; and two from the Beskids Mountains in Southern Poland. The trial was organised as eight blocks each consisting of sixteen 5 × 5 seedling plots to which the provenances were randomly assigned. The trial was thinned in 1993 leaving approximately 1500 stems ha^{-1}.

A sample of increment cores for density assessment was taken in the spring of 1996 when diameters and heights were also measured. Whole-plot estimates of volume and dry matter yield were based on repeated inventories for diameter and sub samples for height. Three sample trees were chosen from each plot; one large, one medium-sized and one small. Annual ring widths were measured and basic densities of segments of three annual rings were determined using the water displacement method (Olesen, 1973).

Analysis of provenance study

The parameters of basic density level model (Olesen, 1976) disc density and ring width were analysed in a repeated analysis of variance:

$$Y_{ijklm} = \mu + \varphi_i + \tau_j + \beta_k + \delta_{l(k)} + \varphi\delta_{il(k)} + \tau\delta_{jl(k)} + \varepsilon_{(ijkl)m} \qquad (1)$$

where Y_{ijklmn} is the dependent variable, basic density or ring width; μ is the overall mean; φ_i is block (fixed effect); τ_j is tree size class (fixed effect); β_k is zone (fixed); $\delta_{l(k)}$ is provenance within zone (random); and $\varepsilon_{(ijklm)n}$ is random error. Zone denotes a grouping of provenances according to broad geographic origin. In Paper I the provenances are grouped into Swedish, Western continental and Polish.

Table 2. *General information about the sites*

	The provenance study	The fibre property study	
	Östad	Asa	Flakaliden
Latitude	57°56'	57°08'	64°07'
Longitude	5°39'	14°45'	19°27'
Height above sea level, m	60	225-250	310-320
Planted	1969	1975	1963
Seed origin	16 European provenances	Unknown	Local provenance
Stocking, stems per hectare	2500	2400	2400
Site index H_{100}^{*}	32 (local provenance)	32	18
Site quality, $m^3ha^{-1}year^{-1}$	11.3	11.3	3.3
Plant stock	4-year-old seedlings	2-year-old seedlings	4-year-old containerised seedlings

[*] Hägglund & Lundmark, 1981

The nutrient optimisation trials at Asa and Flakaliden – the fibre property study

The nutrient optimisation trials at Asa and Flakaliden commenced in 1987. The trials were established to assess the potential production of Norway spruce under given climatic constraints when neither nutrients nor water was limited. Table 2 summarises site data, including the provenance study. The dosage of nutrients was determined by repeated annual foliage analysis and contained nitrogen, phosphorus, potassium as well as required micronutrients. The proportions of the components of the nutrient mix in relation to nitrogen was a key principal in determining the supply. The supply of nutrients should furthermore be balanced so that no leaching of nutrients into groundwater occurred. (Linder, 1995). More information can be found at (http://www-fiberskog.slu.se/index.html; accessed 21-Jul-2003). At Asa, the nutrient optimisation and irrigation (IL) more than doubled volume production approximately 10 years after the commencement of treatments and at Flakaliden there was a four-fold increase in volume production (Bergh *et al.,* 1999). Three different treatments and a control were assessed (Table 3). The IL treatment was liquid fertilization applied daily and F was the same composition of nutrients but was applied annually in solid form. The irrigation was targeted at maintaining a water level at just below field capacity. The treatments were applied to plots 50 × 50 m with 10 m wide buffer zones that received the same treatments as the core plots. Trees were randomly selected from the inner buffer zones. The target number of trees was 20. Sample data are presented in Table 4.

Table 3. *Factors involved in the experiment*

Notation	Irrigation	Fertilization
C	-	-
F	-	Solid
I	Yes	-
IL	Yes	Liquid

Table 4. *Data on the sample trees at the time of sampling (1999). Only samples used in the final analysis are included*

		N	Cambial age (std)		Diameter at 1.3 m under bark, mm (std)	
Asa	C	15	16.8	(1.2)	10.8	(2.5)
	F	10	15.3	(1.8)	11.0	(2.8)
	I	19	16.1	(1.5)	10.9	(3.5)
	IL	19	16.1	(2.4)	13.5	(3.9)
Flakaliden	C	19	20.3	(3.8)	7.7	(2.1)
	F	20	20.0	(5.0)	12.2	(3.1)
	IL	20	22.2	(2.4)	13.9	(1.7)

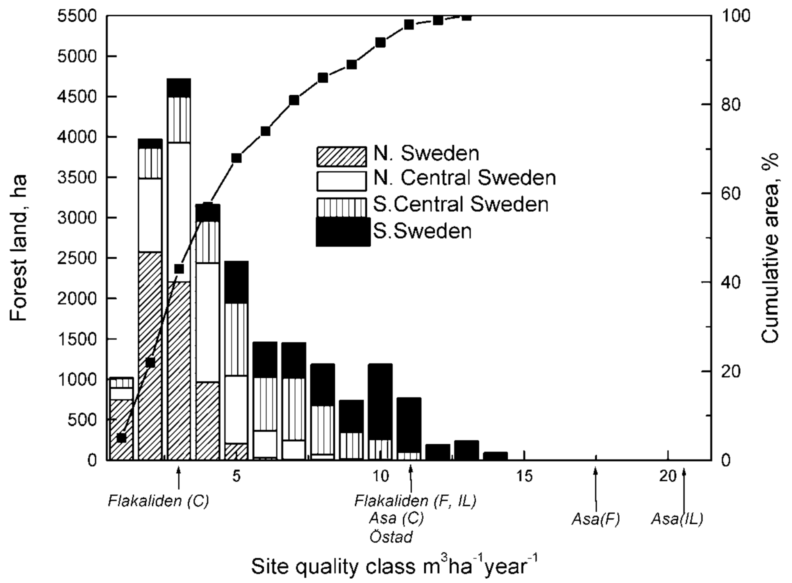

Fig. 1. Site quality classes for forest land in Northern, Northern Central, Southern Central and Southern Sweden (National Forest Survey, 2001) with the Asa, Flakaliden and Östad sites marked as well as the approximate new site classes (provided by Johan Bergh, pers comm.) with nutrient optimisation.

Measurements – the fibre property study

The SilviScan system (CSIRO, Melbourne, Australia) was developed to enable large-scale measurements of wood cell cross-sectional dimensions, density and microfibril angle. It has been used for a range of applications such as the evaluation of genetic material, silviculture, correlations with pulp and paper properties and forest inventory and model building (*e.g.* Evans *et al.*, 1997; Downes *et al.*, 2002; Wimmer *et al.*, 2002).

The samples used are radial strips 2 mm wide tangentially and 6 mm longitudinally, cut from pith to bark either sawn out from large increments cores (12 mm borer) or wood discs (Fig. 2.). The sawn samples are extracted in acetone and conditioned at 20 °C and 40% relative humidity. The conditioning is done to ensure an even and specific moisture content, necessary primarily for the densitometry. The cross-sections of the samples are polished until lumens are filled with dust and cells and cell walls are clearly distinguishable in red transmitted light to enable image analysis. Images are captured by a video camera and tangential and radial cell widths are measured on the cross-sections by image analysis at every 0.05 mm. The sample is placed on a sample holder, which ensures alignment according to cell rows if the cell rows are not perfectly straight within the sample. The growth patterns are registered and used to align the sample according to its true radial direction and for subsequent use during the X-ray densitometry. Cell widths from the SilviScan image analysis are within 7% of those measured manually on photomicrographs (Evans, 1994). X-ray densitrometry is a well-established technique and regarded as both efficient and accurate (Saranpää, 2003). Density measurements were obtained every 0.05 mm. The volume and weight of each sample was measured and the SilviScan measured densities were calibrated using the manually measured sample densities. Cell wall thickness was assumed uniform around the cell and was calculated using the measured density and cell dimensions. The cell wall density was then assumed to be 1500 kgm^{-3}, a figure which corresponds well with *e.g.* Saranpää's (2003) calculations (1509 kgm^{-3}) taking into account the relative proportions of lignin, hemicellulose and cellulose, typical for Norway spruce. Further information on the procedure can be found in Evans (1994) and Evans *et al.* (1995).

The X-ray diffraction pattern has been used by several authors to estimate the angle of the cellulose microfibrils and generally agrees with microfibril angles obtained by microscopical studies (Bergander *et al.*, 2002). The method is however not designed for revealing differences between individual tracheids (Bergander *et al.*, 2002). SilviScan uses the relationship between the variance of the 002 azimuthal diffraction pattern and microfibril angle dispersion. SilviScan microfibril estimations are based on the assumption that there are no differences between tangential and radial walls and the method only considers the S2-layer. In the present study, the microfibril angle was measured with moving averages at every 0.5 cm. This resolution gives information on the general behaviour of the microfibrils. When comparing SilviScan X-ray diffraction estimates of microfibril angle with pit apertures measured using microscopy for radiata pine, the degree of determination was 0.92 (Evans *et al.*, 1996). SilviScan microfibril measurements are described in Evans *et al.* (1996), Evans (1997 and 1999).

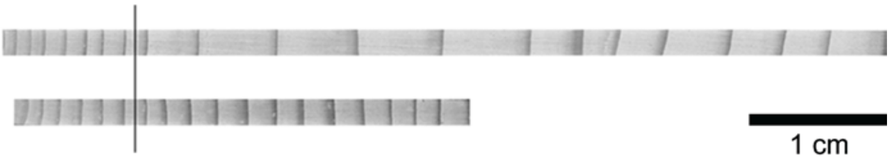

Fig. 2. Two fibre property samples from Flakaliden; IL, upper and C, lower, view from above. Vertical line marks the annual ring formed in 1987, the first year of treatment.

Analysis of the fibre property study

As most wood properties change from the pith outwards, especially within the juvenile wood core, it is essential to include the effect of increasing (or decreasing) mean with distance from pith in the analysis. The distance from pith has been shown to explain the juvenile wood-related development of cell widths (Olesen, 1977; Mäkinen *et al.*, 2002a) whereas cell wall thickness is mainly an effect of physiological intensity (Sirviö & Kärenlampi, 2001b). Density can thus be assumed to depend both ondistance from pith and growth rate. The fibre property data in the present thesis represented repeated measurements over (Papers

II and III) and within (Paper IV) annual rings which means that measurements are not independent. The principal model for analysing the fibre property data was:

$$Y_{ijkl} = \mu + \beta_0 d_k + \beta_1 d_k{}^2 + \beta_2 I_i + \beta_3 F_j + \beta_4 IFd_{ijk} + \beta_5 r_k + \beta_6 n_k + \varepsilon_{ijkl} \quad (2)$$

where: Y_{ijk} represents the dependent variable; μ is the overall mean; β_0 - $\beta 5$ are fixed effects for: *d*, distance from pith; *I*, irrigation; *F*, fertilization; *r,* ring width*;* *n,* cambial age (ring number counted from pith); and ε_{ijkl} is random error. Indices are *i*: 1, 2; *j*:1, 2; *k*: number of rings per sample 1..20 and *l* are number of repetitions (trees)1..20. Effects that were far from being significant ($p > 0.10$) were not included in the final models except for the effects of treatment which were always included. In accordance with the development of MFA from the pith towards the bark, the inverse of distance from pith was used rather than *d*. The interaction effect *IFd* means that the treatments may not only cause a shift of the level of Y_{ijk} but that they may also have a different ratio of development with distance from pith. An interaction effect of treatments and d^2 was included in the model for cell wall thickness thus enabling the curves of the different treatments to have different shapes. The mixed procedure (Proc Mixed) in SAS was used for the analysis (http://statdist.its.uu.se/sas/SASOnlineDocV8/sasdoc/sashtml/onldoc.htm; accessed 30-Jul-2003). A repeated measures analysis of variance was used (*k* repeated measures per sample) and the growth curve parts of the model (*d* and d^2) were included as random components. The covariance matrix was assumed unstructured. *I* and *F* were treated as dummies representing the presence of irrigation and fertilization and assuming the value 1 or 0 depending on whether the sample came from a treated plot or not, and whether the ring had formed prior to, or after 1987, the first year of treatment. At Flakaliden where the I treatment was not sampled, dummies (*I* and *F)* were not used. Instead, three levels (C, F and IL) of treatment, *T,* were included in the model. In order to avoid discrepancies in the data that may occur close to the pith, rings closer to the pith than two rings were excluded from the statistical analysis.

When analysing this type of data, one drawback can be the presence of heteroscedasticity *i.e.* a variable variance. The annual ring 'means' used as observations in Papers II and III did not show any clear trend with distance from pith, except for tangential cell width where some increase in variation with increasing value of the variable could be observed. Generally, the annual ring means presented good statistical properties. The annual ring means were however based on measurements that were more detailed; for the cross-sections, means were obtained every 0.05 mm. Due to the development of fibre dimensions within an annual ring, usually expressed as the presence of earlywood and latewood, the means over annual rings are not based on normal distributions. Therefore a mean and a standard deviation does not provide the information we are accustomed.

A more detailed analysis of the tracheid cross-sections was possible. The data was subdivided into classes of treatment, distance from pith and earlywood/latewood, and a three-parameter Weibull function was fitted to each subset. All wood outside 35 mm from pith was formed after 1987, *i.e.* the first year of treatments, at both sites. The Weibull function (Weibull, 1951) was chosen as it can manage skewed distributions, allows integration and is established for a range of applications *e.g.* tree diameter distribution modelling in conjunction with stand growth models (Matney & Sullivan, 1982; Rennolls *et al.*, 1985; Magnussen, 1986 *etc.*). A two-parameter Weibull was used by Sirivö and Kärenlampi (2001a) to model the distributions of fibre cross-sections in relation to cambial maturation and growth rate. A three-parameter Weibull was chosen for the present work as it fitted the data better than a two-parameter Weibull. A three-parameter Weibull (Eq. 3) consists of: *c* that is a shape parameter dependent on skewness and kurtosis, σ which is a scale parameter, and θ which represents the threshold (estimated minimum). The influence of the respective parameters on the curve is illustrated in Fig. 3. All curves except curve IV have the same threshold, θ, *i.e.* they all originate at 0. A decrease of the scale parameter (σ), draws a more narrow curve with a sharper peak. At a shape parameter (c) of 3.6, the curve is symmetric; an increase makes it skewed to the left and a decrease makes it skewed to the right.

$$f(x) = \frac{c}{\sigma}\left(\frac{x-\theta_0}{\sigma}\right)^{c-1} \exp\left(-\left(\frac{x-\theta_0}{\sigma}\right)^{c}\right) \qquad (3)$$

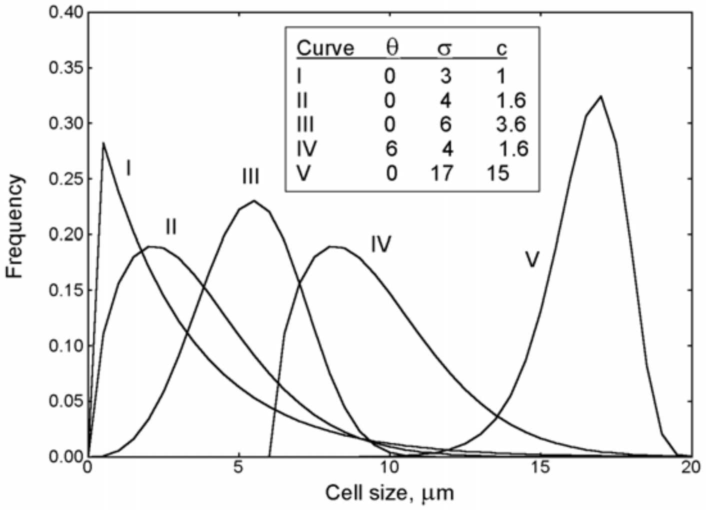

Fig. 3. The principles for the Weibull curve and its parameters: θ, threshold, σ, scale and c, shape. Adapted from Rennolls *et al.* (1985).

Results

Principal results of the studies – by paper

Paper I. Provenance variation in stem wood basic density and dry matter for Picea abies grown on farmland in southern Sweden

Basic density, annual ring width and subsequent volume and dry matter production were significantly affected by geographical zone; Swedish provenances had high basic density but low volume and dry matter yields whereas the Polish provenances had the highest yields and lowest basic densities. The among-provenance variation, especially with regard to basic density, was high for the provenances from Poland. The basic density level showed variation between provenances within zones. This indicated a potential to select high-yielding provenances for which the density is less sensitive to a higher growth rate.

Paper II. Cell wall thickness and tangential and radial cell diameter of fertilized and irrigated Picea abies

Mean annual cell wall thickness was decreased by fertilization (F and IL) on both sites whereas no effect of the irrigation could be detected. Radial cell width was increased by treatment at Flakaliden but at Asa the effect of irrigation and fertilization was reversed when the data structure, *i.e.* development from pith and out and annual ring width was taken into account. Tangential cell width was not affected by treatment at Flakaliden. At Asa fertilization caused a small increase in tangential cell width. Ring width was positively affected by treatment and was an important factor explaining the effects on primarily cell wall thickness and radial cell width.

Paper III. Microfibril angle and density patterns of fertilized and irrigated Picea abies

In the models for MFA and density, growth rate – expressed as a transformation of annual ring width – was very important for the Asa trial when the effect of cambial maturation was taken into account. Effects of fertilization and irrigation remained strong for density, and irrigation was a significant factor explaining MFA. At Flakaliden the development from pith outwards was the dominant factor and the effect of growth rate was comparably low whereas the treatment effect was significant for both density and MFA.

Paper IV. Tracheid distributions of fertilized Picea abies

A Weibull function was used to analyse the distribution of cell wall thickness and tracheid widths. The Weibull function fitted the fibre property distributions well. All variables increased in location and absolute range from pith to bark especially for the earlywood distributions. Earlywood cell wall thickness was more skewed than the distributions of the cell widths. The difference between earlywood and latewood was smaller for the tangential cell width than for the other variables. The

Weibull curves were also compared between treatments at the same distance from pith. Cell wall thickness displayed differences between treatments. Minimum values of earlywood were smaller for fertilized samples. The differences in latewood were more pronounced as both the maximum and general location of the curves shifted towards smaller values for the fertilized wood compared with the control. Weibull functions fitted the cell size distribution data well and appeared to be a feasible method for condensing and analysing cell size data.

Summary of results

The existing variation due to seed source that can be expected to be found in young stands of Norway spruce in Sweden should be within the variation found in Paper I. The range in density from the provenance study was 21 kgm^{-3}, or 6% between the provenance with the highest and lowest basic density. If only mature wood was considered the range was 40 kgm^{-3}, (11%). The three best performing provenances with respect to volume production, yielded on average 41% more than the mean of the three lowest yielding provenances. The three lowest yielding provenances had an average basic density of 350 kgm^{-3} and the three highest yielding had a basic density of 346 kgm^{-3}. (Paper I). The density for the fibre property study ranged from 323 kgm^{-3} (IL) to 370 kgm^{-3} (C) at Asa and from 336 kgm^{-3} (IL) to 400 kgm^{-3} (C) at Flakaliden (Paper III). Consequently the range between the highest and lowest yielding provenances was small and well below the range in density caused by fertilization in the fibre property study.

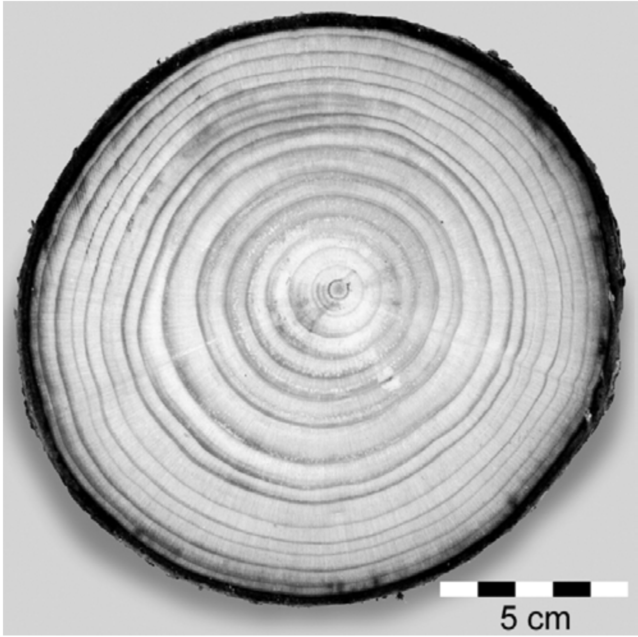

Fig. 4. Disc from IL treatment at Asa.

Variables describing the inherent development from the pith outwards, such as distance- or ring number from pith, and ring width, were the most important factors explaining differences in fibre properties. Ring width may be regarded as an expression of temporal growth rate and an indicator of the ratio between early- and latewood. However, with these independent variables taken into account, a small effect that could be attributed to treatments remained for most properties. The effect of fertilization and irrigation on wood properties acted via an increase in ring width that in turn changed average fibre dimensions. The effect of distance from the pith is also related to the effect of treatment as the treated trees moved more quickly up or down the inherent curve so that at the same cambial age, the faster growing trees produces larger cell widths. Table 5 summarises the effects on fibre and wood properties found in Papers II and III. For MFA, density and the to density closely related cell wall thickness, growth rate was more important at Asa whereas distance from pith was more important at Flakaliden.

Table 5. *Appraisal of the effects on wood and fibre properties reported in Papers II and III, 0 is no effect, * is a weak effect, ** is one of the major effects and *** is the dominant effect which accounts for more than 50% of variation*

	Fertilization and irrigation[a]		Variables related to distance from pith	Ring width	Ring No from pith
Asa	*I*	*F*			
Cell wall thickness	(*)	*	**	***	0
Radial cell width	(*)	**	**	***	**
Tangential cell width	0	*	***	*	**
Density	*	*	**	***	0
MFA	*	0	**	***	*
Flakaliden	*T*				
Cell wall thickness	*		***	***	0
Radial cell width	*		**	***	**
Tangential cell width	0		**	**	**
Density	*		***	**	0
MFA	**		***	*	0

[a] *At Asa, dummies for I and F where analysed, whereas at Flakaliden three levels of T (C,F and IL) were analysed.*

For cell widths the overall differences between treatment means were small (Table 6) especially when compared with the range found between juvenile and mature wood in previous research (Table 1). The effects on cell wall thickness were greater than the effects on cell widths but the tracheids found in the wood of these nutrient optimisation experiments were still within the previously established range.

Table 6. *Mean cross-sectional dimensions from the fibre property study presented by site, wood type and treatment; only wood formed after initiation of treatment is included*

	Cell wall thickness (μm)			Radial cell width (μm)			Tangential cell width (μm)		
	Ew	Lw	All	Ew	Lw	All	Ew	Lw	All
Asa									
C	1.9	3.6	2.2	32.2	22.5	30.8	26.4	24.6	26.1
F	1.8	3.0	1.9	31.4	22.3	30.4	26.6	24.8	26.4
I	2.0	3.5	2.2	31.8	23.0	30.5	26.2	24.2	25.9
IL	1.7	2.9	1.8	32.1	23.6	31.4	26.7	24.7	26.5
Flakaliden									
C	2.0	3.4	2.3	31.4	21.0	29.5	25.6	24.2	25.4
F	1.8	3.0	1.9	32.3	21.4	31.3	26.3	24.3	26.2
IL	1.8	3.2	1.9	33.5	22.0	32.8	27.0	25.0	26.9

When analysing the results from Papers II and III it should be considered that the distribution of wood properties within annual rings is not normal. If the populations were separated into early- and latewood the latewood population was sometimes normal but generally these distributions were also skewed. The distributions of cell width differ little between treatments and the effects on these properties found in Papers II and III can largely be explained by varying ratios of early- and latewood. Fertilized trees did not attain as thick cell walls as the thickest walls of the controls and the thinnest walls of the fertilized trees were thinner than those found in the control trees (Paper IV). The total cell wall distributions after 1987, for C and IL at both Asa and Flakaliden are shown in Fig. 5. The effect of fertilization was similar at both sites, but the minimum of the control was smaller at Asa.

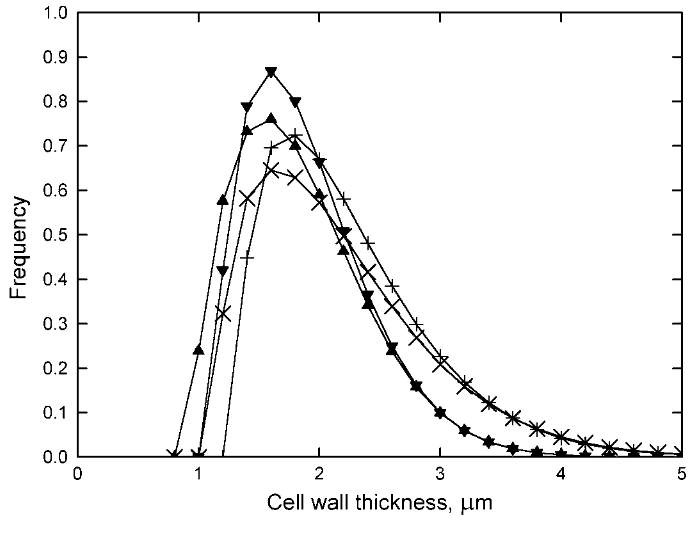

Fig 5. Distribution of cell wall thickness (Weibull curve) for Asa, C, (X), Flakaliden, C, (+), Asa, IL, (▲) and Flakaliden, IL, (▼), all wood after the onset of fertilization (1987).

Discussion and conclusion

The present thesis investigated relationships between heavy fertilization, growth rate, cambial maturation and wood properties that may be applicable for intensive management in practical forestry. The effect of fertilization on wood properties will however also depend on a number of factors not included in the present work. The timing, dosage and frequency of fertilization as well as other silvicultural measures will also have an impact on the result. The site factor is important as the potential growth effect due to fertilization varies throughout the country. The two fibre property sites studied in this thesis were two examples of what might be anticipated at different sites in different parts of the country and should not be regarded as two factors in a factorial experiment, since there were several parameters that differed.

Material and analysis

In the selection of treatments included in the fibre property data, it was originally assumed that only treatments with a documented effect on growth would be interesting to sample for wood properties. Therefore, the plots at Flakaliden that were irrigated but not fertilized were excluded as they had indicated no response in growth (Bergh *et al.*, 1999). The null hypothesis that a response in growth rate causes changes of the wood, has been verified in crude terms in the present thesis. There were however indications of discrepancies from this basic relationship on a smaller scale, for example the irrigated trees at Asa displayed cells that were in some instances unexpectedly small. This means that the original sampling strategy was not optimal for studying nuances of wood formation. In order to assess important effects for future commercial fertilization however, this should not be crucial.

As described in Papers II and III the F sample at Asa was small due to rejection of plots. The trees representing F were thus younger and smaller than they should have been. This of course affected the volume and dry matter calculations in Paper III. However, the statistical models for analysing the effects on wood properties took tree size and cambial age into account. Furthermore all analyses have been run with all combinations of treatments at both Asa and Flakaliden (which lacked the I treatment) to ensure that the presented models would be stable and that the effects presented valid.

A source of error when measuring tracheid dimensions can be that if measurements are not taken at right angles to the longitudinal axis of the tracheid. This can happen if the borer has not hit the tree at right angles to the annual rings, which gives an error in the radial tracheid measurement. Error in the tangential tracheid dimensions can occur if the sample is not properly aligned according to grain angle or that the grain angle varies within the sample. A 10° deviation causes a measurement error of 1.5% or approximately 0.5 μm of a tracheid 30 μm wide.

Yearly climatic fluctuations have not been considered in the models and analyses presented in the thesis. Climate, temperature and precipitation affect wood properties. Maximum latewood density is positively correlated with temperature and latewood proportion increases with late summer rainfall (Wimmer & Grabner, 2000). The plots of wood and fibre properties displayed annual shifts (Papers II and III). Usually these shifts were similar for the different treatments (both with and without irrigation) and are therefore likely to be explained by temperature. Ring width and density were usually mirrored images of each other. At Flakaliden, a drop in ring width in 1995 was not accompanied by an increase in density but rather by a decrease. Extreme cone production at Flakaliden in 1995, especially in the fertilized plots may have redirected resources towards reproduction rather than growth and cell wall thickening. The fluctuations in cell width over years were different between radial and tangential cell widths indicating that they are controlled by different climatic components or that they react differently to the same climatic components.

The treatments are expected to have greater effects on mature rather than on juvenile wood (Zobel & van Buijtenen, 1989). The trees from the fibre property study had not entered the mature stage yet as the cell widths were still increasing and were smaller than those reported for mature wood (Brolin & Norén, 1993; Tyrväinen, 1995). This has implications for the interpretation of the results. The more mature wood in these trials also had suppressed growth rings due to competition which made extrapolation difficult. Thus to analyse the effect of nutrient optimisation with fast growth rates has on wood and fibre properties onmature wood, thinning the stands before too much green crown is lost would be useful.

The irrigation treatment at Asa displayed some unexpected fibre properties. The tangential cell widths of earlywood were smaller (Papers II and IV) and the density and MFA were somewhat greater than for the control. Timell (1986) concluded that compression wood appears to have slightly smaller earlywood cells, and high density and MFA are well known characteristics of compression wood. It is hence possible that irrigation caused the formation of mild compression wood (samples with visible compression wood were rejected when taking the increment cores). Good access to water causes larger cells as cell turgor which is important for cell expansion is dependent on water (Kramer, 1962). Small cells can be the result of moisture stress due to too much water in the soil. (Kramer & Kozlowski, 1960). At Asa, this was regarded as unlikely as water levels were carefully monitored and water levels should vary between field capacity and a 10% deficit. The soil type at Asa is a fine till, a material which, when approaching field capacity, may cause the tree to be unstable and the possible compression wood may therefore be caused by the tree swaying.

Effects of fertilization on wood properties

This work examined some wood properties of interest for pulp- and paper-making. From previous research on other properties (*e.g.* fibre length and wood chemistry), there are indications on how wood from intensively grown stands will perform. It is also possible to interpolate some results from processing different wood assortments and describe possible effects of fertilization on pulp and paper quality. The relationship between wood and fibre properties and pulping performance is however complex and properties may counteract each other so that the result is unpredictable.

The scale at which differences in wood properties affect pulp and paper quality has been demonstrated by several studies on separating different wood assortments according to expected fibre properties. Some of these studies were reported in the introduction to this thesis. When mature wood, usually sawmill chips, are separated from juvenile wood, *e.g.* first thinnings, clear effects on strength and optical properties have been shown (Tyrväinen, 1995; Braaten, 1996; Duchesne *et al.*, 1997; Spångberg, 1998; Persson *et al.*, 2003). The variation in wood properties caused by different growth rates due to differences in site quality or silviculture are usually smaller and their effect on pulp quality is less clear but some detrimental effects on strength and yield have been observed (Klem, 1942; Yngvesson, 1993; Brolin *et al.*, 1995; Spångberg, 1998). The effects on wood properties due to fertilization in the present work were smaller than the differences found between juvenile and mature wood. Since the effects of growth rates are so large in this material, the differences in wood and fibre properties are likely to be greater than differences caused by site and growth rate in the cited studies. It is therefore expected that an intensive fertilization regime will yield pulp with lower strength but better optical and surface properties, although the magnitude of the change will be dependent upon the actual response to fertilization at a commercial rate and is likely to be within the range set by the differences between juvenile and mature wood.

Fertilization has the potential to greatly increase growth rates and dry mass production in Sweden. This can be seen in relation to the already large natural range of production capacity throughout the country (Fig. 1). The increased growth rates will impact wood properties in both positive and negative ways but the impact on wood properties should be evaluated against the increase in wood production.

The main conclusion from the present work is that heavy fertilization may cause the fibres to obtain juvenile characteristics with thin walls and large MFA's, but with somewhat larger cell diameters.

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Acknowledgements

This thesis was funded by the Fibre Forestry programme, a research programme jointly funded by the Swedish University of Agricultural Sciences (SLU) and Stora Enso Skog, Södra, Mellanskog, Skogssällskapet, AssiDomän and Hydro Agri. Further financial contributions have been provided by the Östad foundation and Stora Enso. This support is gratefully acknowledged.

I thank the following:
My supervisor, professor Mats Nylinder, for support, encouragement and for his never-failing ability to focus on the relevant issues. My assistant supervisor, professor Erik G. Ståhl, University of Dalarna, for his contribution and for being a positive force always leaving me feeling rather cleverer than I probably really am.

Dr. Robert Evans CSIRO, Melbourne, Australia, for the use the SilviScan equipment and for help and advice. Ms Shareee Harper for patiently guiding me through the SilviScan process.

Professor Dietrich von Rosen, the department of biometry and informatics, SLU for his kind interest and invaluable help in sorting out the statistics although not all peculiar calculations in this thesis should be blamed on him.

Dr. Johan Bergh (SLU) for assistance in various issues related to the nutrient optimisation trials and for letting me use this unique and highly educational material.

Dr. Bengt Persson, University of Dalarna, for collaboration on paper I – it was a true bliss working with such an efficient, no-nonsense person.

I would never have been able to complete this thesis without the background training provided to me by Mr. Andrew Gordon and Dr. Jenny Grace at Forest Research Insitute of New Zealand who once upon a time interested me in forestry and forest research.

There are many people at the department of Forest Products and Markets (and sister departments of Wood Science and Bioenergy) who have provided help and support through this process. I will mention a few but extend my thanks to everyone who has been at the department(s) during these years. First, I would like to thank Dr. Erik Temnerud for reading and commenting on my papers and for being the only person who is able to bring up the topic of SAS mixed models in casual conversation. I thank Dr. Kalle Spångberg for enlightening me, and others, by providing feministic literature. I thank Mats Warensjö for nice chats on the phone from Umeå. I thank Jacob Edlund for reading my papers and for helping with the formal structure. I thank Dr. Erik Persson and Dr. Armas Jäppinen for reading and commenting on my papers and for their ever positive outlook. I thank Hans Fryk for photos and proofreading.