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JOENSUUN TUTKIMUSKESKUS
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Academic dissertation

To be presented, with the permision of the Faculty of Forestry
of the University of Joensuu, for public criticism in Auditorium M1 of the
University, Yliopistokatu 7, Joensuu, on November 29th, at 12 o'clock noon.

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Abstract

Heräjärvi, H. 2002. Properties of birch (*Betula pendula, B. pubescens*) for sawmilling and further processing in Finland. The Finnish Forest Research Institute, Research Papers 871. 52 p. ISBN 951-40-1856-7, ISSN 0358-4283.

This thesis presents the possibilities to improve the efficiency of birch wood and timber utilisation in the mechanical wood industries, in sawmilling in particular. The principal objective was to describe the variation in selected stem and wood properties of mature silver birch (*Betula pendula* Roth) and white birch (*B. pubescens* Ehrh.) in Finland. The causes of these variations, and the possibilities of modelling them, were also studied. Although the primary aim was to produce scientific bases for the development of sawmilling and further processing of the sawn wood, virtually all of the results and conclusions are also applicable to activities related to veneer and plywood production. The thesis consists of five peer-reviewed articles, and a synthesis based on these articles and current knowledge in the field. The study material consisted of 261 sample trees, originating from 20 mature stands located in southern and central Finland (60-65° N, 24-31° E). As approximately the same tree material was used throughout the articles, they are therefore analogous and comparable.

The study confirmed the considerable variation in the technical, physical and mechanical properties within individual birch stems, between the two species and under different growing conditions. However, the study also showed that even though the properties vary considerably, the variations are, within certain limits, predictable. As far as quality factors are considered, silver birch is overall a more profitable species to grow on mineral soil sites than white birch. However, in mixed stands consisting of conifers and birch, white birch produced high-quality logs with even better knottiness characteristics than silver birch.

If saw logs with a minimum diameter of ca. 10-12 cm, and a minimum length of ca. 2 metres are accepted instead of the conventional log dimensions, then there would be a maximum increase in the proportion of sawable timber out of the total harvesting removal of 40%. The increment was the strongest on drained peatlands, where the harvesting removal mainly consists of pulpwood when only conventional log dimensions are applied. The transition of pulpwood into saw logs also had positive implications for the computational stumpage income of the forest owners.

When the internal knottiness characteristics of the birch stems were investigated, the location of the stem sections containing completely knot-free boards appeared to be moderately well predictable on the basis of the location parameters, as was also the case with the sections containing sound-knotted boards. The stem sections containing boards with both dead and sound knots, as well as the sections with only dead-knotted boards were, however, somewhat mixed in the middle sections of the stems. The modelling method showed considerable potential for further applications.

The basic density, stiffness, strength and hardness of birch wood showed substantial within-stem variations. The density, which is highly correlated with the other properties, clearly increased on moving from the pith to the surface of the stems, and decreased slightly from the stump to the top of the stems. The variation in density ranged between 10-15%. Silver birch had 5-10% higher density values than white birch. No significant differences were found in the mechanical properties and basic density between the stems of white birch grown on mineral soils and on drained peatlands.

Keywords: *Betula pendula*, *Betula pubescens*, branchiness, density, furniture, hardness, hardwood, knottiness, lumber grading, parquetry, plywood, plywood log, sawing, saw log, small-sized log, specific gravity, stem form, stiffness, strength, technical properties, timber, veneer, veneer log.

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Preface

The study was financed by the Academy of Finland, through the Wood Wisdom, Forest Cluster Research Programme for almost three years. The fourth year of the project was funded by the Ministry of Agriculture and Forestry. The Finnish Forest Research Institute Metla made a considerable contribution to the study by providing me the work premises and computer equipment, as well as the possibility to utilise the help of associate personnel. I express my warmest gratitude to these institutions. The steering group of the initial project, Jussi Hautamäki, Esko Ovaskainen, Dr Leena Paavilainen, Olli Saikku, Juhani Saimovaara, Matti Saramäki and Dr Sauli Valkonen presented many useful comments in the different phases of the work.

I'd like to express my gratitude to Professor Erkki Verkasalo from Metla who not only constructed the original study plan and organised the funding but also gave his guidance and helped defeating the numerous challenges I faced in my work during these four years. After this particular project, he was brave enough to recruit me again. I'm also grateful to Professor Jori Uusitalo from the University of Joensuu for his comments to the articles and the final thesis manuscript. Dr Hannu Boren determined my path as a wood technologist by hiring me to a master's thesis project in December 1996. He also strongly contributed the initial stages of my career in Metla in 1998. The both reviewers of the thesis, Assistant Professor Bohumil Kasal from the North Carolina State University, USA, and Dr Kjell Vadla from Skogforsk, Norway, made suggestions that clearly improved the manuscript. Thanks also to Dr John Derome who revised the English language, and to Ms. Seija Sulonen for editing the manuscript into its final form.

Metla provided me with a pleasant and innovative environment to carry on this work. Friends and colleges working in Joensuu positively influenced this study by creating enthusiastic, versatile and enjoyable interaction. The unique forest science community in Joensuu furthered me to understand the preferences appearing in the science world. On the other hand, the almost two-km^2 playground in Jämsä offered a way to keep in mind the challenges appearing in practical forestry.

I am grateful to the following people, who enabled this study by collecting the field data, analysing the specimens or helping in the data analyses: Jaakko Heinonen, Pekka Järviluoto, Tapio Järvinen, Hannu Koivunen, Jukka Lehtimäki, Raino Lievonen, Juha Metros, Tapani Orttenvuori, Erkki Salo, Veijo Salo, Kari Sauvala, Keijo Silfsten, Markku Tiainen, Tapio Ylimartimo, and many other people with a slightly smaller contribution. In addition, the theses I guided during these years, undoubtedly, instructed me as much as the students learned; so, thank you Hanna Kaurala, Jani Lehtimäki and Niko Varis.

Finally, I'd like to thank my mother Aira Heräjärvi for her work during the 1990s, and my companion Saara for her continuing love and support.

Joensuu, October 2002 Henrik Heräjärvi

LIST OF ORIGINAL ARTICLES

This thesis consists of a summary and five articles, which are referred to in the text by Roman numerals I-V:

I **Heräjärvi, H. 2001.** Technical properties of mature birch (*Betula pendula* and *B. pubescens*) for saw milling in Finland. Silva Fennica 35(4): 469-485.

II **Heräjärvi, H. & Verkasalo, E. 2002.** Timber grade distribution and relative stumpage value of mature Finnish *Betula pendula* and *B. pubescens* when applying different bucking principles. Forest Products Journal 52(7/8): 40-51.

III **Heräjärvi, H. 2002.** Internal knottiness with respect to sawing patterns in *Betula pendula* and *B. pubescens*. Baltic Forestry 8(1): 42-50.

IV **Heräjärvi, H. 2002.** Variation of basic density and Brinell hardness within mature Finnish *Betula pendula* and *B. pubescens* stems. Manuscript. 20 p.

V **Heräjärvi, H. 2002.** Static bending properties of Finnish birch wood. Manuscript. 18 p.

In paper II, the manuscript was jointly written by the authors, while H. Heräjärvi alone was responsible for collecting the material and calculating the results.

CONTENTS

1 INTRODUCTION

1.1 Background

Birch species (*Betula* spp.) belong to the deciduous hardwoods. Altogether ca. 40 different birch species are known (Wagenführ 1996). Both of the industrially utilised, treelike species occurring in Europe, silver birch (*Betula pendula* Roth.) and European white birch (*Betula pubescens* Ehrh.), actually have their best genetic quality in Finland (Raulo 1981). The relative advantage of this for Finland is partially a consequence of the systematic disposal of birch as a "non-profitable" species, for instance, in Sweden and Germany up until the late 1970s. In Finland, similar practices were followed during the same period, but fortunately the result is not nearly as desperate as it is in many of the other Central and North European countries. In Europe, birch is currently of industrial importance in Finland, Sweden, Norway, Russia and the Baltic countries. Most of these countries also export birch timber to Central Europe, where it is a valued raw material for a range of wood products.

Silver birch and white birch are morphologically and physiologically relatively similar (see: Sarvas 1949, Kärkkäinen 1985, Wagenführ 1996). The wood and timber of European white birch also resemble American white birch (*Betula papyrifera*), whereas silver birch lies between American white birch and yellow birch (*Betula alleghaniensis*) (e.g., Verkasalo 1990). From the point of view of forestry, however, there are considerable differences between the Finnish birch species, e.g., in their growth and yield capacity. Silver birch yields – at its best – even twice as much wood as white birch on fertile mineral soils within a corresponding period of time (Raulo 1981). On average, the volumetric yield of a white birch stand is ca. 75-80% of that of a silver birch stand (e.g., Koivisto 1959, Siipilehto 1997). On unfertilised peatlands, which are typical sites, e.g., in western Finland, silver birch grows only slightly faster than white birch. It has been concluded that white birch is more efficient in utilising the relatively small amounts of nutrients available on infertile drained peatlands (see: Keltikangas & Seppälä 1977, Saramäki 1977, Ferm & Kaunisto 1983, Kaunisto 1987, Ferm 1990, Niemistö 1991, Gustavsen 1996).

Since the emphasis in Finnish forestry has traditionally been on producing as much wood as possible, the growth and yield of birch stands have been widely studied since the 1940s; initially naturally regenerated forests, but later on cultivated birch stands (Appelroth 1949, Koivisto 1959, Raulo & Koski 1977, Oikarinen 1983, Mielikäinen & Valkonen 1991, Niemistö 1995b, Siipilehto 1997). The fact that birch, white birch in particular, effectively regenerates in young coniferous forests, has led to the situation where the majority of the Finnish birch growing stock is located in mixed stands comprising conifers and birch (e.g., Niemistö 1991, see also Peltola 2001). Therefore, a considerable amount of research has been devoted to the influence of a birch admixture on the growth and yield of young (Karlsson 1978, Andersson 1982, Lehtikangas 1989, Hägg 1990, Mielikäinen & Valkonen 1995, Valkonen 2000, Valkonen & Valsta 2001), as well as mature (Lappi-Seppälä 1930, Jonsson 1961, Mielikäinen 1980, 1985, Agestam 1985, Hägg 1988, Bergstedt et al. 2001) conifer-dominated forests. The overall conclusion of these studies is that a 10 to 20 percent admixture of birch usually improves the growth, quality and stumpage income of the entire stand, especially when dominated by Norway spruce (*Picea abies*), but also in the case of Scots pine (*Pinus sylvestris*).

Hynynen et al. (2002) concluded that the possibilities to increase the utilisation of domestic birch by the forest industries are relatively limited in Finland. Favouring the growing of mixed conifer and birch forests would increase the annual harvesting potential of birch by 15% without reducing the net income from forestry. Silver birch is a profitable second species in forests dominated by Norway spruce, in the case of both one- and two-storey stands. White birch does not increase the profits in stands dominated by Norway spruce. On the other hand, pine-dominated stands with a high proportion of birch are clearly less profitable than pure pine stands. The harvesting costs are also slightly higher in mixed stands compared to those in pure coniferous stands.

The effect of the timing of thinning operations on the quality of the remaining trees in a thinned birch stand is clearly more decisive in coniferous forests. Furthermore, silver birch, due to its faster growth, is more dependent on the timing of thinning than white birch. In principle, a slight delay in thinning increases the death and self-pruning of the branches, while having no dramatic effects on the growth of the stand. Exceeding the optimal thinning time by five years already considerably reduces growth. Different thinning regimes also affect the quality of the remaining trees, primarily through a change in the growth rate (Cameron et al. 1995).

Birch has also been grown as a shelter species for young Norway spruce stands because spruce seedlings are relatively sensitive to frost. Harvesting and hauling the shelter wood at the correct time, without causing any serious physical damage or growth loss to the remaining trees, has been deemed problematic. However, Mård (1998) found that whole-tree harvesting of the shelter wood birch had no marked detrimental effect on the growth of the under-storey Norway spruce.

1.2 Wood and timber properties of birch

Although there are considerable differences in the growth and yield capacity of the two birch species growing in Finland, there are no differences of practical importance in the properties of the wood. Birch wood is generally considered to be a highly valuable raw material for a range of wood products (e.g., Jalava 1943, 1945, Salmi 1987, Sachsse 1988, 1989, Louna & Valkonen 1995, Kivistö et al. 1999, Luostarinen & Verkasalo 2000).

Birch is a diffuse-porous hardwood, and the wood has a homogeneous appearance. Natural birch wood is characterised by a light, sometimes slightly yellowish or, occasionally, reddish colour. The annual rings mainly consist of earlywood, the proportion of latewood being insignificant. According to Jensen (1950), the proportions of vessels, rays and fibres in silver birch wood are ca. 18%, 7% and 75% by volume, respectively. There are no differences of practical importance in the anatomy of silver and white birch wood. In fact, the only specific characteristic distinguishing the two species from each other is in the perforation plates of the vessels; if the average number of bars in the scalariform perforation plate is more than 17.6, the sample is probably white birch. If less, the sample is probably silver birch wood (Bhat & Kärkkäinen 1980). The anatomical characteristics of birch wood have been described in detail by, e.g., Wallden (1934), Jensen (1950), Bhat (1980a, 1980b), Kucera (1980), Bhat & Kärkkäinen (1981a, 1981b) and Wagenführ (1996).

The distribution of different cell types and cell properties vary in both the horizontal and vertical directions within birch stems. According to Bhat & Kärkkäinen (1981a), the proportion of fibres decreases, and the number of vessels and parenchyma cells increases on moving from the stump to the crown of the tree. In the horizontal direction, on the other hand, the proportion of fibres increases on moving from the pith to the surface of the trunk. Similarly, the length, diameter and cell wall thickness of the fibres, as well as the length of the vessel elements, increase from the pith to the surface of the trunk (Bhat & Kärkkäinen 1981a, 1981b). Reaction wood, in this case tension wood, is slightly denser than normal birch wood. In theory, the tension wood of birch could be characterised as an ideal raw material for pulping, since its fibres are longer, the number of vessels is smaller, the lignin and extractive contents are lower, and the cellulose content is higher compared to normal wood (Ollinmaa 1955, 1956).

The wood in birch species has a medium density compared to that of the other European hardwoods. Generally, the wood of silver birch is slightly denser than that of white birch: a mean basic density of ca. 500 ± 20 kg/m^3 compared to ca. 480 ± 20 kg/m^3, respectively (see: Kujala 1946, Hakkila 1966, 1979, Velling 1979, Wagenführ 1996, Verkasalo 1998, IV). In principle, this density provides sufficient strength, stiffness, hardness, resilience and toughness for the requirements of wooden furniture, plank flooring and furnishings. The growth rate does not markedly influence the density of birch wood, but the fast growth of young trees increases the relative proportion of inferior juvenile wood (see: Jalava 1945, Zobel & van Buijtenen 1989, Dunham 1996). Compared to the density, however, defects such as knots, cracks, angled grain and inappropriate moisture content have much grater effects on the mechanical properties of the wood products.

The tensile strength of birch wood is considered to be relatively low compared to the density of the wood, which is also one reason why birch is not often used as structural lumber (Kärkkäinen 1984). Birch wood is also prone to attack by decay fungi when exposed to humid conditions (e.g., Jalava 1957, Kucera & Myhra 1996, Wagenführ 1996). Therefore, birch products are mainly used indoors. Although some good results have been achieved in pressure impregnation tests (see: Vadla et al. 1982, Kucera & Myhra 1996), the impregnation of birch wood has not attained production level. On the other hand, sawn wood of birch is nowadays being increasingly further processed in

Finland by using heat treatment, which improves its dimensional stability and resistance to decay fungi.

Luostarinen & Verkasalo (2000, p. 39-40) have compiled an extensive summary of the anatomical, physical, mechanical and chemical properties of birch wood, and Vadla et al. (1982) have published a comprehensive review on the mechanical properties of birch wood.

As regards the technical properties of birch wood, i.e., the properties influencing the processing of timber or the quality of wood products, many researchers have reported that the quality of birch is at its best when grown in mixed stands dominated by conifers (e.g., Tikka 1949, Heiskanen 1957, Mielikäinen 1980, 1985, Kaurala 2000). The reason for this is not only the earlier death and self-pruning of the lower branches, but also the more favourable stem form and often improved growth. Site fertility is also of great importance for both the growth rate and the technical quality of the stems (see: Appelroth 1949, Heiskanen 1957, Verkasalo 1997b). If forms of external damage – which are by definition relatively common in birch (Heiskanen 1957, Verkasalo 1997b, I) – are excluded, the technical quality of birch trees is perhaps affected the most by the spacing of the stand. A sufficiently dense spacing results in both a good stem form and low branchiness (Appelroth 1949, Niemistö 1995a). A low-density stand with too long tree-to-tree distances results in short, strongly tapering stems with thick, poorly self-pruned branches.

Silver birch is normally considered to be of better technical quality than white birch. This is partly due to the fact that white birch is far more common on infertile peatlands, whereas silver birch supply mainly occurs on fertile mineral soils. When the growing conditions are the same for both birch species, and the growth rate is not taken into account, there are only slight differences in the technical properties of the two species (Kaurala 2000, I). However, owing to the faster growth, higher biological age and subsequently larger average volume in final cutting, silver birch currently provides ca. 70-80% of the logs intended for sawing or veneer and plywood production.

No national quality requirements or grading rules are available for birch saw logs at the present time. The larger sawmills have their own, customer-oriented grading rules. For instance, the largest birch sawmill in Finland, Vilkon Ltd., currently has only one grade for saw logs. The top, over-bark diameter of a log should be between 20 and 65 cm, and the lengths from 3.1 to 5.2 m with a crosscutting tolerance of 3 cm. The relative magnitude of sweep, measured along the entire length of the log, should not exceed 50% of the log's top diameter in centimetres. The number of sound knots is not limited, but their maximum diameter is set at 7 cm. A maximum of five dead knots or knot bumps are allowed, with their diameters limited to 4 cm. Vertical branches, grouped knots, open scars, bark peeling defects, cracks, soft decay, sudden sweep or corkscrew, are not allowed in saw logs (Vilkon Oy 1998).

The principal difference between saw and veneer logs is the minimum diameter requirement. Veneer logs are usually supposed to have a minimum top diameter of 18-20 cm, whereas logs can be sawn, in theory, down to the diameter of pulpwood, i.e., 7 cm. In practice, however, the minimum sawable diameter for birch logs is 10-12 cm. Even then, the log must be fairly short (2-4 m) and as straight as possible. Owing to the very frequent natural crookedness of birch stems, small-diameter saw logs have only a poor efficiency rate for raw material utilisation. Typically, 3-4 m^3 of small-diameter logs are needed to produce 1 m^3 of edged sawn wood, whereas the corresponding relationship is ca. 2.2-2.5:1 in the case of sawing conventional logs by the through-sawing method. The differences between the individual sawing methods have been presented, e.g., by Hoadley (1980) and Sahatavaran…(1999).

In the current paper, the logs of different type were defined as follows:

Conventional log	Veneer or saw log meeting the normal quality and dimension requirements (top diameter at least 18 cm, length 3.1-6.7 m)
Small-diameter log	Saw log meeting the normal quality and length requirements, but smaller than the normal diameter (ca. 10-18 cm)
Small-sized log	Saw log meeting the normal quality requirements, but smaller length (min ca. 2 m) and diameter (ca. 10-18 cm)

Presumably, as long as the production capacity of the birch sawmills remains at its current low level, and no networks are established between the separate units, no uniform national grading rules will be feasible for birch saw logs. This also applies to the grading of sawn wood, billets and glued laminated panels made of birch: the grades for these products are defined in each case by the contracts between the producer and the customer. Some approaches have been made to compile common grading rules for birch products in Finland (Isomäki & Leppänen 1992, Jouhtinen 1994, Keinänen & Tahvanainen 1995). However, none of them have gained wider acceptance. In Sweden, Elowsson (1989) distinguished four grades for sawn wood of birch, based on the requirements of the users: 1) wood for visible uses, either varnished or untreated surface, with massive wood as a speciality, 2) pigmented wood for visible uses with required strength properties, 3) wood with only one side visible, and 4) wood intended for inner layers and for blocks used in non-visible structures.

These categories still reflect moderately well the quality requirements set by the different end-uses of birch. The major problem observed by Elowsson (1989), i.e., few uses for low-quality products (group 4), is still today relevant in the production of upgraded goods from sawn wood of birch both in Finland and Sweden. In actual fact, this is also true in the case of the other hardwoods in mechanical processing (see: Kärki 1997, Kivistö et al. 1999, Luostarinen & Verkasalo 2000). In Norway, the grading rules for birch saw logs and sawn wood have been intensively studied during the past few decades (Kucera 1983, 1984, 1986, Fjærtoft & Bunkholt 1994).

In general, dead knots and different kinds of colour defect, caused by either decay or improper drying, are the most common degrading factors for the quality of sawn wood of birch. The drying method traditionally used for hardwoods, i.e., the drying of through-sawn lumber in an air-conditioned stack, often results in a better drying quality, since the incidence of deformation and cracking is considerably lower than with fast kiln drying of full-edged boards. Nowadays it is often, however, too expensive to use the traditional saw-dry-rip method. In addition, if sawn wood is traded as through-sawn, i.e., without edging, measuring its volume might be complicated, as is illustrated by the following example concerning the width measurement of through-sawn lumber. If the thickness of a board is between 19 and 32 mm, the mean width of the narrower flat (usually the surface) is used. If the board is, on the other hand, thicker than 32 mm, its width is the mean value of the narrower and the wider flat.

1.3 The supply and utilisation of birch

Between the years 1950 and 1975 the annual removal of birch in Finland was higher than the annual growth. During the past two decades, however, the growing stock of domestic birch has increased to a total volume of 305 million m^3. The growing stock is still increasing, since the volume of the annual domestic cuttings is considerably smaller than the reported annual growth of 14 million m^3 (Peltola 2001, Hynynen et al. 2002).

The key question that is always closely related to the wood processing industry is the availability of raw material with respect, on the one hand, to the quantity and, on the other hand, to the quality. The same questions are even more important in the case of birch. The availability of domestic birch timber for the wood product industries has by no means been secured, and the situation is not as simple as the birch resources would suggest. The best-quality birch grows as an admixture in forests dominated by conifers, and comes onto the timber markets only when spruce or pine are harvested. As a result, the birch is often too old and affected by decay and other defects. Furthermore, large amounts of lower-quality white birch are growing on peatlands where harvesting is only possible during a relatively short period in winter. These factors obviously partly explain why the volume of imported birch logs has gradually increased, and reached a level of 0.37 million m^3 in 2000. Out of this volume, plywood and veneer mills consumed 0.35 million m^3, and sawmills 0.02 million m^3 (Peltola 2001) (Figure 1).

Generally, the procurement of raw material for the sawmills has been problematic, since the availability of large-sized and high-quality birch wood has decreased. This trend has led to the gradual replacement of timber from naturally regenerated stands by cultivated timber which, according to current knowledge, is of poorer quality – at least as far as wood density (Hakkila 1966, 1979, Velling 1979, Verkasalo 1998a, Möttönen 2001), susceptibility to discoloration and decay (Hallaksela & Niemistö 1998, Rantanen et al. 2000), and *Phytobia betulae*, a stem miner in birch, defects (Niemistö 1998,

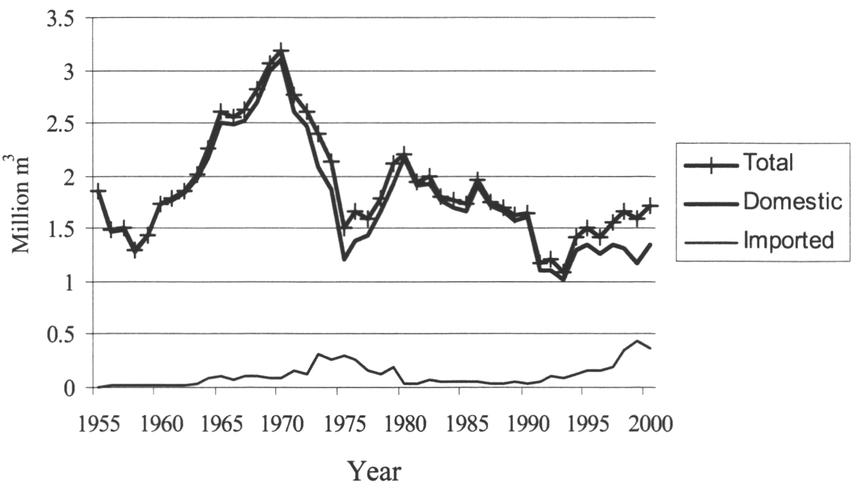

Fig. 1. Wood consumption of the hardwood-based wood product industries in Finland from 1955 to 2000 (Peltola 2001). More than 95% of the total annual volume is birch.

Ylioja et al. 1998, Ylioja 2000, Ylioja et al. 2000, Bonham & Barnett 2001), as well as many external defects (e.g., Niemistö et al. 1997) are concerned.

The oldest cultivated silver birch stands in southern and central Finland have already been thinned twice, and will reach final-cutting tree dimensions within the next ten years. A considerable area of 267,000 hectares of birch-dominated stands, which should be thinned for the first time (young thinning stands) in southern and central Finland during the next five years, represent a major potential source of sawable logs in the near future. Assuming that 15% of the thinning removal in the advanced thinning stands consists of sawable logs (cf. Rantanen et al. 2000), the 96,000 hectares of such stands in southern and central Finland (Table 1) would produce around 100,000 m^3/year of sawable logs, in addition to pulpwood and plywood logs, during the next five years. At the moment, however, the small-sized saw logs are a real commercial assortment only in some areas in Finland, primarily in the eastern parts of the country.

The total area of mature, birch-dominated stands to be cut during the next five years is ca. 76,000 hectares (Table 1). However, this is only a minor source of conventional logs; the majority will be obtained from conifer-dominated stands.

Excluding aspen (*Populus* spp.), which was used by the matchstick industry from the late 19th century up until the early 1980s (see: Kärkkäinen 1981), birch has traditionally been the only industrially utilised hardwood species in Finland. Recently, however, the pulp and paper industries have shown growing interest in European aspen (*Populus tremula*), as well as in hybrid aspen (*Populus tremula x tremuloides*). This is due to the rapid increase in the demand for high-quality magazine paper made of aspen. Therefore, the first short-rotation forests have been established in Finland. Hybrid aspen is expected to produce harvestable pulpwood within less than 30 years in southern Finland. Although the primary goal in growing birch in Finland is to produce saw or

Table 1. **Areas of *already delayed cuttings (1)* and areas *maturing into the cutting stage within the next five years (2)* in birch-dominated stands in the southern and central Finland forestry districts by development class. Calculated on the basis of the results of Tomppo et al. (1998, 1999a, 1999b, 1999c, 2000, 2001) and Korhonen et al. (2000a, 2000b, 2000c, 2001).**

	Development class					
	Young thinning stand		Advanced thinning stand		Mature stand	
	Urgency of cutting					
	1	2	1	2	1	2
Forestry District	Area to cut, 1000 ha					
1. Rannikko						
Etelärannikko	5.6	2.8	3.4	1.7	1.7	3.4
Pohjanmaa	9.1	7.3	1.7	4.0	1.4	1.4
2. Lounais-Suomi	14.9	7.1	5.8	3.0	0.3	0.8
3. Häme-Uusimaa	15.2	8.9	6.5	5.0	2.8	6.2
4. Kaakkois-Suomi	6.3	6.3	1.1	5.0	2.7	4.7
5. Pirkanmaa	13.2	10.2	3.9	4.4	0.8	2.3
6. Etelä-Savo	10.9	13.8	5.1	6.6	6.9	17.4
7. Etelä-Pohjanmaa	15.7	17.9	3.5	6.0	0.9	3.5
8. Keski-Suomi	10.5	18.2	2.3	6.8	0.9	3.2
9. Pohjois-Savo	12.3	20.3	2.4	3.4	0.3	5.2
10. Pohjois-Karjala	20.0	20.6	3.6	11.0	4.9	4.6
All	*133.7*	*133.4*	*39.3*	*56.9*	*23.6*	*52.7*

veneer logs, the production of pulpwood is, at least theoretically considered in the case of white birch (see: Hynynen et al. 2002). In these calculations, white birch was treated as an over-storey species for Norway spruce seedlings and was harvested at an age of 52 years.

Birch has been used in pulp production for less than 50 years in Finland (Saarikoski 1954). Since the first steps by the Haarla Company in the early 1950s, the production of birch pulp has increased tremendously. In the year 2000, the Finnish pulp industry consumed ca. 13 million m^3 of birch, whereas that of the wood product industries was ca. 1.7 million m^3 (Peltola 2001). There was a considerable difference in the degree of domesticity between the two end-uses: approximately half of the pulpwood birch was imported, while only one fourth of the saw or veneer logs were not domestic. Although no statistics are available, based on the geographical distribution area of the two birch species, as well as the dimension and quality demands set for logs, most of the timber imported for the plywood, veneer and saw mills were probably silver birch.

The principal end-uses for birch veneers are furnishings, whereas plywood is widely used, e.g., for furniture and containers, as well as miscellaneous building materials where high stiffness, bending strength and/or hardness are required (e.g., Feihl 1964, Meriluoto 1965, Lutz 1977, Verkasalo 1997a, b, Vadla 1999, Heräjärvi 2002). Additional special end-uses for high-quality birch veneers and plywood include airplane structures and musical instruments.

Sawn wood of birch is mainly further processed into high-quality furniture, flooring, panels, mouldings and a range of joinery products, where the requirements are focussed either on visual quality or on mechanical strength, and sometimes on both groups of properties (e.g., Jalava 1943, 1949, Kataikko 1996, Luostarinen & Verkasalo 2000). For bulk products, such as construction purposes, solid birch wood is unnecessarily heavy, too decay-susceptible, and also a relatively expensive material. Therefore, birch-based products are considered as speciality goods rather than bulk products.

In the wood product industries, the costs of the raw materials are exceptionally high compared to the other costs in the entire production chain. During some stumpage price peaks, the raw material costs have been as high as 80% of the total production costs. For any company turning out bulk products, such a situation – at least when it occurs repeatedly – is calamitous. When manufacturing special products with a larger added value, however, the direct raw material costs are not as significant.

According to Peltola (2001), the average unit values of the main groups of wood products (sawn wood, plywood, particle boards and fibreboards) exported from Finland in 2000 varied between 175 €/m^3 (spruce sawn goods) and 546 €/m^3 (plywood). Exported sawn hardwoods had an average unit value of 425 €/m^3, with a total value of 10.9 million €. However, most of the sawn hardwood was not exported before further processing into billets, components, furniture or parquets, which increased their unit values compared to unprocessed sawn wood.

Traditionally, birch sawmills in Finland has utilised only conventional, i.e., large-diameter logs. Although the sawing of small-diameter logs has been discussed since the 1930s at least (see: Kuoppamäki 1932), the first serious efforts to produce sawn wood from logs with top diameters of only 10 to 18 cm were not made until the late 1990s. Since then, almost all the new, or planned, hardwood sawmills have been based on the use of small-sized logs from either domestic thinning stands or from abroad. The new processing capacity for small-sized birch logs has resulted in an increased need for sawable raw material of ca. 0.1-0.2 million m^3. Simultaneously, the Finnish woodworking industries have been faced with tightening competition for market shares of sawn wood, glued laminated boards and furniture made of birch. The principal competitors are in Russia, the Baltic countries, and recently also in China.

In Finland, no species-specific studies have been made on the consumption of different hardwood species by the sawmills since the early 1990s. There are, nevertheless, no statistical data backing up the assumptions of considerable changes until the present time concerning the results achieved by Pajuoja & Suihkonen (1994), which indicated that 10,000 m^3 of aspen and 6,000 m^3 of alder (*Alnus glutinosa, A. incana*) were sawn in Finland in 1993. At that time the corresponding combined volume of the two birch species was 180,000 m^3. However, due to deficiencies in the statistics, Kärki (1995) presented a subjective estimate for the consumption of alder saw logs as large as 20,000 m^3 in Finland in 1995. Similarly, Verkasalo (1999) also stated that the actual consumption of aspen in wood product manufacturing should be at least double that presented by Pajuoja & Suihkonen (1994).

At the present time, less than ten hardwood sawmills have industrial-scale (annual timber consumption more than 10,000 m^3) production in Finland, more than 50% of the birch sawn wood still being produced by the small-sized private sawmill operators

(Peltola 2001). The total sawn wood production of the largest birch sawmills in 2001 remained under 20,000 m^3, which is actually not more than 10-20% of the production of a medium-sized softwood sawmill. The mills that utilise conventional logs are characterised by relatively outdated machinery. Single-blade circular saws and frame saws, as well as labour-intensive visual grading and sorting of sawn wood, are common practices.

According to Peltola (2001), 84% (ca. 1.4 million m^3) of the mechanically processed birch timber was used in the plywood factories in Finland in 2000. Sawmills used 0.2 to 0.25 million m^3 of birch timber, and ca. 0.06 million m^3 of very high-quality and large logs (diameter at least 24 cm) were used for the domestic production of special veneers by slicing or rotary cutting. The larger Finnish birch sawmills, as well as plywood factories, are located in eastern and central Finland, near to the sources of the best-quality domestic birch. Transportation costs for the logs imported from Russia are also low because of the short transportation distance to the mills on the Finnish side of the border.

1.4 Raw material research: a basis for functional refining chains

The changing raw material supply, new processing techniques and products, as well as the developing internationalised markets, have recently generated a number of novel needs for research on birch wood. The manufacturer's requirements for practical information on the specific properties of hardwoods in general have, at the same time, continuously increased (Verkasalo 1998b). This is obviously the outcome of the customer-oriented production system, as well as the limited raw material availability.

Wood product companies utilising birch are often small in size, but they manufacture products of high value. In the companies, it is common that the capabilities concerning the business economics and marketing have not enough been taken cognisance of. This is especially the case for new companies, which have an urgent need to produce as much as possible in order to gain cash flow. As a result, many companies drift into economical difficulties. On the other hand, it would appear that the importance of research and development (R&D) has been well accepted also in small-sized companies with a moderately short history.

According to Jaakkola & Tunkelo (1987), successful product development should correspond to the demands of production, marketing, and material economics, as well as the competition. The objectives of product development are therefore, 1) to enhance the profitability of the enterprise, 2) to maintain or improve its market position, and 3) to ensure the continuance of production. The actual development process of new technologies is a continuum of research, innovations, tests, pilot-production and marketing efforts. Basic research – underlying the continuum – is the fundamental source of information that provides the tools needed for rational and cost-efficient production. As applied research, such as practical R&D projects, is usually more visible than basic research, it can be more precisely focussed on the current needs of industry.

Implementation of a new processing technique or the launching of a new wood product presupposes that all the levels of its development chain must not only become acquainted with it, but also internalise the actual needs for it. This is enabled by a two-way flow of information. First, the research units are provided with the basic knowledge and the methodological expertise required at the productive levels. Second, the feedback of the customers and users of the machinery, i.e., the producers of sawn wood, veneer or plywood, is just as important as it provides an invaluable source of know-how based on their practical experience.

The average end-user of a wood product has virtually no awareness of possible changes, such as altered processing techniques within the refining chain that occurs as a result of the development process. Although they are not usually interested in the actual refining process, the end-users are certainly aware and interested in the quality and safety questions of the product, as well as whether the product is domestic or imported. Therefore, the end-user provides the most important feedback for the entire process: the decision on whether or not to purchase the product. In a traditional framework that starts from the top of the chain, the feedback information has to pass through several steps before it reaches the research level. This, combined with the fact that the forestry sector is known for its disability to react flexibly to changes in the markets, inevitably lengthens the time-span between the launching of new innovations and the actual production. Keeping this in mind, the transfer of research knowledge between separate operators is nowadays facilitated by different kinds of innovation fora and campaigns, research seminars, networks and centres of expertise. Such organisations transfer not only the research knowledge directly to the higher levels, but also the feedback information and practical experience directly to the research level, thus permitting faster reactions to the altered R&D needs.

It appears that the most successful concepts in the wood product industries have been those utilising the advantages provided by networks. According to Humala & Peltoniemi (2001), typical indicators of successful business concepts within the wood product industries are 1) customer orientation as a basis for product development, 2) globalisation, 3) increasing the amount of total deliveries, and 4) understanding the importance of e-business (i.e., internet-based operations) and information technology as tools for marketing and sales.

Laaksonen & Rajala (1987) stated that the product development within the majority of the Finnish furniture industries (70%) was highly stigmatised by accommodation and adaptation. The companies produced a very similar range of furniture, and their crucial weakness was therefore copying and lack of innovations. Another occasional problem was too much confidence in the power of creative ideas, which have obviously gone too far in replacing systematic research and product development (Tiensuu 1999). The campaigns centered around innovations and consumption promotion launched in Finland during the 1990s, have gradually altered the way of thinking. However, their true influence cannot be evaluated until a few more years have passed.

In order to encourage the wood product industries to be more innovative and profit-making in the future, it is essential for the R&D organisations to focus their energies on studying the properties and utilisation of wood raw material (Harstela et al. 2001). As an example of this we can take a processing phase that has traditionally caused difficulties within the refining chain of birch, i.e., drying sawn wood. The comprehensive studies that have recently been carried out have generated a wide range of new knowledge, for instance, about the chemical processes taking place inside birch wood during drying (Jørgensen et al. 1995, Paukkonen et al. 1999, Isomäki 2001, Lahtinen & Tolonen 2001, Luostarinen et al. 2001, Mononen et al. 2001, Möttönen 2001, Piispanen & Saranpää 2001).

In a broad sense, wood science is related to numerous branches of research, ranging from molecular chemistry to, e.g., strength grading and timber structure engineering. Subsequently, the methodologies used in research are both versatile and diverse. Due to the inhomogeneous micro- and macrostructure, anisotropy and presence of a wide range of chemical compounds, such as extractives and sugars, the behaviour of wood during the different upgrading processes is often unexpected. Testing the theories and hypotheses experimentally is not an easy task, while the presence of outliers and non-interpretative phenomena is more likely to be a rule than an exception. Materials such as metals, concrete and plastics differ from wood in having a homogeneous structure, which often makes it easier to model their properties and behaviour.

Even more interesting is the challenge when the tree species studied is very variable, not only with respect to its wood material, but also to its external characteristics, such as size, stem form and branchiness. These are inevitably characteristics that influence, for instance, the possibilities to machine the timber. In this sense, birch is a virtuoso in that it has a myriad of different appearances, depending on genotype, geography, competition, site fertility and moisture etc. In actual fact, the external properties are of more interest in the case of birch because the structure of the wood is not very variable: the differences between earlywood and latewood are slight, the existence of heartwood is a debatable question, the moisture gradient of green wood is small, and the annual ring width has only a minor effect on the wood density (Jalava 1957, Kärkkäinen 1985, Zobel & van Buijtenen 1989, Dunham et al. 1999, IV).

Birch thus exhibits a number of positive properties with respect to the actual wood material. Sometimes, however, it is much more than the basic wood properties that influence the success of a wood product in the markets. For instance, birch and aspen are practically the only light-coloured North-European tree species available for furniture and joinery. In the furniture markets, darker-coloured products still have a stable market share, whereas the demand for light-coloured products fluctuates over time, depending not only on the price levels but also to a considerable extent on fashion trends (Luostarinen & Verkasalo 2000).

All the abovementioned pitfalls and drawbacks are characteristic of the birch-based business, the predominant aims of which are high quality and high-value products. Although many problem-oriented research projects have brought about considerable advances in the field, a number of questions still remain unanswered.

1.5 State of the art in birch raw material research

Much research work has been devoted to studying the properties, quality and utilisation of birch as a raw material for the plywood and veneer industries in Finland (e.g., Luostarinen 1932, Lehonkoski 1949, Leino 1949, Meriluoto 1965, Heiskanen 1966, Kärkkäinen 1978, 1986a, Verkasalo 1997a,b). On the other hand, it is notable that, prior to the 1990s, only one Finnish article was published that focussed on sawing and further processing of birch (Jalava 1943). This obviously reflects the fact that, already for decades, the birch plywood industries and, later on the pulpwood industries, have alone accounted for most of the hardwood use in Finland. Therefore, it is also obvious that research has concentrated on growth and yield of trees. Considering the raw material balance, current technology, as well as the forest product markets, it would appear that the most promising way to enhance the use of birch is, however, sawing and further processing (Luostarinen & Verkasalo 2000).

Basic research knowledge is widely available on the external properties (e.g., Walldén 1934, Kujala 1946, Heiskanen 1957, Kärkkäinen 1980, Niemistö 1995a, Niemistö et al. 1997, Verkasalo 1997b, Viherä-Aarnio & Velling 1999, Kaurala 2000), as well as the internal structure (e.g., Hakkila 1966, 1979, Velling 1979, Bhat 1980a, 1980b, Bhat & Kärkkäinen 1980, 1981a, 1981b, Ferm 1990, Novitskaya 1998), of the two birch species. However, the knowledge applicable in todays's industry is more limitedly available. In addition, a number of articles have been published discussing the value of birch trees and logs (e.g., Meriluoto 1965, Heiskanen 1966, Kärkkäinen 1986a, Fjærtoft & Bunkholt 1994, Verkasalo 1997a,b, Gobakken 2000).

Nevertheless, there is a serious shortage of both updated basic knowledge and practical know-how concerning the mechanical processing of all Finnish hardwood species. This is especially the case with birch, which in comparison to the other domestic hardwoods, is of much greater importance to industries. Many of the studies dealing with the variation of birch wood material are 30, even 70 years old. It is well known that silvicultural practices, as well as the genotype of the trees, have changed tremendously since those days. Although birch is the only Finnish hardwood species with large-scale industrial implications for the sawmills, insufficient attention has so far been paid to developing birch sawing.

Based on an extensive literature study, Luostarinen & Verkasalo (2000) presented a list of subjects – including both basic and applied research – that needed to be investigated for the development of the sawmilling and further processing of birch in Finland. The list included, among other topics, the following subjects. 1) They emphasised the need for knowledge concerning the possibilities to increase cuttings of domestic birch timber (thinning stands, plantations and mixed stands with birch). 2) The expected timber recovery of different assortments and income from timber sales were found to be important when harvesting different types of birch stands. 3) The quality requirements for different assortments of birch timbers, bucking stems, sorting timber, and channelling the timber flow for different uses, were emphasised. 4) Solving the practical problems related to sawing birch (i.e., yield and grades of sawn wood, selection of sawing patterns, technical solutions and production economy). 5) The market expectations and success factors of birch products should be studied.

1.6 Objectives of the study

The principal objective of this thesis was to study the variation in the stem and wood properties of mature silver birch (*Betula pendula* Roth.) and white birch (*B. pubescens* Ehrh.) in Finland. The causes and possibilities of controlling the variation were also studied. The work was carried out with the goal of producing scientific bases for development processes in the birch-based wood product industry and, in particular, enhancing the raw material utilisation of birch in sawmilling. However, virtually all of the results and conclusions presented in this thesis are also applicable to the activities related to veneer and plywood production.

The thesis consists of five articles with scientifically verified results, and a synthesis based on current knowledge and author's personal opinions. The outlines of a functional birch wood product refining chain are presented in practical terms as the ultimate conclusion of the thesis.

The articles (I-V) form a chain starting from the technical properties of birch trees grown in different conditions, continuing with a study of the different principles involved in bucking trees into logs, a study on the possibilities of improving the lumber grade distributions by selecting optimal sawing patterns according to the knottiness and, finally, analysing the variation in density and selected mechanical properties of the wood within birch stems. The objectives of the individual articles were:

- To compare the external properties and quality of mature birch trees at different sites and under different growing conditions (I),
- To study the influence of different bucking principles on the timber recovery and stumpage income of typical birch stems and stands (II),
- To examine the internal knottiness characteristics of birch, as well as the possibilities to predict the knottiness grades for boards (III),
- To model the variation in the basic density of birch wood within stems, and to study the relationship between the Brinell hardness and the basic density (IV),
- To study the relationships between the specific gravity at 12% moisture content, modulus of elasticity and modulus of rupture, and their variation within birch stems (V).

2 MATERIALS AND METHODS

All results were based on actual measurements of stand, tree, timber, sawn wood and wood properties as well as results of statistical analysis. Papers I-V more comprehensively covered the properties of birch stands, trees, logs and sawn wood, but only selected mechanical and physical properties. The study proceeded systematically such that the specimens prepared for the preceding sub-study were further utilised for the following sub-study. Hence, the same materials were used in the studies covered by papers I-V. The results of the individual papers are, in this sense, analogous and comparable.

Paper I described the overall structure of the sample stand and the tree material. The material consisted of a total of 261 sample trees, originating from 20 different mature stands in southern and central Finland (60-65° N, 24-31° E). In Finland, silver birch mainly grows on mineral soils, whereas white birch is common on both mineral soils and drained peatlands (see: Peltola 2001). The experimental stands for the study were selected in accordance with these principles. Six different strata were determined in advance for sampling:

1. Pure silver birch stands on fertile mineral soils,
2. Mixed stands of conifers and silver birch on fertile mineral soils,
3. Pure white birch stands on fertile mineral soils,
4. Mixed stands of conifers and white birch on fertile mineral soils,
5. Pure white birch stands on fertile drained peatlands,
6. Mixed stands of conifers and white birch on fertile drained peatlands.

The structure of the sample stands was first determined by measuring the diameter at breast height (dbh, i.e., at 1.3 m), stand density, basal area, mean age and mean diameter of the trees by tree species. On the average, 13 trees per stand were then sampled using stratified random sampling. The measured dbh series of the potential sample trees in a given stand, i.e., trees that were visually estimated to have at least one sawable log, with a minimum of 50 trees in each stand, was sorted in ascending order. The sorted dbh series was divided into three groups, each with an equal number of trees, and three to six trees were randomly sampled from each of the three groups as sample trees. The number of sample trees varied according to the number of trees potentially available in the stand in question. In larger stands with more than 100 candidates sample trees, six trees were selected per group, giving a total number of 18 sample trees in the stand. In smaller stands, conversely, a smaller number of trees were subsequently selected as sample trees. This procedure ensured that small, medium and large trees were represented in each stand, while, at the same time, all the sample trees were randomly selected. In addition, the sampling frequency was the same in all the stands, even though the number of trees in the populations varied.

Processing the stems into logs, logs into sawn wood, and sawn wood into smaller specimens, as well as the individual measurements made for the purposes of the individual sub-studies, are described in detail in papers I-V. The processing and measuring procedures are therefore not repeated here in detail.

In papers I and II, analysis of covariance was used to equalise the results for different stands to a comparable level with respect to certain background factors, such as stand density, tree age etc. Paper I was based solely on objective measurements of the technical properties. The results consisted of the following stem characteristics: differences in stem size, taper, number of knots per metre of stem, heights of the different crown layers, and the occurrence of decay between the most common sites and growing conditions for the two birch species. The conventional log sections (d = 180 mm) and the small-diameter log sections (d = 120…180 mm) were examined separately. The timber quality characteristics of the pulpwood sections (d = 70…120 mm) were not analysed; only their relative volumetric proportions out of the entire stem were calculated. The variations and predictability of the properties of interest were studied within and between the six strata. Two site fertility classes (Omt / Rhtkg and Mt / Mtkg) (see: Laine 1989, Kuusipalo 1996) and two crown layers (dominant and co-dominant trees as distinguished by Mielikäinen 1987) were also compared.

Paper II focussed on bucking the 261 birch stems, i.e., cross-cutting them into different timber assortments, in order to determine the differences in log recoveries between four different bucking principles. Bucking the stems into conventional veneer logs and pulpwood was first compared with bucking into conventional saw logs and pulpwood. Bucking into conventional log-lengths was, on the other hand, compared with the outcome when shorter log lengths were allowed. The volumes of the logs in theoretical bucking were calculated using the KPL software of the Finnish Forest Research Institute (Heinonen 1994). In addition to the volumes of the saw or veneer logs representing different grades, the theoretical values (as m^{-3}) of the sample trees were also presented in paper II. A value index was compiled on the basis of the true values paid for the corresponding assortments in southern Finland at the end of the 1990s (Peltola 2001). The index value of 100 represented the value of 1 m^3 of veneer logs.

The material used in paper III consisted of 10,251 boards, two metres in length and 25 mm in green thickness, sawn from the 261 sample trees. The location of the different sawn wood grades within the birch stems was studied with respect to the most important factor affecting the quality of sawn wood, i.e., knots. A polytomous logistic regression (PLR) technique was used for predicting the odds that a board of known location would belong to one of the following knottiness grades: 1) knot-free, 2) dead knots only, or both dead and sound knots, and 3) sound knots only.

In paper IV, two lots of clear wood specimens were prepared. The larger lot consisted of 6,304 specimens for analysing the variation in basic density (kg/m^3) between and within silver and white birch stems, and the smaller lot (578 specimens) for analysing the variations in Brinell hardness according to EN 1534 in a radial direction. The specimens for the larger lot were prepared such that the vertical, as well as the horizontal, variation in basic density within the stems could be examined. The relationship between Brinell hardness and basic density was determined on the basis of the smaller lot. The accuracy and cost-efficiency of the test method according to EN 1534 were also discussed.

Static stiffness (modulus of elasticity (MOE) according to ISO 3349) and bending strength (modulus of rupture (MOR) according to ISO 3133) of birch wood were studied in paper V. A total of 610 small, clear specimens, were prepared in order to be able to analyse both the horizontal and vertical within-stem variation of the two properties. In addition, the specific gravity at 12% moisture content (ρ_{12}) was determined on the specimens. The interdependences between MOE, MOR and ρ_{12} were then studied using linear regression and correlation analysis.

Finally, a subjective view of a cost-efficient, functional birch wood product processing chain was compiled. The proposal was presented as the author's own synthesis of the information obtained from articles I-V and the literature, and has therefore no comprehensive, overall experimental basis.

3 RESULTS

3.1 The reviewed studies

3.1.1 Properties of birch stems (I)

Paper I showed that silver birch has larger dimensions and more advantageous stem form than white birch when grown on similar sites. On mineral soils, birch trees grown in mixed stands dominated by conifers were slightly larger than the trees grown in pure birch stands.

Volumetrically, the highest proportion of the log section was obtained from silver birch stems. For the trees grown on peatlands, as well as the smaller co-dominant trees on mineral soils, the theoretical proportion of the small-sized log section out of the entire log volume was, at its maximum, as much as 50%. The number and diameter of different types of branch were, in most cases, successfully predicted using analysis of covariance. In general, the diameter of the branches of silver birch was clearly larger than those of white birch. On the other hand, dry and rotten branches were more common in the log sections of white birch than in those of silver birch. The self-pruning of white birch was often superior to that of silver birch, especially when the trees were grown as a co-dominant species in stands dominated by conifers. Although the slower healing-over process in the case of white birch exposes the stubs to decay fungi, the occurrence of decay or surface defects was relatively similar in both birch species. As much as 59% of the sample trees had some kind of surface defect; however, most of the defects were not of a very serious type. More than one third of the surface defects were caused by woodpeckers, primarily in the upper parts of the stems. Surface defects of a more serious type, i.e., wounds that reduce the grade of the logs, were mostly caused during earlier thinnings in the stands.

The decay found in the cross-sections of the logs was mostly heart-rot (70%) that had originated from the root system. Of all the cases of decay, 5% were assessed as being caused by vertical branches, 5% by normal rotten branches, and 2% by surface cracks. Woodpeckers and different kinds of external surface bruising had caused 14% of the decay cases.

Paper I concluded that white birch – if originally of proper quality – can also prove to be a high-quality species in conifer-dominated stands especially. Furthermore, smaller trees growing on mineral soils, as well as those grown on peatlands, have a large potential for producing small-sized saw logs. However, it is normally more profitable to grow silver birch on mineral soils.

3.1.2 Bucking birch stems into logs (II)

The results presented in paper II indicate that the current bucking principles do not result in optimum bucking of birch stems into logs. Allowing shorter lengths and smaller diameters for saw logs increased the log recovery and, thus, also the total value of individual birch stems. In addition, smaller and poorer-quality stems could be utilised when small-sized logs were allowed. The results also indicated a higher total value for the stems when they were bucked according to the saw log bucking principles, compared to bucking according to the veneer log bucking principles.

The study showed that allowing small-sized saw logs (top diameter 12-18 cm), in addition to conventional saw logs (top diameter more than 18 cm) and pulpwood (top diameter more than 7 cm but less than the requirements of logs), systematically increased the log recovery and the stumpage value of the entire birch stem, compared to the routine when conventional veneer logs (top diameter more than 18 cm) and pulpwood were bucked. Depending on the type of stand, bucking stems into conventional and small-sized saw logs and pulpwood instead of bucking into conventional veneer logs and pulpwood resulted in a 10 to 40% higher stumpage value m^{-3}. Allowing very short (theoretical minimum 0.5-metre-long) logs increased, in turn, the value of the stem by as much as 50% even compared to the conventional log lengths. Furthermore, when the stems were bucked into shorter than normal logs, the grade distribution and value of the trees clearly improved.

When the sample trees were bucked into conventional log lengths, the proportion of logs out of the stem volume varied from 31 to 73% when saw log bucking rules were applied, and from 9 to 60% when veneer log bucking rules were applied, respectively. On mineral soils, the proportion of logs was, on the average, 10 to 30% higher when saw logs were bucked than when veneer logs were bucked. On peatlands, on the other hand, there were no significant differences. Irrespective of the assortment bucked, more than 70% of the total stem volume on peatlands ended up as pulpwood, whereas the average proportion was close to 50% on mineral soils.

Shortening the log lengths would increase the proportion of logs in a stem and, hence, affect the entire volume of logs obtained from a similar volume of harvested trees. When conventional log lengths were used, the average proportion of small-diameter saw logs, obtained in addition to large-diameter logs, varied between 4 and 25% out of the total volume of the tree, depending on the stratum, site and crown layer in question. When short logs were allowed, on the other hand, the corresponding proportion varied between 6 and 33%. As a rule, the potential section of small-diameter logs was clearly more efficiently utilised when short logs were allowed.

With an index value of 100 for 1 m^3 of veneer logs, the value indices of the sample trees varied between 36 and 95 in the case of saw log bucking, and between 29 and 73 in the case of veneer log bucking. Bucking the stems into large and small-diameter saw logs and pulpwood instead of veneer logs and pulpwood resulted in higher value indices, irrespective of whether conventional or short log lengths were used.

3.1.3 Knottiness characteristics of sawn wood (III)

Based on the results of paper III, the location of the stem sections containing really knot-free boards was moderately well predictable on the basis of the location parameters, as was also the case with the sections with sound-knotted boards. The stem sections containing boards with both dead and sound knots, as well as the sections with solely dead-knotted boards were, however, mixed to some extent within the middle part of the stem.

There were no marked differences in the overall grade distribution by knottiness between the six strata studied. Each of the three grades made up ca. one third of the total number of boards. As the total lumber grade distributions were analysed without taking into account the effect of the location parameters, it appeared that strata 1 and 2 had the most similar distributions, whereas stratum 3 was slightly different from the other strata in having a larger proportion of sound-knotted boards and a smaller proportion of knot-free boards. Strata 4, 5 and 6 were relatively similar to each other in the overall lumber grade distributions. Depending on the stratum in question, the overall proportion of boards correctly classified by the polytomous logistic regression (PLR) varied between 70.9 and 75.3%. At its lowest, however, no more than 33% of the grade 2 boards were sorted out by the PLR, whereas the proportions of correctly classified boards representing grades 1 and 3 were typically close to 80%.

In general, silver birch butt logs from the stump up to a height of six metres, as well as white birch butt logs up to four metres, mainly contained knot-free boards over a distance of 75 mm from the pith outwards. At these heights, the inner boards were rather equally distributed between the three grades. Sound-knotted boards were, as expected, mainly located in the small-sized top parts of the stems. When moving downwards along the stem, sound-knotted boards were gradually replaced by dead-knotted and, finally, by knot-free boards.

3.1.4 Density and selected mechanical properties of birch wood (IV,V)

Silver birch wood, with a mean basic density of 512 kg/m^3, was ca. 5-10% denser than white birch (478 kg/m^3). Vertically, the overall within-stem variation in basic density was not as large as horizontal variation. The basic density decreased slightly from the base to the top of trees, and increased more strongly from the pith to the surface. Thus, the heaviest wood (silver birch: ca. 540 kg/m^3; white birch: ca. 490 kg/m^3) occurred near the surface of the butt-logs. The vertical variation in the white birch stems was smaller than that in the silver birch stems.

The Brinell hardness, which is of particular importance for flooring materials, veneer and plywood since it describes the ability of a surface to resist an intrusion by an external object, was linearly correlated with the basic density of the birch wood. It therefore also varied in a similar manner to basic density within the birch stems. The average Brinell hardness of silver birch wood was 23.4 MPa ($s = 4.4$) and that of white birch 20.5 MPa ($s = 3.8$).

The test method according to EN 1534 was found to be reliable but unnecessarily laborious. However, when solid wood is studied, the only way to obtain information about the anisotropic behaviour of wood in axial, radial or tangential directions during the hardness test, is to manually measure the diameter of the residual indentation at two times at right angles to each other. For practical purposes, however, such accuracy is not usually needed. An alternative test procedure that is faster and easier to implement was suggested in paper IV. Hence, when testing solid wood, and when the hardness value itself is of more interest than the anisotropic structure of wood, the depth of the indentation (or its diameter, calculated on the basis of the depth) can be used for determining hardness. The advantage of using depth measurement would be the considerably decreased time consumption, while all the variables needed could be measured automatically.

The results in paper V indicated clear linear relationships between MOE and MOR. The specific gravity of birch wood at 12% moisture content (ρ_{12}) was, furthermore, linearly correlated with both MOE and MOR. However, the relationship between MOR and ρ_{12} was stronger than that between MOE and ρ_{12}. In the case of silver birch, the mean values for MOE and MOR were 14.5 GPa and 114 MPa, whereas white birch had means of 13.2 GPa and 104 MPa, respectively. The ranges of MOE were very similar in the two birch species, ca. from 8 to 20 GPa, whereas the ranges of MOR, 70-160 MPa for silver birch and 60-140 MPa for white birch, indicated a more obvious between-species difference. The mean values of both MOE and MOR for silver birch were ca. 9% higher than those for white birch. The within-stem variation in the bending strength and stiffness was similar to the variation in the basic density (IV).

The observed variation in the bending properties within individual birch stems do not necessarily justify, for instance, the sorting of raw materials into different end-use grades. However, it is obvious that, if special products with as high a bending strength as possible are to be manufactured, this might be sufficient motivation for sorting the raw materials into different grades according to their within-tree origin. Hence, even a 10-15% increment in the bending strength or stiffness of the product can be attained over unsorted raw materials.

3.2 Synthesis: elaborated birch wood product processing chain

As shown in articles I-V, rather many of the quality factors controlling the variation in birch trees can be modelled. In order to put these possibilities into practice, however, novel methods are required for selecting suitable birch stands, and for bucking stems into logs and sawing logs into lumber. The quality and value of the products could also be improved by utilising the within-tree variation in the properties of interest. The main results of articles I-V are summarised in Chapter 3.1. In this synthesising chapter, the outline of a cost-efficient birch wood product processing chain is presented. Some of the resulting suggestions are purely hypothetical in the light of current technology.

Firstly, the birch timber purchased should be utilised to as high a degree as possible. This is accomplished by a comprehensive selection of the stands to be purchased (I). Hence, as much as 50% of the raw material obtained from mature birch stands (II), and 30% of that obtained from advanced thinning birch stands (Rantanen et al. 2000, Lehtimäki 2002, Lehtimäki et al. 2002), can be sawn. In addition, horizontal integration with other companies is necessary. By focusing on its core competence area, a company has at least theoretical possibilities to achieve competitiveness in global markets. The partnership companies, such as the pulping industries, particleboard manufacturers, fibreboard manufacturers or firewood retailers, should be able to utilise all the surplus raw material.

The limitations set by the raw material supply and the quality of the standing trees should be taken into account by allowing the use of different types of log in production. Therefore, both a circular saw or a frame saw for processing the conventional logs, and a high-speed, multi-blade saw for processing the small-sized logs, are needed. Allowing short logs with minimum lengths of e.g., two metres considerably increases the proportion of sawable timber out of the total volume of timber purchased (II). In addition, the seasonal variations in log quality, as well as in the orders for different grades of sawn wood, could be balanced, for instance, by utilising the snow-storing of logs. This should be put into practice by using different stockpiles for logs of different grade.

Accepting small-sized logs means that a company obviously has to pay higher prices for stands marked for cutting, compared to other companies using conventional dimension requirements for logs. However, the higher overall prices put a company in a more favourable position when there is competition for marked stands between different companies. Being successful in these competitions diminishes the size of the timber procurement area, reducing the transportation costs. Paying competitive price levels for suitable stands also improves the image of a company and, thus, facilitates raw material procurement (see II). Increasing the proportion of small-sized logs out of the total timber flow decreases the proportion of pulpwood. Simultaneously, however, the proportion of by-products in the actual sawing process increases. The problem of marketing surplus products is thus partly shifted from roundwood to chips.

Since the production of most birch-consuming companies consists of items with short dimensions, it should also be possible to cut logs with a large diameter to relatively short lengths in the forest. Such a bucking practice facilitates, first of all, obtaining sawable logs from trees with sweep or even a crooked stem form (see: I, II) and, secondly, maximum utilisation of the knot-free wood lying close to the surface of strongly tapering butt logs (see III). Logs with a straight, full-boled (i.e., slightly tapering) appearance can be sawn using conventional log lengths, if necessary.

The effective utilisation of raw material calls for highly developed mechanisms for grading sawn wood according to its appearance before the optimised cut-off (III). Some of the slightly or one-sided discoloured pieces of sawn wood, or those with visually counterproductive or loosened dead knots, are currently used for low value products (e.g., pallets), hidden structures (e.g., backside of panels) or products that will be covered by a paint coating or facing veneer. The more severely discoloured, decayed or otherwise damaged pieces might end up in energy production. However, one alternative end use for some pieces of sawn wood with dead knots, blotched decay or other undesired defects, might be found in, e.g., mouldings. This is possible after optimised cutting into short blocks, 15-20 cm minimum size, finger jointing and, finally, finishing products with the desired quality and dimensions.

By grading sawn wood not only according to its appearance, but also according to its density, might result in the manufacturing of products with as high a stiffness, strength or hardness as, e.g., beech (*Fagus sylvatica*) (Wagenführ 1996, IV, V). This necessitates using either the information available about the board's original within-stem location (IV), or a method for scanning the wood density afterwards.

4 DISCUSSION AND CONCLUSIONS

4.1 Sources of error and possibilities of generalising the results

In empirical studies, it is almost impossible to avoid totally the human errors associated with the measurement of the samples and data processing. In most cases, the most distinctive errors can be identified and corrected using visualisation and cross-tabulation of the data before the actual analyses.

When collecting the data for paper I, the following attributes were determined using subjective, visual evaluation: site, mean age of the trees by species on the sample plots, crown layer of individual sample trees, properties describing the overall quality of log and small-sized log sections, and reasons for the existence of decay and surface defects. The following characteristics were, on the other hand, determined using unambiguous measurement, counting or calculating: number of stems per hectare, basal area, mean height and diameter of the trees by species on the sample plots; and, on all the sample trees, diameter, volume, tapering, number and size of branches, height of the crown layers, and the amount of sweep in logs. Both the evaluated and measured characteristics can include errors. There is, nevertheless, no reason to assume that there are any systematic trends in the error terms; both over- and underestimates can occur equally in the data.

The relatively small number of experimental stands, altogether 20, might be considered inadequate for some of the aims of the study. Because of the limited budget available, some compromises were necessary in the labour-intensive material collection stage. However, the aim of paper I was not to make an extensive inventory, but to find typical, representative stands characterising the six predetermined strata. The number of experimental stands is adequate for such a purpose.

The covariance models presented in paper I showed some interactions between the predictor variables. In order to verify that the models are truly unbiased, a larger set of data should be analysed or, alternatively, the models should be tested using another independent dataset. The coefficients of determination of some of the models concerning the branchiness characteristics presented in paper I were as low as less than 20%. Thus, the residual variation was considerable, which should be taken into account when applying the models.

In paper II, the grades for logs were determined in strict accordance with the grading rules. In some cases, however, this was impossible to do in practice. Therefore, in order to avoid dispensable theoretical accuracy, slight short cuts were taken when judged necessary. Such situations occurred most frequently in cases where the grading rules were applied to small-sized logs. For instance, if, according to the original grading rules, five sound knots were allowed in a log within a length of 1.5 metres, three of them were allowed within the length of one metre in the applied grading rules, even though the correct number should have been 3.3 knots. In fact, perhaps the most crucial weakness of paper II is that the grading rules applied were meant for grading conventional logs. When applied to small-sized logs, some of the requirements were not justified. During the period when the material was collected (1998-1999), there were, however, no practical grading rules available for small-sized birch logs. Nowadays the situation is different; some sawmills in eastern Finland have already implemented such grading rules. The existing grading rules for small-sized birch saw logs set limitations on the dimensions, amount of sweep and occurrence of heart rot and surface damage, whereas the requirements set for branchiness are relatively free. Stem sections with vertical branches are rejected from saw logs. In addition, logs with many dead branches are, in theory, avoided. However, practice has shown that these logs are almost equally as good raw material as logs with living branches only; in young trees from thinning stands, which are the principal source of raw material of small-sized logs, the dead branches turn into sound knots relatively soon on moving from the surface to the pith of the log.

The following conclusions concerning the results presented in paper II and the current situation in the bucking of small-sized logs can be made on the basis of the above facts and arguments. The grading rules for small-sized saw logs of birch currently used in practice are slightly less strict than those used in paper II. Therefore, the differences between the log recoveries and stumpage incomes reported in paper II would in actual fact be even larger if the current grading rules were applied.

The sawing machinery currently in use can handle log lengths of less than two metres. However, the real problem today is the debarking machinery, which cannot process such short bolts. Debarking the logs, on the other hand, is necessary if slabs suitable for pulp chips are required. So far, shorter bolts with average lengths of ca. three metres are sawn only in the few sawmills in eastern Finland that use small-sized logs.

Methodologically, paper III explored a new way of modelling the knottiness characteristics of trees or sawn wood; according to the literature survey, similar method has not earlier been applied for this purpose. Polytomous logistic regression provided logically interpretative results that indicated moderately promising options for further applications. However, there were still some deficiencies in the models, the first of which was related to their applicability in the light of current technology. Maintenance of information about the log's location within the stem, as well as that of a board within the log, is difficult to arrange in practice. Overcoming this problem would result in better optimisation of the sawing patterns and, subsequently, optimal recovery of the most desired, i.e., knot-free and sound-knotted lumber grades.

The phase that was perhaps the most prone to errors during collection of the data for paper III, was the coding of the boards according to their within-log location. Owing to suspected mistakes in coding, ca. 2% of the boards were rejected from the final data. However, more than 10,000 boards still remained for the analyses. The actual counting and measuring of knots were not especially susceptible to errors, apart from the problems related to measuring the size of diagonally cut knots. The polytomous regression models presented in paper III also indicated considerable residual variations, since, depending on the model, only 35-85% of the boards were correctly classified according to their knottiness. The practical applicability of these models should also be verified using an independent dataset.

Possible errors in the within-stem density variations presented in paper IV are related to manual measurement of the volume and weight of the specimens. Mistakes could also have been made in coding the 6,304 small specimens. At least some of the incorrectly coded or measured specimens were eliminated from the data as distinct outliers during the subjective evaluation. The results subsequently indicated a reasonable residual variation, which was still large enough to decrease the coefficient of determination of the models down to a modest level. In fact, the more accurate way to model the basic density variation would have been to use non-linear models for the lower heights, and linear models only for the upper heights within the stem. This would have further reduced the residual variation. The only slightly strange finding was the clear decrease in basic density near to the surface of the birch stems, at near-stump heights (IV).

The accuracy and weaknesses of determining Brinell hardness according to standard EN 1534 were discussed in detail in paper IV. There is still the possibility of human errors and mistakes caused by malfunctioning devices. However, there were no indications of measuring errors.

Small, clear specimens were used in the static bending tests carried out for paper V. Problems related to this kind of test are highly dependent on the successful preparation of the specimens, i.e., avoiding cross grain, spiral grain, knots, cracks, splits and the presence of decayed wood, while still maintaining the standardised dimensions of the specimens. Most of these requirements are moderately easy to follow in the case of birch. However, the orientation of grain in birch wood varies naturally, thus making it more difficult to find suitable specimens. In this study, the 20 x 20 x 340 mm specimens for the bending tests were prepared from 25-mm thick and 2-metre long boards. Such large billets enabled successful preparation of the specimens; after the test had been performed, none of the specimens gave results that could be considered to be outliers.

It is justified, within the framework of this study, to state that the smaller the unit studied, the more reliably can the results be generalised. This is simply due to the fact that the fieldwork was expensive and laborious, and thus restricted number of stands and trees that could be measured. At the stand level, the results represent the stands in question, with only limited possibilities for generalisation after comprehensive evaluation of the similarity of the stands. In contrast, at the between-tree and within-tree levels, the results can be more widely generalised to cover ca. 60- to 110-year-old birch trees growing on fertile mineral soils or on peatlands in southern and central Finland.

4.2 Comparison with the findings of previous publications

In paper I, the small-sized log sections obtained from the top parts of the trees contained more dead knots than would have been expected on the basis of earlier studies (cf.

Heiskanen 1957, Verkasalo 1997b). The result that the stems of trees growing in mixed stands were larger was at least partially due to the silviculture practices used in conifer-dominated stands; only the best birch trees are usually left growing, in addition to the coniferous main species (cf. Mielikäinen 1980, 1985). Therefore, the correct conclusion is not that birch grows better in mixed stands dominated by conifers but, more likely, that birch trees left growing in mixed stands represent the best possible vitality and quality.

The results in paper I also indicated that white birch has a slightly longer knot-free stem section than silver birch when grown in conifer-dominated stands. This is obviously the consequence of thinner branches and, subsequently, higher susceptibility for self-pruning after the branches have died. However, this result only reflects the external quality of the trees: owing to the slower rate of growth, white birch heals over the remaining stubs more slowly than silver birch, and therefore produces only a small amount of knot-free wood material on the surface of the stem.

Apart from the models for assessing the value and distribution of saw log grades for standing birch trees in mixed stands of Norway spruce and birch in Norway (Gobakken 2000), practically no other studies on the commercial grades of birch saw logs were found in the literature. As discussed in paper II, the questions associated with the length of the logs being sawn or veneered are closely related to the machinery used, as well as to the requirements of the final products. The prevailing bucking practice in Finland, with an average log length of ca. four metres (e.g., Luostarinen & Verkasalo 2000, II), does not seem to be optimal, while there is a constant state of competition for high-quality raw material between the plywood industry and the sawmills. This competition has resulted in a call for more efficient raw material utilisation.

Excluding the studies concerning the quality of plywood (Meriluoto 1965, Heiskanen 1966, Verkasalo 1997a,b), the study carried out by Kärkkäinen (1986b) was actually the only article discussing the internal knottiness structure of Finnish birch stems prior to III. The general conclusion concerning naturally regenerated, mature birch trees is that the knottiness structure by knot type within the stems is far more complicated than, for example, that of pine. In the case of Scots pine (*Pinus sylvestris*), Blomqvist & Nylinder (1988) found that it was possible to separate butt-logs from other bolts on the basis of the log taper. According to, e.g., Jäppinen & Nylinder (1997) and Lundgren (2000), a considerable amount of information can be obtained about the internal quality of a tree on the basis of the log taper of Scots pine. Generalisation of this statement to cover also birch will be a task of future studies.

In fact, it is entirely possible that the knottiness structure of mature birch trees cannot be predicted on the basis of a log's external characteristics, to the degree of accuracy required for industrial purposes. Instead, predicting the knottiness structure of regularly thinned and even-aged cultivated birch trees might be easier.

In comparison to the results reported earlier for the basic density (kg/m^3) of cultivated birch (e.g., Hakkila 1966, 1979, Velling 1979, Verkasalo 1998a, Möttönen 2001), it appears that the differences were of definite practical relevance. Younger trees had, on the average, 5-20% lighter wood than older trees. This indicates a respective difference in, e.g., strength and stiffness properties. However, it is by no means certain that young birch trees with a low average density could not, in the future, reach the density level of the mature trees studied here. According to Hakkila (1979), Bhat (1980b) and Nepveu & Velling (1983a, 1983b), the wood produced by birch cambium is the denser the higher is the age of the cambium. The average differences observed at stem and log levels will, therefore, probably diminish as the tree ages. The densest wood is still primarily obtained from mature trees. From the silvicultural point of view, the fast growth rate of cultivated birch does not have a significant lowering effect on the basic density (Zobel & van Buijtenen 1989, Tsoumis 1991, Dunham et al. 1999, IV). The results indicated that, at its best, birch wood with a basic density of 550 kg/m^3 could be obtained from the butt-logs of silver birch, whereas 500 kg/m^3 is a good density level for white birch. These densities are actually rather close to the average density of beech (Kärkkäinen 1985, Wagenführ 1996), which is obviously the most serious competitor for birch wood in the central European furniture markets.

No comparable results were available from studies where exactly the same method (EN 1534) for determining the Brinell hardness had been used. Although Lassila (1926) mentioned that the correlation between density and hardness was not as clear as "what could be expected", significant correlations were found between the two properties in the study in hand. Kucera (1984) reported a similar dependence. The results obtained in paper IV for Brinell hardness were generally in accordance with the earlier publication of Jalava (1945).

Compared to the static bending and stiffness properties of full-sized sawn wood (Dunham et al. 1999), the small clear specimens had 10-40% higher MOE and 40-55% higher MOR. This is affected not only by the defects, such as knots and cracks appearing in sawn wood, but even more by the factors related to the environmental testing conditions. For instance, humidity produces different moisture gradients in different-sized pieces of wood (Bodig & Jayne 1982, Skaar 1988, Siau 1984, 1995). Thus, the resultant influence of moisture gradient differs between the two pieces. It is evident that, so far, factors related to the conditions of the test environment, such as moisture content or moisture gradient, have greater effects on the strength and stiffness of birch products than the biological within-stem variation (Conners & McLain 1988).

4.3 Conclusions

Understanding the interrelationships between wood properties and processing techniques is essential in order to successfully utilise raw materials with a limited availability. The objective of the current thesis was to produce new, scientifically verified information on the properties and more efficient use of birch in the wood product industries, especially in sawmilling and further processing. The technical properties of the two Finnish birch species were studied at the between-stand (stand structure by species, spacing and soil type), between-tree (birch species, growing position of the tree) and within-tree (horizontal and vertical variation) levels. The study showed that, even if the properties vary considerably between the two birch species, under different growing conditions and sites, as well as within individual tree stems, the variation is predictable within certain limits. Furthermore, the results indicated that improving the efficiency of raw material utilisation by rationalising the bucking of birch stems into saw logs, and sorting the sawn wood according to its within-stem origin, would potentially have substantial economic impacts on the incomes of forest owners and wood product companies.

For more than a hundred years, the needs of the wood product industries have created a demand for high-quality birch logs and, as a result, facilitated the development of a silvicultural tradition in Finland where birch is also considered, alongside Scots pine and Norway spruce, as an economically potential tree species. The first cultivated birch stands are currently already forty years old, and will reach the final cutting size within the next ten years. However, the area of afforested fields has diminished due to the cessation of governmental subsidies for this purpose. This, together with the overlarge elk and deer stocks have decreased the area of annual birch plantations down to 50% of the peak level of 20,000 ha in the early 1990s (Peltola 2001). Such a development will inevitably influence the availability of birch timber up until, at the latest, the end of the 2020s. At that time, the optimised utilisation of the raw material obtained from birch stands, trees, logs, and sawn wood, will become even more necessary than it is at the present.

Generally, new methods are needed for processing wood products according to the customer's requirements, i.e., for colour, durability, easy-to-build, modifiable and innovative designs etc. These areas, complemented with a considerably advanced marketing know-how, require a lot of research and development work in the future. The key issue is to produce, as effectively as possible, versatile products with the desired properties. This necessitates the precise utilisation of both high-quality and poorer-quality raw materials.

The future raw material needs of the pulp industry are uncertain. However, according to Werner et al. (2000), even 15% of the birch pulpwood volume delivered to the pulp mill contains timber that could be used for sawing. In order to improve the quality of timber, silviculture should more energetically focus on growing quality, instead of the traditional practice of growing quantity.

It seems that the most considerable change that will occur in birch sawmilling during the next few years is related to the increasing utilisation of small-sized logs, mainly obtained from thinning forests. The status of a special product, which birch lumber has traditionally held, will gradually change to become more of a bulk product. This is a consequence of the high-speed, high-capacity sawmills with chipper-canters, optimising log rotators, and equipment permitting curve sawing. Such machines can process not only hardwood logs with a diameter of less than 100 mm, but also log lengths of clearly less than two metres. This is a considerable difference compared to the traditional, individually performed "quality sawing" of conventional logs. Although sawing conventional birch logs is often profitable at a modest annual capacity of 2,000 to 5,000 m^3, the minimum capacity of a sawmill utilising small-sized logs is at least 20,000 m^3, and preferably even higher. The recent expansion in the production capacity of birch lumber might cause problems in marketing the products.

Birch products with visible sound knots are already now desirable for furniture manufacture, whereas even a few years ago almost only knot-free lumber was accepted (Luostarinen & Verkasalo 2000). The efficiency of raw material use will increase along with the development of the machinery. Manufacturing refined products, such as billets and components, will become more and more rational and cost-efficient; a similar development can already be seen in the mechanical processing of softwoods. The utilisation of short, but high-quality blocks will grow in the future, for instance, by applying finger jointing.

Development work has been going on for decades to obtain dried birch lumber with a stable light colour and only slight deformations. It will probably still take considerable time before the most promising methods, i.e., low-pressure dryers or HFV dryers (High Frequency Vacuum), are ready for cost-efficient productive use. These methods exhibit, however, high potential for developing wood dryers that provide a controllable light colour, as well as only minor cracking and deformation behaviour, for such complex-to-dry species as many of the hardwoods, including birch, are.

A number of novel potential end-uses for birch have opened up along with the production of heat-treated lumber. Not only the darkened colour and the lowered equilibrium moisture content that results in reduced hygroexpansion, but also the improved ability to resist decay have considerably broadened the end uses of hardwoods in the direction of moister applications than has so far been possible. Heat-treatment seems to have many positive marketing benefits, and the method may contribute to increased consumption of hardwood products, once standard-quality products are produced and the markets have became truly open. So far, there is a considerable over-pricing in the markets for heat-treated wood. This is typical for new products with exiguous competition in production. The increase in production levels, resulting in more competition, will probably reduce the price of heat-treated wood within a time-span of a few years.

Another interesting modification system for birch wood is the compression treatment, in which the elastic performance of the wood material is temporarily increased and, subsequently, the possibilities for various designs ameliorated. Although different compression methods have been known for at least 60 years (see: Wegelius 1943), obviously only two companies have so far utilised a similar technique in Finland.

In addition to modification techniques, improving wood properties is also enabled by the engineered wood products (EWP), i.e., wood that has been veneered, sliced or stranded, and then glued together again, to give enhanced homogeneity and the desired dimensions. If we exclude plywood and LVL, Finland has, however, been clearly left behind in research and development of EWP (see: Poutanen 2000, Harstela et al. 2001).

As a conclusion, further research is mostly needed in the following areas. 1) Silvicultural methods should be developed in a way that also takes into account the quality of valuable hardwoods. 2) The possible disadvantages resulting from the rapid growth of cultivated birch should be compensated through, e.g., tree breeding, processing techniques or new end products. 3) More effective utilisation of wood should be incorporated at all levels of processing chains, i.e., harvesting, bucking, primary processing and further processing; all these operations require active research. 4) A considerable amount of research should be devoted to marketing and sales since, so far, the advantages provided by high quality, certified raw materials are by no means fully exploited.

Although positive trends have recently been seen in the manufacturing of wood products from birch, the wood product industries should, as lines of business, still be kept in a reasonable perspective. In Finland, for instance, the pulp industries account for more than 88% of the annual industrial consumption of birch wood (Peltola 2001). Furthermore, the competition caused by the rapidly increasing production capacity in Russia and the Baltic countries, augurs considerable challenges for the Finnish wood product industries. However, there is no reason to anticipate any sudden reductions in Finnish, birch-based wood product manufacturing in the near future. The obvious threats can be countered by using the advantages provided by active silvicultural practices, resulting in high-quality raw materials, elaborated logistics and wood procurement infrastructure, advanced production machinery, marketing expertise and active wood material research.

REFERENCES

Agestam, E. 1985. A growth simulator for mixed stands in Sweden and two examples of yield in birch-pine and birch-spruce mixed stands. Rapp. Instn. Skogsskötsel. Sveriges LantbrUniv. 14: 235-252.

Andersson, B. 1982. Lövträdens inverkan på unga tallars överlevnad och tillväxt I Västerbottens kust- och inland. Sveriges SkogsvFörb. Tidskr. 6: 11-24. (In Swedish).

Appelroth, E. 1949. Koivun kasvattamisesta. Metsätal. Aikakausl. 1/1949: 14-15. (In Finnish).

Bergstedt, A., Kucera, B., Nylinder, M., Saranpää, P. & Ståhl, E. 2001. (Eds.). Wood quality of Norway spruce grown in mixture with birch and in monoculture. Finnish For. Res. Inst., Research Papers 822. 49 p.

Bhat, K.M. 1980a. Pith flecks and ray abnormalities in birch wood. Silva Fenn. 14(3): 277-285.

- 1980b. Variation in structure and selected properties in Finnish birch woods: I. Interrelationships of some structural features, basic density and shrinkage. Silva Fenn. 14(4): 384-396.

- & Kärkkäinen, M. 1980. Distinguishing between Betula pendula Roth. and B. pubescens Ehrh. on the basis of wood anatomy. Silva Fenn. 14(3): 294-304.

- & Kärkkäinen, M. 1981a. Variation in structure and selected properties of Finnish - & Kärkkäinen, M. 1981b. Variation in structure and selected properties of Finnish birch woods: IV. Fibre and vessel length in branches, stems and roots. Silva Fenn. 15(1): 10-17.

Blomqvist, H. & Nylinder, M. 1988. Relation between geometry, yield and quality for sawlogs of pine, Results from investigations at Rockhammar sawmill. The Swedish University of Agricultural Sciences, Department of Forest Products. Report No 205. 50 p. + App. 12 p. (In Swedish with English summary).

Bodig, J. & Jayne, B.A. 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold, New York. 712 p.

Bonham, V.A. & Barnett, J.R. 2001. Formation and structure of larval tunnels of Phytobia betulae in Betula pendula. IAWA Journal 22(3): 289-294.

Cameron, A.D., Dunham, R.A. & Petty, J.A. 1995. The effects of heavy thinning on stem quality and timber properties of silver birch (Betula pendula Roth). Forestry 68: 275-285.

Conners, T.E. & McLain, T.E. 1988. Modelling moisture gradient effects on bending properties. Wood Fiber Sci. 20(2): 226-242.

Dunham, R.A., Cameron, A.D. & Petty, J.A. 1999. The effect of growth rate on the strength properties of sawn beams of silver birch (Betula pendula Roth). Scand. J. For. Res. 14: 18-26.

Elowsson, T. 1989. Conditions for manufacturing of semi-processed birch wood – a branch of production with a bright future. The Swedish University of Agricultural Sciences, Department of Forest Products. Report No 206. 69 p. + App. 78 p. (In Swedish with English summary).

EN 1534: Wood and parquet flooring – Determination of resistance to indentation (Brinell) – Test method. European Standard. CEN 2000.

Feihl, A.O. 1964. Rotary cutting of curly yellow birch. Department of Forestry, Forest Products Research Branch. Publication No 1086. Canada. 18 p.

Ferm, A. 1990. Development and decay of young Betula pubescens coppice stands on peatland. Folia For. 744. 17 p. (In Finnish with English summary).

- & Kaunisto, S. 1983. Aboveground leafless biomass production of naturally generated birch stands in a peat cut-over area at Aitoneva, Kihniö. Folia For. 558. 32 p. (In Finnish with English summary).

Fjærtoft, F. & Bunkholt, A. 1994. Grading Rules for Sawlogs and Sawnwood of Birch, - Results of Sawing Experiments. Norwegian For. Res. Inst., Skogforsk. Research Paper 18/1994: 1-17. (In Norwegian with English abstract).

Gobakken, T. 2000. Models for assessing timber grade distribution and economic value of standing birch trees. Scand. J. For. Res. 15: 570-578.

Gustavsen, H.G. 1996. Site index model approach for drained peatland forest stands. Suo 47(2): 37-46.

Hakkila, P. 1966. Investigations on the basic density of Finnish pine, spruce and birch wood. Comm. Inst. For. Fenn. 61(5): 1-98.

- 1979. Wood density survey and dry weight tables for pine, spruce and birch stems in Finland. Comm. Inst. For. Fenn. 96(3): 1-59.

Hallaksela, A.-M. & Niemistö, P. 1998. Stem discoloration of planted silver birch. Scand. J. For. Res. 13(2): 169-176.

Harstela, P., Kettunen, J., Kiljunen, N. & Meristö, T. 2001. Normitaloudesta yrittäjyyteen, Puuntuotannon tulevaisuus Suomessa. Finnish For. Res. Inst., Research Notes 819. 69 p. + App. 8 p. (In Finnish).

Heinonen, J. 1994. Koealojen puu- ja puustotunnusten laskentaohjelma KPL. Käyttöohje. Finnish For. Res. Inst., Research Paper 504. 80 p. (In Finnish).

Heiskanen, V. 1957. Quality of the common birch and the white birch on different sites. Comm. Inst. For. Fenn. 48(6): 1-99. (In Finnish with English summary).

- 1966. Studies on the defects of birch, their influence on the quality and quantity of rotary cut veneer, and their consideration in veneer birch grading. Acta For. Fenn. 80(3): 1-128. (In Finnish with English summary).

Heräjärvi, H. 2002. Utilisation of birch in mechanical wood industry in Finland. In: Hynynen, J. & Sanaslahti, A. (Eds.). Management and utilization of broadleaved tree species in Nordic and Baltic countries – Birch, aspen and alder. Proceedings of Workshop held in Vantaa, Finland, May 16 to 18, 2001. Finnish For. Res. Inst., Research Papers 847. Pp. 73-82.

Hoadley, R.B. 1980. Understanding wood. A craftsman's guide to wood technology. The Taunton Press, Inc. Newton, Connecticut. 256 p.

Humala, I. & Peltoniemi, J. 2001. Puutuotealan pk-yritysten asiakaslähtöisten liiketoimintakonseptien kehittäminen. Kauppa- ja teollisuusministeriön tutkimuksia ja raportteja 1/2001. 82 p. (In Finnish).

Hynynen, J., Härkönen, K., Lilleberg, R., Mielikäinen, K., Repola, J. & Siipilehto, J. 2002. Koivua Suomesta – koivuvarojen kehitysnäkymät. Finnish For. Res. Inst., Research Notes 840. 53 p. (In Finnish).

Hägg, A. 1988. The profitability of a birch admixture in coniferous forests. The Swedish University of Agricultural Sciences, Department of Forest Products. Report 201. 62 p. + App. 24 p. (In Swedish with English summary).

- 1990. The profitability of using self-regenerated birch for shaping the quality of planted pine. The Swedish University of Agricultural Sciences, Department of Forest Products. Report 214. 26 p. + App. 7 p. (In Swedish with English summary).

ISO 3133: Wood - Determination of ultimate strength in static bending. International Organization for Standardization.

ISO 3349: Determination of modulus of elasticity in static bending. International Organization for Standardization.

Isomäki, O. 2001. Huonekaluvalmistajan vaatimukset koivun kuivaukselle. In: Riekkinen, M. & Kärki, T. (Eds.). Koivun kuivausmenetelmät 2000-vuosituhannelle, Seminaaripäivän esitelmät. Finnish For. Res. Inst., Research Notes 810. Pp. 49-51. (In Finnish).

- & Leppänen, H. 1992. Uusia laatuluokitusehdotuksia puusepänteollisuudelle. Puumies 4: 24-26. (In Finnish).

Jaakkola, J. & Tunkelo, E. 1987. Tuotekehitys – ideoista markkinoille. Ekonomia-series. 250 p. (In Finnish).

Jalava, M. 1943. Huonekaluteollisuuteen käytettävän koivusahatavaran laatuluokituksesta. Metsätal. Aikakausl. 6-7/1943: 248-249. (In Finnish).

- 1945. Strength properties of Finnish pine, spruce, birch and aspen. Comm. Inst. For. Fenn. 33(3): 1-66. (In Finnish with English summary).

- 1949. Koivun ja koivuteollisuuden merkitys Suomessa. Metsätal. Aikakausl. 1/1949: 3-6. (In Finnish).

- 1957. Puun käyttöön vaikuttavat ominaisuudet. In: Jalava, M., Lihtonen, V., Heiskanen, V. & Sippola, H. (Eds.). Metsäkäsikirja, 2. osa. Pp. 755-791. (In Finnish).

Jensen, W. 1950. Studium av björkens anatomi. Paperi ja Puu B, 4a: 7-10. + 23 pictures. (In Swedish).

Jonsson, B. 1961. Yield of mixed coniferous forests. Medd. Stat. Skogsforskn. Inst., Band 50(8): 1-143. (In Swedish with English summary).

Jouhtinen, T. 1994. Koivusahatavaran laatuluokitus. Insinöörityö. Lahden teknillinen oppilaitos. Publications 6. (In Finnish).

Jäppinen, A. & Nylinder, M. 1997. Automatic sorting of spruce (Picea abies (L.) Karst.) sawlogs by grade. Holz als Roh- und Werkstoff 55: 301-305.

Jørgensen, P.F., Tronstad, S. & Tengs, A. 1995. Tørkning av bjørk, Resultater av 9 tørkeforsøk. KanEnergi og Norsk Träteknisk Institutt, Rapport 29. 46 p. + App. 10 p. (In Norwegian).

Karlsson, L. 1978. A study of the influence of broad-leaved thicket on plantations of spruce in southern Sweden. Rapp. Uppsats. Instn. Skogsföryngr. Skogshögsk. 102: 1-54. (In Swedish with English summary).

Kataikko, M-S. 1996. Huonekaluvalmistajien tarpeet sahaamisen lähtökohtana. Taitemia 5. Kuopion käsi- ja taideteollisuusakatemia. 126 p. + app. 41 p. (In Finnish).

Kaunisto, S. 1987. Effect of fertilization and soil preparation on the development of Scots pine and silver birch plantations on peat cutover areas. Folia For. 681. 23 p. (In Finnish with English summary).

Kaurala, H. 2000. Sahakoivun ominaisuudet ja laatu puhtaissa koivikoissa ja kuusikoivusekametsiköissä. Pro gradu -thesis. University of Joensuu, Faculty of Forestry. 82 p. + App. 10 p. (In Finnish).

Keinänen, E. & Tahvanainen, V. 1995. Pohjolan jalot puut. Erikoispuiden mitta-, laatu- ja käsittelyopas. Taitemia-series. 160 p. (In Finnish).

Keltikangas, M. & Seppälä, K. 1977. The economics of growing birch stands on drained peatlands. Silva Fenn. 11(1): 49-68. (In Finnish with English summary).

Kivistö, J., Sipi, M., Kantola, A. & Niemelä, T. 1999. Koivun, haavan sekä terva- ja harmaalepän mekaaninen jalostus ja lopputuotteet Suomessa vuonna 1999. Postikysely- ja haastattelututkimuksen tulosten yhteenveto. University of Helsinki, Department of Forest Resource Management. Publications 20. 56 p. + App. 15 p. (In Finnish).

Koivisto, P. 1959. Growth and yield tables. Comm. Inst. For. Fenn. 51(8): 1-49. (In Finnish with English summary).

Korhonen, K.T., Tomppo, E., Henttonen, H., Ihalainen, A. & Tonteri, T. 2000a. Lounais-Suomen metsäkeskuksen alueen metsävarat ja niiden kehitys 1964-98. Metsätieteen aikakauskirja 2B/2000: 337-411. (In Finnish).

-, Tomppo, E., Henttonen, H., Ihalainen, A. & Tonteri, T. 2000b. Hämeen-Uudenmaan metsäkeskuksen alueen metsävarat 1965-99. Metsätieteen aikakauskirja 3B/2000: 489-566. (In Finnish).

-, Tomppo, E., Henttonen, H., Ihalainen, A., Tonteri, T. & Tuomainen, T. 2000c. Pirkanmaan metsäkeskuksen alueen metsävarat 1965-1999. Metsätieteen aikakauskirja 4B/2000: 661-739. (In Finnish).

-, Tomppo, E., Henttonen, H., Ihalainen, A., Tonteri, T. & Tuomainen, T. 2001. Pohjois-Karjalan metsäkeskuksen alueen metsävarat 1966-2000. Metsätieteen aikakauskirja 3B/2001: 495-576. (In Finnish).

Kucera, B. 1980. Fysiske og anatomiske egenskaper hos lavlandsbjørk. Norges ladbruksvitenskapelige forskningsråd, Slutrapport 343. Oslo. 15 p. (In Norwegian).

- 1983. Kvalitetskrav til skurlast av lauvtre. Agricultural University of Norway, Department of Wood Technology & The Norwegian Institute of Wood Working and Wood Technology. 19 p. (In Norwegian).

- 1984. Bjørkevirkets mekaniske, teknologiske og fysiske egenskaper. Norges ladbruksvitenskapelige forskningsråd. Slutrapport Nr. 500. 21 p. (In Norwegian).

- 1986. Målereglement for tømmer av lauvtre. Norges ladbruksvitenskapelige forskningsråd. Slutrapport Nr. 607. 16 p. (In Norwegian).

- & Myhra, H.H. 1996. Egenskaper hos de viktigste norske lauvtrær. Norsk Treteknisk Institutt, Rapport 33. 58 p. (In Norwegian).

Kujala, V. 1946. Some recent research data on birches. Comm. Inst. For. Fenn. 34(1): 1-36. (In Finnish with English summary).

Kuoppamäki, K. 1932. Lajittelun merkitys harvennushakkausten pienikokoisten koivujen tarvepuuksi sahauksen kehittäjänä. Metsätal. Aikakausk. 5-6/1932: 169-170. (In Finnish).

Kuusipalo, J. 1996. Suomen metsätyypit. Kirjayhtymä, Helsinki. 144 p. (In Finnish).

Kärki, T. 1995. Erikoispuutavaran käsitteen analyysi ja sen empiirinen sovellus Savo-Karjalassa. Pro gradu -thesis. University of Joensuu, Faculty of Forestry. 89 p. (In Finnish).

- 1997. Sahauskelpoisen erikoispuun laatuvaatimukset ja käyttö Savo-Karjalan alueella. Metsätieteen aikakauskirja – Folia Forestalia 1/1997: 37-48. (In Finnish).

Kärkkäinen, M. 1978. Theoretical model for the veneer yield. Comm. Inst. For. Fenn. 95(2): 1-42. (In Finnish with English summary).

- 1980. Observations on the out-of-roundness and deviations from nominal lengths of birch logs. Silva Fenn. 14(3): 286-293. (In Finnish with English summary).

- 1981. Haapa- ja poppelilajien (Populus) käyttö. Silva Fenn. 15(2): 156-179. (In Finnish).

- 1984. The proper attitude towards birch in forestry. Silva Fenn. 18(1): 71-100. (In Finnish with English summary).

- 1985. Puutiede. Sallisen kustannus Oy, Sotkamo, Finland. 415 p. (In Finnish).

- 1986a. Value relations of birch veneer logs and stems. Silva Fenn. 20(1): 45-57. (In Finnish with English abstract).

- 1986b. Model of knottiness of wood material in pine, spruce and birch. Silva Fenn. 20(2): 107-116. (In Finnish with English abstract).

Laaksonen, M. & Rajala, A. 1987. Suomen huonekaluteollisuuden rakenne ja toimintatavat. Vaasan korkeakoulun julkaisuja. Studies 128. (In Finnish).

Lahtinen, T. & Tolonen, Y. 2001. Koivusahatavaran kuivauskaavat alipainekuivauksessa. In: Luostrinen, K., Möttönen, V., Asikainen, A., Pakkanen, T., Saranpää, P. & Tolonen, Y. (Eds.). Koivun puuaineksen kemia ja värinmuutokset kuivauksessa, Konsortion loppuraportti. University of Joensuu, Faculty of Forestry. Research Notes 134. Pp. 58-75. (In Finnish).

Laine, J. 1989. Metsäojitettujen soiden luokittelu. Suo 40: 37-51. (In Finnish).

Lappi-Seppälä, M. 1930. Untersuchungen über die Entwicklung gleichaltriger Mischbestände aus Kiefer und Birke. Comm. Inst. For. Fenn. 15: 1-241. (In German with Finnish summary).

Lassila, I. 1926. The mechanico-technical properties of wood; their study and its objects. Reprinted from Acta For. Fenn. 186 p. (In Finnish with English summary).

Lehonkoski, N.A. 1949. Vanerikoivujemme nykyinen laatu. Metsätal. Aikakausl. 1/1949: 16-18. (In Finnish).

Lehtikangas, P. 1989. Koivusekoituksen vaikutus nuorten mäntyjen oksikkuuteen. Pro gradu -thesis. University of Joensuu, Faculty of Forestry. 55 p. + App. 2 p. (In Finnish).

Lehtimäki, J. 2002. Sahauskelpoisen harvennuskoivun korjuu ja kertymät sekä sahatavaran saanto ja laatu. Pro gradu –thesis. University of Joensuu, Faculty of Forestry. 63 p. + App. 3 p. (In Finnish).

Lehtimäki, J., Heräjärvi, H. & Verkasalo, E. 2002. Harvennuskoivu sahauksessa ja jatkojalostuksessa. In: Riekkinen, M. & Verkasalo, E, (Eds.). Itä-Suomen puunlaatu ja –käyttö. Tutkimuspäivä Kuopiossa 23.10.2001. Finnish For. Res. Inst., Research Paper 855. Pp. 23-38. (In Finnish).

Leino, E.N. 1949. Vaneriteollisuus ja sen raaka-aineet. Metsätal. Aikakausl. 1/1949: 19-20. (In Finnish).

Louna, T. & Valkonen, S. 1995. Kotimaisen raaka-aineen asema lehtipuiden teollisessa käytössä. Finnish For. Res. Inst., Research Paper 553. 38 p. (In Finnish).

Lundgren, C. 2000. Predicting log type and knot size category using external log shape data from a 3D scanner. Scand. J. For. Res. 15: 119-126.

Luostarinen, K. & Verkasalo, E. 2000. Birch as sawn timber and in mechanical further processing in Finland. A literature study. Silva Fenn. Monographs 1. 40 p.

-, Asikainen, A. & Möttönen, V. 2001. Koivusahatavaran värinmuutokset kuivauksessa. In: Luostrinen, K., Möttönen, V., Asikainen, A., Pakkanen, T., Saranpää, P. & Tolonen, Y. (Eds.). Koivun puuaineksen kemia ja värinmuutokset kuivauksessa, Konsortion loppuraportti. University of Joensuu, Faculty of Forestry. Research Notes 134. Pp. 41-57. (In Finnish).

Luostarinen, O.V. 1932. Faneripuun laatuvaatimukset ja koivumetsämme. Metsätal. Aikakausk. 9/1932: 215-220. (In Finnish).

Lutz, J. 1977. Wood Veneer: Log Selection, Cutting, and Drying. U.S. Dep. Agric., Tech. Bull. No. 1577. 137 p.

Meriluoto, J. 1965. The Influence of raw material factors on the quantity and quality of rotary cut birch veneer. Acta For. Fenn. 80(1): 1-155. (In Finnish with English summary).

Mielikäinen, K. 1980. Structure and development of mixed pine and birch stands. Comm. Inst. For. Fenn. 99(3): 1-82. (In Finnish with English summary).

- 1985. Effect of an admixture of birch on the structure and development of Norway spruce stands. Comm. Inst. For. Fenn. 133: 1-79. (In Finnish with English summary).

- 1987. Puukohtaisten tunnusten mittaaminen ja arviointi. In: Metsikkökokeiden maastotyöohjeet. Finnish For. Res. Inst. Research Paper 257. Pp: 43-65. (In Finnish).

- & Valkonen, S. 1991. Effect of thinning method on the yield of middle-aged stands in southern Finland. Folia For. 776. (In Finnish with English summary).

- & Valkonen, S. 1995. Kaksijaksoisen kuusi-koivusekametsikön kasvu. Folia Forestalia – Metsätieteen aikakauskirja 1995(2): 81-97. (In Finnish).

Mononen, K., Hiltunen, E., Heikkinen, S., Alvila, L. & Pakkanen, T. 2001. Uuteaineiden merkitys kuivauksen aiheuttamissa koivun puuaineksen värinmuutoksissa. In: Luostrinen, K., Möttönen, V., Asikainen, A., Pakkanen, T., Saranpää, P. & Tolonen, Y. (Eds.). Koivun puuaineksen kemia ja värinmuutokset kuivauksessa, Konsortion loppuraportti. University of Joensuu, Faculty of Forestry. Research Notes 134. Pp. 22-40. (In Finnish).

Mård, H. 1998. Short-term growth effects of whole-tree harvest in early thinnings of birch (Betula spp) and Picea abies. Scand. J. For. Res. 1998(13): 317-323.

Möttönen, V. 2001. Istutuskoivun ominaisuudet sahatavarana; kaatoajankohdan, varastointiajan ja kasvupaikan vaikutus saheiden värin- ja muodonmuutoksiin kuivauksessa. In: Verkasalo, E., Sipi, M., Möttönen, V. & Kärki, T. (Eds.). Kotimaisen koivun, haavan ja lepän ominaisuudet ja niiden hyödyntäminen mekaanisessa puuteollisuudessa, Tutkimuskonsortion tulosten yhteenveto. Metsäntutkimuslaitos, Helsingin yliopisto, Joensuun yliopisto. 71 p. (In Finnish).

Nepveu, G. & Velling, P. 1983a. Individual genetic variability of wood quality in Betula pendula. Folia For. 575: 1-21. (In Finnish with English summary).

- 1983b. Variabilité génétique individuelle de la Qualité du Bois chez Betula pendula Roth. Silvae Genetica 32 (1983): 37-49. (In French).

Niemistö, P. 1991. Growing density and thinning models for Betula pubescens stands on peatlands in northern Finland. Folia For. 782. 36 p. (In Finnish with English summary).

- 1995a. Influence of initial spacing and row-to-row distance on the crown and branch properties and taper of silver birch (Betula pendula). Scand. J. For. Res. 1995(10): 235-244.

- 1995b. Influence of initial spacing and row-to-row distance on the growth and yield of silver birch (Betula pendula). Scand. J. For. Res. 1995(10): 245-255.

- 1998. Ruskotäplät istutettujen rauduskoivujen rungoissa. Metsätieteen aikakauskirja – Folia Forestalia 1998(2): 133-149. (In Finnish).

-, Hukki, P. & Verkasalo, E. 1997. Kasvupaikan ja puuston tiheyden vaikutus rauduskoivun ulkoiseen laatuun 30 –vuotiaissa istutuskoivikoissa. Metsätieteen aikakauskirja – Folia Forestalia 1997(3): 349-374. (In Finnish).

Novitskaya, L.L. 1998. Structure of the wood formed during the regeneration of the tissues of birch stems. In: Kurjatko, S. & Kúdela, J. (Eds.). Wood structure and properties ’98. Arbora publishers. Pp. 33-37.

Oikarinen, M. 1983. Growth and yield models for Silver birch (Betula pendula) plantations in southern Finland. Comm. Inst. For. Fenn. 113: 1-75. (In Finnish with English summary).

Ollinmaa, P. 1955. On the anatomic structure and properties of the tension wood in birch. Acta For. Fenn. 64(3). 263 p. (In Finnish with English summary).

- 1956. Vetopuun rakenteesta ja ominaisuuksista. Paperi ja Puu 12: 603-611. (In Finnish).

Pajuoja, H. & Suihkonen, V. 1994. Raakapuun käyttö Suomessa vuonna 1993. Finnish For. Res. Inst., Department of Forest Utilisation, Forest Statistics Communication 229. 7 p. (In Finnish).

Paukkonen, K., Luostarinen, J., Asp, J. & Asikainen, A. 1999. Koivusahatavaran muodon- ja värinmuutokset kuivauksessa. Metsätieteen aikakauskirja 2/1999: 227-238. (In Finnish).

Peltola, A. 2001. (Ed.). Finnish statistical yearbook of forestry. SVT, Agriculture, forestry and fishery. Finnish For. Res. Inst. 374 p.

Piispanen, R. & Saranpää, P. 2001. Rauduskoivun varastoravintoaineet ja puuaineksen värinmuutos kuivauksessa. In: Luostrinen, K., Möttönen, V., Asikainen, A., Pakkanen, T., Saranpää, P. & Tolonen, Y. (Eds.). Koivun puuaineksen kemia ja värinmuutokset kuivauksessa, Konsortion loppuraportti. University of Joensuu, Faculty of Forestry. Research Notes 134. Pp. 7-21. (In Finnish).

Poutanen, T. 2000. Puurakentamisen mahdollisuudet. In: Seppälä, R. (Ed.). Suomen metsäklusteri tienhaarassa. Tekes publications. 138 p. (In Finnish).

Rantanen, A., Jalonen, O. P. & Pitkänen, P. 2000. Etelä-Savon lehtipuuvarojen teknistaloudellinen hyödyntäminen. Helsingin yliopiston maaseudun tutkimus- ja koulutuskeskus, Mikkeli. Publications 72. 47 p. (In Finnish).

Raulo, J. 1981. Koivukirja. Kustannus Oy. Gummerus, Saarijärvi. 132 p. (In Finnish).

- & Koski, V. 1977. Growth of Betula pendula Roth progenies in Southern and Central Finland. Comm. Inst. For. Fenn. 90(5): 1-39.

Saarikoski, J. 1954. Selluloosaa koivusta. Suomen Kuvalehti 30/1954. Pp. 9-11. (In Finnish).

Sachsse, H. 1988. Holzqualität von Birken, Die Baumart Birke und ihre anatomischen Holzeigenschaften. Holz als Roh- und Werkstoff 46: 441-446. (In German with English summary).

- 1989. Holzqualität von Birken, Strukturelle und physikalisch-mekanische Eigenschaften von Birkenhölzern. Holz als Roh- und Werkstoff 47: 27-30. (In German with English summary).

Sahatavaran kaupallinen laatulajittelu EN-1611-1 Euroopassa. 1999. Metsäteollisuus ry. 56 p. (In Finnish).

Salmi, J. 1987. Wood properties and uses of birch. Sorbifolia 18(3): 123-132. (In Finnish with English abstract).

Saramäki, J. 1977. Development of white birch (Betula pubescens Ehrh.) stands on drained peatlands in northern central Finland. Comm. Inst. For. Fenn. 91(2): 1-59.

Sarvas, R. 1949. Puumaiset koivulajimme. Metsätal. Aikakausl. 1/1949: 9-13. (In Finnish).

Siau, J.F. 1984. Transport processes in wood. Springer-Verlag, Berlin-Heidelberg-New York-Tokio. 245 p.

- 1995. Wood: Influence of moisture on physical properties. Virginia Polytechnic Institute and State University, Department of Wood Science and Forest Products. 227 p.

Siipilehto, J. 1997. Koivun kasvumallit ja niiden mukaiset tuotosennusteet. In: Niemistö, P. & Väärä, T. (Eds.). Rauduskoivu tänään – ja tulevaisuudessa, Tutkimuspäivä Tampereella 12.3.1997. Finnish For. Res. Inst., Research Notes 668: 85-101. (In Finnish).

Skaar, C. 1988. Wood-water relations. Springer-Verlag, Berlin-Heidelberg. 283 p.

Tiensuu, V. 1999. Suomen huonekaluteollisuus, lähtökohdat 2000-luvulle. Muotoilun tutkimuslaitoksen tutkimuksia 1/1999. 75 p. (In Finnish).

Tikka, P.S. 1949. Perä-Pohjolan koivikoiden laadusta. Referat: Über die Beschaffenheit der Birkenbestande in Nord-Finnland. Acta For. Fenn. 57(4): 1-34. (In Finnish with German summary).

Tomppo, E., Henttonen, H., Korhonen, K.T., Aarnio, A., Ahola, A., Heikkinen, J., Ihalainen, A., Mikkelä, H., Tonteri, T. & Tuomainen, T. 1998. Etelä-Pohjanmaan metsäkeskuksen alueen metsävarat ja niiden kehitys 1968-97. Metsätieteen aikakauskirja – Folia Forestalia 2B/1998: 293-374. (In Finnish).

-, Henttonen, H., Korhonen, K.T., Aarnio, A., Ahola, A., Heikkinen, J. & Tuomainen, T. 1999a. Keski-Suomen metsäkeskuksen alueen metsävarat ja niiden kehitys 1967-96. Metsätieteen aikakauskirja 2B/1999: 309-387. (In Finnish).

-, Henttonen, H., Korhonen, K.T., Aarnio, A., Ahola, A., Heikkinen, J. & Tuomainen, T. 1999b. Pohjois-Savon metsäkeskuksen alueen metsävarat ja niiden kehitys 1967-96. Metsätieteen aikakauskirja 2B/1999: 389-462. (In Finnish).

-, Korhonen, K.T., Henttonen, H., Ihalainen, A., Tonteri, T. & Heikkinen, J. 1999c. Kymen metsäkeskuksen alueen metsävarat ja niiden kehitys 1966-98. Metsätieteen aikakauskirja 3B/1999: 603-681. (In Finnish).

-, Korhonen, K.T., Ihalainen, A., Tonteri, T., Heikkinen, J. & Henttonen, H. 2000. Skogstillgångarna inom Kustens skogscentral och deras utveckling 1965-98. Metsätieteen aikakauskirja 1B/2000: 93-232. (In Swedish).

-, Henttonen, H., Ihalainen, A., Tonteri, T. & Tuomainen, T. 2001. Etelä-Savon metsäkeskuksen alueen metsävarat 1966-2000. Metsätieteen aikakauskirja 2B/2001: 309-388. (In Finnish).

Tsoumis, G. (1991). Science and technology of wood. Structure, properties and utilization. Van Nostrand Reinhold, New York. 494 p.

Vadla, K. 1999. Finérutbytte og –kvalitet hos stammekvistet og ikke stammekvistet furu, bjørk og osp. Norsk institutt for skogforskning, Rapport 13/1999. 21 p. + App. 3 p. (In Norwegian).

-, Berg, N. & Foslie, M. 1982. Birch as a raw material and building material (a literature survey). Norsk institutt för skogforskning, Rapport 6/1982. 60 p. (In Norwegian with English summary).

Valkonen, S. 2000. Kuusen taimikon kasvattamisen vaihtoehdot Etelä-Suomen kivennäismailla: Puhdas kuusen viljelytaimikko, vapautettu alikasvos ja kuusi-koivusekataimikko. Finnish For. Res. Inst., Research Papers 763. 83 p. + 4 Articles. (In Finnish).

- & Valsta, L. 2001. Productivity and economics of mixed two-storied spruce and birch stands in Southern Finland simulated with empirical models. For. Ecol. Manage. 140(2-3): 133-149.

Velling, P. 1979. Wood density in two Betula pendula Roth Progeny trials. Folia For. 416. 24 p. (In Finnish with English summary).

Verkasalo, E. 1990. Birch and aspen as a raw material for mechanical forest industries in the United States. Finnish For. Res. Inst., Research Paper 367. 93 p. (In Finnish with English summary).

- 1997a. Evaluating the potential of European white birch (Betula pubescens) for veneer and plywood by timber and wood quality. In: Nepveu, G. (Ed.). Proceedings of the IUFRO Division 6 WP5.01.04 Biological Improvement of Wood Quality Workshop “Connection between silviculture and wood quality through modelling and simulation software”. Kruger National Park, South Africa, 26-31 August, 1996, pp. 431-439. INRA-Nancy, France.

- 1997b. Quality of European white birch (Betula pubescens Ehrh.) for veneer and plywood. Finnish For. Res. Inst., Research Paper 632. 483 p. + App. 59 p. (In Finnish with English abstract).

- 1998a. Raudus- ja hieskoivun laatu puuaineen tiheyden perusteella arvioituna. In: Niemistö, P. & Väärä, T. (Eds.). Rauduskoivu tänään – ja tulevaisuudessa, Tutkimuspäivä Tampereella 12.3.1997. Finnish For. Res. Inst., Research Paper 668. Pp. 127-140. (In Finnish).

- 1998b. Koivu, haapa ja leppä mekaanisen puuteollisuuden raaka-aineena: käytön näkymiä ja tutkimuksen ongelmanasettelua. Metsätieteen aikakauskirja – Folia Forestalia 2/1998: 254-257. (In Finnish).

- 1999. Haavan ominaisuudet ja käyttömahdollisuudet mekaanisessa puunjalostuksessa. In: Hynynen, J. & Viherä-Aarnio, A. (Eds.). Haapa – monimuotoisuutta metsään ja metsätalouteen. Vantaan tutkimuskeskuksen tutkimuspäivä Tammisaaressa 12.11.1998. Finnish For. Res. Inst., Research Paper 725. Pp. 107-122. (In Finnish with Swedish abstract).

Viherä-Aarnio, A. & Velling, P. 1999. Growth and stem quality of mature birches in a combined species and progeny trial. Silva Fenn. 33(3): 225-234.

Wagenführ, R. 1996. Holzatlas. 4. neubearb. Aufl. Leipzig, Fachbuchverl. 688 p. (In German).

Walldén, P. 1934. Tutkimuksia koivupuun anatoomisen rakenteen ja teknillisten ominaisuuksien keskinäisestä riippuvaisuudesta solumittauksien perusteella. Acta For. Fenn. 40: 329-366. (In Finnish with German summary).

Wegelius, E. 1943. Puristettu puu. Metsätal. Aikakausl. 6-7/1943: 135-139. (In Finnish).

Werner, M., Ryttler, L. & Stener, L.G. 2000. Improved utilization of hardwoods for secondary conversion. SkogForsk Redogörelse 3/2000, Uppsala, Sweden. 28 p. (In Swedish with English summary).

Vilkon Oy. 1998. Sahakoivun laatuvaatimukset. 1.1.1998. Mimeograph. 1 p. (In Finnish).

Ylioja, T. 2000. Relationship between Phytobia betulae and its host tree Betula spp. University of Joensuu, Faculty of Forestry. 26 p. + 5 Articles.

-, Saranpää, P., Roininen, H. & Rousi, M. 1998. Larval tunnels of Phytobia betulae (Diptera: Agromyzidae) in birch wood. J. Econ. Entom. 91: 175-181.

-, Roininen, H., Heinonen, J. & Rousi, M. 2000. Susceptibility of Betula pendula clones to Phytobia betulae, a dipteran miner of birch stems. Canad. J. For. Res. 30: 1824-1829.

Zobel, B.J. & van Buijtenen, J.P. 1989. Wood variation – its causes and control. Springer Verlag, Berlin. 363 p.

Total of 163 references

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Technical Properties of Mature Birch (*Betula pendula* and *B. pubescens*) for Saw Milling in Finland

Henrik Heräjärvi

Heräjärvi, H. 2001. Technical properties of mature birch (*Betula pendula* and *B. pubescens*) for saw milling in Finland. Silva Fennica 35(4): 469–485.

The purpose of this study was to investigate the variation in selected technical properties of mature (age > 60 years) birch stems in southern and central Finland. Technical properties were defined as the natural external characteristics that cause differences in the usability of a certain section of stem in the mechanical wood industry, saw milling in particular.

On mineral soils, birch stems in mixed stands were slightly larger than those in pure birch stands. On peatlands, however, birch stems in pure stands were larger than those in mixed stands. The average stem form of silver birch was straighter than that of white birch. Small-sized log sections of white birch, as well as those of codominant silver birch, typically contain many dead knots. On mineral soils, coniferous admixture had a positive effect on self-pruning of white birch. Self-pruning of silver birch was as good in pure birch stands as in mixed stands of spruce and birch. Occurrence of decay did not differ significantly between the two birch species.

Not only silver birch, due to the growth and yield of the stand, but also vigorous and good-quality white birch, because of the possibility to provide high-quality logs, can be maintained profitably as an admixture in coniferous forests until final cutting.

Keywords silver birch, white birch, technical properties, saw milling, log, small-sized log
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1 Introduction

In Finland, two birch species are used industrially in mechanical wood processing: silver birch (*Betula pendula* Roth) and white birch (*Betula pubescens* Ehrh.). Birch makes up 14.6 percent of the total volume of growing stock in Finland. Regionally, 67 percent of the birch stock (186 mill. m^3) and 73 percent (9.4 mill. m^3) of the annual growth of birch is located in southern Finland (Sevola 1999). Mature, pure birch stands are, almost without exception, of natural origin and situated in former burnt-over clearings. Silver birch makes up 32 percent of the total birch stock in southern Finland, which is the predominant production area for large-dimensioned birch. As silver birch makes up only 9 percent of the birch stock in northern Finland, white birch makes up most of the total birch supply in the country (Sevola 1999).

According to Niemistö (1991), only 45 percent of the supply of white birch grows in birch-dominated stands, the rest being an admixture in stands dominated by Scots pine or Norway spruce. Most of the silver birch supply also grows in mixed forests (Verkasalo 1997). Of the forest land area, silver birch is the dominant species on only 1.9 percent of the whole country and on 3.3 percent in southern Finland, whereas the corresponding percentages for white birch are 5.9 and 4.3 (Sevola 1999). Silver birch usually grows on fertile mineral soils; white birch also survives on peatlands in nutrient-poor and wet conditions.

Along with the raw material resources, the plywood factories and sawmills, which use birch, are also located in southern and central Finland. Birch is traditionally used in large quantities for veneer and plywood manufacture, 1–1.5 million m^3 annually since the 1960's (e.g., Heiskanen 1966, Verkasalo 1997). Of the annual volume of birch lumber production (50 000–100 000 m^3), more than 70 percent is produced in small private saw mills (Sevola 1999, Luostarinen and Verkasalo 2000). Most of the sawn wood is produced from large logs (top diameter ≥ 18 cm), where the aim is to obtain high-quality products with no or few knots. Some entrepreneurs who manufacture lumber with sound knots for furniture and parquetry have recently based their production on small-sized birch logs. Considering saw mills it is of special importance to obtain logs with no deformations such as crooks or forks.

The benefits of birch admixture for coniferous forests have been studied e.g., by Mielikäinen (1980, 1985), Hägg (1988), Lehtikangas (1989), Mielikäinen and Valkonen (1995), and Valkonen (2000). These studies examined mainly the effects of birch admixture on the growth and yield of conifers.

In most Scandinavian studies, the stem of silver birch is considered to be straighter than that of white birch (e.g., Kujala 1946, Heiskanen 1957, Verkasalo 1997). On the other hand, results on type and number of knots in different birch species vary. For example, Kujala (1946) and Heiskanen (1957) stated that knots are thicker in silver birch than in white birch. Verkasalo (1997) found the same type of difference, noting, in addition, that the difference increases with the age of the tree. The technical properties of birch veneer logs and their influence on the recovery and quality of rotary cut veneer were studied, e.g., by Heiskanen (1966), Meriluoto (1966) and Verkasalo (1997). The technical properties and quality of young (age <50 a) birch, as well as their growth and yield were studied, e.g., by Niemistö (1994, 1997a, 1997b), Niemistö et al. (1997), Verkasalo (1997) and Viherä-Aarnio and Velling (1999).

Several partially contradictory studies were made concerning the differences between the technical properties of the birch species. Silver birch were found to grow faster on fertile sites, which also explains why, on average, silver birch stems are bigger than those of white birch at the same age. So far, however, no studies have focused on the needs of sawmills. Nevertheless, according to, e.g., Kataikko (1996), the biggest problem in wood procurement for the Finnish birch saw mills is the shortage of high-quality raw material. The availability of raw material fluctuates over time and varies greatly in quality (Kivistö et al. 1999).

The purpose of this study was to investigate the variation in selected technical properties of mature (age >60 years) birch stems in southern and central Finland. Technical properties were defined as the natural external characteristics that cause differences in the usability of a certain section of stem in the mechanical wood industry, saw milling in particular. In this study, both birch species were studied and the most important growing conditions (forest site, stand structure by species) were taken into consideration. The results are intended to meet the needs and potential applications of the users of large or small-sized birch logs.

2 Material and Methods

Test stands representing typical birch stands in each planned stratum were sampled for this study. The material was composed of 261 sample trees measured and felled from 20 mature (age>60 years) birch stands located in southern and central Finland. The locations of the stands are presented in Fig. 1, and some key characteristics are shown in Table 1. Sample trees from at least three stands were included in each of the following, predetermined strata:

- Pure silver birch stand, mineral soil (Stratum 1)
- Mixed silver birch–spruce stand, mineral soil (Stratum 2)
- Pure white birch stand, mineral soil (Stratum 3)
- Mixed white birch–spruce stand, mineral soil (Stratum 4)
- Pure white birch stand, peatland (Stratum 5)
- Mixed white birch–pine stand, peatland (Stratum 6).

Of the mineral soils, OMT and MT types (Lehto and Leikola 1987) were represented. Of the drained peatland forest site types, the herb-rich type (Rhtkg) and *Vaccinium myrtillus* type I (Mtkg) (Laine 1989) were included in the study.

Of the stands, thirteen were owned by the Finnish Forest Research Institute, six were privately owned and one was owned by the Forest and Park Service of Finland. The stands for each stratum were selected according to requirements

Table 1. Key characteristics of the sample stands.

Stand nr. (Stratum)	Tree species	Site	Age, a (mean)	Basal area, m^2/ha	$D_{1.3}$, mm (mean)	Height, dm (mean)
1 (4)	White birch	OMT	80	8	243	252
	Spruce		80	17	268	252
2 (4)	White birch	OMT	75	11	242	241
	Spruce		73	13	261	249
3 (1)	Silver birch	MT	77	28	208	239
4 (1)	Silver birch	OMT	90	34	253	271
5 (2)	Silver birch	OMT	90	12	250	260
	Spruce		90	26	210	220
6 (2)	Silver birch	MT	90	11	294	258
	Spruce		72	18	232	226
7 (5)	White birch	Mtkg	83	17	244	230
8 (5)	White birch	Mtkg	80	17	186	169
9 (6)	White birch	Mtkg	80	8	183	169
	Pine		90	16	255	192
10 (6)	White birch	Rhtkg	80	12	200	185
	Pine		98	18	271	212
11 (3)	White birch	MT	60	15	257	218
12 (3)	White birch	OMT	85	19	262	217
13 (3)	White birch	MT	70	15	182	230
14 (4)	White birch	OMT	70	9	224	217
	Spruce		70	18	255	226
15 (4)	White birch	MT	75	6	239	224
	Spruce		100	26	281	235
16 (5)	White birch	Mtkg	60	16	200	179
17 (1)	Silver birch	OMT	90	20	290	265
18 (2)	Silver birch	MT	70	4	232	207
	Spruce		100	27	264	228
19 (2)	Silver birch	OMT	75	13	281	255
	Spruce		79	8	253	222
20 (6)	White birch	Mtkg	78	5	240	241
	Pine		115	25	286	245
All stands: birch			76	20	231	224
Birch / conifer			78 / 86	10 / 19	234 / 256	224 / 224

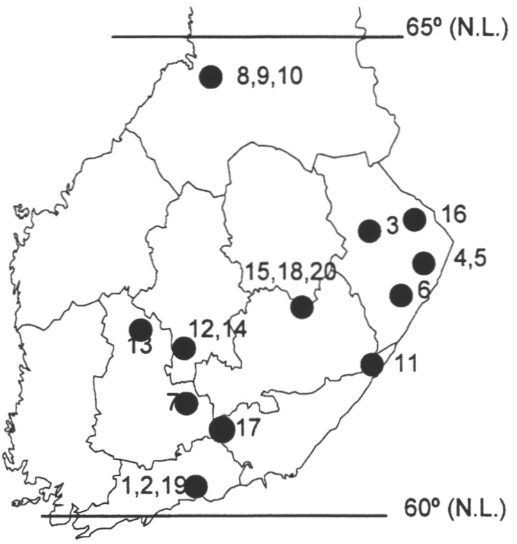

Fig. 1. Locations of the sample stands in southern and central Finland.

for minimum area, age and location. For each stand, good or fair silvicultural condition was also required. The locations of the stands followed the natural distribution of the birch resources.

After selection of the sample stand, the material was sub-divided into categories by forest site type and crown layer of individual sample tree. Thus, three different levels of growing conditions were studied: *stratum*, *site* and *crown layer*. Sample trees represented both dominant and codominant trees in each stratum. Sites represented both *Oxalis-Myrtillus* type (OMT) and *Myrtillus* type (MT) on mineral soil and herb-rich site (Rhtkg) and *Vaccinium myrtillus* type I (Mtkg) as corresponding drained peatland (Lehto and Leikola 1987, Laine 1989). Pure white birch stands on herb-rich sites were not, however, included in this study because no suitable stands were found (Table 2).

In each stand, *basal area* was measured for each tree species, as well as *number of stems per hectare* and *mean height* and *diameter*. Mature trees and undergrowth were measured separately. On average, 13 birch were selected as sample trees in a stand using stratified random sampling. The sample trees represented the entire diameter range from 14 cm upwards.

Table 2. Number of sample trees by stratum, site and crown layer.

Stratum	Site				
	OMT / Rhtkg Crown layer		MT / Mtkg Crown layer		
	1	2	1	2	
	Count				Σ
1	18	8	14	4	44
2	19	6	14	6	45
3	8	2	27	9	46
4	17	9	3	18	47
5			27	18	45
6	5	10	2	17	34
Σ	67	35	87	72	261

Before felling, the following characteristics were measured or evaluated for each sample tree:

- minimum and maximum $d_{1.3}$, mm
- maximum butt crook between 0 and 4 m, mm/4m
- crown layer (1 = dominant tree, 2 = codominant tree)
- assessment of quality of butt log (class 1, 2 or 3, reject)
- assessment of quality of intermediate and top logs (class 1, 2 or 3, reject).

For each sample tree, *distance* (dm) from, *direction* (°) to, $d_{1.3}$ (mm) and *tree species* of the five closest neighbour trees representing approximately similar age and size class were measured in order to determine the possible effects of competition on the variables studied. The *competition index* was calculated according to Hegyi (1974):

$$CI_j = \sum_{i=1}^{n} \left(d_i / d_j\right) / D_{ij} \tag{1}$$

where CI_j indicates the competition directed towards tree j, n is the number of measured neighbour trees, d_i is the diameter at breast height of neighbour tree i, d_j is the diameter at breast height of tree j, and D_{ij} is the distance between trees i and j.

After felling, the true length and the vertical locations of diameters 24, 20, 18, 14, 12, 10, and 7 cm were measured for each sample tree. The diameters represent alternative minimum commercial diameters of certain assortments made from birch stems. The stems were flush delimbed (i.e., close to the surface), and the knot bumps, scars and grooves were cut open so that their true appearance in the wood could be verified. Furthermore, the stem was systematically cut into two- or four-metre bolts. Each of the following characteristics was measured separately for each two-metre section from the stump to the height where the diameter was 12 cm: 1) the presence of heart-rot was verified at the cross-cut sections; 2) knot bumps, fresh, dry and rotten knots and vertical branches were counted; 3) the locations of the lowest dead and fresh knots were measured, as well as the location of the highest dead knot; 4) the diameter of the thickest knot of each knot type was measured; 5) the defects in stem form, including crook (mm/2m = maximum deviation from straight line between the base and the top of a bolt) were evaluated or measured, as were the defects on the surface of an individual log.

The crown limits were determined on the basis of the true type of knots; i.e., types of knots were defined from the surface of a bolt after flush delimbing. *Knotfree section* means the stem part from the stump to the lowest knot bump or knot. *Section of dead knots* means the stem part from the lowest knot bump or dead knot to the lowest fresh knot. *Section of fresh and dead knots* means the stem part from the lowest fresh knot to the beginning of the *fresh-knot section.* The top of the tree is the section that contains only fresh knots; at most, one small ($d \leq 10$ mm) dead knot was allowed per metre.

In this study, the *log section* was defined as the stem section where the diameter exceeds 18 cm. The *small-sized log section* was defined as the stem section where the diameter is 12 to 18 cm. The *tapers* (mm/m) for the log section (T_l) and small-sized log section (T_{sl}) (mm/m) were calculated according to the following formulae:

$$T_l = \frac{d_{1.3} - 180\,(\mathrm{mm})}{h_{18} - 1.3\,(\mathrm{m})} \tag{2}$$

$$T_{sl} = \frac{180 - 120\,(\mathrm{mm})}{h_{12} - h_{18}\,(\mathrm{m})} \tag{3}$$

where $d_{1.3}$ indicated the diameter at breast height (mm), h_{18} the height where the diameter was 180 mm (m) and h_{12} the height where the diameter was 120 mm (m). Only those trees where the log section or the small-sized log section was longer than two metres were included in the calculations.

The volumes of log and small-sized log sections were calculated by Newton's formula:

$$V = \frac{1}{6}\sum_{i=1}^{n}\left(g_{0i} + 4g_{0.5li} + g_{1i}\right)l_i \tag{4}$$

where g_{0i} indicates the basal area at the butt end of section i, $g_{0.5li}$ the basal area in the midpoint of section i and g_{1i} the basal area at the top of section i. The length of section i is marked as l_i. According to Kangas and Päivinen (1994), Newton's formula produces unbiased estimates for the volumes of trees or bolts.

Those variables that were not normally distributed were either *logarithm* or *square root* transformed for the statistical analyses. When the transformed variables were returned into their original scales, the biases were minimised by adding either $s^2/2$ (with *logarithm* transformed variables) or s^2 (with *square root* transformed variables) to the transformed predicted values before the predicted values were calculated in the original scale (Lappi 1993).

The between-stand variation in those background factors that could have effects on the studied properties of sample trees was equalised by analysis of covariance. The principle of analysis of covariance is to use information about the relationship of the variable (Y) for the covariant (X) in order to estimate what would be the values of the variable in each treatment, if all measurements were made at the same value of X (Underwood 1997). Covariants, which turned out to be significant, were included in the model. In other words, differences between stands were adjusted to the mean value of the covariant. The covariants tested were:

- Number of stems / hectare (mean 516)
- Basal area, m^2/ha (mean 25.2)
- Competition Index (mean 0.133)
- Mean age of birch, a (mean 77)

Due to the uniformity of the results, in each analysis stratum (1–6), site (1 and 2) and crown layer (1 and 2) were separated systematically, whether there turned out to be significant differences between the categories or not. The difference was determined to be significant at the

Table 3. ANCOVA-table for the analyses on diameter and volume (F = fixed factor; C = covariant; I = interaction).

Variable	Source	df	MS	F	p
$d_{1.3}$, mm R^2=0.524	Stratum (F)	5	8576.776	5.814	0.000
	Site (F)	1	1.553	0.001	0.974
	Crown layer (F)	1	87359.145	59.222	0.000
	Mean age (C)	1	16832.431	11.411	0.001
Tree volume, dm^3 R^2=0.654	Stratum (F)	5	210.033	14.964	0.000
	Site (F)	1	0.342	0.024	0.876
	Crown layer (F)	1	838.509	59.739	0.000
	Mean age (C)	1	254.631	18.141	0.000
	Nr of stems / ha (C)	1	198.298	14.128	0.000
	Stratum × crown layer (I)	5	33.314	2.373	0.040

0.05 risk level. Only significant interactions are presented along with the other results in the ANCOVA-tables.

Table 4. Means (and *standard errors*) of stem diameters at breast height by stratum, site and crown layer.

Stratum	Site			
	OMT / Rhtkg Crown layer		MT / Mtkg Crown layer	
	1	2	1	2
	$d_{1.3}$, mm			
1	273 (*11*)	229 (*14*)	258 (*10*)	233 (*19*)
2	292 (*9*)	221 (*16*)	300 (*10*)	208 (*16*)
3	253 (*14*)	178 (*28*)	247 (*8*)	225 (*13*)
4	259 (*9*)	225 (*13*)	266 (*22*)	221 (*9*)
5			236 (*8*)	182 (*18*)
6	228 (*17*)	199 (*12*)	220 (*27*)	179 (*9*)

3 Results

3.1 Stem Size

Stands were adjusted to conform to each other by using mean age of birch trees as covariant. Analyses of covariance concerning the diameters and volumes are presented in Table 3. Diameters at breast height (Table 4) differed significantly between the strata and the crown layers. Differences between the sites, however, were not significant.

The largest trees were the dominant silver birch in mixed stands (stratum 2). On MT sites, silver birch stems were even slightly thicker than on OMT sites. There is, however, no logical explanation for this finding.

The stem volumes for the strata 1 to 6 were adjusted by using mean age of the birch and number of stems per hectare as covariants. Volumes differed significantly between the strata and the crown layers. Differences between sites were not significant. A significant interaction was observed between the stratum and the crown layer. Volumes of log section and small-sized log section were not satisfactorily predictable on the basis of stand-level information. Thus, in Fig. 2 the percentages of log and small-sized log volumes are presented according to the original, non-adjusted data. In the case of large silver birch, the theoretical proportion of log section, assessed with the diameter as the only limitation, was nearly 90% of the total volume of the tree. The percentage of small-sized logs was greatest in small trees that had only a small log section.

3.2 Stem Form

On average, in 50 percent of silver birch the log section was assessed as straight. Considering white birch on mineral soils, the corresponding percentage was 41 and on peatland 35. Fig. 3 presents the distributions of trees by assessed shape of the log section and the small-sized log section. The proportion of straight small-sized log sections was largest in pure birch stands on

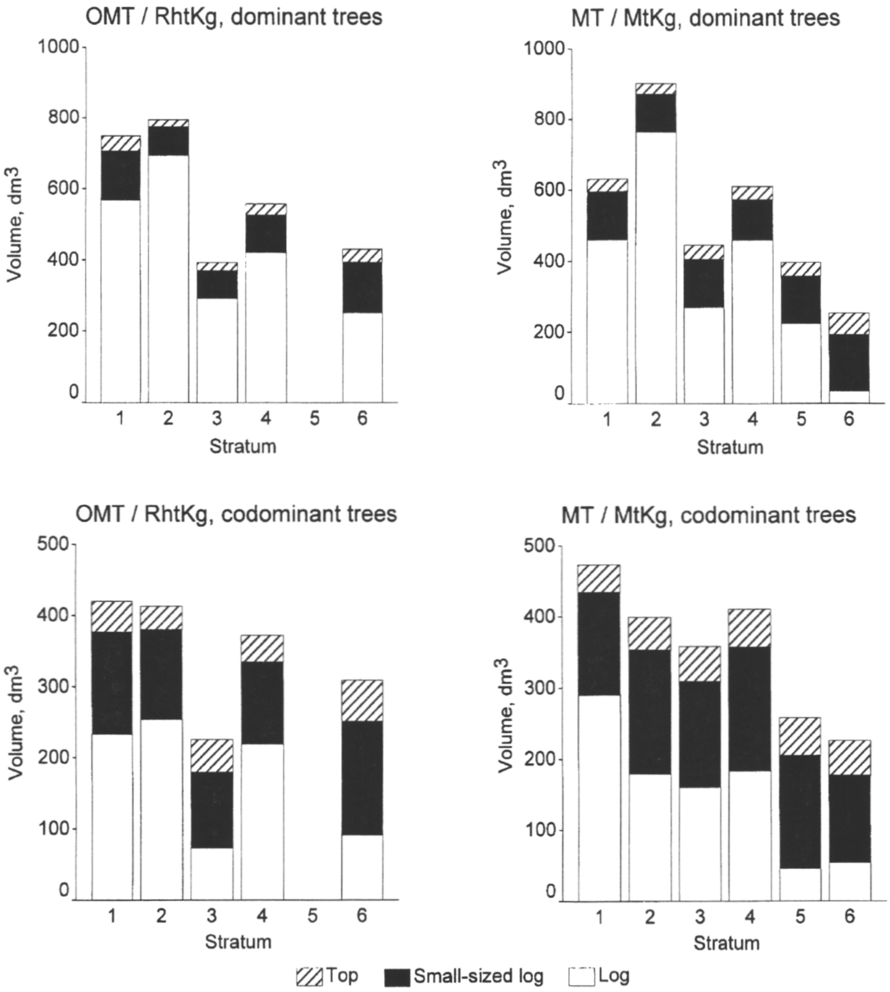

Fig. 2. Mean volumes of log, small-sized log and top sections of stem by stratum, site and crown layer. Notice the different scales of volume for dominant and codominant trees.

mineral soils (40%). The proportion of bolts that were deformed by vertical branches was very large in pure white birch stands on mineral soils. On the other hand, on mineral soils, both silver birch and white birch had a straight small-sized log section more frequently in pure birch stands than in mixed stands.

Taper (mm/m) was calculated separately for the log section (diameter > 18 cm) and the small-sized log section ($18 > d \geq 12$ cm). None of the covariants studied had a significant effect on the taper of the log section. On the other hand, tapers of small-sized log sections were adjusted to conform to each other by using the average competition index as a covariant. The ANCOVA-table for the stem form characteristics is presented in Table 5.

The taper of the log section ranged from 12 to 24 mm/m (mean 16 mm/m). Tapering of the log section was largest in white birch stems on peatlands. Differences between the strata were significant, but sites and crown layers did not differ significantly from each other. In mixed stands, average taper of the log section was 5 to 15 percent smaller than in pure birch stands. Butt swelling was, as expected, most obvious in the

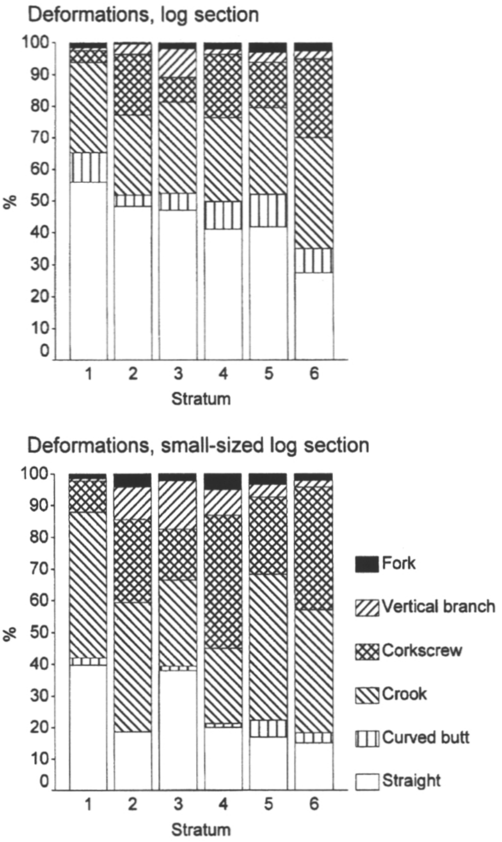

Fig. 3. Distributions of birch stems by the deformation of log ($d \geq 18$ cm) and small-sized log ($12 \leq d < 18$ cm) section by stratum, assessed in two-metre sections.

largest silver birch stems.

The taper of the small-sized log section ranged from 11 to 16 mm/m (mean 13 mm/m). Small-sized log tapers differed significantly between strata. Differences between sites and crown layers, however, were not significant. In general, the variation in small-sized log taper was small and corresponded to the average taper of the whole stem. In white birch stems on peatlands, the small-sized log section consisted mainly of butt logs, whereas in birch stems on mineral soils, the small-sized log section was located in the top of the stem, because of the larger size of trees. This could not, however, be seen from the results on taper.

Amount of butt crook from stump to height of four metres ranged from 30 to 67 mm (mean 47 mm). No significant differences could be seen between the strata and the crown layers. Sites, on the other hand, differed significantly from each other. On average, the four-metre butt section of trees growing on OMT or Rhtkg sites had a 10 to 20 mm larger crook than trees on MT or Mtkg sites.

3.3 Crown Limits

Coniferous mixture had virtually no effect on the heights of the crown limits of silver birch. On the other hand, white birch was considerably better

Table 5. ANCOVA-table for the analyses of taper and crookedness of log section and small-sized log section (F = fixed factor; C = covariant; I = interaction).

Variable	Source	df	MS	F	p
Taper of log section, mm/m R^2=0.285	Stratum (F)	5	73.837	4.933	0.000
	Site (F)	1	24.479	1.635	0.203
	Crown layer (F)	1	21.097	1.409	0.237
	Stratum × site (I)	4	51.316	3.428	0.010
Taper of small-sized log section, mm/m R^2=0.225	Stratum (F)	5	27.965	4.583	0.001
	Site (F)	1	10.874	1.782	0.183
	Crown layer (F)	1	0.857	0.140	0.708
	CI (C)	1	186.800	30.615	0.000
Crook, mm/2m R^2=0.152	Stratum (F)	5	0.028	0.734	0.599
	Site (F)	1	0.509	13.547	0.000
	Crown layer (F)	1	0.001	0.041	0.840
	Basal area (C)	1	0.540	14.389	0.000
	Stratum × site (I)	4	0.100	2.561	0.039

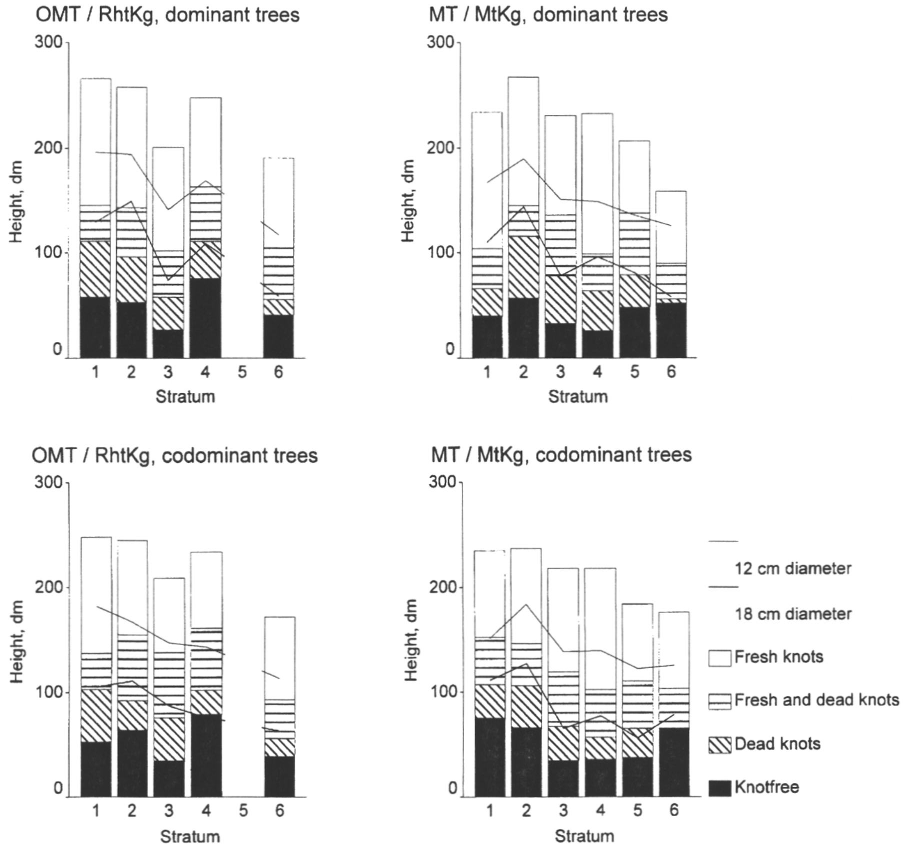

Fig. 4. Mean heights of crown limits, and log and small-sized log sections by stratum, site and crown layer.

naturally pruned in mixed stands than in pure birch stands. In general, the log section contained no knots or, at its most, some knot bumps or dead knots on mineral soils. On drained peatlands, the log section was usually totally knotfree, which is due to the small size of the trees and, consequently, the small size of log section. Fig. 4 presents average crown limits by stratum, site and crown layer. Mean vertical positions of log and small-sized log diameters are also presented. The total height of the bar shows the mean height of birch stems in the stratum in question.

According to the analysis of covariance (Table 6), the length of the knotfree section differed significantly between strata. Differences between sites and crown layers were not significant. Competition index was the only significant covariant. Thus, the more competition occurs with birch, the more effective the self-pruning process is. The growth of the tree, on the other hand, decreases as the number of living branches decreases.

The lengths of the stem sections that contained only dead knots differed significantly between strata, sites and crown layers. Competition index was used as covariant. The lengths of stem sections with dead and fresh knots also differed significantly between strata and sites. Differences between crown layers, on the other hand, were not significant. In this analysis, basal area was used as covariant.

Significant interactions were observed between strata and site in the analyses of all crown limits (Table 6).

Table 6. ANCOVA-table for analyses of the crown limits (F = fixed factor; C = covariant; I = interaction).

Variable	Source	df	MS	F	p
Length, dm					
Knotfree	Stratum (F)	5	1957.133	4.475	0.001
R^2=0.357	Site (F)	1	534.170	1.221	0.270
	Crown layer (F)	1	804.377	1.839	0.176
	CI (C)	1	7026.454	16.066	0.000
	Stratum × site (I)	4	3938.450	9.005	0.000
Dead knots	Stratum (F)	5	4686.057	11.165	0.000
R^2=0.487	Site (F)	1	1950.046	4.646	0.032
	Crown layer (F)	1	2085.732	4.970	0.027
	CI (C)	1	4024.043	9.588	0.002
	Stratum × site (I)	4	3555.500	8.471	0.000
Dead and fresh knots	Stratum (F)	5	2998.169	3.261	0.007
R^2=0.368	Site (F)	1	6471.431	7.039	0.009
	Crown layer (F)	1	1287.369	1.400	0.238
	Basal area (C)	1	6997.418	7.612	0.006
	Stratum × site (I)	4	3976.748	4.326	0.002
Whole tree	Stratum (F)	5	15063.826	56.263	0.000
R^2=0.826	Site (F)	1	956.878	3.574	0.060
	Crown layer (F)	1	9057.616	33.830	0.000
	CI (C)	1	1402.225	5.237	0.023
	Mean age (C)	1	9521.856	35.564	0.000
	Nr of stems / ha (C)	1	3951.689	14.759	0.000
	Stratum × site × crown layer (I)	14	937.646	3.502	0.000

3.4 Number and Size of Knots

The number of fresh knots per log metre was adjusted by using the average competition index as covariant. The strata differed significantly from each other in number of fresh knots per log metre (Table 7). On the other hand, differences between sites and crown layers were not significant. The number of fresh knots per metre in the small-sized log was also adjusted by using the competition index. Differences between the strata were significant, contrary to those of the sites and crown layers.

The number of dry knots per log metre also differed significantly between strata, but sites and crown layers did not. The competition index was used as covariant. Number of dry knots per small-sized log metre was also adjusted by using the competition index. Differences between strata, sites and crown layers were insignificant.

The number of rotten knots per log metre was adjusted by using the mean age of birch and the number of stems per hectare as covariants. The strata differed from each other but the sites and crown layers did not. No significant covariants were found for the number of rotten knots per metre in the small-sized log. Differences between strata, sites and crown layers were also insignificant.

The number of knot bumps per log metre was adjusted by using the average competition index. Differences between strata were significant; on the other hand, sites and crown layers did not differ significantly from each other. The number of knot bumps per metre in the small-sized log was adjusted by using the average competition index and the mean age of birch. Differences between strata were significant; conversely, site and crown layer did not have any significant effect.

The number of vertical branches per log metre was so small that analysis of covariance was not useful for verifying the differences. The number of vertical branches per metre in the small-sized log was analysed, however, and the differences between strata were significant. More than 90 percent of all vertical branches were fresh.

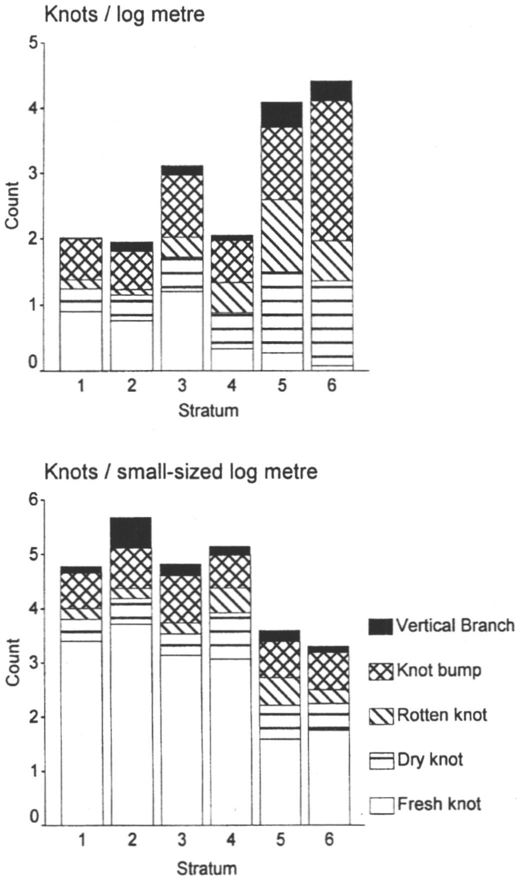

Fig. 5. Average number of different kinds of knots per log and small-sized log metre, by stratum.

The log section contained, on average, less than one fresh knot per metre. In strata 4 to 6, the number of fresh knots on the log section was of no practical importance. Vertical branches, as well as knot bumps, were more common in birch grown on peatland than in those grown on mineral soils. Dry and rotten knots were more common in the log sections of white birch than silver birch. On average, the total number of knots per log metre was four on peatlands, three in pure white birch stands on mineral soils and two in silver birch stands as well as in mixed stands of white birch and spruce on mineral soils (Fig. 5).

In the small-sized log section, fresh knots were dominant on mineral soils. In white birch on peatlands, 50 to 60 percent of the knots were also fresh (Fig. 5). On mineral soils, the differences between silver birch and white birch were small. On average, the total number of knots per metre in a small-sized log was five on mineral soils and three on peatlands. Knot bumps were common not only on the lower parts of the stem but also between fresh knots in the top part of the stem.

The diameter of the thickest fresh knot in the log section varied from 25 mm in stratum 6 to 43 mm in stratum 2. Differences between sites and crown layers were not significant (Table 8). On mineral soils, the diameter of the thickest fresh knot in the log section differed only slightly between silver birch and white birch (39 mm and 38 mm, respectively). In the small-sized log section, diameter of the thickest fresh knot varied from 29 mm in stratum 3 to 42 mm in stratum 1. On mineral soils, the thickest fresh knot in the small-sized log section of silver birch was, on average, 41 mm and that of white birch was 31 mm. When the size of the tree was taken into account, the differences in the size of fresh knots between the two birch species practically disappeared.

The diameter of the thickest dry knot in the log section varied from 16 mm in stratum 6 to 22 mm in stratum 1. On mineral soils, dry knots in the log section of silver birch were, on average, 4 mm thicker than those of white birch. In principle, the sizes of dry knots in the log section differed only slightly between strata. In a small-sized log section, the diameter of the thickest dry knot varied from 13 mm in stratum 6 to 21 mm in stratum 5. On mineral soils, diameter of the thickest dry knots in the small-sized log section did not differ between the birch species.

The diameter of the thickest rotten knot in the log section varied from 17 mm in stratum 3 to 30 mm in stratum 1. In general, rotten knots were bigger in the log section of silver birch than in that of white birch. Mean difference between the two birch species was 9 mm on mineral soils, and 7 mm altogether, respectively. The size of the thickest rotten knot in the small-sized log section varied from 13 mm in stratum 6 to 22 mm in stratum 2. In the small-sized log section, rotten knots were considerably bigger in silver birch than in white birch.

Only a few vertical branches appeared in the log section of codominant trees. In dominant trees, the diameter of the thickest vertical branch

Table 7. ANCOVA table for analyses of the number of different type of knots per metre in the log and small-sized log (F = fixed factor; C = covariant; I = interaction).

Variable	Source	df	MS	F	p
Knots per metre in the log section					
Fresh	Stratum (F)	5	1.501	2.849	0.017
R^2=0.346	Site (F)	1	0.409	0.776	0.379
	Crown layer (F)	1	0.391	0.742	0.390
	CI (C)	1	5.876	11.155	0.001
Dry	Stratum (F)	5	3.048	5.501	0.000
R^2=0.310	Site (F)	1	0.835	1.508	0.221
	Crown layer (F)	1	0.158	0.285	0.594
	CI (C)	1	6.594	11.902	0.001
Rotten	Stratum (F)	5	3.044	11.104	0.000
R^2=0.371	Site (F)	1	0.154	0.563	0.454
	Crown layer (F)	1	0.000	0.000	0.989
	Mean age (C)	1	1.100	4.011	0.047
	Nr of stems / ha (C)	1	3.719	13.565	0.000
Knot bumps	Stratum (F)	5	4.126	4.307	0.001
R^2=0.438	Site (F)	1	0.791	0.825	0.365
	Crown layer (F)	1	0.043	0.045	0.832
	CI (C)	1	28.302	29.546	0.000
	Stratum × site (I)	4	5.268	5.500	0.000
	Stratum × site × crown layer (I)	4	3.445	3.597	0.008
Knots per metre in the small-sized log section					
Fresh	Stratum (F)	5	23.596	6.603	0.000
R^2=0.286	Site (F)	1	4.525	1.266	0.262
	Crown layer (F)	1	4.783	1.338	0.248
	CI (C)	1	45.600	12.760	0.000
	Stratum × site (I)	4	16.191	4.531	0.002
Dry	Stratum (F)	5	0.501	1.417	0.219
R^2=0.179	Site (F)	1	1.304	3.685	0.056
	Crown layer (F)	1	0.017	0.048	0.827
	CI (C)	1	1.621	4.582	0.033
Rotten	Stratum (F)	5	0.388	1.792	0.115
R^2=0.135	Site (F)	1	0.336	1.551	0.214
	Crown layer (F)	1	0.002	0.010	0.919
Knot bumps	Stratum (F)	5	1.411	4.041	0.002
R^2=0.321	Site (F)	1	0.911	2.608	0.108
	Crown layer (F)	1	0.069	0.197	0.658
	CI (C)	1	6.986	20.003	0.000
	Mean age (C)	1	2.080	5.956	0.015
Vertical branches	Stratum (F)	5	2.027	3.609	0.004
R^2=0.143	Site (F)	1	1.159	2.063	0.152
	Crown layer (F)	1	0.025	0.045	0.832
	Stratum × crown layer (I)	5	1.375	2.448	0.035
	Site × crown layer (I)	1	2.288	4.073	0.045

Table 8. ANCOVA table for analyses of the diameter of the thickest knot by knot type in the section of log and small-sized log (F = fixed factor; C = covariant; I = interaction).

Variable	Source	df	MS	F	p
Thickest knot in the log section					
Fresh	Stratum (F)	5	153.028	2.119	0.070
R^2=0.271	Site (F)	1	24.681	0.342	0.560
	Crown layer (F)	1	2.237	0.031	0.861
	Stratum × site (I)	3	407.680	5.645	0.001
	Stratum × site × crown layer (I)	2	279.187	3.866	0.024
Dry	Stratum (F)	5	52.391	1.440	0.217
R^2=0.183	Site (F)	1	22.830	0.628	0.430
	Crown layer (F)	1	73.436	2.019	0.159
Rotten	Stratum (F)	5	170.618	1.956	0.104
R^2=0.304	Site (F)	1	18.765	0.215	0.645
	Crown layer (F)	1	14.926	0.171	0.681
Thickest knot in the small-sized log section					
Fresh	Stratum (F)	5	430.352	3.226	0.008
R^2=0.186	Site (F)	1	33.318	0.250	0.618
	Crown layer (F)	1	3.777	0.028	0.867
	Nr of stems / ha (C)	1	832.330	6.239	0.013
Dry	Stratum (F)	5	85.564	3.990	0.002
R^2=0.286	Site (F)	1	179.240	8.358	0.005
	Crown layer (F)	1	39.068	1.822	0.180
	Nr of stems / ha (C)	1	287.450	13.404	0.000
Rotten	Stratum (F)	5	473.253	8.491	0.000
R^2=0.596	Site (F)	1	723.232	12.976	0.001
	Crown layer (F)	1	661.811	11.874	0.001
	Stratum × site (I)	4	611.805	10.977	0.000
	Stratum × crown layer (I)	5	619.923	11.123	0.000
Vertical branch	Stratum (F)	5	669.250	1.323	0.269
R^2=0.263	Site (F)	1	757.895	1.498	0.226
	Crown layer (F)	1	1067.309	2.110	0.152

in the log section ranged from 57 mm in stratum 2 to as much as 160 mm in stratum 1. In all dominant white birch, the mean diameter of vertical branch in the log section was 70 mm. In the small-sized log section, vertical branches appeared in both dominant and codominant trees. Diameter of the thickest vertical branch in the small-sized log section varied from 47 mm in stratum 4 to 70 mm in stratum 1.

3.5 Surface Defects and Decay

Surface defects were detected from the stump up to the height where the stem diameter was 5 cm. Altogether, 59 percent of the trees had some kind of surface defect. The majority of the defects (38%) were caused by woodpeckers. These defects, however, had caused no serious damage to the wood, and they were located primarily in the upper parts of the stem. The percentage of more serious defects, firstly, a different kind of open scars was 23 and, secondly, that of overgrown scars was 21. Thirdly, 6% of the defects were surface cracks and, finally, 1% were caused by harvesting operations. Of the all surface defects, 11% were caused for some reason other than those listed above, e.g., steel objects nailed into the stem.

The occurrence of decay was analysed in five cross-sections: at heights of 0, 4, 8, 12 and 16

Table 9. Percentages of trees with observed decay at heights of 0, 4, 8, 12 and 16 metres by stratum (– = no observations available in this category).

Stratum	Height 0 m Decay type % Hard	0 m Soft	4 m Hard	4 m Soft	8 m Hard	8 m Soft	12 m Hard	12 m Soft	16 m Hard	16 m Soft
1	80	17	55	0	56	1	24	3	6	0
2	76	7	72	1	43	1	25	0	17	0
3	34	10	26	0	1	5	5	0	6	0
4	45	17	39	4	1	2	2	0	10	0
5	59	9	47	8	30	0	10	0	–	–
6	52	14	26	4	15	1	16	0	–	–

metres. Because no covariants correlated with decay, no adjustments were made. The observed percentages of hard and soft decay at different heights by the stratum are presented in Table 9.

The most common type of decay was heart-rot originating from the root system, which made up 70% of all observations. Heart-rot is caused by ageing of the tree, which decreases its ability to resist decay fungi. Woodpeckers had caused 9%, and different kind of scars 5% of the decay. Other reasons found for decay were vertical branches (5%), rotten knots (5%) and surface cracks (2%). For three percent of the cross-sections, the reason for decay could not be determined.

4 Discussion

The objective of this study was to examine the natural variations in the technical properties of mature silver and white birch in southern and central Finland, especially for saw milling. In order to best serve the needs of the mechanical wood industry, the results were presented separately for the normal log and small-sized log sections. The material was divided into six strata according to birch species and growing conditions. The strata were further divided into categories by site (OMT / Rhtkg and MT / Mtkg) and crown layer (dominant trees and codominant trees). The number of sample stands was 20; a total of 261 sample trees were cut from the stands. In order to make each stand comparable to the others, analysis of covariance was used. Thus, differences in certain background factors between the stands were adjusted to the same level.

The sample stands represented typical cases of pure birch forests and mixed forests of conifers and birch at final cutting age. The number of sample stands had to be limited because the field work is both laborious and expensive. In this study, the number of sample trees (Table 2) cannot be considered representative in the following categories studied: codominant silver birch on the MT site in stratum 1, codominant white birch on the OMT site in stratum 3, dominant white birch on the MT site in stratum four and dominant white birch on Mtkg site in stratum 6. Only two to four trees were sampled from those categories. The remaining eighteen categories were represented by 5–27 sample trees, which can be considered to be a representative number. The results, however, should not be generalised without a comprehensive study of the silvicultural history and the present situation of the stand in question.

Geographically, the sample stands were situated in central and eastern Finland, which are the most important areas for growing stock of large birch and therefore are the areas where birch is used in veneer and saw mills. In western and northern Finland, the growing stock of birch consists mainly of poor-quality and small-sized white birch, which, so far, is used mainly as raw material for pulp mills.

In many cases, significant interactions were observed between the stand and the tree factors studied. This is understandable considering, for instance, light conditions and root competition in pure birch stands and in mixed stands of birch and conifers. Significant interaction, for instance, between the stratum and the crown layer, implies that changes in variable z between crown layers one and two in stratum x, are not identical to the changes of the same variable between the same crown layers in stratum y.

The natural differences in spacing between pure birch stands and mixed spruce-dominated stands were not considered in this study. In order to estimate the differences in technical properties, all stand types were adjusted to the same level of given covariants, spacing, among other things. This procedure also made the results easier to present.

When the dominant trees on MT sites are excluded, there were no significant differences in stem size between the birch in pure birch stands and those in mixed stands dominated by conifers (Fig. 2). On mineral soils, birch stems were slightly larger in mixed stands than in pure birch stands. On peatlands, however, the difference between pure and mixed stands was opposite. Mielikäinen (1985) found that it is advantageous to maintain a silver birch admixture in the spruce-dominated stand in order to maximise the growth of both tree species. The maximum percentage of silver birch was 25. White birch admixture did not have the same effect. Compared to this study, Heiskanen (1957) presented results on diameters at a slightly lower level. In his study, however, crown layers were not separated. Verkasalo (1997) also presented smaller diameters for silver birch on MT site and for white birch on Rhtkg and Mtkg sites. Geographically, Verkasalo's material differed from the material of this study by being concentrated in western Finland, where the growth conditions are poorer than in central and southern Finland.

The average stem form of silver birch was straighter than that of white birch. In particular, white birch stems on peatland were deformed by curved butts. This may be due to, e.g., sinking of the ground after ditching. Heiskanen (1957) and Verkasalo (1997) also found that peatland birch are more crooked than those growing on mineral soils.

Fig. 4 shows the heights of the crown limits by stratum, site and crown layer. White birch stems were well self-pruned in mixed stands on OMT sites, and the log section of those trees was almost totally knotfree. Small-sized logs with fresh knots, which are nowadays wanted by furniture manufacturers, were best obtained from the largest (dominant) silver birch. Small-sized log sections of white birch, as well as those of codominant silver birch, typically contain many dead knots. As a difference from the only comparable previous study (Verkasalo 1997), the stem section that contains both fresh and dead knots was considerably longer. In Verkasalo's study, however, numbers and types of knots and knot bumps were measured *before* the bolts were delimbed. In this study the results are presented as the number of different types of knots on the surface of the bolt *after* flush delimbing. Thus, the real appearance of knot bumps, and fresh, dry and rotten knots may have been better identified in this study.

In the section of the small-sized log, the thickest fresh knot was, on average, 10 mm larger in diameter in silver birch than in white birch. Rotten knots and vertical branches were also larger in silver birch. On the other hand, the size of dry knots in the section of small-sized log did not differ between birch species. The number of knot bumps per log metre was considerably larger in peatland white birch than in birch growing on mineral soils (Fig. 5). This is explained by the slow growth of trees on peatlands; self-pruned knots do not heal over rapidly when the tree grows slowly.

The occurrence of decay was, surprisingly, not statistically significantly dependent on the mean age of the stand. This may be due, for example, to the fairly small deviation in age between the stands (77 ± 15 a). Silver birch, which were, on average, slightly older than white birch, were, nevertheless, more often decayed than the white birch. According to Heiskanen (1957) and Verkasalo (1997), in both birch species decay increases with the age of the tree.

Due to the great risk of natural hazards, the amount, size and seriousness of the surface defects are not, in general, predictable. Surface defects usually cause some kind of damage also in the wood of birch. Spreading of the damage, however, cannot be easily estimated; e.g., season, weather and time-span of exposure affect the sensitivity to decay fungi. Thus, observations on surface defects are not recommended to be generalised in case of this study, as well as most other studies.

According to the results of the study, most of the technical properties of birch differ only slightly between pure birch stands and mixed stands of birch and conifers. The only notable exception is that in mixed stands of conifers and white birch the proportion of knotfree section of stem is significantly longer than in pure white birch stands. Thus, not only silver birch, because of the growth and yield of the stand, but also vigorous and good-quality white birch, because of the possibility to provide high-quality logs, can be maintained profitably as an admixture in coniferous forests until final cutting.

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References

Hägg, A. 1988. Lönsamheten av björkblandningen i barrskog. Summary: The profitability of a birch admixture in coniferous forests. The Swedish University of Agricultural Sciences, Department of Forest Products. Report 201. Uppsala 1988. 62 p. + 10 app.

Hegyi, F. 1974. A simulation model for managing jack pine stands. In: Fires, G. (Ed.), Growth models for tree and stand simulation. Rapp. Uppsats. Instn. Skogsprod. Skogshögsk. 30: 74–89.

Heiskanen, V. 1957. Raudus- ja hieskoivun laatu eri kasvupaikoilla. Summary: Quality of the common birch and the white birch on different sites. Communicationes Instituti Forestalis Fenniae 48(6). 99 p.

— 1966. Tutkimuksia koivujen vikaisuuksista, niiden vaikutuksesta sorvaustulokseen sekä niiden huomioonottamisesta laatuluokituksessa. Acta Forestalia Fennica 80(3). 28 p. (In Finnish).

Kangas, A. & Päivinen, R. 1994. Metsän mittaus. Silva Carelica 27. University of Joensuu, Faculty of Forestry. 172 p. (In Finnish).

Kataikko, M-S. 1996. Huonekaluvalmistajien tarpeet sahaamisen lähtökohtana. Kuopio. Taitemia-series. Publications 5. 116 p. (In Finnish).

Kivistö, J., Sipi, M., Kantola, A. & Niemelä, T. 1999. Koivun, haavan sekä terva- ja harmaalepän mekaaninen jalostus ja lopputuotteet Suomessa vuonna 1999. Postikysely- ja haastattelututkimuksen tulosten yhteenveto. University of Helsinki, Department of Forest Resource Management. Publications 20. 56 p. + 14 app. (In Finnish).

Kujala, V. 1946. Koivututkimuksia. Communicationes Instituti Forestalis Fenniae 34(1). 34 p. (In Finnish).

Laine, J. 1989. Metsäojitettujen soiden luokittelu. Suo 40: 37–51. (In Finnish).

Lappi, J. 1993. Metsäbiometrian menetelmiä. Silva Carelica 24. University of Joensuu, Faculty of Forestry. 182 p. (In Finnish).

Lehtikangas, P. 1989. Koivusekoituksen vaikutus nuorten mäntyjen oksikkuuteen. Pro gradu thesis. University of Joensuu, Faculty of Forestry. 55 p. + 2 app. (In Finnish).

Lehto, J. & Leikola, M. 1987. Käytännön metsätyypit. Kirjayhtymä Ltd. 96 p. (In Finnish).

Luostarinen (Paukkonen), K. & Verkasalo, E. 2000. Birch as sawn timber and in mechanical further processing in Finland. A literature study. Silva Fennica Monographs 1. 40 p.

Meriluoto, J. 1966. Raaka-ainetekijöiden vaikutus sorvatun koivuviilun määrään ja laatuun. Summary: The influence of raw material factors on the quantity and quality of rotary cut birch veneer. Acta Forestalia Fennica 80. 155 p.

Mielikäinen, K. 1980. Mänty-koivusekametsiköiden rakenne ja kehitys. Summary: Structure and development of mixed pine and birch stands. Communicationes Instituti Forestalis Fenniae 99(3). 82 p.

— 1985. Koivusekoituksen vaikutus kuusikon rakenteeseen ja kehitykseen. Summary: Effect of an admixture of birch on the structure and development of Norway spruce stands. Communicationes

Instituti Forestalis Fenniae 133. 79 p.

— & Valkonen, S. 1995. Kaksijaksoisen kuusi-koivusekametsikön kasvu. Folia Forestalia – Metsätieteen aikakauskirja 1995(2): 89–97. (In Finnish).

Niemistö, P. 1991. Hieskoivikoiden kasvatustiheys ja harvennusmallit Pohjois-Suomen turvemailla. Folia Forestalia 782. 36 p. (In Finnish).

— 1994. Influence of initial spacing and row-to-row distance on the crown and branch properties and taper of silver birch (Betula pendula). Scandinavian Journal of Forest Research 1995(10): 235–244.

— 1997a. Istutustiheyden ja rivivälin vaikutus rauduskoivun kasvuun ja ulkoiseen laatuun. In: Niemistö, P. & Väärä, T. (Eds.), Rauduskoivu tänään – ja tulevaisuudessa. Tutkimuspäivä Tampereella 12.3.1997. Metsäntutkimuslaitoksen tiedonantoja 668: 17–36. (In Finnish).

— 1997b. Istutuskoivun ulkoinen laatu pelto- ja metsämailla. In: Niemistö, P. & Väärä, T. (Eds.), Rauduskoivu tänään – ja tulevaisuudessa. Metsäntutkimuslaitoksen tiedonantoja 668: 103–114. (In Finnish).

— , Hukki, P. & Verkasalo, E. 1997. Kasvupaikan ja puuston tiheyden vaikutus rauduskoivun ulkoiseen laatuun 30-vuotiaissa istutuskoivikoissa. Metsätieteen aikakauskirja – Folia Forestalia 1997(3): 349–374. (In Finnish).

Sevola, Y. 1998. (Ed.). Metsätilastollinen vuosikirja 1999. Finnish Statistical Yearbook of Forestry. Jyväskylä. 352 p.

Underwood, A.J. 1997. Experiments in ecology: their logical design and interpretation using analysis of variance. Cambridge University Press. 504 p.

Valkonen, S. 2000. Kuusen taimikon kasvattamisen vaihtoehdot Etelä-Suomen kivennäismailla: Puhdas kuusen viljelytaimikko, vapautettu alikasvos ja kuusi-koivusekataimikko. Metsäntutkimuslaitoksen tiedonantoja 763. 83 p. + 4 subarticles. (In Finnish).

Verkasalo, E. 1997. Hieskoivun laatu vaneripuuna. [Quality of European white birch (Betula pubescens Ehrh.) for veneer and plywood]. Finnish Forest Research Institute, Research Paper 632. 483 p. + App. 59 p.

Viherä-Aarnio, A. & Velling, P. 1999. Growth and stem quality of mature birches in a combined species and progeny trial. Silva Fennica 33(3): 225–234.

Total of 27 references

II

TIMBER GRADE DISTRIBUTION AND RELATIVE STUMPAGE VALUE OF MATURE FINNISH *BETULA PENDULA* AND *B. PUBESCENS* WHEN APPLYING DIFFERENT BUCKING PRINCIPLES

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ABSTRACT

The aim of this study was to investigate the effect of the bucking principle on the timber grade distribution and relative value of mature Finnish birch trees and stands (*Betula pendula* and *B. pubescens*) of natural origin. Bucking birch stems into sawlogs of conventional diameter (≥ 18 cm) and also small-diameter logs (12 to 18 cm), with their respective grading rules, was compared to bucking into veneer logs (diameter ≥ 18 cm) with their grading rules. In addition, bucking into standard log lengths (2.9 to 6.7 m) was compared with allowing atypically short log lengths (down to 0.5 m). The effect of the bucking principle on the relative value of birch was analyzed on the basis of the real stumpage prices of individual assortments and grades. The material consisted of 261 birch trees from 20 southern or central Finnish birch stands. A considerable increase in timber recovery was found when small-diameter logs were also bucked. Depending on the stand structure and forest site type, bucking stems into large-diameter and small-diameter sawlogs and pulpwood instead of bucking into conventional veneer logs and pulpwood resulted in 10 to 40 percent higher value per cubic meter. Furthermore, when stems were bucked into logs shorter than normally cut, the grade distribution and value of trees improved.

European white birch (*Betula pubescens*) and silver birch (*B. pendula*) are the third and fourth most abundant tree species in Finland. Concerning the two birch species, the mean annual increment was 13.4 Mm^3 during the period from 1982 to 1999 (23). Wood and timber quality being in question, European white birch greatly resembles American white birch (*Betula papyrifera*), whereas silver birch lies between American white birch and yellow birch (*Betula alleghaniensis*) (16,25,29). Irrespective of the differences between the external and internal characteristics of the two Finnish birch species, silver birch and white birch are not separated at mills; the differences in the properties of wood material are relatively small (e.g., 9,15).

In Finland, the main users of birch are pulp mills, with the consumption of 11 Mm^3 of birch in 1999, considering both domestic (5 Mm^3) and imported (6 Mm^3) wood. In addition, plywood industries used 1.1 Mm^3 and sawmills 0.2 Mm^3 of birch (23). Birch plywood is used for products in which high bending strength and hardness are required, for example, flooring in heavy vehicles and their containers, construction plywood, and concrete mouldings. In addition, the best-quality veneers are commonly utilized as decorative face material for furniture. Birch lumber, especially knot-free lumber from large-diameter butt logs, is traditionally used in high-quality and high-value products such as furniture, panels, flooring, and joinery. Recently, birch lumber with sound knots, obtained especially from selective thinnings, was introduced for furniture manufacture, as well.

Birch sawlogs are often harvested following approximately the similar bucking rules applied to veneer logs. Only a few larger sawmills have their own grading systems for birch sawlogs. The

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main difference in bucking stems into sawlogs or veneer logs is the required minimum diameter. It is usually 18 cm for veneer logs, whereas sawlogs are usable, in theory, down to a diameter of 7 to 8 cm. The minimum practical diameter for a conventionally sawable birch log was 18 cm, but industrial-scale sawing of small-diameter logs down to 10 to 12 cm was started recently (15). The best-quality and largest butt logs of birch are often used as special veneer logs for slicing or rotary cutting, as well. These are notably more valuable than the conventional veneer logs or sawlogs (e.g., 4,15).

The most important factor for successful production of birch veneer (e.g., 8,16,17,19,26,27) or lumber (e.g., 12, 15) is the quality of the raw material. Birch logs, especially small-dimensioned ones, often have crooks and other defects in the stem form. In addition, older trees (white birch > 80 yr.; silver birch > 100 yr.) usually contain rot; either heart rot in the butt log originating from the root system or stem rot with an irregular extent within a stem caused by dead branches or external damage (e.g., 7,8, 20,21,27). Finnish birch species have thick and strong branches, which makes delimbing and timber scaling by a mechanized harvester difficult. In addition, birch wood is vulnerable to rapid discoloration through bark-free log sections. Thus, the most valuable birch stems are often cut manually.

For large-diameter sawlogs with a top diameter of at least 18 cm, log lengths of 3 to 5.5 meters are typically used. Small-diameter sawlogs (top diameters between 10 and 18 cm) must necessarily be shorter, from 2.5 to 3.0 meters in length, in order to obtain a reasonable lumber recovery (15). This is a result of the crookedness of small-diameter birch timber. Long, straight, top-logs are rare and even a slight sweep or taper in a small-diameter log reduces the recovery of lumber. However, the transportation vehicles as well as sawmill machinery and log-processing equipment set the lower limits for log lengths. Current technology can process logs to a minimum length of about 2 meters. Shorter, down to 0.5-meter bolts, can be sawed with special bandsaws, but, so far, their production capacity is not adequate for industrial uses. Such short logs with no visible defects are sometimes used for rotary-cutting veneer for very demanding end uses, as well.

Excluding the models for assessing the value and distribution of sawlog grades for standing birch trees in mixed stands of Norway spruce and birch in Norway (2), few other studies considering the commercial grades of birch sawlogs were found in the literature. Related studies concerning many other tree species have been published (e.g., 3,22,24). Fjærtoft & Bunkholt (1) presented an evaluation of the relationships and consistency of the Norwegian birch sawlog grades with the sawnwood grades. On the other hand, when birch veneer logs are in question, studies have been made on the relationships between the properties of raw material and the quality of veneers (8,19,27). In addition, Kärkkäinen (10) simulated rotary cutting of birch veneer logs and compared the value relations for different log sizes on the basis of the veneer quality. Heiskanen (7) and Verkasalo (27) assessed commercial recoveries of veneer logs in various types of birch stands, in Finland, based on measurements and the visual evaluation of standing birch trees. So far, no studies have been published concerning the differences in timber recoveries between bucking birch stems into sawlogs and veneer logs. In addition to this issue, which is important for forest owners and timber procurement organizations, improved utilization of the valuable birch raw material by, for example, allowing shorter log lengths than what have been applied conventionally, is a question of definite interest.

The framework of this study consists of two basic objectives. First, the distribution of timber assortments and grades of birch when bucking according to conventional sawlog or veneer log bucking rules (bucking principle A), or bucking into atypically short sawlogs or veneer logs (bucking principle B) are compared. Secondly, comparisons are made for the relative value of birch stems when the alternative bucking principles for sawlogs or veneer logs are applied. In addition, the results from the analyses are exemplified at the stand-level by calculating the total harvesting recovery of birch sawlogs and veneer logs per hectare in illustrative, average stands. All results concern final cuttings of mature birch trees and stands only.

MATERIALS AND METHODS

The material for this study was sampled from 20 mature birch stands in southern and central Finland, whose mean age ranged from 63 to 108 years. Normal silviculture according to the Finnish regime (i.e., regularly thinned, no abnormal external damages in trees, no pruning or fertilization) was required for each accepted stand. Sampling of the stands was based on six strata representing the most typical growing circumstances for Finnish silver and white birch, as regards site, soil, and composition of species. Between the six strata, the number of sample stands, their arithmetic mean age, and their diameter at 1.3 meters ($d_{1.3}$) height varied as follows:

1. Pure silver birch stands on mineral soils: 3 stands, 86 years, 250 mm;
2. Mixed Norway spruce and silver birch stands on mineral soils: 4 stands; for birch: 81 years, 264 mm;
3. Pure white birch stands on mineral soils: 3 stands, 72 years, 234 mm;
4. Mixed Norway spruce and white birch stands on mineral soils: 4 stands; for birch: 75 years, 237 mm;
5. Pure white birch stands on drained peatlands: 3 stands, 74 years, 210 mm;
6. Mixed Scots pine and white birch stands on drained peatlands: 3 stands; for birch: 79 years, 208 mm.

Both the fertile *Oxalis - Myrtillus* type and slightly poorer *Myrtillus* type (later abbreviated as OMT and MT) of the mineral soil sites, and, both herb-rich drained peatland forest (Rhtkg) and slightly poorer *Vaccinium myrtillus* drained peatland forest type 1 (Mtkg) of the peatland sites, were represented (13, 14). However, pure white birch stands on herb-rich drained peatland forest sites were not included in this study, due to their relatively small area and therefore their minor importance for forestry and forest industries in Finland.

In pure birch stands, five sample plots were established, from 20 by 20 to 30 by 30 meters in size, depending on the density of the stand. The $d_{1.3}$ series of all trees on the plot from 14 cm upward was measured and arranged in an increasing order. Thereafter, the series was divided into three partitions equal in number of trees. Next, one tree was randomly selected from each partition as a sample tree, with the condition that the tree

TABLE 1. — Grading system applied for birch sawlogs.[a]

	Grade			
Property	1[b]	2	3	4
Allowed lengths (m)	2.9, 3.5, 4.6, 5.7, 6.3	3.1, 3.4, 4.0, 4.3, 4.6, 4.9, 5.2	3.1, 3.4, 4.0, 4.3, 4.6, 4.9, 5.2	3.1, 3.4, 4.0, 4.3, 4.6, 4.9, 5.2
Top diameter over bark (cm)	Min 24	Min 12	Min 12	Min 12
Type of log	Knot-free butt log	Knot-free butt log or intermediate log	Butt-, intermediate- or top log	Knotty large-diameter or small-diameter logs[c]
Sweep	Not allowed	2 cm/1.5 m	2 cm/1.5 m	Large-diameter log: 3 cm/1.5 m Small-diameter log: 2 cm/1.5 m
Grooves, scars	Not allowed	Not allowed	Not allowed	Allowed
Crooks	Not allowed	Not allowed	Small allowed	Allowed
No. of knots	0	2 to 3	5/1.5 m	6/1.5 m
Sound knots	Not allowed	Small allowed	3 knots, max diameter 7 cm	3 knots, max diameter 10 cm
Black knots	Not allowed	Not allowed	5 knots, max diameter 3 cm	3 knots, max diameter 5 cm
Rotten knots	Not allowed	Not allowed	Not allowed	2 knots, max diameter 5 cm
Cracks	Not allowed	Not allowed	Not allowed	Allowed
Discoloration	Max 33% of top diameter over bark	Max diameter 4 cm	Max diameter 5 cm	Max 50% of top diameter over bark

[a] Grades 1 and 2 (28), grades 3 and 4 (11).

[b] Instead of sawing, the defect-free and large-diameter grade 1 sawlogs are actually intended for longitudinal flat slicing or rotary cutting of special veneers (e.g., 15).

[c] Large-diameter log = top diameter at least 18 cm; small-diameter log = top diameter 12 to 18 cm.

should be of satisfactory quality, i.e., it should have at least one saw or veneer log according to external evaluation of standing tree. In this way, smaller, average, and larger trees from the plot were represented in the sample and the requirements for random sampling were met simultaneously.

In mixed stands of birch and conifers, no sample plots with a predetermined area were established, because no regular structure was met in these stands. Instead, the $d_{1.3}$ of at least 50 birch trees was measured in the entire stand with the condition that at least the 2 closest neighbor trees must be coniferous. Hence, the hypothesis that the properties of birch in pure birch stands differ from those in stands dominated by conifers was studied. The $d_{1.3}$ series obtained was arranged and divided into three partitions similar to the procedure in pure birch stands. Next, on average, five birch trees were randomly selected from each partition as sample trees.

Basal area, number of stems per hectare, mean diameter, mean age, and mean height were measured by tree species from each sample plot or stand. Furthermore, site class was determined on the basis of the ground vegetation.

In total, 261 sample trees were cut and studied in detail. The quality and suitability of the sample trees for mechanical processing were visually evaluated. The heights of the crown limits were measured, and the relative growing position of the sample tree was evaluated, i.e., whether the tree represented the dominant (=1) or co-dominant (=2) crown layer. In addition, distances and directions to, as well as the $d_{1.3}$ of the five closest neighbor trees were measured in order to study the effect of competition on the properties of the sample trees.

After the measurements of the sample plots and standing trees, the sample trees were felled and flush delimbed. Each tree was bucked theoretically, i.e., without actual crosscutting, in four different ways by using a visual evaluation and measurements of knot and stem diameters, sweep, etc. First, bucking the stems into sawlogs was accomplished by following the grading system of Vilkon Inc. (28), the major birch sawmilling company in Finland, for grades 1 and 2, completed by the grading rules published in the practical guide book of Keinänen and Tahvanainen (11) for grades 3 and 4 (**Table 1**). Secondly, bucking the stems into veneer logs was accomplished by a commonly used grading system (18) (**Table 2**). Besides these basic bucking practices for conventional commercial log lengths, theoretical bucking of stems into sawlogs and veneer logs was performed by allowing atypically short log lengths, i.e., from 0.5 m upwards.

Except for grade 1 sawlogs, for which the minimum diameter of 24 cm was required, sawlogs were bucked by using the minimum top diameter of 12 cm, which relates to commercial small-diameter logs. Thus, sawlogs included here were both commercial large-diameter and currently introduced small-diameter logs. When bucking the stems into conventional sawlog or veneer log

TABLE 2. — Grading system applied for birch veneer logs (18).

	Grade[a]		
	1	2	3
Allowed lengths (m)			
Butt logs	3.3, 4.9, 6.3, 6.7	3.3, 4.9, 6.3, 6.7	3.3, 4.9, 6.3, 6.7
Intermediate and top logs	4.6, 6.0, 6.7	4.6, 6.0, 6.7	4.6, 6.0, 6.7
Minimum top diameter over bark (mm)	200	180	180
No. of knots[b]			
Fresh	- -	4	Allowed
Dry, rotten, or large knot bumps[c]	- -	- -	1/5 of the diameter without bark
Diameter of knots[d] (cm)			
Fresh	- -	2.5	6.5
Dry and rotten	- -	1.5	2.5
Sweep, calculated from the minimum diameter of the section studied[e]	5%	12%	12%
Scars, grooves, wounds[f]	- -	Small	0.6 m on one side, depth 10% of the minimum diameter
Bark peeling defects[f]	- -	- -	0.3 m allowed
Hard heart rot or cracks in pith	33% of the diameter without bark in all grades		
Not allowed: knot groups[g], vertical branch, decayed scar, soft decay, surface crack, corkscrew, sudden crook, strange object.			
A part of stem with two or more defects allowed for grade 3 is not accepted in a veneer log.			

[a] Grade within the length of 1.5 meters.

[b] Knots smaller than 0.5 cm in diameter are not included in the number of knots in grades 2 and 3.

[c] Large knot bump is a knob from which a dry or rotten knot is found when flush delimbed.

[d] The diameter of knot is measured from the dark part of the knot perpendicularly to the stem.

[e] Too crooked stem parts can be accepted for veneer logs by making a jump cut.

[f] Along with the over-healed scars and bark peeling defects no swelling is allowed.

[g] Knot groups: at least three knot bumps and/or 2.5-cm knots within the distance of 0.17 m.

lengths, the minimum top diameter and length for pulpwood were 7 cm and 2.0 meters, respectively. On the other hand, when bucking the stems into short logs, the volume in pulpwood material, material resulting from jump cuts, and material in the unmerchantable top (diameter less than 7 cm) were added together in one category, and no predetermined lengths were used for them. Thus, the log recovery was optimized. Very short, i.e., down to 0.1 meter, jump cuts were allowed between the stem sections with a different grade both when bucking the stems into conventional and short log lengths.

The vertical locations of bucking points were recorded for each sample tree, as well as the grade of each section and the reasons for their grade reduction. On the basis of the diameter measurements on bark, taper curves were constructed separately for each sample tree, and, furthermore, the volume of each individual stem section with a different grade was calculated. The data were processed by using the KPL software of the Finnish Forest Research Institute (6). Next, the percentages of different grades of the total volume of trees were calculated. The results from the different stands and strata were adjusted to conform to each other by analysis of covariance, using measured stand-level variables describing the density and mean age of the stand as covariates.

The theoretical value per cubic meter for each sample tree, based on the recovery of different assortments, was calculated on the basis of the recovery and price level of timber assortments and grades obtained. The value per cubic meter for each tree representing certain stratum, site, and crown layer was analyzed as an index:

$$I = \sum_{i=1}^{n} P_i * (V_i / 100) \qquad [1]$$

where i is the grade; P is the percentage of the grade i from the total volume of tree; V is the value per cubic meter of the grade. The value per cubic meter for conventional veneer log grades 1, 2, and 3, as well as large sawlog grades 2, 3, and 4, was set at 100. The value per cubic meter for small-diameter sawlog grades 2, 3, and 4 was set at 65 and, furthermore, for grade 1 sawlogs, which represent the top-quality, the value per cubic meter was 160. The value per cubic meter used for pulpwood was 32. These relative values are based on the average stumpage prices of the assortments in question paid in southern Finland at the end of the 1990s (23). In this theoretical evaluation, price levels used for logs in the bucking principle B were similar to those used in the bucking principle A and also applied in real birch timber markets in Finland. In practice, bucking stems into shorter logs would obviously increase the harvesting, transporting, and sawing costs and, thus, decrease the stumpage prices.

Finally, the results were illustrated on stand level in separate strata and sites by calculating the total harvesting recovery of sawlogs and veneer logs per hectare. The recoveries were calculated for an average stand, where the number of stems per hectare and the mean age of the trees complied with the values observed in the sample stands.

TABLE 3. — Analyses of covariance of percentages of various grades when bucking the stems into sawlogs and veneer logs (F = fixed factor; C = covariant; I = interaction).

Variable	Source	Df	MS	F	p
Percentages of grades when bucking into conventional-length sawlogs $r^2 = 0.712$	Stratum (F)	5	0.055	3.311	0.006
	Site (F)	1	0.000	0.002	0.964
	Crown layer (F)	1	0.086	5.176	0.023
	Grade (F)	4	3.460	209.220	0.000
	Mean age of the stand (C)	1	0.105	6.349	0.012
	Stratum × grade (I)	20	0.033	2.004	0.006
	Stratum × site × crown layer × grade (I)	64	0.021	1.289	0.071
Percentages of grades when bucking into short sawlogs $r^2 = 0.405$	Stratum (F)	5	0.714	5.031	0.000
	Site (F)	1	0.680	4.790	0.029
	Crown layer (F)	1	0.788	5.552	0.019
	Grade (F)	4	5.418	38.187	0.000
	Mean age of the stand (C)	1	0.629	4.433	0.035
	Stratum × crown layer × grade (I)	44	0.319	2.251	0.000
	Stratum × site × grade (I)	39	0.350	2.467	0.000
	Stratum × site × crown layer × grade (I)	36	0.195	1.373	0.071
Percentages of grades when bucking into conventional-length veneer logs $r^2 = 0.388$	Stratum (F)	5	0.018	0.596	0.703
	Site (F)	1	0.030	1.008	0.316
	Crown layer (F)	1	0.453	15.210	0.000
	Grade (F)	4	0.020	0.658	0.621
	Mean height of the stand (C)	1	0.713	23.961	0.000
	Stratum × site (I)	4	0.065	2.168	0.072
	Stratum × grade (I)	19	0.043	1.460	0.095
	Stratum × site × crown layer × grade (I)	47	0.049	1.645	0.006
Percentages of grades when bucking into short veneer logs $r^2 = 0.494$	Stratum (F)	5	0.652	0.852	0.513
	Site (F)	1	0.023	0.030	0.863
	Crown layer (F)	1	0.579	0.757	0.385
	Grade (F)	3	50.310	65.737	0.000
	Mean age (C)	1	1.851	2.419	0.120
	Stratum × grade (I)	30	1.612	2.106	0.001
	Crown layer × grade (I)	6	4.205	5.495	0.000
	Stratum × crown layer × grade (I)	33	1.168	1.526	0.030
	Stratum × site × crown layer × grade (I)	61	0.898	1.173	0.177

RESULTS

RECOVERY OF TIMBER ASSORTMENTS AND THEIR GRADE DISTRIBUTIONS

The percentages of different timber assortments and grades when bucking the stems into sawlogs or veneer logs were calculated by models based on the analysis of covariance (**Table 3**). In addition to the significant covariates, others describing the density of the stand (basal area, number of stems per hectare, and competition index according to Hegyi (5)) were tested. None of these characteristics had a statistically significant effect on the percentages of different grades. Several significant interactions were discovered; the percentages of assortments and grades were not proportional between the various strata, sites, and crown layers. It is notable that neither the stratum nor site factors had a significant effect on the percentages of different grades when the stems were bucked into veneer logs. Both stratum and site were, however, separated as factors in order to maintain the comparability of the results between sawlog and veneer log bucking. Results on the recovery of different timber assortments and grades are shown by stratum in **Tables 4** through **6**.

When the stems were bucked into conventional log lengths, the log percentages of stems varied from 31 to 73 when sawlog bucking rules were applied, and from 9 to 60 when veneer log bucking rules were applied. On mineral soils, the percentage of logs was, on average, 10 to 30 percent higher when sawlogs were bucked than when veneer logs were bucked. On peatlands, conversely, no significant differences were observed. Irrespective of the assortment bucked, more than 70 percent of the total volume of trees on peatlands ended up as pulpwood, whereas on mineral soils the average percentage was close to 50.

TABLE 4. — Average volume of an individual birch tree as well as adjusted percentages of different assortments per site and crown layer in silver birch stands on mineral soils (Strata 1 and 2).[a]

	Site							
	OMT				MT			
	Crown layer							
	1		2		1		2	
	Sawlog or veneer log length							
Basic bucking principle	A	B	A	B	A	B	A	B
Stratum 1	Percent of the total volume of tree							
Sawlog bucking								
Grade 1	- -	24	- -	- -	- -	11	- -	- -
Grade 2	5	9	11	35	13	15	10	- -
Grade 3	9	14		8	13	14	17	19
Grade 4	35	30	31	17	33	28	28	14
Pulpwood (*d* ≥ 12 cm)	34		38		34		38	
Pulpwood, (*d* = 7 – 12 cm)	3		8		5		6	
Jump cuts and uncommercial top	14	23[b]	12	40[b]	2	32[b]	1	67[b]
Σ	100	100	100	100	100	100	100	100
Veneer log bucking								
Grade 1	- -	27	- -	37	- -	22	- -	- -
Grade 2	20	17	23	25	16	18	- -	27
Grade 3	18	6	6	- -	15	18	23	- -
Pulpwood (d ≥ 18 cm)	38		35		34		33	
Pulpwood (d = 7 – 18 cm)	16		26		23		35	
Jump cuts and uncommercial top	9	50[b]	10	38[b]	12	42[b]	9	73[b]
Σ	100	100	100	100	100	100	100	100
	Average volume of total tree (dm^3)							
	839		532		578		458	
Stratum 2	Percent of the total volume of tree							
Sawlog bucking								
Grade 1	- -	13	- -	- -	- -	9	- -	- -
Grade 2	14	17	0	26	3	11	0	13
Grade 3	4	20	6	19	13	19	5	29
Grade 4	29	20	55	34	31	23	25	16
Pulpwood (d ≥ 12 cm)	42		21		39		50	
Pulpwood (d = 7 – 12 cm)	3		6		2		9	
Jump cuts and uncommercial top	8	30[b]	12	21[b]	12	38[b]	11	42[b]
Σ	100	100	100	100	100	100	100	100
Veneer log bucking								
Grade 1	4	24	0	12	0	29	0	13
Grade 2	17	16	12	25	34	18	0	10
Grade 3	11	13	0	5	17	7	12	- -
Pulpwood (d ≥ 18 cm)	54		54		30		29	
Pulpwood (d = 7 – 18 cm)	8		24		10		47	
Jump cuts and uncommercial top	6	47[b]	10	58[b]	9	47[b]	12	77[b]
Σ	100	100	100	100	100	100	100	100
	Average volume of total tree (dm^3)							
	812		481		790		348	

[a] Sawlog or veneer log lengths: A = conventional log lengths; B = short logs down to 0.5 m; - - indicates insufficient or no observations.

[b] Includes pulpwood, jump cuts, and uncommercial top.

TABLE 5. Average volume of an individual birch tree as well as adjusted percentages of different assortments per site and crown layer in white birch stands on mineral soils (Strata 3 and 4).[a]

	Site							
	OMT				MT			
	Crown layer							
	1		2		1		2	
	Sawlog or veneer log length							
Basic bucking principle	A	B	A	B	A	B	A	B
Stratum 3	Percent of the total volume of tree							
Sawlog bucking								
Grade 1	- -	20	- -	- -	- -	13	- -	12
Grade 2	21	24	0	7	9	26	17	22
Grade 3	0	11	0	40	11	9	0	12
Grade 4	30	7	34	6	28	7	31	8
Pulpwood ($d \geq 12$ cm)	29		40		40		41	
Pulpwood, ($d = 7 - 12$ cm)	10		17		6		5	
Jump cuts and uncommercial top	10	38[b]	9	47[b]	6	45[b]	6	46[b]
Σ	100	100	100	100	100	100	100	100
Veneer log bucking								
Grade 1	5	30	0	- -	0	17	0	- -
Grade 2	9	13	0	- -	18	25	6	- -
Grade 3	24	- -	0	- -	9	5	11	- -
Pulpwood ($d \geq 18$ cm)	41		39		10		27	
Pulpwood ($d = 7 - 18$ cm)	9		52		44		47	
Jump cuts and uncommercial top	12	57[b]	9	100[b]	19	53[b]	9	100[b]
Σ	100	100	100	100	100	100	100	100
	Average volume of total tree (dm^3)							
	515		332		475		359	
Stratum 4	Percent of the total volume of tree							
Sawlog bucking								
Grade 1	- -	19	- -	- -	- -	- -	- -	- -
Grade 2	25	24	14	36	0	29	5	24
Grade 3	14	15	0	14	32	12	6	11
Grade 4	19	10	35	14	28	5	23	11
Pulpwood ($d \geq 12$ cm)	33		36		30		52	
Pulpwood ($d = 7 - 12$ cm)	5		9		4		10	
Jump cuts and uncommercial top	4	32[b]	6	36[b]	6	54[b]	4	54[b]
Σ	100	100	100	100	100	100	100	100
Veneer log bucking								
Grade 1	6	30	4	25	0	27	0	24
Grade 2	23	15	10	16	0	15	3	23
Grade 3	9	13	8	15	33	7	2	6
Pulpwood ($d \geq 18$ cm)	38		39		40		27	
Pulpwood ($d = 7 - 18$ cm)	16		27		24		59	
Jump cuts and uncommercial top	8	42[b]	12	44[b]	3	51[b]	9	47[b]
Σ	100	100	100	100	100	100	100	100
	Average volume of total tree (dm^3)							
	604		418		535		326	

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[a] Sawlog or veneer log lengths: A = conventional log lengths; B = short logs down to 0.5 m; - - indicates insufficient or no observations.

[b] Includes pulpwood, jump cuts, and uncommercial top.

TABLE 6. Average volume of an individual birch tree as well as adjusted percentages of different assortments per site and crown layer in white birch stands on peatlands (Strata 5 and 6).[a]

	Site							
	Rhtkg				Mtkg			
	Crown layer							
	1		2		1		2	
	Sawlog or veneer log length							
Basic bucking principle	A	B	A	B	A	B	A	B
Stratum 5	Percent of the total volume of tree							
Sawlog bucking								
Grade 1	- -	- -	- -	- -	- -	11	- -	- -
Grade 2	- -	- -	- -	- -	5	24	4	26
Grade 3	- -	- -	- -	- -	10	13	2	11
Grade 4	- -	- -	- -	- -	16	20	19	11
Pulpwood ($d \geq 12$ cm)	- -	- -	- -	- -	57		51	
Pulpwood, ($d = 7 - 12$ cm)	- -	- -	- -	- -	8		18	
Jump cuts and uncommercial top	- -	- -	- -	- -	4	32[b]	6	52[b]
Σ	- -	- -	- -	- -	100	100	100	100
Veneer log bucking								
Grade 1	- -	- -	- -	- -	2	28	0	17
Grade 2	- -	- -	- -	- -	1	14	4	14
Grade 3	- -	- -	- -	- -	7	10	0	- -
Pulpwood (d ≥ 18 cm)	- -	- -	- -	- -	37		7	
Pulpwood (d = 7 – 18 cm)	- -	- -	- -	- -	36		76	
Jump cuts and uncommercial top	- -	- -	- -	- -	17	48[b]	13	69[b]
Σ	- -	- -	- -	- -	100	100	100	100
	Average volume of total tree (dm^3)							
					360		208	
Stratum 6	Percent of the total volume of tree							
Sawlog bucking								
Grade 1	- -	- -	- -	- -	- -	- -	- -	- -
Grade 2	12	41	0	25	0	57	2	30
Grade 3	0	19	3	17	0	- -	0	12
Grade 4	9	9	15	13	25	- -	7	8
Pulpwood (d ≥ 12 cm)	68		61		61		64	
Pulpwood (d = 7 – 12 cm)	8		16		9		19	
Jump cuts and uncommercial top	3	31[b]	5	45[b]	5	43[b]	8	50[b]
Σ	100	100	100	100	100	100	100	100
Veneer log bucking								
Grade 1	7	19	0	20	0	15	0	30
Grade 2	0	21	0	21	32	18	6	22
Grade 3	0	- -	6	11	0	- -	0	- -
Pulpwood (d ≥ 18 cm)	41		16		9		7	
Pulpwood (d = 7 – 18 cm)	37		64		43		71	
Jump cuts and uncommercial top	15	60[b]	14	48[b]	16	67[b]	16	48[b]
Σ	100	100	100	100	100	100	100	100
	Average volume of total tree (dm^3)							
	322		248		314		210	

[a] Sawlog or veneer log lengths: A = conventional log lengths; B = short logs down to 0.5 m; - - indicates insufficient or no observations.

[b] Includes pulpwood, jump cuts, and uncommercial top.

TABLE 7. — Value indices of birch trees by stratum, site, and crown layer when bucking the stems into conventional-length or atypically short sawlogs or veneer logs.[a]

	Site							
	OMT/Rhtkg				MT/Mtkg			
	Crown layer							
	1		2		1		2	
	Bucking principle							
	A	B	A	B	A	B	A	B
Stratum	Value per cubic meter index							
	Sawlog bucking							
1	60.1	95.4	53.9	69.5	68.0	80.5	67.3	50.4
2	61.1	84.8	66.1	81.0	59.8	76.2	46.8	66.7
3	61.7	83.5	50.8	64.0	60.6	73.5	59.9	72.2
4	69.1	85.9	59.6	70.4	69.1	60.6	52.1	59.6
5	- -	- -	- -	- -	50.4	78.7	45.0	58.8
6	44.6	75.2	41.9	64.7	45.3	63.6	35.6	60.6
	Veneer log bucking							
1	55.3	64.4	48.5	72.6	49.2	69.8	44.8	48.8
2	51.8	66.4	37.0	59.0	63.8	67.4	36.3	46.0
3	54.0	59.6	29.1	30.4	44.3	62.4	40.7	30.4
4	55.3	69.8	43.1	68.5	53.5	63.7	32.5	66.4
5	- -	- -	- -	- -	30.2	65.8	30.6	51.5
6	32.0	57.6	31.6	65.8	48.6	52.8	30.6	65.8

[a] Bucking principles: A = conventional log lengths, B = short logs down to 0.5 m. Relative stumpage value per cubic meter of veneer logs = 100. For description of strata: see Materials and Methods.

When conventional log lengths were applied, altogether not more than seven grade 1 sawlogs were obtained from the material of 261 sample trees. Thus, the percentage of grade 1 sawlogs was close to 0. When bucking into short sawlogs, the recovery of grade 1 from the dominant trees increased clearly, from 0 to as high as 24 percent of the total volume. Similar consequences concerning the differences in grade distribution between bucking into sawlogs or veneer logs of conventional and short log lengths were observed throughout the material. Therefore, either higher percentages within the same grade or higher percentages in better grades were obtained when shorter log lengths were applied. When conventional log lengths were used, the average proportion of small-diameter sawlogs, obtained in addition to large-diameter logs, varied between 4 and 25 percent from the total volume of tree, depending on stratum, site, and crown layer in question. When short logs were allowed, on the other hand, the corresponding percentage varied between 6 and 33. As a rule, the potential section of small-diameter logs was clearly more efficiently utilized when short logs were allowed.

RELATIVE VALUES OF THE STEMS

In **Table 7**, the value indices describe the theoretical value of a tree, if the volume of the birch tree was 1 m^3 or, additionally, if 1 m^3 of birch with that kind of timber grade distribution were harvested. In this way, the basic bucking principles A and B, as well as bucking into sawlogs or veneer logs are compared. The values per cubic meter for logs in the bucking principle B are purely theoretical due to the theoretical hypothesis that the same prices were paid for atypically short logs as for conventional logs.

The value indices of trees varied between 35.6 and 95.4 for sawlog bucking, and between 29.1 and 72.6 for veneer log bucking. As a rule, bucking the stem into large- and small-diameter sawlogs and pulpwood instead of veneer logs and pulpwood resulted in a higher value per cubic meter index, irrespective of whether conventional or short log lengths were used. Only a few exceptions occurred in these findings.

ILLUSTRATION OF THE RESULTS AT THE STAND LEVEL

The total harvesting recovery of sawlogs and veneer logs per hectare was calculated for an average 77-year-old stand by using the stem numbers per hectare presented in **Table 8**, which were measured in the stands sampled in this study.

Generally, the differences in timber recovery were considerable between the mineral soils and peatlands (**Figs. 1** and **2**). Depending on the stratum, on OMT and Rhtkg sites, the margin between the bucking principles A and B ranged from 5 percent to as high as 60 percent. The margin between the recoveries when bucking the stems into sawlogs or veneer logs was nearly at the same level. On MT and Mtkg sites, the general trends between bucking into sawlogs or veneer logs, as well as using the bucking principles A or B, were fairly similar to those on OMT and Rhtkg sites. Some dissimilarities were discovered, however, in strata 1 and 4 where the recovery of conventional sawlogs was equal to or even larger than that of short sawlogs. In stratum 4, the recovery of veneer logs was practically equal in the bucking principles A and B, as well.

Regarding the value per hectare estimations, the effect of coniferous trees in strata 2, 4, and 6, as well as the effect of smaller than log-size trees should be considered. Particularly on peatlands, the smaller or poorer-quality pulpwood trees have a considerable positive influence on the total economic value of the stand. Despite the requirements for satisfactory silvicultural condition in pure birch stands on mineral soils, an average of 10 to 30 birch stems of pulpwood quality per hectare were present, as well. In mixed stands of conifers and birch, the average number of pulpwood stems was less than 10 stems per hectare.

DISCUSSION

The aim of this study was to examine theoretically the differences between the timber grade distribution and relative value of mature birch stems when two different combinations of assortments and two combinations of log lengths were applied to bucking the same trees. First, bucking the stems into sawlogs was compared with bucking them into veneer logs, with residual pulpwood. Second, for both sawlogs and veneer logs, bucking into conventional log lengths ranging from 2.9 to 6.7 meters was compared with bucking into atypically short logs down to 0.5 meters. Moreover, the results were exemplified by calculating the harvesting recovery of each of the four assortments per hectare in a typical pure or mixed stand of birch.

Except for diameter, quality specifications used for birch sawlogs in this study were a little more restrictive, in practice, than those used for veneer logs (**Tables 1** and **2**). Due to the extensive variation in the properties of individual birch trees, the results for the timber grade distribution, even if presented at the level of individual trees, as in this paper, are not necessarily accurate in the evaluation of timber grades within an individual birch tree. Thus, the results characterize the average grade distribution of a large number of harvested trees. In addition, the results are highly dependent on the grading system applied. Besides the two combinations of assortments studied in this article, small-diameter birch sawlogs can be harvested along with conventional veneer logs. As a result, the percentage of pulpwood section decreases and the value per cubic meter index obviously increases. This kind of procedure may, however, face difficulties in practice, because it usually presumes that an individual buyer can either sell or use both veneer logs and small-diameter sawlogs, which is not often the case.

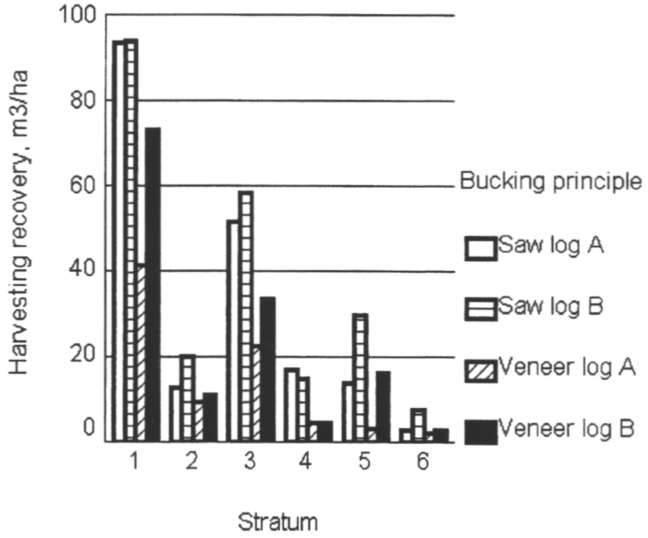

Fig. 1. — Harvesting recovery (m³/ha) of birch sawlogs or veneer logs when using conventional log lengths (bucking principle A) or short log lengths down to 0.5 meters (bucking principle B) on OMT (strata 1 to 4) and Rhtkg sites (stratum 6).

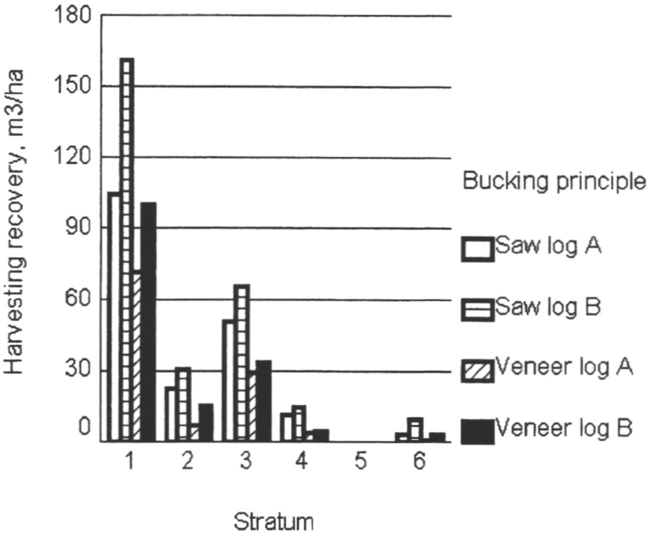

Fig. 2. — Harvesting recovery (m³/ha) of birch sawlogs or veneer logs when using conventional log lengths (bucking principle A) or short log lengths down to 0.5 meters (bucking principle B) on MT (strata 1 to 4) and Mtkg sites (strata 5 and 6).

The option of harvesting small-diameter sawlogs (diameter 12 to 18 cm) in addition to large-diameter logs (diameter ≥ 18 cm) increased the total timber recovery, as well as the value of harvested stems significantly compared to bucking them into veneer logs and pulpwood only. Bucking shorter than conventional sawlogs or veneer logs down to 0.5 m increased not only the total recovery of commercial assortments, but also the recoveries of better grades. In

TABLE 8. — Number of birch stems per hectare used in calculations of the harvesting recoveries.[a]

Stratum	Site			
	OM /Rhtkg		MT/Mtkg	
	Crown layer			
	1	2	1	2
	No. of stems per hectare (sawlog stems/veneer log stems)			
1	200/200	100/50	200/200	100/50
2	20/20	50/30	20/20	50/30
3	150/150	100/50	150/150	100/50
4	20/20	50/30	20/20	50/30
5	- -	- -	100/80	50/20
6	30/20	20/5	30/20	20/5

[a] Sawlog or veneer log stem contains at least one sawlog or veneer log of conventional log lengths. For veneer log stems, a $d_{1.3}$ of 20 cm was required, whereas for sawlog stems, the corresponding requirement was only 14 cm.

fact, defect-free grade 1 sawlogs, for which a 24-cm diameter was required, became a noteworthy assortment only when short log lengths were allowed. Although the quality requirements for grade 1 sawlogs and grade 1 veneer logs differ only slightly (**Tables 1** and **2**), grade 1 sawlogs are, in fact, considerably more valuable. Thus, when the best sawlog grade was obtained in the bucking principle B, the value of the tree increased more rapidly compared to the situation where the best veneer log grade was obtained.

When the bucking principle B was applied, the length distribution of logs focused strongly on shorter log lengths, especially in the upper parts of the stem. Typically, several less than 1-m-long bolts of good quality were discovered between the whorls of branches or between two crooks. The value per cubic meter indices for the bucking principle B, in **Table 7**, are purely theoretical because similar price levels were assumed for respective assortments despite the fact that the log lengths were too short for current markets for sawlogs or veneer logs.

The same stand density, i.e., number of stems per hectare, was used for both bucking principles A and B when the harvesting recoveries per hectare were calculated (**Figs. 1** and **2**, **Table 8**). The numbers of sawlog and veneer log stems were, however, determined only on the basis of the conventional bucking principle A. When shorter logs were allowed, actually a larger number of stems per hectare would yield logs appropriate for mechanical processing. Hence, the difference in the recovery between the bucking principles A and B would obviously increase. In this study, the distribution of different assortments is the one calculated for an average birch tree (**Tables 4**, **5**, and **6**). This procedure, however, assumes that the frequency distribution of the $d_{1.3}$ is normal, i.e., equal number of both larger and smaller trees than the average tree exist in the given stand. This is not necessarily true; in practice, the $d_{1.3}$ frequency distribution often complies with, for instance, Poisson distribution rather than normal distribution.

In general, harvesting shorter logs than what is currently applied would clearly increase the percentage of commercial timber per tree. Moreover, the timber grade distribution would focus more on better grades. This would also have a definite effect on the stumpage income for the forest owner. Considering the industrial utilization, presently such short bolts are not applicable for sawing purposes. However, the high-quality raw material might be utilized more efficiently than now. In order to obtain more timber from the same number of harvested trees and the same stand, shorter parts of stems could be used for mechanical wood processing. The fact that birch lumber is widely used in short billets and components for furniture and joinery supports the concept of allowing logs shorter than currently to be sawed. On the other hand, shortening of applicable log lengths would obviously increase the costs of harvesting, transportation, and processing. It seems, however, that even by using the conventional bucking rules, bucking the stems into large- and small-diameter sawlogs and pulpwood instead of bucking into veneer logs and pulpwood provides higher value per cubic meter for birch.

LITERATURE CITED

1. Fjærtoft, F. and A. Bunkholt. 1994. Grading rules for sawlogs and sawnwood of birch: Results of sawing experiments. Res. Pap. 18/1994:1-17. Norwegian Forest Res. Inst., Skogforsk, Norway. (In Norwegian with English abstract).
2. Gobakken, T. 2000. Models for assessing timber grade distribution and economic value of standing birch trees. Scandinavian J. of Forest Res. 15:570-578.
3. Hakala, H. 1992. Financial result of sawing pine logs as influenced by top diameter and other associated factors. Acta Forestalia Fennica 226. 74 pp. (In Finnish with English summary, tables and figures).
4. Haskell, H.H. 1957. The longitudinal slicing of redwood and yellow birch veneer. USDA Forest Serv., Forest Prod. Lab., Madison, WI. 20 pp.
5. Hegyi, F. 1974. A simulation model for managing Jack pine stands. *In*: Growth Models for Tree and Stand Simulation. G. Fires, ed. Rapp. Uppsats. Instn. Skogsprod. Skogshögsk. 30:74-89.
6. Heinonen, J. 1994. Koealojen puu- ja puustotunnusten laskentaohjelma KPL. Käyttöohje. [Software for calculating tree and stand characteristics KPL, Users Manual]. Res. Pap. 504. Finnish Forest Res. Inst., Joensuu, Finland. 80 pp. (In Finnish).
7. Heiskanen, V. 1957. Quality of the common birch and the white birch on different sites. Comm. Inst. For. Fenn. 48(6):1-99. (In Finnish with English summary, tables and figures).
8. __________. 1966. Studies on the defects of birch, their influence on the quality and quantity of rotary cut veneer, and their consideration in veneer birch grading. Acta Forestalia Fennica 80(3):1-128. (In Finnish with English summary, tables and figures).
9. Kärkkäinen, M. 1985. Puutiede. [Wood Science]. Karisto Oy. Hämeenlinna. 415 pp. (Textbook in Finnish).
10. __________. 1986. Value relations of birch veneer logs and stems. Silva Fennica 20(1): 45-57. (In Finnish with English abstract, tables, and figures).
11. Keinänen, E. and V. Tahvanainen. 1995. Pohjolan jalot puut. [Exotic and Uncommon Domestic Hardwoods in Finland]. Kuopion käsi- ja taideteollisuusakatemia, Kuopio. 160 pp. (Textbook in Finnish).
12. Kivistö, J., M. Sipi, A. Kantola, and T. Niemelä. 1999. Mechanical processing and end-products of birch, aspen and alder in Finland in 1999. Summary of the Results of an Inquiry and Interviews. Pub. 20. Univ. of Helsinki, Dept. of Forest Resource Management. 56 pp. + 14 app. (In Finnish with English abstract).
13. Kuusipalo, J. 1996. Suomen metsätyypit. [Finnish Forest Site Types]. Kirjayhtymä, Helsinki. 144 pp. (Textbook in Finnish).
14. Laine, J. 1989. Metsäojitettujen soiden luokittelu. [Classification of drained peatlands]. Suo 40:37-51. (In Finnish).
15. Luostarinen, K. and E. Verkasalo. 2000. Birch as sawn timber and in mechanical fur-

ther processing in Finland. A Literature Study. Silva Fennica Monographs 1. 40 pp.

16. Lutz, J. 1975. Manufacture of veneer and plywood from United States hardwoods with special reference to the south. Res. Pap. FPL 255. USDA Forest Serv., Forest Prod. Lab., Madison, WI. 8 pp.
17. __________. 1977. Wood veneer: Log selection, cutting, and drying. Tech. Bull. No. 1577. USDA, Washington, DC. 137 pp.
18. Maataloustuottajain Keskusliitto ry. and Koivukeskus ry. 1973. Vanerikoivujen yleiset laatu- ja mittausmääritelmät. [Grading and scaling of birch veneer logs]. Helsinki. 2 pp. (In Finnish).
19. Meriluoto, J. 1965. The influence of raw material factors on the quantity and quality of rotary cut birch veneer. Acta Forestalia Fennica 80(1):1-155. (In Finnish with English summary, tables, and figures).
20. Mielikäinen, K. 1980. Structure and Development of Mixed Pine and Birch Stands. Comm. Inst. For. Fenn. 99(3):1-82. (In Finnish with English summary, tables and figures).
21. __________. 1985. Effect of an admixture of birch on the structure and development of Norway spruce stands. Comm. Inst. For. Fenn. 133:1-79. (In Finnish with English summary, tables, and figures).
22. Reed, D.D., G.W. Lyon, and E.A. Jones. 1987. A method for estimating log grade distribution in sugar maple stands. Forest Sci. 33:565-569.
23. Sevola, Y. 1999. (ed.) Finnish Statistical Yearbook of Forestry. SVT Maa-, metsä- ja kalatalous 1999:6. 352 pp.
24. Uusitalo, J. 1997. Pre-harvest measurement of pine stands for sawing production planning. Acta Forestalia Fennica 259. 56 pp.
25. Verkasalo, E. 1990. Birch and aspen as a raw material for mechanical forest industries in the United States. Res. Pap. 367. Finnish Forest Res. Inst., Joensuu, Finland. 93 pp. (In Finnish with English summary, tables and figures).
26. __________. 1996. Evaluating the potential of European white birch (*Betula pubescens*) for veneer and plywood by timber and wood quality. Workshop 1996 IUFRO S5.01-04 - Poster Communications. IUFRO, Vienna, Austria. pp. 431-439.
27. __________. 1997. Quality of European white birch (*Betula pubescens* Ehrh.) for veneer and plywood. Res. Pap. 632. Finnish Forest Res. Inst., Joensuu, Finland. 483 pp. + App. 59 pp. (In Finnish with English abstract).
28. Vilkon Inc. 1998. Sahakoivun laatuvaatimukset. [Grading rules for birch saw logs]. Hirvensalmi, Finland. 2 pp. (In Finnish).
29. Wagenführ, R. 1996. Holzatlas. 4. Verlag. VEB Fachbuchverlag Leipzig. 688 pp. (Textbook in German].

III

Internal Knottiness with Respect to Sawing Patterns in *Betula pendula* and *B. pubescens*

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The objective of this study was to examine the internal knottiness structure, and define the possibilities to predict – on the basis of the board's within-stem location – the knottiness grades of boards sawn from mature *Betula pendula* and *B. pubescens*. The differences of the knottiness between the alternative growing conditions and trees representing different crown layers were also studied. The sample trees were sawn into unedged boards with a 25-millimetre green thickness and a 2-metre length. Boards were graded according to the existence of knots into three categories (1: knot-free, 2:only dead knots or both dead and sound knots, 3: only sound knots). Polytomous logistic regression (PLR) models were constructed to predict the grades for the boards based on their location within the stem. Generally, *B. pendula* butt logs from the stump up to six metres, as well as *B. pubescens* butt logs up to four metres contained mainly knot-free boards from a 75-millimetre distance from the pith outwards. At those heights, the inner boards were rather equally distributed between the grades 1, 2 and 3. Sound-knotted boards were, as expected, mainly situated in the small-sized top parts of the stems. At the lower heights, sound-knotted boards were gradually replaced by dead-knotted, and finally, knot free boards. In all growing conditions studied, knot-free and sound-knotted boards were separated in a satisfactory accuracy by the PLR models. Boards with only dead knots or with a mixed knottiness structure were slightly more poorly classified.

Key words: *Betula pendula*, *Betula pubescens*, grading, knottiness, lumber.

Introduction

In the biological sense, the terms knot, branch and limb stand for the same thing. Branch is, however, commonly referred to the outside of stem part of the limb, whereas knot means the part inside the stem. As far as wood-product industry is considered, thus, knots are of grater importance. Knots are, in fact, the most common defect affecting the grading of lumber and veneers both in softwood products (cf. Heiskanen 1965, Kärkkäinen 1985, Hakala 1992, Samson 1993, Uusitalo 1994, 1997) and in hardwood products (cf. Meriluoto 1965, Heiskanen 1966, Kärkkäinen 1986, Verkasalo 1997, Kivistö et al. 1999, Luostarinen & Verkasalo 2000). The influence of the knots is twofold. Firstly, they decrease the mechanical strength and stiffness of wood intended for structural uses, such as construction and framing (e.g., Zobel & van Buijtenen 1989, Madsen 1992, Boren 2001). Secondly, knots influence the surface characteristics, i.e., visual appearance of sawn wood or veneer either positively or negatively, depending on the end-use of the product. In structural wood products especially, the existence of a knot is, thus, normally considered a negative feature.

North European birch species, *Betula pendula* and *B. pubescens*, have mostly been utilied in visible uses, for instance, as facing materials on lower-quality wood products, as well as for decorative purposes (e.g., Louna & Valkonen 1995, Luostarinen & Verkasalo 2000, Forbes et al. 2001). Therefore, their appearance is often the dominating factor. In uses such as furniture or floorings, also high mechanical performance is still required.

Sound knots inside the stem are normally physiologically connected with the surrounding wood material and, as long as alive, they grow in diameter along with the growth of the stem. On the other hand, the overgrowing stem wood treats a dead knot as an external object; the new overgrown wood material is not connected with a dead knot anymore. Thus, the stem wood embraces the knot. After pruning the branch, either naturally or artificially, the overgrowing stem wood begins healing-over the stub. The healing-over time depends on the speed of the growth, as well as the size of the stub. Clear wood with a straight grain pattern starts growing on the stub after the healing-over process has finished (e.g., Kärkkäinen 1985, Mäkinen & Colin 1999, Wood handbook 1999).

All branches visible on the surface of the stem, hence, are originated from the pith of the tree. However, an exception is made by the epicormic branches (or sometimes called "water sprouts") caused by resting buds on the surface of the stem and which, therefore, cannot be seen in the inner wood material. Their existence is related to damages in the foliage caused by, for instance, frost or an increased amount of light available in the lower parts of the stem (Heiskanen 1957). Epicormic branches may be a degrading factor for veneers obtained near the surface of the butt-logs. Some hardwoods, such as oak, ash and alder species are especially prone to produce epicormic branches. Older birch trees with poor foliage sometimes grow them, as well.

Since the goal of growing trees is usually to maximise the quantity and quality of saw or veneer timber, where the knot-free grades are the most valuable, young trees are sometimes artificially pruned in order to produce as much knot-free butt-log as possible. For instance, Uusvaara (1993) showed that the percentage of the best grades in artificially pruned Scots pine butt-logs was 57, whereas, non-pruned logs provided the best grades with only 22% from the entire lumber volume. Concerning birch trees intended for veneer, plywood or sawn wood production, artificial pruning undoubtedly increases the value of the stem at least as much as is the case with Scots pine. Birch is, nevertheless, highly susceptible for discolouration, especially when living branches of over 20 millimetres in diameter are pruned. Moreover, pruning methods and correct timing have a significant influence on the successful healing-over process, as well as on the resistance to the decaying fungi (cf. Blomqvist 1879, Heiskanen 1958, Zobel & van Buijtenen 1989, Verkasalo & Rintala 1998).

In addition to artificial pruning, tree branchiness can be controlled by tree breeding, i.e., improving the genetic material. Furthermore, silvicultural practices, such as between tree spacing and correctly scheduled thinnings influence the number, growth, suppress, dying and self-pruning of branches (cf. Zobel & van Buijtenen 1989, Mäkinen 1999).

Principally, when hardwoods have been utilized by the wood-product industries, the aim has been to obtain as much knot-free – or to some extent sound-knotted – products as possible. Dead knots are mainly degrading factors. Holes in facing veneers caused by loosened dead knots must be repaired by a patch or, alternatively, veneers with dead knots must be sorted for the inner layers of plywood. Hardwood lumber with dead knots is typically used in hidden structures of furniture or in low-value products, such as packaging materials (Luostarinen & Verkasalo 2000).

Kärkkäinen (1986) modelled the internal knottiness structure of birch on the basis of the development of the dead branch height and the living crown height at different age of trees. The models were based on the biological development, whereas the natural variability was not taken into consideration. Therefore, no attention could be paid on the fact that the external crown layers, not to mention the internal knottiness structure of birch species are not as straightforward as the crown layers of many softwood species are. Heräjärvi (2001) showed that in birch, small dry and rotten branches are common not only below the living crown, but also in it, between the larger living branches. It is obvious that this influences also the internal knottiness structure of birch stems.

Much work has been devoted in order to develop simulation programs for hardwood lumber grading according to appearance (cf. Hallock & Galiger 1971, Klinkhachorn et al. 1988, Samson 1993, Steele et al. 1994). However, softwoods have been of even more interest, especially in the Nordic countries (cf. Björklund 1997, Björklund & Petersson 1999, Lundgren 2000), where more than 90% of the sawn wood production consists of softwoods. Uusitalo (1994) defined two generic methods for using logistic regression for studying the lumber grade distributions within a tree stem. Firstly, he stated that at least in theory, the lumber grade should be a proper outcome for a polytomous logistic regression model. Secondly, he suggested that either polytomous or binary logistic regression should be a proper tool for predicting the number of boards representing a certain grade within one saw log. He also successfully applied the latter method for Scots pine (Uusitalo 1997).

Considering *Betula pendula* and *B. pubescens*, the studies of Kärkkäinen (1986) are the only articles published on the structure of the internal knottiness. No applications are presented for the practical needs, such as for studying the distributions of different lumber grades or for determining the optimal sawing patterns for processing birch logs. This is, undoubtedly, affected by the fact that compared to sawing softwoods, sawing birch has traditionally played a minor role in the Nordic countries. The increasing economical importance of birch as sawn wood completed with the limited availability of high-quality birch logs has raised an interest in improving the efficiency of birch utilization in all countries near the Baltic Sea region.

The objective of this article was to study the internal knottiness structure of mature *Betula pendula* and *B. pubescens* by theoretical modelling of the knottiness structure of 2-metre long and 25-millimetre thick boards on the basis of their location within birch stem. A similar modelling method has not been introduced earlier for this purpose. The results are intended, in particular, for facilitating the selection of sawing patterns for birch saw logs.

Materials and methods

The material consisted of 261 mature (age: 68-108 years) birch trees selected from 20 randomly chosen stands in southern, central and eastern Finland. *B. pendula* stands were, on average, slightly older compared to the *B. pubescens* stands. This is analogous to the natural difference between the biological lifecycles of the two species. All stands were located on mineral soils or peatlands representing average or good fertility. Heräjärvi (2001) presented the key characteristics of the sample stands and measurement methods in more detail. The stands were required to meet the normal silvicultural status according to the Finnish practice and no exceptional treatments, such as artificial pruning or birch bark peeling were allowed. Stands were categorised into six strata in the following manner:

Stratum 1	Pure *Betula pendula* stands on mineral soils (3 stands, mean age for birch 86 years, mean diameter at breast height (dbh) for birch 250 mm)
Stratum 2	Mixed stands of conifers and *B. pendula* on mineral soils (4 stands, 81 years, 264 mm)
Stratum 3	Pure *B. pubescens* stands on mineral soils (3 stands, 72 years, 234 mm)
Stratum 4	Mixed stands of conifers and *B. pubescens* on mineral soils (4 stands, 75 years, 237 mm)
Stratum 5	Pure *B. pubescens* stands on drained peatlands (3 stands, 74 years, 210 mm)
Stratum 6	Mixed stands of conifers and *B. pubescens* on drained peatlands (3 stands, 79 years, 208 mm)

Only trees having a dbh of more than 140 millimetres were regarded as potential sample trees. In addition, at least one sawable log was to be obtained from each applicable sample tree. On average, 13 trees per stand were sampled using stratified random sampling. The basis for the stratification was that a representative dbh series from 140 millimetres upwards was wanted. The competitive status (dominant, co-dominant), dbh, crown limits, as well as characteristics of the technical quality of each sample tree were assessed before felling.

After felling and delimbing, the sample trees were crosscut into logs with lengths of two or four metres. Each log was coded using a felt-tip pen, thus, enabling its identification and location in the stem afterwards. In addition, an arrow was drawn at the top end of each log so that during sawing, all the logs from one tree could be positioned in respect to the other logs obtained from the same tree. Logs having a top-diameter of 120 millimetres or more were transported to a sawmill.

The logs were sawn pith-centrally without edging into the green thickness of 25 millimetres using a circular saw. In practice, each trunk from the base up to the height where the diameter was approximately 120 millimetres was, hence, systematically divided into two- or four-metre long and 25-millimetre thick sections. Immediately after sawing, the boards obtained were coded according to their origin and location in the log. The four-metre boards were handled as two two-metre boards. Altogether 10,251 two-metre-long sections were obtained.

Type (sound, dead), size and number of knots were measured from each board. Knots were measured in perpendicular to the grain direction; therefore, measuring diagonally cut knots did not necessarily reflect their true size. Only knots having a diameter of more than 5 millimetres were considered when the boards were graded into the following, non industry-based, categories:

Grade 1 (Knot-free)	at most 1 knot (diameter ≥ 5 mm) / 2 m, smaller knots allowed
Grade 2 (Dead-knotted or mixed)	at least 2 dead knots (diameter ≥ 5 mm) / 2 m, irrespectively of the other knots
Grade 3 (Sound-knotted)	others

In this study, sound knot did not necessarily stand for a living knot, but one having at least 50% of its circumference tightly connected with the surrounding wood. Dead knot, on the other hand, could be either dry or rotten. Epicormic branches were not included into the analyses due to their unsystematic existence and exceptional structure.

The differences in the knottiness grades between the study groups, i.e., strata and crown layers, were studied firstly using the nonparametric Mann-Whitney

U –test. Secondly, the odds for falling into a given grade by the knottiness, was modelled for each board based on its known location (relative distance from the pith, % of the top radius of the log: X1; relative distance from the stump, % of the height of the tree: X2), by using the Polytomous Logistic Regression (PLR). According to Hosmer & Lemeshow (1989), PLR can be used when the test subjects are to be classified into more than two groups according to the values of the predictor variables. This type of regression is similar to the binary logistic regression, but it is often more applicable since the dependent variable is not restricted into two categories.

While the logistic regression is applied to classify the data into two or more subsets, it is necessary the subsets to be of approximately the same size. If one subset is exceptionally small in number of observations in comparison to the others, the model will probably fail in classification into that subset. As seen in Table 1, grade 3 has clearly larger number of boards compared to grades 1 and 2. In this case, however, the difference between the group sizes was not considered counterproductive, since all three grades still had thousands of observations. The total number of boards accepted into the analyses was 10,050, while 201 boards were excluded from the analyses because of their highly divergent knottiness characteristics, obviously caused by an error either in the coding or in the measuring.

The goodness-of-fit of the PLR models were studied by the deviance chi-square –test, which in principle, corresponds to the residual sum of squares in the linear regression model. The significance of individual variables was tested using the Wald –test statistics obtained by comparing the maximum likelihood estimate of the slope parameter to the estimate of its standard error. Roughly, when the value of Wald statistics exceeds the value of 2, the variable is considered significant (Hosmer & Lemeshow 1989). Odds ratios, being presented for the PLR models as well, approximate how much more likely or unlikely it is for the outcome to be present in the given group than in the reference group.

Results

Tested by the Mann-Whitney test, the lumber grade distributions between the dominant and the co-dominant trees did not differ significantly (Z: -0.167, p: 0.868). This was rather unexpected since, externally, the relative size of the living crown of the co-dominant trees is usually clearly smaller and more suppressed than the crown of the dominant trees.

Since the total lumber grade distributions were examined (without taking into account the effect of the location parameters), it appeared that strata 1 and 2 had similar distributions, whereas, stratum 3 was different from any other stratum by having a larger percentage of sound-knotted boards and a smaller percentage of knot-free boards. Strata 4, 5 and 6 were fairly similar to each other in the overall lumber grade distributions (Table 1, Figure 1). Circa one third of the boards belong to each of the three grades. Thus, the overall distributions in the two strata with *Betula pendula* trees were similar to each other, whereas the four strata with *B. pubescens* trees had more variation

Table 1. Number of measured two-metre boards by grade and stratum. Strata: 1: pure *Betula pendula* stands on mineral soils; 2: mixed stands of conifers and *B. pendula* on mineral soils; 3: pure *B. pubescens* stands on mineral soils; 4: mixed stands of conifers and *B. pubescens* on mineral soils; 5: pure *B. pubescens* stands on drained peatlands; 6: mixed stands of conifers and *B. pubescens* on drained peatlands. Grades: 1: knot-free; 2: dead-knotted or mixed; 3: sound-knotted

Stratum	Grade			
	1	2	3	*Total*
		Number of boards		
1	554	639	1,001	*2,194*
2	605	669	1,157	*2,431*
3	338	416	826	*1,580*
4	467	563	754	*1,784*
5	315	437	581	*1,333*
6	195	185	348	*728*
Total	*2,474*	*2,909*	*4,667*	*10,050*

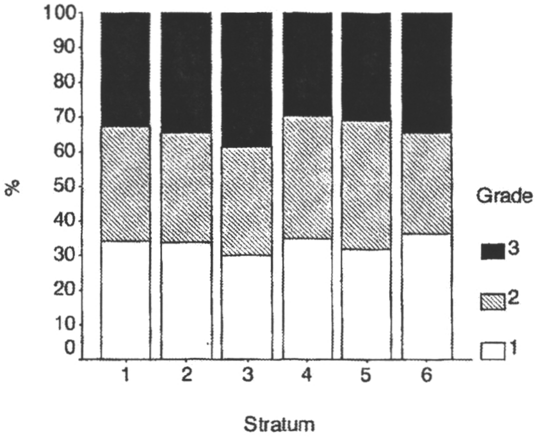

Figure 1. Lumber grade distributions within the six strata. For description of strata and grades, see: Table 1

between the knottiness grade distributions. The two birch species differed from each other only slightly.

Once the location parameters were taken into account, the between strata differences in the lumber grade distributions became more apparent. Figure 2 presents the distributions of grades according to the location parameters and strata, calculated on the basis of the observed data. Due to the stem tapering, both volumetrically and numerically most of the actual lumber recovery was situated in the lower parts of the stem. The diagrams in Figure 2 are generalisations, since the size variations of trees within one stratum were not considered. Thus, for instance, the vertical location of ten metres stood for the relative height of between 46% and 60%, while different-sized trees were examined. The absolute scale location parameters were used in Figure 2, instead of the relative values seen in the actual models (Tables 2 and 3), since the absolute scale was more easily visualised.

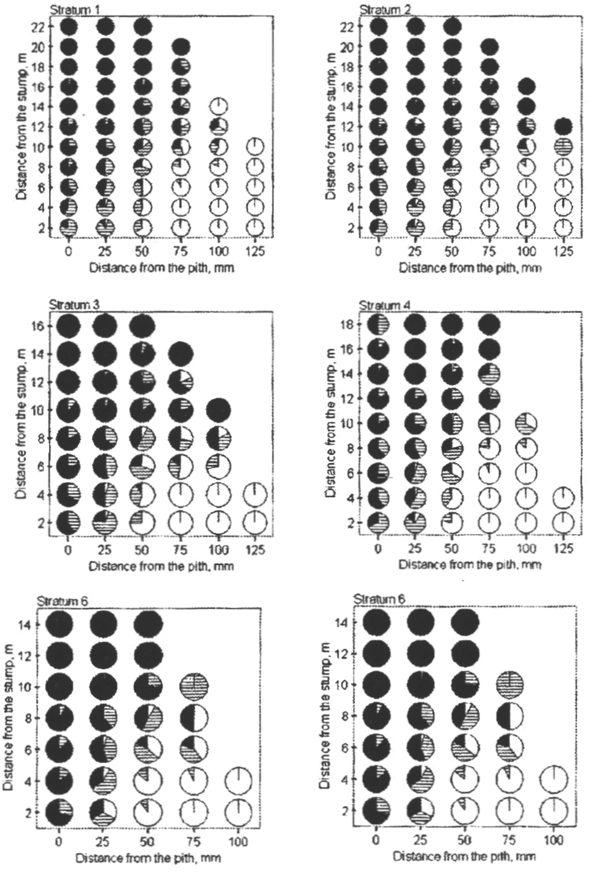

Figure 2. Falling of boards obtained from different within-tree locations into separate knottiness grades. Slices represent percentages of separate grades in a large sample. White: grade 1, lineation: grade 2, black: grade 3. For description of strata and grades, see: Table 1

Table 2. Polytomous logistic regression models predicting the odds for a board of falling into the grades 1, 2 or 3 (Grade 3 = reference group) in strata 1, 2 and 3. For description of strata and grades, see: Table 1

Stratum	Grade	Variable	Coefficient (S.E.)	Wald	Odds ratio (95% CI)
1	1	Constant	-0.325 (0.276)	1.385	
		X1	0.164** (0.008)	443.852	1.178 (1.160; 1.196)
		X2	-0.258** (0.011)	543.056	0.772 (0.756; 0.789)
	2	Constant	2.347** (0.165)	201.856	
		X1	0.077** (0.007)	115.194	1.080 (1.065; 1.095)
		X2	-0.114** (0.006)	410.023	0.892 (0.883; 0.902)
Correctly classified: grade 1: 83.2%, grade 2: 55.9%, grade 3: 83.2%, overall: 75.3%.					
Model fit:					
Deviance Chi-square		1602.241			
Df		2660			
P		1.000			
2	1	Constant	-0.244 (0.260)	0.882	
		X1	0.164** (0.008)	419.519	1.178 (1.159; 1.196)
		X2	-0.276** (0.012)	521.856	0.759 (0.741; 0.777)
	2	Constant	2.027** (0.149)	184.685	
		X1	0.028** (0.003)	81.531	1.028 (1.022; 1.035)
		X2	-0.096** (0.005)	410.639	0.908 (0.900; 0.917)
Correctly classified: grade 1: 86.4%, grade 2: 49.3%, grade 3: 84.2%, overall: 75.2%.					
Model fit:					
Deviance Chi-square		1703.181			
Df		2816			
P		1.000			
3	1	Constant	-1.030** (0.327)	9.915	
		X1	0.153** (0.009)	280.330	1.166 (1.145; 1.187)
		X2	-0.270** (0.015)	309.706	0.763 (0.740; 0.786)
	2	Constant	1.325** (0.169)	61.199	
		X1	0.031** (0.004)	71.758	1.032 (1.024; 1.039)
		X2	-0.093** (0.006)	247.011	0.911 (0.901; 0.922)
Correctly classified: grade 1: 83.1%, grade 2: 44.7%, grade 3: 83.9%, overall: 73.4%.					
Model fit:					
Deviance Chi-square		1265.362			
Df		1876			
P		1.000			

X1: relative distance from the pith, percent of the top radius of the log.
X2: relative distance from the stump, percent of the height of the tree.
**=Significant at 1% level, *=significant at 5% level.

Generally, *B. pendula* butt logs from the stump up to six metres, as well as *B. pubescens* butt logs up to four metres contained mainly knot-free boards from a 75-millimetre distance from the pith outwards. At those heights, the inner boards were rather equally distributed between the grades 1, 2 and 3. Sound-knotted (grade 3) boards were mainly situated in the small-sized top parts of the stems, and were gradually replaced by dead-knotted boards and finally knot free boards at the lower heights.

The location parameters were the only significant predictors for the lumber grade. Adding other explanatory variables, such as the basal area of the stand, age of the tree, height of the living crown or dbh to the location parameters, improved the efficiency of the models only slightly. The PLR models predicting the falling of boards into separate knottiness grades are presented in Tables 3 and 4. According to the deviance tests, the models fit to the data. Depending on the stratum in question, the overall percentage of

Table 3. Polytomous logistic regression models predicting the odds for a board of falling into the grades 1, 2 or 3 (Grade 3 = reference group) in strata 4, 5 and 6. For description of strata and grades, see: Table 1

Stratum	Grade		Estimated		
		Variable	Coefficient (S.E.)	Wald	Odds ratio (95% CI)
4	1	Constant	-0.846** (0.312)	7.346	
		X1	0.155** (0.009)	321.457	1.168 (1.148; 1.188)
		X2	-0.261** (0.013)	382.405	0.770 (0.750; 0.791)
	2	Constant	1.970** (0.168)	136.732	
		X1	0.019** (0.003)	38.008	1.020 (1.013; 1.026)
		X2	-0.085** (0.005)	268.023	0.918 (0.909; 0.928)
Correctly classified: grade 1: 86.5%, grade 2: 52.8%, grade 3: 77.3%, overall: 72.0%.					
Model fit:					
Deviance Chi-square	1443.968				
Df	2102				
P	1.000				
5	1	Constant	-1.168** (0.376)	9.658	
		X1	0.161** (0.010)	270.460	1.175 (1.152; 1.197)
		X2	-0.269** (0.016)	294.806	0.764 (0.741; 0.788)
	2	Constant	1.732** (0.193)	80.684	
		X1	0.035** (0.004)	90.061	1.035 (1.028; 1.043)
		X2	-0.094** (0.006)	217.829	0.911 (0.899; 0.922)
Correctly classified: grade 1: 79.7%, grade 2: 56.5%, grade 3: 77.3%, overall: 71.0%.					
Model fit:					
Deviance Chi-square	1066.722				
Df	1578				
P	1.000				
6	1	Constant	-1.006* (0.415)	5.884	
		X1	0.148** (0.012)	147.866	1.159 (1.132; 1.187)
		X2	-0.229** (0.018)	155.312	0.795 (0.767; 0.825)
	2	Constant	0.333 (0.242)	1.892	
		X1	0.040** (0.005)	57.628	1.041 (1.030; 1.051)
		X2	-0.067** (0.008)	68.576	0.936 (0.921; 0.950)
Correctly classified; grade 1: 83.6%, grade 2: 33.0%, grade 3; 83.9%, overall: 70.9%.					
Model fit:					
Deviance Chi-square	618.347				
Df	886				
P	1.000				

X1: relative distance from the pith, percent of the top radius of the log.
X2: relative distance from the stump, percent of the height of the tree.
**=Significant at 1% level, *=significant at 5% level.

correctly classified boards varied between 70.9 and 75.3. At its lowest, however, no more than 33% of the grade 2 boards were sorted out by the PLR, whereas the percentages of correctly classified boards representing grades 1 and 3 were typically close to 80.

The knot-free boards (grade 1), as well as the sound-knotted boards (grade 3) were satisfactorily separated from the boards representing grade 2 by the PLR. Grades 2 and 3, however, mixed in the middle sections of the stem. This was due to the unsystematic distribution of dead knots within the externally dead-knotted (i.e., above the knot-free base and below the living crown) stem section of birch. Grades 2 and 3 were, thus, clearly overlapping within the mid-parts of the trunk. Figure 3 illustrates the observed knottiness grade distribution in stratum 1, based on which it is understandable that the models partly failed in classifying between the grades 2 and 3.

Next, an example is given in order to illustrate the interpretation of the results of the PLR models. The deviance chi-square test statistics indicate that the models fit to the data, as they are less than their respective degrees of freedom (cf. Hosmer & Lemeshow 1989). Bearing in mind that grade 3 was determined to be a reference group grades 1 and 2 are to be compared to it. In stratum 1, we have the X1 variable with an estimated coefficient of 0.164, Wald statistics of 443.852 and odds ratio of 1.178. Wald statistics determine, in practice, the significance of an individual variable, showing in this case, high significance. Odds ratio of 1.178 indicates that an increment of one unit (=percent) in predictor variable X1 increases the odds of obtaining the grade 1 board by 17.8% compared to the reference group, grade 3. Similarly, in the case of a negative coefficient X2 with the odds ratio value of 0.772, compared to the reference group, the odds of obtaining the grade 1 board decreases by 26.8% (1.00-0.772=0.268), as the value of X2 increases by 1%.

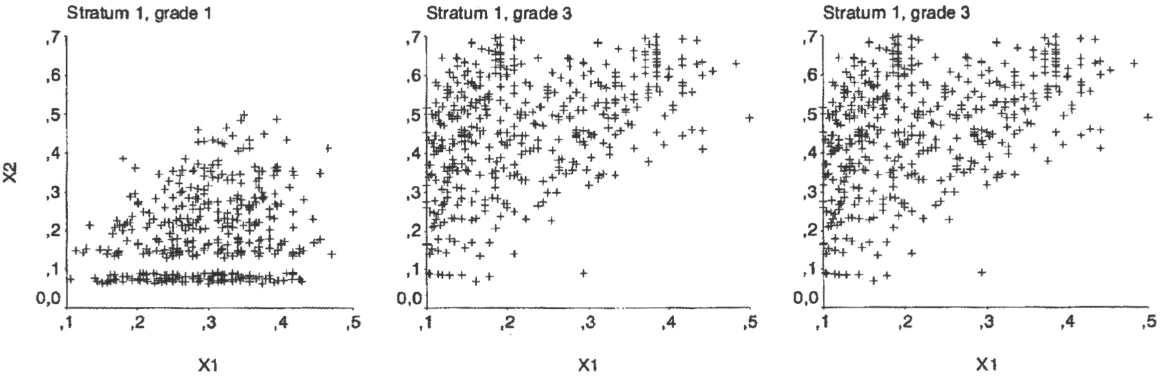

Figure 3. Distribution of knottiness grades 1, 2 and 3 in stratum 1 according to the location parameters X1 (relative distance from the pith, % of the top radius of the log) and X2 (relative distance from the stump, % of the height of the tree). For description of strata and grades, see: Table 1

Discussion and conclusions

The knottiness structure between the two birch species and between the growing conditions showed considerable differences. Generally, in pure *B. pubescens* stands (stratum 3), the percentage of the knot-free boards was slightly smaller and the percentage of the sound-knotted boards slightly larger in comparison to the other strata studied. The differences between the grade distributions of *B. pendula* grown in pure birch stands and in mixed stands of conifers and birch were actually smaller than what could be expected. According to the literature, the density of the stand, as well as the competitive position of an individual tree, inevitably influences its knottiness properties (cf. Merkel 1967, Kellomäki & Tuimala 1981, Kellomäki 1984, Hägg 1988, 1990, Lämsä et al. 1990, Kellomäki et al. 1992, Niemistö 1995, Niemistö et al. 1997). In this study, however, this effect was not observed, while the range of the stand densities was fairly small (cf. Heräjärvi 2001). Moreover, the location parameters as predictors for the lumber grades were so dominating that they faded out the less significant predictors, such as stand density, dbh and heights of the crown limits. The *B. pendula* stands were, on average, slightly older than the *B. pubescens* stands; this might have influenced the comparisons of the knottiness distributions between the two species. However, the between-species variation was not of key importance in this study.

It appeared that the location of especially dead, i.e., dry and rotten knots within birch stems is difficult to model with the methodology chosen. During the sampling and analyses of the materials it was noticed that even large, externally dry or even rotten branches turned into sound knots quite soon after they were investigated further inside the stem.

Concerning the methodological framework of this study, polytomous logistic regression was found suitable for predicting the odds of obtaining knot-free and sound-knotted lumber from birch trees. One possible source of bias related to this kind of modelling is the correlation between the within-tree and within-stand measurements. Such correlation was not observed in this study, which might be due to the natural variability of knottiness characteristics even within one, uniformly treated stand. The mixed knottiness structure in the mid sections of the stems still prevented the models from being able to separate grades 2 and 3 from each other with the accuracy wanted. This was partly affected by the grading practice where fairly long, two-metre boards were classified into one grade as a whole. It is obvious that the shorter the boards are, the better is the accuracy of the models. Undoubtedly, this would be true also in the case of thinner boards.

A similar modelling method has not been introduced earlier for predicting the lumber grade distributions. This method would probably be more applicable to softwoods with the monopodial growing regime (cf. Zobel & van Buijtenen 1989, Kellomäki & al. 1992), which generally results into straighter stem form. From the point of view of the practical applicability, the challenge in this kind of modelling is that the location of the log within the tree should be known in order to select the optimum sawing patterns. Excluding the easily recognisable butt logs, such information is not available in the current sawmills. Nevertheless, a coding or measuring method of some kind, based on the log taper, for instance, would obviously be possible for detecting the logs original vertical location in the stem (cf. Blomqvist & Nylinder 1988, Jäppinen & Nylinder 1997, Lemieux et al. 2000, Lundgren 2000). This question was not approached within the framework of this article.

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References

Björklund L. 1997. The interior knot structure of Pinus sylvestris stems. Scand. J. For. Res. 12: 403-412.

- & Petersson H. 1999. Predicting knot diameter of Pinus sylvestris in Sweden. Scand. J. For. Res. 14: 376-384.

Blomqvist A. G. 1879. Om uppqkistning af träd [Of pruning of standing trees]. Finska Forstföreningens ströskrifter 1. Helsingfors. 18 p. (In Swedish).

Blomqvist H. & Nylinder M. 1988. Relation between geometry, yield and quality for sawlogs of pine, Results from investigations at Rockhammar sawmill. The Swedish University of Agricultural Sciences, Department of Forest Products. Report No 205. 50 p. + App. 12 p. (In Swedish with English summary).

Boren H. 2001. Factors affecting the knottiness, twisting and mechanical properties of pith enclosed round and sawn timber of Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) from thinnings in Southern Finland. Finnish For. Res. Inst., Research Papers 807, 2001. 164 p.

Forbes C.L., Jahn L.G. & Araman P.A. 2001. An investigation of hardwood plywood markets. Part 2. Fixture manufacturers. For. Prod. J. 51(6): 25-31.

Hakala H. 1992. Financial result of sawing pine logs as influenced by top diameter and other associated factors. Acta For. Fenn. 226. 74 p. (In Finnish with English summary).

Hallock H. & Galiger L. 1971. Grading hardwood lumber by computer. Res. Pap. FPL 157. USDA Forest Serv., For. Prod. Lab., Madison, Wisconsin.

Heiskanen V. 1957. Quality of the common birch and the white birch on different sites. Comm. Inst. For. Fenn. 48(6): 1-99. (In Finnish with English summary).

- 1958. Studies on pruning of birch. Comm. Inst. For. Fenn. 49(3): 1-68. (In Finnish with English summary).

- 1965. On the relations between the development of the early age and thickness of trees and their branchiness in pine stands. Acta For. Fenn. 80(2): 1-62. (In Finnish with English summary).

- 1966. Studies of the defects of birch, their influence on the quality and quantity of rotary cut veneer, and their consideration in veneer birch grading. Acta For. Fenn. 80(3): 1-128. (In Finnish with English summary).

Heräjärvi H. 2001. Technical properties of mature birch (Betula pendula and B. pubescens) for saw milling in Finland. Silva Fenn. 35(4): 469-485.

Hosmer D.W. Jr. & Lemeshow S. 1989. Applied Logistic Regression. John Wiley & Sons, Inc. 307 p.

Hägg A. 1988. The profitability of a birch admixture in coniferous forests. The Swedish University of Agricultural Sciences, Department of Forest Products. Report No 201. 62 p. + App. 24 p. (In Swedish with English summary).

- 1990. The profitability of using self-regenerated birch for shaping the quality of planted pine. The Swedish University of Agricultural Sciences, Department of Forest Products. Report No 214. 26 p. + App. 7 p. (In Swedish with English summary).

Jäppinen A. & Nylinder M. 1997. Automatic sorting of spruce (Picea abies (L.) Karst.) sawlogs by grade. Holz als Roh- und Wrkstoff 55: 301-305.

Kellomäki S. 1984. Observations on the influence of stand density on branchiness of young Scots pines. Silva Fenn. 18(2): 101-114. (In Finnish with English summary).

-, Lämsä P., Oker-Blom P. & Uusvaara O. 1992. Männyn laatukasvatus [Growing of quality pine]. Silva Carelica 23. 133 p. (Text book in Finnish).

- & Tuimala A. 1981. Effect of stand density on branchiness of young Scots pines. Folia For. 478: 1-27. (In Finnish with English summary).

Klinkhachorn P., Franklin J.P., McMillin C.W., Conners R.W. & Huber H.A. 1988. Automated computer grading of hardwood lumber. Forest Prod. J. 38(3): 67-69.

Kivistö J., Sipi M., Kantola A. & Niemelä T. 1999. Koivun, haavan sekä terva- ja harmaalepän mekaaninen jalostus ja lopputuotteet Suomessa vuonna 1999, Postikysely- ja haastattelututkimuksen tulosten yhteenveto. [Mechanical processing and final products of birch, aspen and alder species in Finland in 1999. Summary of postal inquiry and interviews]. University of Helsinki, Department of Forest Resource Management. Publications 20. 56 p. + 14 app. (In Finnish).

Kärkkäinen M. 1985. Puutiede [Wood science]. Karisto Oy. Hämeenlinna. 415 p. (Textbook in Finnish).

- 1986. Model of knottiness of wood material in pine, spruce, and birch. Silva Fenn. 20(2): 107-116. (In Finnish with English abstract).

Lemieux H., Beaudoin M. & Grondin F. 2000. A model for the sawing and grading of lumber according to knots. Wood Fiber Sci. 32(2): 179-188.

Louna T. & Valkonen S. 1995. Kotimaisen raaka-aineen asema lehtipuiden teollisessa käytössä [Domestic raw material in industrial use of hardwooods]. Finnish For. Res. Inst., Research Papers 553. 38 p. (In Finnish).

Lundgren C. 2000. Predicting log type and knot size category using external log shape data from 3D log scanner. Scand. J. For. Res. 15: 119-126.

Luostarinen K. & Verkasalo E. 2000. Birch as sawn timber and in mechanical further processing in Finland. A literature study. Silva Fenn. Monographs 1. 40 p.

Lämsä P., Kellomäki S. & Väisänen H. 1990. Branchiness of young Scots pines as related to stand structure and site fertility. Folia For. 746. 22 p. (In Finnish with English abstract).

Madsen B. 1992. Structural behaviour of timber. Timber engineering Ltd. Canada. 405 p. + App. 27 p.

Meriluoto J. 1965. The influence of raw material factors on the quantity and quality of rotary cut birch veneer. Acta For. Fenn. 80(1): 1-155. (In Finnish with English summary).

Merkel P. 1967. The effect of tree spacing on branch sizes in spruce. Allg. Forst Jagdztg. 138(6): 113-124. (In German with English summary).

Mäkinen H. 1999. Growth, suppression, death, and self-pruning of branches of Scots pine in southern and central Finland. Can. J. For. Res. 29: 585-594.

- & Colin F. 1999. Predicting the number, death, and self-pruning of branches in Scots pine Can. J. For. Res. 29: 1225-1236.

Niemistö P. 1995. Influence of initial spacing and row-to-row distance on the crown and branch properties and taper of silver birch (Betula Pendula). Scand. J. For. Res. 10: 235-244.

-, Hukki P. & Verkasalo E. 1997. Kasvupaikan ja puuston tiheyden vaikutus rauduskoivun ulkoiseen laatuun 30-vuotiaissa istutuskoivikoissa [Influence of site and stand density on the external quality of planted 30-year-old silver birch stands]. Metsätieteen aikakauskirja – Folia Forestalia 3/1997: 349-374. (In Finnish).

Samson M. 1993. Method for assessing the effect of knots in the conversion of logs into structural lumber. Wood Fiber Sci. 25(3): 298-304.

Steele P.H., Harless T.E.G., Wagner F.G., Kumar L. & Taylor F.W. 1994. Increased lumber value from optimum orientation of internal defects with respect to sawing pattern in hardwood sawlogs. Forest Prod. J. 44(3): 69-72.

Uusitalo J. 1994. Predicting lumber quality of pine stems. University of Helsinki, Department of Forest Resource Management. Publications 3. 53 p. (In Finnish with English summary).

- 1997. Pre-harvest measurement of pine stands for sawing production planning. Acta For. Fenn. 259. 56 p.

Uusvaara O. 1993. Quality and value of sawn goods from pruned Scots pine stands. Folia For. 816. 26 p. (In Finnish with English summary).

Verkasalo E. 1997. Quality of European White Birch (*Betula pubescens* Ehrh.) for Veneer and Plywood. Finnish For. Res. Inst., Research Paper 632. 483 p. + App. 59 p. (In Finnish with English abstract).

- & Rintala P. 1998. Rauduskoivun pystykarsintavikojen riippuvuus oksien paksuudesta, laadusta ja karsinnan vuodenajasta [Dependence of pruning defects on knot diameter, knot quality and season]. Metsätieteen aikakauskirja – Folia Forestalia 2/1998: 151-178. (In Finnish).

Wood handbook – Wood as an engineering material. 1999. Gen. Tech. Rep. FPL-GTR-113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p.

Zobel B.J. & van Buijtenen J.P. 1989. Wood variation – its causes and control. Springer Verlag, Berlin. 363 p.

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ИССЛЕДОВАНИЕ ХАРАКТЕРИСТИК ВНУТРЕННЕЙ СУЧКОВАТОСТИ БЕРЁЗЫ (*B. PENDULA* И *B. PUBESCENS*) ПРИ УСТАВКИ ПИЛЫ

Х. Херяйарви

Резюме

Целью данного исследования является: изучение структуры внутренней сучковатости деревьев, и рассмотрение определения степени сучковатости досок, получаемых при распиливании спелой березы (*Betula pendula и B. pubescens*), на основе расположения доски внутри ствола. Для достижения поставленной цели были изучены различия в сучковатости деревьев в разных условиях произрастания, а также рассмотрены деревья образующие разные ярусы в древостое. Учетные деревья были распилены на необрезные доски с толщиной свежей древесины 25 миллиметров, и высотой 2 метра. Доски были отсортированы в зависимости от сучковатости на три группы (1: без сучков, 2: только сухие сучки или и сухие, и здоровые сучки, 3: только здоровые сучки). Модели политомической логистической регрессии (ПЛР) были разработаны для определения степени сучковатости досок. В процессе разработке ПЛР было установлено: большинство комлевых бревен березы бородавчатой (*B. pendula*) с комля до высоты 6 метров, так как комлевые бревна березы пушистой (*B. pubescens*) с комля до высоты 4 метра содержат в основном бессучковые доски (75 миллиметров от сердцевины наружу). В этих высотах внутренние доски довольно ровно разделились на степени 1, 2 и 3. Доски со здоровыми сучками, находятся в основном в маломерной верхней части ствола. На более низких высотах доски со здоровыми сучками постепенно превращаются в доски с сухими сучками и под конец в бессучковые доски. В моделях ПЛР на всех исследованных условиях произрастания бессучковые доски, и доски со здоровыми сучками значительно отличались друг от друга. Доски только с сухими сучками или со смешанной структурой сучковатости были немного хуже классифицированы.

Ключевые слова: *Betula pendula*, *Betula pubescens*, классификация, сучковатость, пиломатериал

IV

Title: **Variation of basic density and Brinell hardness within mature Finnish *Betula pendula* and *B. pubescens* stems**

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Abstract

The aim of this study was to analyse the variation in basic density between different horizontal and vertical locations within mature Finnish *Betula pendula* and *B. pubescens* stems. In addition, the dependence of Brinell hardness in radial direction, which is of importance especially for the parquetry, veneer and plywood industries, on the basic density was investigated. Furthermore, the sources of error in the Brinell hardness test according to EN 1534 were analysed. Both basic density and Brinell hardness were measured from small, defect-free specimens. The average basic density of *B. pendula* and *B. pubescens* were 512 kgm^{-3} and 478 kgm^{-3}, respectively. Concerning both birch species, wood material near the pith was clearly less dense than near the surface of the stem. The average Brinell hardness of *B. pendula* specimens was 23.4 MPa, and that of *B. pubescens* specimens was 20.5 MPa. Brinell hardness was found to be positively correlated with basic density. Therefore, the assumption that Brinell hardness varies within a birch stem similarly to basic density is confirmed. The test method according to the EN 1534 standard was found to be precise enough but unnecessarily laborious for hardness tests. Finally, an alternative method is suggested for determining Brinell hardness on an industrial scale.

Key words: *basic density, Brinell hardness, Betula pendula, Betula pubescens, furnishing, parquet, veneer, plywood.*

1. Introduction

The quality of wood can be characterized by a number of different properties, depending on their importance to the end-use of the product. Density, which denotes the weight of the wood substance contained in a unit volume, is an important quality indicator for basically all uses of wood. Density depends primarily on the ratio between the volume of the cell walls and the volumes of the intracellular and intercellular spaces, since the specific gravity of the cell wall substance is practically constant (Hakkila 1966).

Several different ways to define density are used in literature. Usually, however, the dry-matter weight of a wood specimen is compared to its volume. The definition of volume, on the other hand, varies depending on whether it has been measured from an oven-dry specimen or from a specimen with certain moisture content. If the volume of a specimen is measured when its moisture content is above the fibre saturation point, the term basic density of wood is used for the density value obtained (e.g., Hakkila 1966, Kärkkäinen 1985, Wagenführ & Schreiber 1989).

Density is correlated with the mechanical properties of wood. Hence, the variation of the density of the wood material can be used for indirect description of strength for different tree species, or fractions of wood from different locations within a single stem. For instance, in waferboard manufacturing, tree species of different densities are mixed together in order to obtain maximum internal bond strength and bending strength to the product (Gertjejansen & Hedquist 1982, Pagano & Gertjejansen 1989).

Weight, which is a direct derivative of density, influences especially the usability of the wood material for different purposes. It is of special importance in transporting vehicles such as aircraft and ships, considering both their construction and load-bearing capacity. Heavier materials are more expensive to transport, in particular by air or sea. On the other hand, the density of wood plays a significant role in industrial timber and wood chip scaling.

B. pendula wood material has often been observed to be denser than *B. pubescens* wood (e.g., Kujala 1946, Hakkila 1966, 1979, Velling 1979, Wagenführ & Schreiber 1989, Verkasalo 1998, Verkasalo et al. 2001). Kujala (1946) observed a considerable increment of 200 kgm^{-3} in the density of birch wood from the pith to the surface. Similar, even if not as considerable as Kujala's (1946), observations were presented in the studies by Jalava (1945), Hakkila (1966), Tamminen (1970) and Verkasalo (1998). Vertically, the variation of density is smaller but, however, the density decreases from the stump to the top of a birch tree (Jalava 1945, Kujala 1946, Hakkila 1966, Tamminen 1970, Velling 1979, Verkasalo 1998). It has also been shown that birch produces denser wood as the tree ages (Hakkila 1979, Bhat 1980, Verkasalo 1998). Bearing in mind the correlation between density and mechanical and physical properties of wood, it appears that the variation of density within a stem may have significance also for different end-uses of birch products.

The hardness of wood is often considered an operational or a practical property rather than an individual mechanical property. This is affected by the fact that hardness is actually derived from several different forces such as friction, shearing and compressive forces appearing during the test (Kollmann & Côté 1968). The varying definitions for hardness can roughly be summarized as follows: hardness is the ability of a material to resist an intrusion by an external object. As for wood, the definition, however, leaves many possibilities for clarifications. In fact, the value of hardness is, more than any other mechanical property, dependent on the testing conditions and methods used (e.g., Kúdela 1998). For instance, even a 4-5 times higher hardness was observed for latewood than for earlywood in Lassila's (1926) studies on Finnish softwoods. Therefore, when testing hardness, it is essential to focus the measurements on either earlywood or latewood, or at least report if the results represent both earlywood and latewood. According to Lassila (1926), the hardness of wood is dependent on 1) the amount of force used, 2) tree species, 3) the internal structure of wood, 4) the position of tested surface (radial, axial or tangential), 5) the moisture content of wood, 6) the temperature of wood, 7) the weight of wood. The first mentioned, however, should not influence the results, as far as current expectations for an objective measurement method are considered. Lassila (1926) also, surprisingly, mentioned that density itself obviously has not as clear a correlation with hardness as "what could be expected".

Dunham et al. (1999) studied the effects of the growth rate on the strength properties of sawed beams of cultivated *Betula pendula.* They concluded that the growth rate neither has a significant effect on the density of birch wood, nor on its mechanical strength. They also found a relatively high correlation ($r^2 = 0.45$) between the density and hardness of birch wood.

In Europe, the most widely used method for determining the hardness of wood material is the Brinell test, whereas, in North and South American studies the most commonly used method is the Janka test (e.g., Siimes & Liiri 1952, Niemz & Stübi 2000). In the Brinell test according to EN 1534, a constant force and predetermined time are used to indent a round steel ball with a certain diameter into the specimen, after which the size of the residual indentation on the face of the specimen is measured. In the Janka test, on the other hand, a round steel ball is indented into the specimen by half of its diameter, and the force required directly gives the hardness in N/mm^2. The Janka method is not widely accepted in Europe since there is a considerable possibility of failure due to the cell wall compression (Niemz & Stübi 2000).

Schwab (1990) compared different methods for determining the hardness of solid wood, and concluded that the Brinell test gives the most reliable results. The justification for the argument was that in the Brinell test only, the variation of the wood material in two different directions is, at least somehow, taken into consideration. Earlier, Kontinen & Nyman (1977) compared two different methods for determining the Brinell hardness. Firstly, they calculated the results using the depth of the residual indentation formed on the specimen. Secondly, the results were calculated by using the diameter of the indentation. The hardness values obtained by measuring the diameter were ca. 60-160% higher than those obtained by measuring the depth of the indentation. This was due to the revert of the indentation after the load had been removed. Therefore, Kontinen & Nyman (1977) concluded that using the depth of the indentation is a better and more accurate method. Similar conclusions were published by Niemz & Stübi (2000). Jalava (1945) used "the combined Brinell-Janka test", where a steel ball with an area of 1 cm^2 was indented into wood until the depth of its radius by using a constant speed of 0.8 mm/s, and the force needed for the procedure was measured. This method was actually very similar to the traditional Janka hardness method.

The hardness of wood is of importance in plank floorings and facing furniture veneers, as well as kitchen and office furnishing. Nevertheless, hardness is the most important characteristic for wood intended for parquet manufacturing (e.g., Lutz 1977). Birch wood material is in keeping with all these end-uses due to its mechanical strength, as well as homogeneity of appearance and colour. So far, no results have been published regarding the variation of hardness within birch stems. Furthermore, few studies have been published either for softwoods or hardwoods, where the current standard EN 1534 was used.

The objective of this article was, firstly, to detect the variation of basic density within mature *Betula pendula* and *Betula pubescens* stems, as well as the possibilities to predict it on the basis of location parameters. Secondly, the dependence of Brinell hardness measured according to EN 1534 on the basic density was studied.

2. Materials and methods

Two different lots of specimens were prepared: one for the basic density tests (lot 1, 6304 specimens) and another for the Brinell hardness tests (lot 2, 650 specimens). The basic density of the specimens, however, was measured from both lots. Thus, the dependence of Brinell hardness on basic density could be detected from lot 2, and then, generalized into lot 1. With a larger number of specimens, lot 1 was used to detect the horizontal and vertical variation of basic density within birch trees. Only defect-free specimens were allowed for both lots 1 and 2.

The specimens originated from 89 *Betula pendula* (age 60-141) and 171 *Betula pubescens* (age 60-120) stems sampled from 21 stands altogether, which were located in southern, central and eastern Finland (61-65° N, 24-31° E). All *B. pendula* trees grew on fertile mineral soils (*Oxalis - Myrtillus* type (OMT) and *Myrtillus* type (MT)). 79 of the *B. pubescens* trees were located on drained peatlands (herb-rich drained peatland forest (Rhtkg) and *Vaccinium myrtillus* drained peatland forest type 1 (Mtkg)) and 92 on mineral soils (OMT, MT).

The material for the basic density tests was prepared from discs, which were systematically cut from the heights of 0, 4, 8, 12 and 16 metres of each tree. From smaller trees, however, the highest disc obtained was from 12, or in some cases from 8 metres. The discs were sawed into ca. 20 x 20 x 40 mm specimens, as shown in Fig. 1. Each specimen was coded by stand number, sample tree number, and vertical and horizontal location within the sample tree.

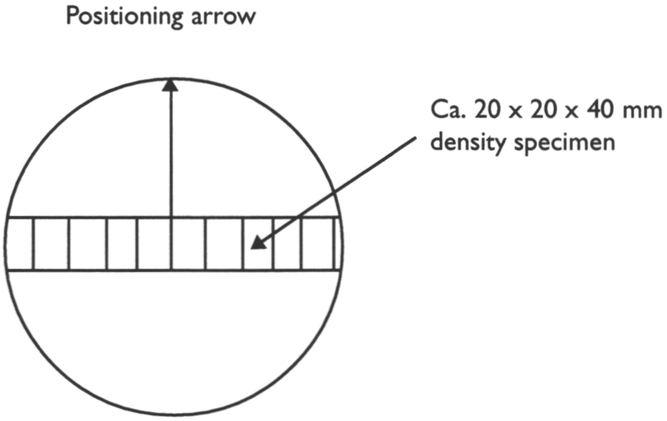

Fig. 1. Alignment of the basic density specimens within the sample disc. Positioning arrow was parallel in all discs within individual birch tree; thus density specimens from different heights were located parallel, as well.

Basic density was determined for both lots of specimen as follows:

$$D = M_0 / V_g \tag{1}$$

where D denotes the basic density (gcm^{-3}) of the specimen, V_g denotes the green volume of specimen, i.e., the volume (cm^3) when the moisture content of wood is above the fibre saturation point, and M_0 denotes the dry-matter weight of the specimen (g). For further calculations the density values were transformed into kgm^{-3}.

The Brinell hardness specimens were prepared of lumber pieces sawed pith-centrally into 25-mm fresh thickness. The location of the specimen in the lumber-piece was determined so that the test could be performed exactly into radial direction, into defect-free wood, and into earlywood only. As shown in literature, the test for Brinell hardness is highly dependent on the location of the test point regarding earlywood and latewood (e.g., Lassila 1926). Birch wood being in question, however, the latewood rings are very narrow compared to the earlywood rings, thus, hardly affecting the overall properties of wood.

All specimens within a single tree were tested in parallel direction. The minimum thickness allowed for the specimens after planing the surface was 18 mm, the minimum length in parallel to grain direction was 100 mm, and the minimum width in tangential direction was 100 mm. In practice, most of the specimens were larger than the above-mentioned minimum dimensions. Considering the Brinell hardness specimens, the moisture content at the moment of testing was determined according to the following formula:

$$MC = ((M_1 - M_0)/M_0) \times 100 \tag{2}$$

where MC denotes the moisture content of the specimen during the Brinell hardness test (percentage of water weight of the specimen dry-matter weight), M_1 is the weight of the specimen at the moment of testing (g), and M_0 is the dry-matter weight of the specimen (g).

The Brinell hardness was tested according to EN 1534 in the wood laboratory of the University of Joensuu. The machine used was FMT-Mec100 by Matertest Ltd. In the laboratory, a constant relative humidity of 65% ± 3%, and temperature of 20°C ± 2°C were maintained, in conditions where the equilibrium moisture content of wood ends up close to 12%. Before testing, the specimens were acclimatized in the test laboratory at least for four weeks.

In the Brinell hardness test according to EN 1534, a constant force of 1 kN was used, and the diameter of the residual indentation on the face of the test specimen was measured with an accuracy of ± 0.1 mm two times, at right angles to each other. A break period of three minutes was taken between the removal of the load and the moment of measurement. This break is due to the possible revert of the indentation after the load has been removed. An electronic calliper was used for the diameter measurements. Diameters were measured both parallel and perpendicular to the grain in order to take into account the inhomogeneous structure of wood in different dimensions. The mean value of the two diameter measurements was used in calculating the result:

$$HB = \frac{2 \times F}{\pi \times D\left[D - \left(D^2 - d^2\right)^{1/2}\right]} \tag{3}$$

where *HB* is the Brinell hardness in MPa (= Nmm^{-2}), *p* is the pi factor (≈ 3.14), *F* is the nominal force in newtons, *D* is the diameter of the steel ball in millimetres (10 mm in this study), and *d* is the mean diameter of the residual indentation in millimetres.

In addition to the mean value and outermost values, the characteristic value for Brinell hardness was calculated by the formula (EN 1534):

$$X_k = m - (t_{05} \times s) \tag{4}$$

where X_k is the characteristic value for the Brinell hardness in MPa, m is the mean value of the sample, t_{05} is the Student coefficient for a one sided 5% liability (=1.645 for the lot sizes tested), and *s* is the standard deviation of the studied lot.

The basic density variations being in question, the differences between the sites and birch species were, firstly, tested using analysis of variance. For the further tests, the observations were grouped in accordance with the results of the above-mentioned tests. The dependence of the basic density on location parameters, as well as on average annual ring width at a 1.3-metre height, was studied using regression analysis. In addition, mean values for the variation of basic density from the pith to the surface were calculated for the heights of 0, 4, 8, 12 and 16 metres and, in order to illustrate the variations, smoothed as continuous lines using spline-function. The dependence of Brinell hardness on the basic density was studied by linear regression analysis.

The Brinell hardness test method is often characterized by uncertainty or even unreliability. In particular, the manual measurement of the diameter of the residual indentation is considered a highly error-susceptible phase of the test (e.g., Kontinen & Nyman 1977, Niemz & Stübi 2000). Measuring the diameter precisely, particularly in parallel to the grain direction, was found difficult also in this study. Therefore, a magnifying glass and colouring the surrounding, i.e., the non-pressed surface of the specimen by a graphite crayon were used to increase the accuracy of measurements.

The possible sources of error, which are related to the test method, were also intensively evaluated during the analysis of the results. Firstly, the possible systematic error, as well as the size of the error in individual measurements caused by the manually used calliper, was studied. For this reason, also the depth of the residual indentation was measured automatically by the test machine. The depth-measurement started when the nominal value of force directed towards the steel ball exceeded 5 N in the beginning of the test. The maximum depth value observed during the test was recorded. As a result of the two measurements, the correlation could be calculated between the depth of the indentation measured by the machine and the diameter of the indentation measured manually. Secondly, in order to assess the size of the within-specimen variation in Brinell hardness, a sample of 50 specimens was tested by making two adjacent indentations close to each other in one specimen.

3. Results

Basic density

The differences between the specimens from different sites and birch species were studied by using the non-parametric Mann-Whitney U –test. Considering *B. pendula* trees, the average basic density differed both from *B. pubescens* grown on mineral soil ($p = 0.000$, $Z = -21.694$), and from *B. pubescens* grown on peatland ($p = 0.000$, $Z = -18.187$). On the other hand, no difference was observed in the test between the average basic density of *B. pubescens* trees grown on mineral soil compared to the trees of the same species grown on peatland ($p = 0.978$, $Z = -0.027$). Based on this evaluation, in further calculations *B. pubescens* trees were not grouped according to the site, only the two birch species were studied separately.

B. pendula being in question, the average basic density of the wood material was 512 kgm^{-3}, and *B. pubescens* 478 kgm^{-3} respectively (Table 1).

Table 1. Mean values, standard deviations and the observed outermost values for basic density (kgm^{-3}) of the specimens of mature Finnish birch

Species	Number of specimens	Mean	Std. Deviation	Minimum	Maximum
		Basic density, kgm^{-3}			
B. pendula	2564	512	42	411	653
B. pubescens	3740	478	31	392	579
Total	6304	492	40	392	653

Linear regression models were constructed to predict the variation of the basic density in different horizontal and vertical locations of the stem. In addition, the effect of average growth ring width on the basic density was studied. The models are presented in Table 2. Despite the statistical significance of the models, their usability is not very high due to the large possible variation (for both species ca. ± 80 kgm^{-3} above or below the predicted value) shown in unstandardized residuals (Fig. 2). According to regression analysis, however, *B. pendula* basic density was more dependent on the vertical location than that of *B. pubescens*. This was, undoubtedly, affected by the clearly divergent horizontal density structure of *B. pendula* wood at stump height compared to the above-stump heights. Subsequently, excluding the stump height, the average horizontal variation of the basic density of *B. pendula* wood seemed very similar at different heights of the tree (Fig. 3). The mean values of *B. pubescens* stems indicated, on the other hand, that the average basic density more likely increases from the stump upwards (Fig. 4). The absolute vertical variations of *B. pubescens* were, nevertheless, smaller than those of *B. pendula*. Considering both birch species, the wood material near the pith was clearly lighter than near the surface of the stem. An interesting finding was that near the stump height of both birch species, the average basic density of the outermost specimen (distance more than 100 mm from the pith) was somewhat smaller than within the distance of 50-100 mm from the pith. This may be affected by the divergent grain orientation near the stump caused by butt swelling or a buttressed base.

In addition to the location parameters, the basic density of *B. pubescens* wood material was clearly dependent on the average growth rate of a tree at a 1.3-metre height, whereas no such dependence was observed for *B. pendula*.

Table 2. Models for predicting the variation of basic density (kgm^{-3}) within mature birch stems by species.

Model (species)	Variable	Unstandardized coefficients (B) and standard errors (S.E.)			
		B	S.E.	t	p
1					
(*B. pendula*)					
RMSE: 0.036	Intercept	479.997	5.387	89.098	0.000
R^2: 0.265	X_1	94.286	4.635	20.343	0.000
Sig. 0.000	X_2	-37.327	4.473	-8.345	0.000
N: 2564	X_3	-3.458	2.802	-1.234	0.217
2					
(*B. pubescens*)					
RMSE: 0.029	Intercept	474.557	3.210	147.835	0.000
R^2: 0.151	X_1	51.135	3.078	16.613	0.000
Sig. 0.000	X_2	4.244	2.704	1.570	0.117
N: 3740	X_3	-14.677	1.635	-8.976	0.000

X_1: Relative distance from the pith, % from the radius of tree at given height
X_2: Relative distance from the stump, % from the total height of tree
X_3: Average annual ring width at 1.3-m height, mm

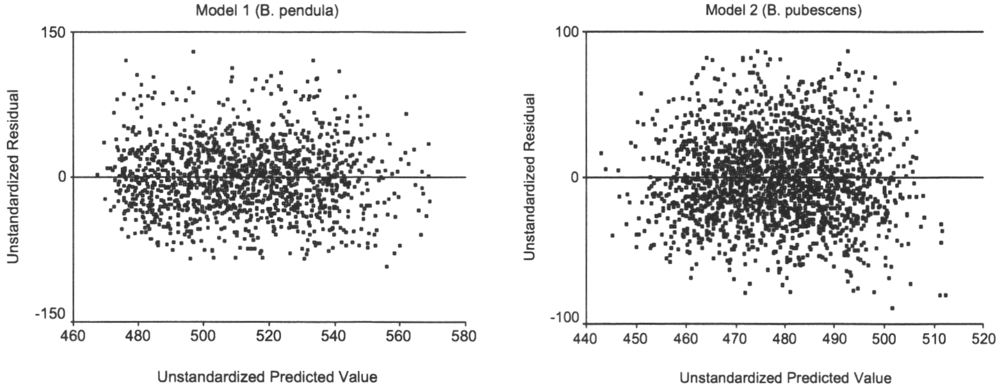

Fig. 2. Unstandardized residuals for models 1 and 2.

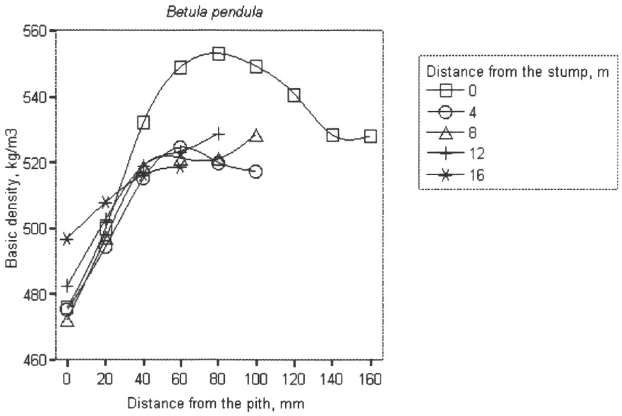

Fig. 3. Variation of basic density of *Betula pendula* at different heights from the pith to the surface.

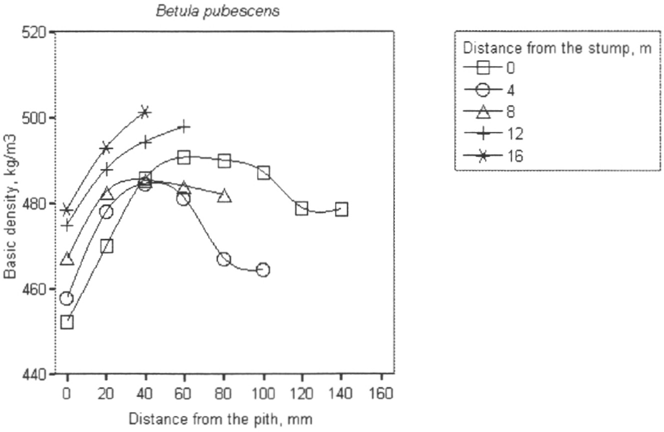

Fig. 4. Variation of basic density of *Betula pubescens* at different heights from the pith to the surface.

Brinell hardness

The moisture content of the Brinell hardness specimens, at the moment of testing, varied between 9.76% and 13.66% (mean 11.76%). The two-tailed Pearson correlation coefficient (0.893) between the depth of the residual indentation of the steel ball measured by the machine and the diameter of the residual indentation measured manually, was highly significant, which can be seen from the scatter plot in Fig. 5, as well. No systematic over- or underestimate could be seen either. This reflects that no considerable revert of the indentation occurred during the waiting period of three minutes from the removal of the load to the moment of measurement. Hence, both measurement practices can be considered equally reliable.

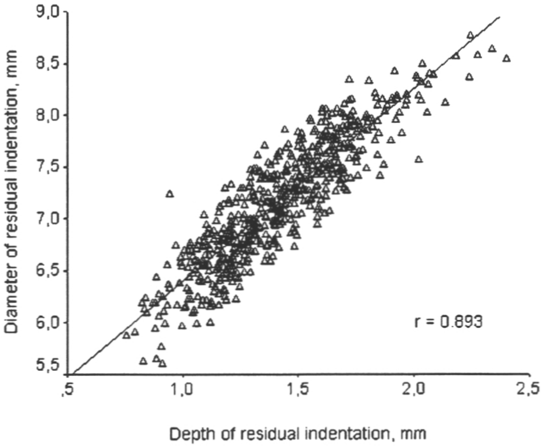

Fig. 5. Correlation between the depth of residual indentation measured by the machine and the diameter (mean value of the measurements perpendicular and parallel to the grain) of the residual indentation measured manually during the Brinell hardness tests.

The reliability of the results of Brinell hardness was also studied by assessing the degree of variation between the two tests within one specimen. Considering the sample of 50 specimens, which were tested by two adjacent indentations, the average difference between the two results for Brinell hardness was 6.6% (min 0.2%, max 18.0%). According to this evaluation, the results for the rest of the specimens tested with one indentation only, were trustworthy.

The average Brinell hardness of all *B. pendula* specimens was 23.4 MPa, and *B. pubescens* specimens 20.5 MPa respectively. The means and characteristic values, as well as the outermost observations for radial Brinell hardness of defect-free earlywood of Finnish birch species are presented in Table 3.

Table 3. Number of specimens measured (N), means, standard deviations, the observed outermost values and characteristic values for the Brinell hardness of mature Finnish birch.

Species	N	Mean	Std. Deviation	Min	Max	Characteristic value
		Brinell hardness, MPa				
B. pendula	261	23.37	4.40	13.31	37.38	16.13
B. pubescens	358	20.53	3.81	12.49	32.92	14.26
Total	*619*	*21.73*	*4.30*	*12.49*	*37.38*	*14.66*

The dependence of Brinell hardness on the basic density was evident. Based on the results, the Brinell hardness of birch wood is at its highest (ca 35 MPa for *B. pendula*, ca. 30 MPa for *B. pubescens*, if the highest observations are excluded) where the basic density of wood is high, i.e., generally near the surface of the stem and near the stump. Respectively, Brinell hardness is at its lowest (ca. 15 MPa for both birch species) where the basic density is low, i.e., generally near the pith and in the upper parts of the stem.

The linear regression models for predicting the Brinell hardness are shown in Table 4, and the unstandardized residual plots for the two models in Fig. 6.

Table 4. Models for predicting the Brinell hardness of mature Finnish *Betula pendula* and *B. pubescens* on the basis of basic density of wood material.

Model (species)	Variable	Unstandardized coefficients (B) and standard errors (S.E.)			
		B	S.E.	t	p-value
3 (*B. pendula*) RMSE: 2.7715	Intercept	-35.297	3.054	-11.556	0.000
R^2: 0.620 Sig. 0.000 N: 229	X_1	116.447	6.046	19.261	0.000
4 (*B. pubescens*) RMSE: 2.6166	Intercept	-29.304	2.454	-11.944	0.000
R^2: 0.544 Sig. 0.000 N: 349	X_1	104.182	5.118	20.358	0.000

X_1: Basic density (kgm^{-3}) of the specimen.

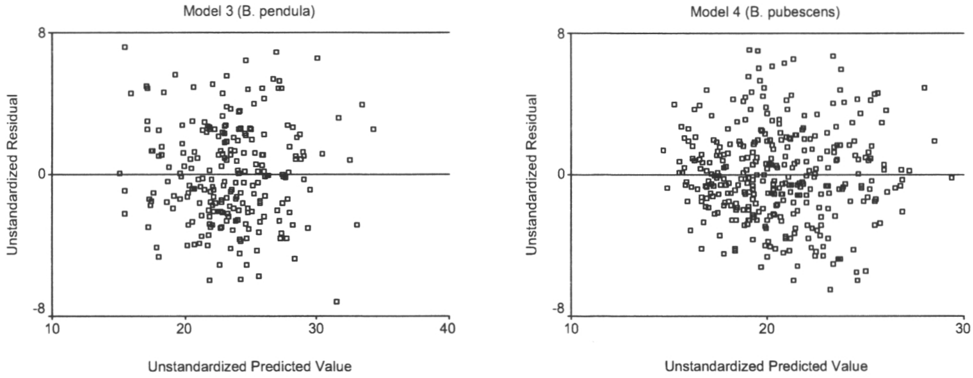

Fig. 6. Unstandardized residuals for models 3 and 4.

4. Discussion

The objective of this article was to analyse the variation of basic density (kgm^{-3}) between the different horizontal and vertical locations of mature Finnish *Betula pendula* and *B. pubescens* stems. In addition, the dependence of Brinell hardness (MPa) of birch wood on the basic density was investigated. Also the sources of error in the Brinell hardness test according to EN 1534 were analysed. Both basic density and Brinell hardness were measured from small, defect-free specimens. The annual rings of birch wood mainly consist of earlywood, which therefore defines largely the mechanical properties of birch. Hence, the Brinell hardness tests were focused on earlywood only, which makes the results best applicable for the practical purposes. In practice, due to the knots, decay or, for example, irregular grain structure, characteristic values for the entire stem are somewhat lower than those observed in these measurements.

There is probably variation on the density or hardness results between the separate sample stands. Except for the birch species, this variation was not analysed in this study. The results concern the entire wood flow procured to the wood processing industry, while the applicability of the results relates to the planning of end-uses, as well as sawing, veneering or other processing of the separate sections of birch stems. The possible differences between separate stands cannot be detected on the basis of the results.

Significant differences for the basic density between the two birch species were found. In general, the average values of *B. pendula* were a little higher than those published previously (e.g., Hakkila 1966, 1979; Velling 1979). However, the results of Verkasalo (1998) were very similar to the results of this study, excluding that Verkasalo (1988) found that density values differ between *B. pubescens* stems grown on mineral soil and on peatland. In this study, the densities between trees grown at the two sites did not differ. On the other hand, while the raw material properties of young birch stands inevitably reflect to the continuously increasing utilization of birch wood from thinning forests for both mechanical and chemical wood industry, it is notable that the average basic density of younger, both naturally born birch trees (e.g., Hakkila 1966, Verkasalo 1998), and, in particular, planted birch trees (Velling 1979, Verkasalo 1998) is remarkably lower than that of mature trees. Considering *B. pendula*, the average growth rate at the 1.3-metre height did not have a significant effect on the basic density of the wood material, whereas, *B. pubescens* density was more clearly dependent on the growth rate. This may be a positive matter remembering the above-mentioned density differences between planted and natural *B. pendula* trees, as well as the expanding utilization of birch from cultivated forests.

The results concerning the horizontal and vertical variation of basic density were, generally, consistent with the results of Hakkila (1966). Some dissimilarities were observed, for instance, in the vertical variation of *B. pubescens* wood density. In this study, the average basic density from the stump upwards slightly increased, whereas, Hakkila (1966) observed slight decrease in the respective examination. In both studies, nevertheless, the vertical variation of basic density concerning *B. pubescens* wood material was insignificantly small from the practical point of view.

The horizontal variation of the basic density at stump height was found unexpected for both birch species. Near the pith, the density was at its lowest level, then gradually increased toward the surface, but near the surface, surprisingly began decreasing again. The same phenomenon was also observed at a four-metre height in *B. pubescens*. At stump height, a logical explanation for the decrease of density near the surface of the stem would be the abnormal grain orientation caused by butt swelling. This is, however, not probable anymore at a four-metre height.

No publications were found in which exactly the same method (EN 1534) for measuring the Brinell hardness of untreated birch wood was used. Möller & Otranen (1999), however, measured the hardness of heat-treated birch wood using the same method, and noticed that heat-treatment does not influence the perpendicular to the grain Brinell hardness of wood. In parquetry industry, actually, the same method is commonly used in quality control and testing of new products. Unfortunately, these results are not published. In the studies by, for example, Kontinen & Nyman (1977) and Niemz & Stübi (2000) on wood-based panels and boards, however, the test method differed only slightly from EN 1534.

Despite the comprehensive acclimatization of the specimens in standard environmental conditions (20°C, 65% RH), the difference in moisture content between the driest and the moistest specimens during the test was still almost 4%. At least for particleboards (Niemz & Stübi 2000), such variation has an influence of several percents the hardness result. Undoubtedly, the increment of moisture content decreases the Brinell hardness of solid wood, as well. However, Brinell hardness was found to be correlated with the basic density, which was also noticed by, for example, Kucera (1984). Therefore, the assumption that Brinell hardness varies within the birch stem in a similar way as the basic density does, is reasoned.

The Brinell hardness test method was found fairly reliable, but very laborious. According to the evaluations of the possible errors caused by manual measurement of indentation on the face of the specimen, no systematic error was found. Both under- and overestimates occurred but, generally, the deviations were small. Considering the hardness testing of wood, the reason for the manual measurement of the diameter of the indentation in two perpendicular directions is stated by the inhomogeneous structure of wood in axial, radial and tangential directions. Kontinen & Nyman (1977) studied the hardness of wood-based panels and found significant differences between the hardness results depending on whether the diameter or the depth of the residual indentation was used in calculations. The reason for this was the resilient behaviour of the materials tested: the indentation reverted after the load had been removed. In this study, both measurement methods were found reliable and no significant differences were observed. It is evident, however, that the speed of the revert of the indentation depends not only on whether the material is solid wood or wood based panel, but considering solid wood, also on the elasticity of the tree species in question.

As a conclusion, if solid wood is studied, the only way to obtain information on the anisotropic behaviour of wood in axial, radial or tangential directions during the hardness test, is to measure the diameter of the indentation manually two times at right angles to each other. For practical uses, however, such accuracy is not usually needed. Hence, when testing solid wood, and when the hardness value itself is of more interest than the anisotropic structure of wood, the depth of the indentation (or the diameter, calculated on the basis of the depth) can be used for determining hardness. Similarly, if the material is very elastic, as is the case with some wood-based panels, the depth measurement is a more exact method (Niemz & Stübi 2000). The advantage obtained by using the depth measurement, would be the considerably lowered time consumption, while all variables could be measured automatically.

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References

Bhat, K.M. 1980. Variation in structure and selected properties of Finnish birch wood. I. Interrelationships of some structural features, basic density and shrinkage. Silva Fennica 14: 384-396.

Dunham, R.A., Cameron, A.D. & Petty, J.A. 1999. The effect of growth rate on the strength properties of sawn beams of silver birch (Betula pendula Roth). Scand. J. For. Res. 14: 18-26.

EN 1534: 2000 E. Wood and parquet flooring – Determination of resistance to indentation (Brinell) – Test method. European Standard. CEN 2000. 10 p.

Gertjejansen, R. & Hedquist, D. 1982. Influence of paper birch on the properties of aspen waferboard: a mill trial. For. Prod. J. 32(11/12): 33-34.

Hakkila, P. 1966. Investigations on the basic density of Finnish pine, spruce and birch wood. Comm. Inst. For. Fen. 61(5): 1-98.

Hakkila, P. 1979. Wood density survey and dry weight tables for pine, spruce and birch stems in Finland. Comm. Inst. For. Fen. 96(3): 1-59.

Jalava, M. 1945. Strength properties of Finnish pine, spruce, birch and aspen. Comm. Inst. For. Fen. 33(3): 1-66. (In Finnish with English summary).

Kollman, F.F.P. & Côté, W.A. 1968. Principles of wood science and technology. Volume 1. Solid wood. Springer Verlag. Berlin – Heidelberg – New York. 592 p.

Kontinen, P. & Nyman, C. 1977. Hardness of wood-based panel products and their coating and overlays. Paper and Timber 9/1977 (In Finnish with English summary).

Kucera, B. 1984. Bjørkevirkets mekaniske, teknologiske og fysiske egenskaper. Norges landbruksvitenskapelige forskningsråd, Slutrapport nr. 500. 21 p. (In Norwegian).

Kúdela, J. 1998. Analysis of wood hardness. In: Kurjatko, S. & Kúdela, J. (eds.). Proceedings of the seminar on Wood Structure and Properties '98. Arbora publishers, Zvolen, Slovakia. Pp. 199-203.

Kujala, V. 1946. Some recent research data on birches. Comm. Inst. For. Fen. 34(1): 1-36. (In Finnish with English summary).

Lassila, I. 1926. The mechanico-technical properties of wood; their study and its objects. Reprinted from Acta Forestalia Fennica. 186 p. (In Finnish with English summary).

Lutz, J.F. 1977. Wood veneer: log selection, cutting, and drying. U.S. Dep. Agric., Tech. Bull. No. 1577. 137 p.

Möller, K. & Otranen, L. 1999. Heat treatment of timber. Publications of the Institute of Environmental Technology. Nr. 4. Mikkeli 1999. 115 p. (In Finnish).

Niemz, P. & Stübi, T. 2000. Investigations of hardness measurements on wood based materials using a new universal measurement system. In: Stanzl, S. E. & Reiterer, A. (eds.). Proceedings of the international symposium on Wood Machining, Properties of wood and wood composites related to wood machining. Vienna, Austria, 27.-29.9.2000. Pp. 51-61.

Pagano, K. & Gertjejansen, R. 1989. The effect of mixing high and low density hardwoods on bond development in waferboard. For. Prod. J. 39(2): 45-48.

Siimes, F.E. & Liiri, O. 1952. Investigations of the strength properties of wood I. Tests on small clear specimens of Finnish pine (Pinus sylvestris). Technical Research Centre of Finland VTT, Report 103. 88 p. (In Finnish with English summary).

Tamminen, Z. 1970. Moisture content, density and other properties of wood and bark. III Birch. Rapp. Instn. Virkeslärä Skoghögsk. 63: 1-99. (In Swedish with English summary).

Velling, P. 1979. Wood density in two Betula pendula Roth progeny trials. Folia Forestalia 416: 1.24. (In Finnish with English summary).

Verkasalo, E. 1998. Raudus- ja hieskoivun laatu puuaineen tiheyden perusteella arvioituna. [Quality of European silver and white birch evaluated on the basis of wood density]. In: Niemistö, P. & Väärä, T. (eds.). Rauduskoivu tänään – ja tulevaisuudessa, Tutkimuspäivä Tampereella 12.3.1997. Finnish Forest Research Institute. Research notes 668: 127-140. (In Finnish).

Verkasalo, E., Sipi, M., Möttönen, V. & Kärki, T. Kotimaisen koivun, haavan ja lepän ominaisuudet ja niiden hyödyntäminen mekaanisessa puuteollisuudessa, Tutkimuskonsortion tulosten yhteenveto. Joensuu 2001. 71 p. (In Finnish).

Wagenführ, R. & Schreiber, C. 1989. Holzatlas. 3. Auflage. VEB Fachbuchverlag Leipzig. 720 p.

V

Title: **Static Bending Properties of Finnish Birch Wood**

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Abstract

Due to the increased need of manufacturing highly specialised products of birch, questions have arisen whether the stiffness and strength properties vary within the stems in a notable extent. The aim of this study was to determine the modulus of elasticity (MOE) and the modulus of rupture (MOR) in the radial bending test for small, defect-free specimens of Finnish *Betula pendula* and *B. pubescens* wood originated from mature trees. The dependency of MOE and MOR on the specific gravity of birch wood was studied, and the relationship between MOE and MOR was modelled at the different heights and at the different distances from the pith of the tree. For *B. pendula*, the mean values for MOE and MOR were 14.5 GPa and 114 MPa, whereas *B. pubescens* had means of 13.2 GPa and 104 MPa, respectively. The results showed clear linear relationships between the MOE and MOR, irrespectively on the birch species or the within-stem location. Both MOE and MOR increased from the pith towards the surface of the tree and decreased from the base to the top of the tree. It is obvious that if special products with as high stiffness and bending strength as possible are manufactured, sorting of raw materials into different grades according to their within-tree origin becomes necessary. Hence, 10-15% increment in the bending properties of the product might be attained.

Key words: *Betula pendula*, *Betula pubescens*, elasticity, stiffness, strength

1. Introduction

The success of birch-made wood products relates not only to the pleasant and calm visual appearance of birch wood material, but also to its durability and favourable elastic and strength properties. Of these, the ability to resist bending stresses is often characterised as the most important, while bending is the most common stress appearing in different kinds of wood products (Siimes & Liiri 1952, Bodig & Jayne 1982, Madsen 1992, Boren 2001).

Considering engineering materials in general, mechanical properties, i.e., elastic, strength and vibration properties are especially important in long-span structures, such as bridges, roofs and ceilings. Sawn goods made of birch, however, are not used for construction purposes but, e.g., for floorings and cabinetry. Therefore, the favourable elastic and strength properties are different type of advantage for birch: the better bending properties the material has, the wider is the range of end-uses, and the more graceful components can be used in the final products. In many construction purposes, as well as in transporting, such as air- or waterborne vehicles, even more important is the strength-weight –ratio of the material. During the first half of the twentieth century, the needs of the aircraft industry most strongly contributed to the quantity of research work connected to the strength of wood (Jalava 1945).

The bending properties of an object can be determined by the relationship between the magnitude of an external force and the deflection of the object caused by the force. A force (or load) per unit area is called the *stress*, and it is expressed in N/mm^2 or Pa. Under the influence of exterior forces, which generate the stresses, the stressed object changes in shape and size. This change is called the *deformation*. All materials deform under the action of forces, whether they are the result of applied external loads or internal thermal or moisture stresses (Jastrzebski 1978, Bodig & Jayne 1982). According to Jastrzebski (1978), the engineering materials can be divided into three main divisions by the mechanism involved in their deformation under applied forces. These are elastoplastic, viscoelastic, and elastic materials. Three basic types of deformations are involved in the response of the material to the applied force, respectively, plastic, viscous and elastic.

Under tension and compression, deformation is measured in millimetres (mm), and is distinguished into the *total deformation* and *strain*, which is *deformation per unit length* (i.e., the ratio of the total to the initial length of the object). The relationship between the stress and strain, known as Hooke's law, defines the *modulus of elasticity* MOE (e.g., Bodig & Jayne 1982, Tsoumis 1991):

$$MOE = \frac{S}{d} \tag{1}$$

where MOE = modulus of elasticity (Pa or N/mm^2), S = load per unit area (Pa or N/mm^2), d = unit deformation (mm/mm). Thus, *MOE characterises the stiffness of an object, i.e., its ability to resist deformations caused by external loads*. The relationship between S and d is constant only up to the *proportional limit*, after which the similar stress increment causes relatively greater strain increment in comparison to the proportional region. In the case of wood, the stress-strain relation from zero up to the proportional limit is often linear. However, elastic behaviour of a material does not necessarily require stress-strain linearity, only complete and instantaneous recovery of deformation after removal of the load. Conversely, linearity of the stress-strain relation of a material does not necessarily imply elastic behaviour (Bodig & Jayne 1982).

Even when stressed by light loads, wood is an elastic material only when the load influences a short period of time. A long-time exposure causes visco-elastic (recoverable) or/and visco-plastic (permanent) deformations, which is called *creep* (e.g., Bodig & Jayne 1982, Koponen et al. 1988). In static bending test, the load applied is either static or slowly increased. However, for some purposes also dynamic bending tests are performed. Toughness, i.e., the ability of a material to absorb energy in dynamic bending, refers to the resistance against sudden loading. This property is important for wood uses such as tool handles and sport items.

After the stressed object has, according to some definition, failed, the object has reached its maximum load-carrying capacity, which is called strength. The strength of a material in bending, *modulus of rupture MOR, expressed in Pa (or N/mm^2), reflects the stress needed to break the object*. In practice MOR indicates the highest stresses in the outermost fibres of wood when the beam breaks under the influence of a load. Depending on the tree species, MOR varies usually between 55 and 160 MPa, being almost equal to the tensile strength in axial direction. Therefore the value of MOR is sometimes applied as an index for the value of axial tensile strength (Tsoumis 1991).

Stiffness is not a material property, whereas MOE is. Stiffness, as well as bending strength is derived from three different stresses appearing in beam during bending. On the convex side, the fibres are exposed to compression, whereas, on the concave side, tension is present. Theoretically, the centre line of the beam is free of stresses and called, thus, neutral plane or neutral axis. In practice, however, the fibres between the compression region and tension region are exposed to shear stresses which vary not only across the cross section but also along the beam, being dependent on, e.g., the manner of loading (e.g., centre, three-point, uniform) and the geometry of the cross section. The shear stresses, being highest near the neutral axis and close to zero near the surfaces of the beam, tend to make the upper part of the beam slide over its lower part (Tsoumis 1991).

Linear relationship between MOE and MOR is widely acknowledged, both in case of small-sized clear specimens of wood and structural lumber (Jalava 1945, El-Osta et al. 1979, Samson & Sotomayor-Castellanos 1991, Madsen 1992, Verkasalo & Leban 2000). Since determining exact value for MOR necessitates breaking the object, MOE is often used as a predictor for MOR. Two non-destructive techniques for determining MOE are used commonly by the wood product industries: machine stress rating of lumber (MSR) and ultrasonic veneer grading in laminated veneer material production (Ross et al. 1997).

Verkasalo (1992) classified the factors affecting to the elastic and strength properties into two main groups, firstly to the ones related to the wood structure, and secondly to the others related to the environmental conditions. The previous ones are typically properties like density, microfibril angle of the S_2 layer of the cell wall, or abnormalities, such as knots or reaction wood (Kollman & Côte 1968, Kärkkäinen 1985, Boren 2001). The latter ones may be, for instance, moisture content, temperature or chemical treatment (Bodig & Jayne 1982). Zhou & Smith (1991) observed that the strength of *Picea glauca* lumber is also affected by drying schedules of different severity. Mildly and carefully dried wood represented the maximum strength increase as a result of drying. Knots were, however, found the major strength reducing factors in full size lumber. Hsu & Walters (1975) observed that maintaining the soil moisture in the range of 30 to 60% of the field capacity, and providing a moderate amount of nitrate fertilizer, increased the bending strength and stiffness of *Pinus taeda*. In addition to these, also within-species geographical variations have been reported. Jalava (1945) concluded that Scots pine (*Pinus sylvestris*) wood is at its strongest in central Finland, while the strength of southern and northern Finnish Scots pine was poorer. Norway spruce (*Picea abies*) being in question, the strength decreased systematically from southern to northern parts of the country. Such geographical dependences could not be found for birch.

Principally, two kinds of tests for the mechanical properties of wood are made. Firstly, tests made for small, defect-free specimens with predetermined dimensions and controlled environmental conditions are necessary, when the basic properties of the given species are studied. Secondly, when structural lumber or any kind of wood product with all its strength-reducing defects is studied, full-sized samples are needed for the tests (Bodig & Jayne 1982, Madsen 1992, Boren 2001). One advantage in using a small-sized specimen instead of full-sized lumber is the decrease in the effect of the moisture gradient on the results (see: Gerhards 1982, Conners & McLain 1988).

For the most part, elastic and strength properties of wood are positively correlated with its density, or specific gravity (Palka 1973, Kärkkäinen 1985). The dependences between the specific gravity and MOE or MOR, as well as the dependences between

MOE and MOR, have often found to be linear (e.g., Jalava 1945, Zhou & Smith 1991, Verkasalo 1992, Boren 2001). On the other hand, Zhang (1997) stated that MOR is just almost linearly dependent on the specific gravity of wood, whereas the dependence of MOE is clearly less linear. Some articles are also published where both linear and non-linear relationships between the specific gravity and bending properties of wood are shown (Bodig & Goodman 1973, Bodig & Jayne 1982, Leban & Haines 1999).

Due to the increased need of manufacturing highly specialised products of birch, questions have arisen concerning the magnitude of variation of strength and stiffness within the stems. The aim of this study was to determine the modulus of elasticity (MOE) and the modulus of rupture (MOR) in the radial bending test for small, defect-free specimens of Finnish *Betula pendula* and *B. pubescens* wood originated from mature trees. The dependency of MOE and MOR on the specific gravity was studied, and the relationship between MOE and MOR was modelled at the different heights and at the different distances from the pith of the tree.

2. Materials and Methods

The study material of 610 specimens was collected between the years 1998 and 2000 from 89 sample trees situated in southern and central Finland. The material comprised of both *B. pendula* and *B. pubescens*. The main characteristics of the stands from which the sample trees originated, were presented in detail by Heräjärvi (2001).

A series of specimens was manufactured from each tree so that both the horizontal and the vertical variation in the properties of interest could be detected. Vertically, the specimens were situated at the heights of 3±1 m, 7±1 m, 11±1 m and 15±1m. The range of two metres was allowed in order to ensure the possibility of obtaining a defect-free and straight-grained specimen. The abovementioned heights were selected with the purpose of obtaining specimens from the theoretical butt log, intermediate log, top log and small-sized log or pulpwood section of the stem. The logs from the sample trees were pith centrally sawn into 25-mm boards, after which the specimens were manufactured from the boards so that a representative series was obtained in the horizontal (radial) direction. Finally, the 340 mm long defect-free specimens were planed as exactly as possible into the dimensions of 20 x 20 mm.

The specimens were conditioned in a normal climate (65% ± 3% RH, 20°C ± 2°C temperature) for at least four weeks before testing in order to stabilise their moisture content at a 12% level. After acclimatisation, the exact dimensions and weight of each specimen were recorded in order to determine the *weight density*. Next, the weight density was converted into the *specific gravity* at 12% moisture content using the equation (Siau 1984):

$$\rho_{12} = \frac{\rho}{(1+MC/100)\times \rho_w} \tag{2}$$

where ρ_{12} = specific gravity at 12% MC, ρ = weight density of the specimen, N/cm^3, ρ_w = weight density of pure water at 20°C and 1 atm (1 N/cm^3), and MC = moisture content (= 12%).

The bending tests were performed in the wood laboratory of the Finnish Forest Research Institute, Vantaa Research Centre. MOE was tested in accordance with the ISO standard 3349 using a four-point bending test, and MOR in accordance with the ISO standard 3133 using a three-point bending test, respectively. All tests were performed in the radial direction. The results were calculated according to the equations:

$$MOE = \frac{PL^3}{36bd^3\Delta} \tag{3}$$

$$MOR = \frac{3PL}{2bd^2} \tag{4}$$

where P = load at some point below the proportional limit (in the case of MOE) and the maximum load (in the case of MOR) (N), L = distance between supports for the beam (mm), b = beam width (mm), d = beam thickness (mm), Δ = deflection corresponding to the load P.

Pearson correlations were calculated between the study variables in order to detect their interdependencies. Thereafter, simple linear regression models were constructed for studying the relationships between ρ_{12} and MOE, ρ_{12} and MOR, as well as MOE and MOR at the different locations within birch trees.

The sample mean is an unbiased estimator to the population mean (Edwards 1979). However, the smaller the sample is, the more uncertainty is related to the estimate. In order to illustrate the reliability of the models, also the 95% confidence intervals were constructed for the regression lines.

3. Results and Discussion

Results by Species

B. pendula being in question, the mean values for MOE and MOR were 14.5 GPa and 114 MPa, whereas *B. pubescens* had means of 13.2 GPa and 104 MPa, respectively. The ranges of MOE were very similar for the two birch species, approximately from 8 to 20 GPa, whereas the ranges of MOR (70-160 MPa for *B. pendula* and 60-140 MPa for *B. pubescens*) indicated the between-species difference. Considering both MOE and MOR, mean values for *B. pendula* were ca. 9% higher than those for *B. pubescens*. Significant (<0.01 level) correlations were observed between ρ_{12}, MOE and MOR within both birch species (Table 1).

Table 1. Numbers of specimens measured (N), means, standard deviations and the outermost values for the specific gravity (ρ_{12}), MOE and MOR for *Betula pendula* and *B. pubescens*. Below the Pearson correlations between the study variables by species.

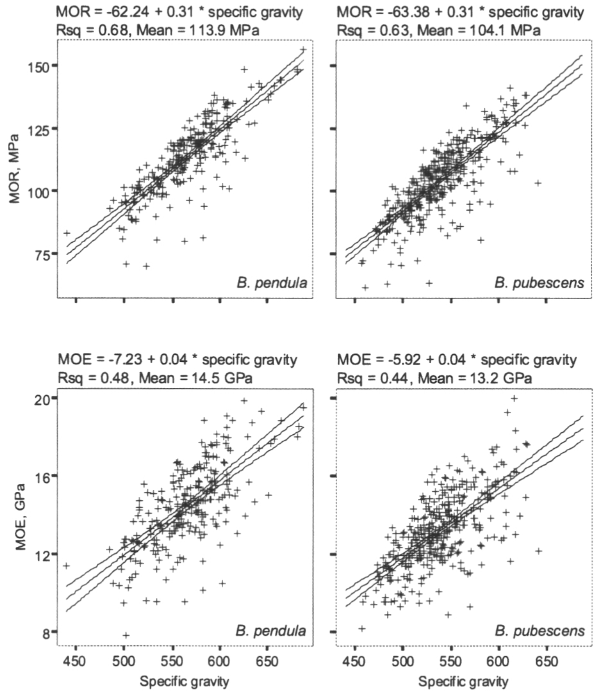
Species (N)	*B. pendula* (249)			*B. pubescens* (361)		
	ρ_{12}	MOE, GPa	MOR, MPa	ρ_{12}	MOE, GPa	MOR, MPa
Mean	565.9	14.5	113.9	538.1	13.2	104.1
Std. Deviation	38.7	2.1	14.8	35.7	1.9	14.1
Min	440.1	7.8	69.8	456.9	8.2	61.3
Max	687.3	19.9	156.6	640.8	20.0	141.4
			Pearson correlations			
ρ_{12}	1.000			1.000		
MOE, GPa	0.694	1.000		0.663	1.000	
MOR, MPa	0.827	0.877	1.000	0.792	0.860	1.000

Principally, the average MOE and MOR values of the current study were quite similar to those published earlier (Table 2). Compared to the small, defect-free specimens, MOE of sawn wood is ca. 10-40% and MOR ca. 40-55% smaller. The comparisons to the earlier studies, however, can be made at a general level only, since either the two birch species were not analysed separately or the materials were not collected from comparable geographical areas. In this study, the geographical variation could not be detected, since the material originated from a fairly limited area in southern and central Finland (see: Heräjärvi 2001).

Table 2. Bending properties of birch wood, species combined. A comparison of the averages of the current study with those obtained from the literature.

Characteristics	Small defect-free specimen			Sawn wood
	Current study	Jalava (1945)	Vagenführ (1996)	Dunham et al. (1999) (only *B. pendula*)
MOE, GPa	13.7	14.1 – 15.4	14.5 - 16.5	8.1 - 12.7
MOR, MPa	108.1	98.6 – 110.9	76 – 155	47.4 - 63.8

Based on the high correlations, the dependence of MOE on the specific gravity at 12% moisture content (ρ_{12}) was modelled using linear regression. In the case of both birch species, the models rather resulted in overestimates than in underestimates (Fig. 1). The relationship between ρ_{12} and MOE was slightly stronger in *B. pendula* compared to *B. pubescens*. Furthermore, the relationship between ρ_{12} and MOR was considerably stronger than that between ρ_{12} and MOE. Similar phenomena were also noticed for many other tree species (Smulski 1991). Furthermore, Zhang (1997) found that MOE in the ring-porous species was more concisely dependent on the specific gravity than in the diffuse-porous species. Birch species belong to the diffuse-porous category (Kärkkäinen 1985, Tsoumis 1991). Some exceptionally high specific gravity values with low MOR were observed in this study. This possibly reflects the presence of tension wood.



MOR = -62.24 + 0.31 * specific gravity
Rsq = 0.68, Mean = 113.9 MPa

MOR = -63.38 + 0.31 * specific gravity
Rsq = 0.63, Mean = 104.1 MPa

MOE = -7.23 + 0.04 * specific gravity
Rsq = 0.48, Mean = 14.5 GPa

MOE = -5.92 + 0.04 * specific gravity
Rsq = 0.44, Mean = 13.2 GPa

Fig. 1. Linear regression lines as well as the 95% confidence intervals for predicting MOE (below) and MOR (above) of *Betula pendula* and *B. pubescens* wood material on the basis of the specific gravity at 12% moisture content.

Considering MOR, the differences between the two birch species were more obvious than in the case of MOE. The relationships between MOE and MOR were clearly linear for both birch species (Fig. 2). In the case of *B. pubescens*, a slight non-linearity might be observed. However, applying non-linear models would have produced hardly any advantage compared to the currently used linear models.

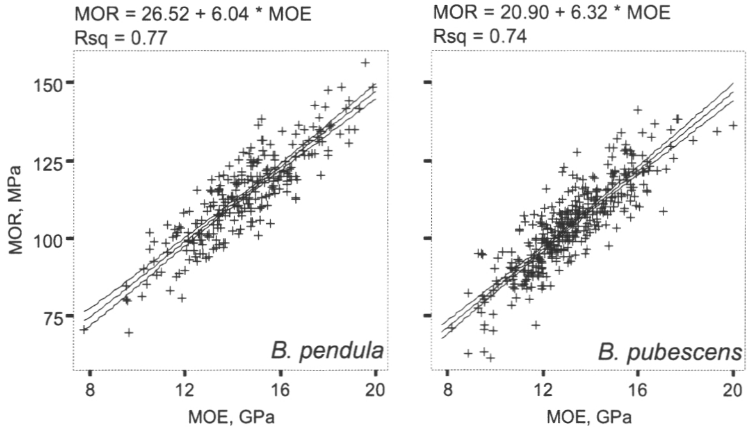


Fig. 2. Linear regression lines as well as the 95% confidence intervals indicating the dependence of MOR on MOE by birch species.

Vertical Variations

The variations in the bending strength and stiffness were studied more detailed at different vertical and horizontal locations of birch stems. The linear regression models predicting the variations of MOR on the basis of MOE at the heights of 3±1, 7±1, 11±1 and 15±1 metres are presented in Figure 3 for *B. pendula* and in Figure 4 for *B. pubescens*. The slope parameters actually seemed very similar at the different heights, excluding 11±1 metres, where the slope was considerably less steep than at the other heights. This was the case for both birch species. In practise, this means that a given increment in the MOE value causes a relatively smaller increment in the MOR value at the height of 11±1 metres compared to the other heights. No logical explanation could be found for this observation.

MOR values decreased more clearly within *B. pendula* than within *B. pubescens*, when the stems were studied higher up. Considering the end-uses, the overall differences between the different heights were insignificant. Hakkila (1979) and Bhat (1980) showed that old birch trees produce denser wood than the young trees. In other words, the density of the wood material produced is positively correlated with the age of the cambium. This observation is consistent with the findings of this study, where the density-related strength values decreased from the base to the top of trees.

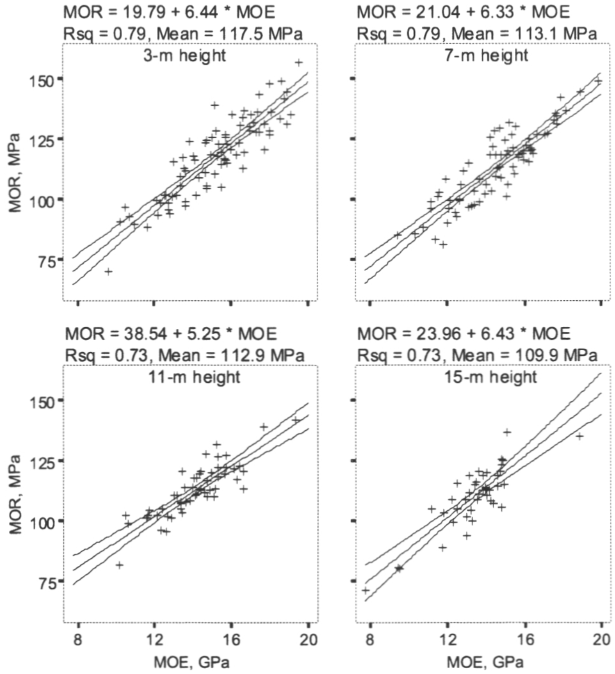


Fig. 3. Linear regression lines as well as the 95% confidence intervals indicating the dependence of MOR on MOE at the heights of 3±1m, 7±1m, 11±1m and 15±1m within *Betula pendula* stems.

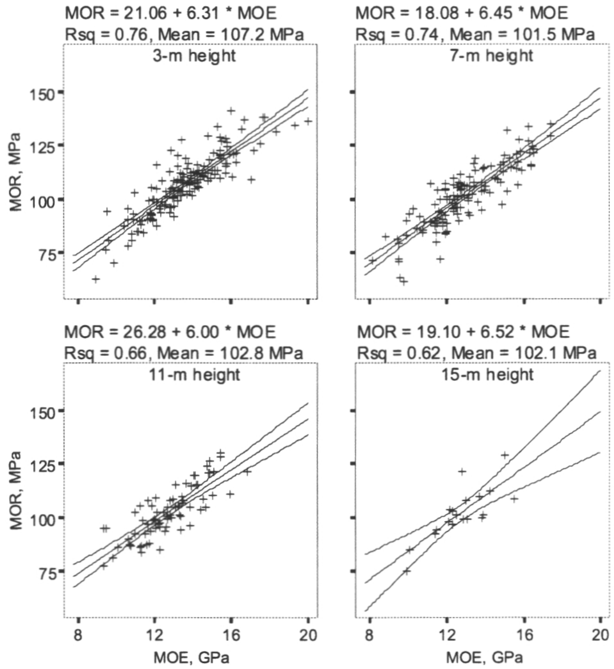


Fig. 4. Linear regression lines as well as the 95% confidence intervals indicating the dependence of MOR on MOE at the heights of 3±1m, 7±1m, 11±1m and 15±1m within *Betula pubescens* stems.

Horizontal Variations

Horizontally, the variations in the strength and stiffness were more obvious than vertically. As a rule, MOE and MOR increased from the pith outwards. Within *B. pendula* stems, the increment of MOR from the pith towards the surface was, on average, from 105 to 126 MPa, and within *B. pubescens* stems from 98 to 111 MPa, respectively (Figs. 5 and 6). This means a range of 10-15%, which can be considered a substantial effect also from the point of view of the final products.

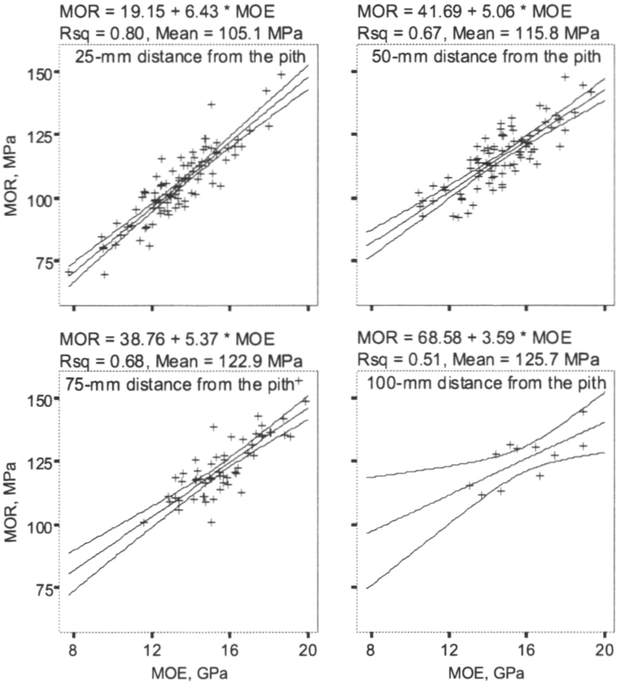


Fig. 5. Linear regression lines as well as the 95% confidence intervals indicating the dependence of MOR on MOE at the distances of 25, 50, 75 and 100 mm from the pith within *Betula pendula* stems.

The numbers of observations were not adequate for reliable models in some of the extreme cases, which can be seen from the confidence intervals (Figs. 4 and 5). Adding new explanatory variables, such as the growth rate (annual ring width), to the models might have improved their efficiency. On the other hand, Tsoumis (1991) stated that growth rate should have only slight direct influence on the wood density (or specific gravity) of a diffuse-porous species such as birch. Furthermore, according to Dunham et al. (1999), more than 100% increment in the annual ring width decreased the density of *B. pendula* specimens only by 10%. Based on these observations, it is reasonable to assume that also in this study, the growth rate wouldn't have considerable effects on the

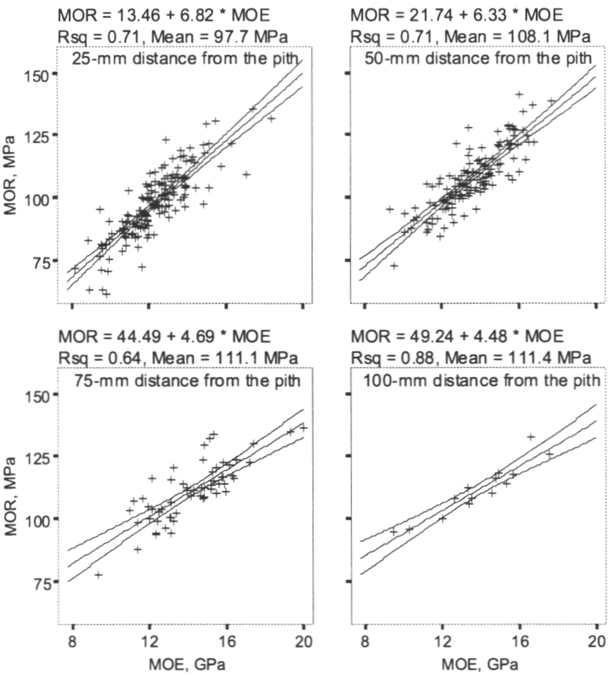


Fig. 6. Linear regression lines as well as the 95% confidence intervals indicating the dependence of MOR on MOE at the distances of 25, 50, 75 and 100 mm from the pith within *Betula pubescens* stems.

specific gravity; incorporation of growth rate may still have improved the efficiency of the models for MOE and MOR.

On the basis of the results, the following conclusions can be drawn. The variations in MOE clearly indicate the changes in the bending strength (MOR) of birch wood. On the other hand, the dependence of the bending strength on the specific gravity of birch wood is not as concise as it is in the case of some other tree species, conifers in the first hand (e.g., Bodig & Jayne 1982, Madsen 1992, Boren 2001). Within an individual birch stem, the minor variations in the bending properties do not give any cause for immediate actions in, for instance, sorting of raw materials into different end-use grades. So far, factors related to the environmental conditions, such as moisture content, moisture gradient (Conners & McLain 1988) or even planing method (Naderi & Hernández 1999), have larger effects on the strength and stiffness of wood products. According to Koponen et al. (1988), the effect of moisture on the elasticity of wood is at its largest in the tangential direction, and at smallest in the longitudinal direction. Still is unknown, what is actually the effect of reaction wood, i.e., tension wood in the case of birch, on the mechanical properties of sawn goods. According to the results of this study, it is obvious that if special products with as high bending strength as possible are manufactured, sorting of raw materials into different grades according to their within-tree origin becomes necessary. Hence, 10-15% increment in the bending strength or stiffness of the product might be attained.

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References

Bhat, K.M. 1980. Variation in structure and selected properties of Finnish birch wood. I. Interrelationships of some structural features, basic density and shrinkage. Silva Fennica 14: 384-396.

Bodig, J. & Goodman, J.R. 1973. Prediction of elastic properties of wood. Wood Science 5(4): 249-261.

Bodig, J. & Jayne, B.A. 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold, New York. 712 p.

Boren, H. 2001. Factors affecting the knottiness, twisting and mechanical properties of pith enclosed round and sawn timber of Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) from thinnings in Southern Finland. Finnish Forest Research Institute, Research Papers 807, 2001. 164 p.

Conners, T.E. & McLain, T.E. 1988. Modelling moisture gradient effects on bending properties. Wood Fiber Sci. 20(2): 226-242.

Dunham, R.A., Cameron, A.D. & Petty, J.A. 1999. The effect of growth rate on the strength properties of sawn beams of silver birch (Betula pendula Roth). Scand. J. For. Res. 14: 18-26.

Edwards, A.L. 1979. Multiple regression and the analysis of variance and covariance. W. H. Freeman and Company. 302 p.

El-Osta, M.L.M., Badran, O.A. & El-Wakeel, A.O.K. 1979. Prediction of modulus of rupture from modulus of elasticity for some Egyptian hardwoods. Wood Fiber Sci. 11(3): 147-154.

Gerhards, C.C. 1982. Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. Wood Fiber Sci. 14(1): 4-36.

Hakkila, P. 1979. Wood density survey and dry weight tables for pine, spruce and birch stems in Finland. Comm. Inst. For. Fen. 96(3): 1-59.

Heräjärvi, H. 2001. Technical properties of mature birch (Betula pendula and B. pubescens) for saw milling in Finland. Silva Fennica 35(4): 469-485.

Hsu, J.K. & Walters, C.S. 1975. Effect of irrigation and fertilization on selected physical and mechanical properties of loblolly pine (Pinus taeda). Wood Fiber Sci. 7(3): 192–206.

ISO 3133: Wood - Determination of ultimate strength in static bending. International Organization for Standardization.

ISO 3349: 1975. Determination of modulus of elasticity in static bending. International Organization for Standardization. 5 p.

Jalava, M. 1945. Strength properties of Finnish pine, spruce, birch and aspen. Comm. Inst. For. Fen. 33(3): 1-66. (In Finnish with English summary).

Jastrzebski, Z. 1978. The nature and properties of engineering materials. John Wiley & Sons. New York, Chichester, Brisbane, Toronto, Singapore. 3rd edition. 636 p.

Kärkkäinen, M. 1985. Puutiede [Wood Science]. Sallisen kustannus Oy, Sotkamo, Finland. 415 p. (In Finnish).

Kollman, F. & Côté, W. 1968. Principles of wood science and technology, I Solid wood. Springer Verlag, New York. 592 p.

Koponen, S., Toratti, T. & Kanerva, P. 1988. Puun mekaanisten ominaisuuksien mallittaminen solukon rakenteen perusteella. Helsinki University of Technology, Laboratory of Structural Engineering. Report 5. 121 p. + App. 13 p. (In Finnish).

Leban, J.-M. & Haines, D.W. 1999. The modulus of elasticity of hybrid larch predicted by density, rings per centimeter, and age. Wood Fiber Sci. 31(4): 394-402.

Madsen, B. 1992. Structural behaviour of timber. Timber engineering Ltd. Canada. 405 p. + App. 27 p.

Naderi, N. & Hernández, R.E. 1999. Effect of planing on physical and mechanical properties of sugar maple wood. Wood Fiber Sci. 31(3): 283-292.

Palka, L.C. 1973. Predicting the effect of specific gravity, moisture content, temperature and strain rate on the elastic properties of softwood. Wood Sci. Technol. 7(2): 127-141.

Ross, R.J., McDonald, K.A., Green, D.W. & Schad, K.C. 1997. Relationship between log and lumber modulus of elasticity. For. Prod. J. 47(2): 89-92.

Samson, M. & Sotomayor-Castellanos, J.R. 1991. Constant bending method for determining modulus of elasticity of lumber in structural size. Wood Fiber Sci. 23(4): 520-532.

Siau, J.F. 1984. Transport processes in wood. Springer-Verlag, Berlin-Heidelberg-New York-Tokio. 245 p.

Siimes, F.E. & Liiri, O. 1952. Investigations of the strength properties of wood, I. Tests on small clear specimens of Finnish pine (Pinus sylvestris). Technical Research Centre of Finland VTT, Report 103. 88 p. (In Finnish with English summary).

Smulski, S.J. 1991. Relationship of stress wave- and static bending-determined properties of four northeastern hardwoods. Wood Fiber Sci. 23(1): 44-57.

Tsoumis, G. 1991. Science and technology of wood. Structure, properties and utilization. Van Nostrand Reinhold, New York. 494 p.

Verkasalo, E. 1992. Relationships of the modulus of elasticity and the structure of Finnish Scots pine wood. Silva Fennica 26(3): 155-168.

Verkasalo, E. & Leban, J.-M. 2000. Predicting MOE and MOR of Scots Pine, Norway Spruce and European Fir from Finland and France for the comparison of wood quality. In: Stanzl-Tschegg S E & Reiterer A (Eds.) Properties of wood and wood composites related to wood machining. Proceedings of the International Symposium on Wood Machining, 27-29 September 2000, Vienna, Austria, pp. 91-102.

Wagenführ, R. 1996. Holzatlas. 4. Verlag. VEB Fachbuchverlag Leipzig. 688 p.

Zhang, S.Y. 1997. Wood specific gravity – mechanical property relationship at species level. Wood Sci. Technol. 31: 181-191.

Zhou, H. & Smith, I. 1991. Factors influencing bending properties of white spruce lumber. Wood Fiber Sci. 23(4): 483-500.

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