Dissertationes Forestales 19

Effects of environmental and internal factors of trees and timber treatment on colour of dried birch (*Betula pendula*) wood

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Academic dissertation

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ABSTRACT

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Wood of silver birch (*Betula pendula*) has good properties that lead to its extensive use in mechanical wood industries in Finland. However, a problem with sawn birch timber is the darkening of the wood during kiln drying. The purpose of this study was to investigate the reasons for darkening of silver birch wood in order to suggest a way to avoid it. In these experiments, birch boards were sawn into the dimensions needed for parquet billet boards and dried by conventional and vacuum processes in laboratory kilns. The changes in wood colour and in proanthocyanidin concentration during conventional drying and after all drying processes were measured and compared to factors connected with timber handling, environmental factors and internal factors of the trunks, and selected anatomical characteristics of the wood were measured or observed visually. When different schedules for conventional drying were compared, the higher the temperature, the darker was the colour of the wood at the end of drying. Two critical points in wood colour changes were observed. After the conventional drying processes were started, the colour of wood became lighter until moisture content of about 30%; then darkening started and continued until the moisture content of the wood was ca. 15-20%. After that, during further drying the colour of the wood lightened again. A decrease in concentration of soluble proanthocyanidins, i.e. their polymerisation and/or oxidation to coloured compounds, occurred simultaneously with darkening of the wood. Differences between drying methods in terms of the measured anatomical characteristics that correlated with the colour coordinates were observed; in particular, the parenchyma cells of the wood and the width of the latewood layer were important in darkening during vacuum and conventional drying, respectively. The effect of anatomical differences, which develop during the whole life of a tree, on the colour reaction of wood suggests a new approach for controlling the darkening of birch wood that occurs during drying. With this approach, birch could be tried to breed for lighter wood or development of cells that affect wood darkening could be tried to minimize with silvicultural practices.

Keywords: anatomy, *Betula pendula*, CIEL*a*b*, colour, drying, proanthocyanidins, wood

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LIST OF ORIGINAL ARTICLES

The thesis is based on original publications I-VI.

I Luostarinen, K. & Verkasalo, E. 2000. Birch as sawn timber and in mechanical processing in Finland. A literature study. Silva Fenn. Monographs 1. 40 p. http://www.metla.fi/silvafennica/

II Luostarinen, K. & Luostarinen, J. 2001. Discolouration and deformations of birch parquet boards during conventional drying. Wood Sci. Technol. 35: 517-528. DOI: 10.1007/s002260100109

III Luostarinen, K., Möttönen, V., Asikainen, A. & Luostarinen, J. 2002. Birch (*Betula pendula*) wood discolouration during drying. Effect of environmental factors and wood location in the trunk. Holzforschung 56: 348-354. DOI: 10.1515/HF.2002.055

IV Luostarinen, K. & Möttönen, V. 2004. Effects of log storage and drying on birch (*Betula pendula*) wood proanthocyanidin concentration and discoloration. J. Wood Sci. 50: 151-156. DOI: 10.1007/s10086-003-0547-5

V Luostarinen, K. & Möttönen, V. 2004. Effect of growing site, sampling date, wood location in trunk and drying method on concentration of soluble proanthocyanidins in *Betula pendula* wood with special reference to wood colour. Scand. J. For. Res. 19: 234-240. DOI: 10.1080/02827580410024133

VI Luostarinen, K. 2006. Relationship of selected cell characteristics and colour of silver birch (*Betula pendula*) wood after two different drying processes. Wood Material Science and Engineering 1: 21-28. DOI: 10.1080/17480270600664850

In Study I, Katri Luostarinen wrote the manuscripts for chapters 5 and 6; the manuscripts for chapters 1 and 7 were written by the authors together as was the final version of the whole paper. In Studies II, III, IV, V and VI, Katri Luostarinen made the research plan, was responsible for sampling, preparation of the samples, measurements and analysing the results, as well as she wrote the manuscripts for the papers. The articles are reprinted with kind permissions of the publishers.

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INTRODUCTION

Birches (*Betula pendula* Roth and *B. pubescens* Ehrh.) are the most common deciduous tree species in northern regions, including Finland. Even though their resources are minor compared to those of pine and spruce (Peltola 2006), their use is especially important in the veneer and plywood industries where they make up ca. 42% of all raw material used (Peltola 2006). The proportion of birch logs used in sawing is only ca. 0.6%; but the importance of birch for small sawmills, ca. 6.7%, is greater (Peltola 2006). In addition, sawn birch wood is definitely used in ways that add value to products. For example, the proportion of birch timber in the furniture industry, where good quality of raw material is of key importance, has been 26 %, while the proportions of pine and wooden boards have been 26% and 32%, respectively (Isomäki & Koponen 2004).

Of the two Finnish birch species with log-size trunks, *B. pendula*, silver birch, forms more wood suitable for logs (Louna & Valkonen 1995). Thus, silver birch is more commonly used in sawing than *B. pubescens*, white birch is, due to also the good properties of its wood, i.e. originally light and uniform colour, adequate strength and hardness with moderate density, ease of manual tooling, machining and finishing, and suitability for sawing and further processing of sawn timber. The most important property limiting the use of birch wood is its poor resistance to decay. This, together with the other properties, means that it is used only in interiors in joinery and carpentry for furniture, panelling and flooring and also in bathrooms and kitchens (Louna & Valkonen 1995), where wood is exposed to mild variations in moisture. The features of birches in sawing and further processing are collected and discussed in detail in Study I of this thesis.

Some of the eight issues mentioned as needing further research in Study I (p. 25) have been investigated during the first years of this millennium. Heräjärvi (2002), who carried out a study concerning the properties of birch wood for sawmilling and further processing, concentrated on the technical properties of birch stems from the standpoint of sawmilling, bucking principles in relation to timber grade and value, and some mechanical properties. He concluded that in Finland the whole wood procurement chain needs to be developed. Possibilities to saw small-sized birch logs for the furniture industry (Lindblad et al. 2003) and to use them as a raw material in engineered wood products (EWP), such as oriented strand board (OSB) (Heräjärvi et al. 2003), have been examined with promising results. The timber of planted silver birch, which will become an important source of birch wood in the near future (see Peltola 2006), has also been under investigation: Möttönen et al. (2004) studied the Brinell hardness and the equilibrium moisture content of dried silver birch wood from plantations, discussing their effects on the usability of wood, and Möttönen and Luostarinen (2006) compared the density and shrinkage of natural and planted birches in order to compare the usability of the woods from these two sources, natural birches being slightly better.

According to Study I, based on the results of e.g. Johansson (1996), Kivistö et al. (1999) and Paukkonen et al. (1999), and on information from experts involved in birch timber processing, drying is perhaps the most critical phase in producing birch timber of good quality. Drying conditions strongly affect the colour of birch wood (I), darkening having been shown to be a serious problem for mechanical wood industries that use sawn birch timber (Harinen pers. comm.). Darkening of birch wood occurs in the inner parts of boards so that a surface layer of a few millimetres remains light in colour (Harinen pers. comm.,

Paukkonen et al. 1999). Thus the darkening is specially harmful in parquet and comparable industries, where thin lamellae, ripped from thicker boards, are located side by side in the product. Placed in this way, the light surface layers form light stripes, which on large surfaces are thought to be aesthetically undesirable.

In the case of birch, testing the schedules for raised-temperature dryings has produced no solutions that would be reliable enough to avoid darkening of wood during the drying process (Harinen pers. comm.). Even temperatures as low as warm summer weather in Finland may cause darkening of the inner parts of birch planks (I). Anyway, significant darkening can be avoided by drying at very low temperature, but this is usually too expensive for sawmills: they cannot tie up capital for the long time that drying at low temperature would demand. In addition, it is often impossible for small saw mills to invest for example in vacuum-drying equipment, although it is easier and faster to produce light-coloured birch wood with this method than with the more common conventional warm-air method (Lahtinen pers. comm., Lahtinen 2001). Other drying methods suitable for sawn birch timber but seldom used are high frequency-vacuum drying (Auvinen 2001) and high-temperature drying (Sonninen 2001).

Thus, the failures to avoid darkening in connection with conventional drying have raised questions concerning the causes of colour darkening in birch wood. In general, darkening is believed to be caused mainly by chemical changes in wood. A source of colour changes is degradation reactions of cell wall components (McDonald et al. 2000), but the chemical changes may also be caused by reactions of unstructural wood compounds (Bauch 1984). The natural compounds that take part in darkening during drying differ, at least partly, in different tree species; these compounds include carbohydrates and compounds containing nitrogen (Theander et al. 1993, Kreber et al. 1998, McDonald et al. 2000) or phenolic extractives, including proanthocyanidins (condensed tannins) (Hillis 1985, Haluk et al. 1991, Kreber 1993/1994, 1996, Charrier et al. 1995, Johansson et al. 2000). Proanthocyanidins, which have not been studied earlier in connection with colour changes of birch wood, are oligomers that are composed of flavan-3-ol units (Ferreira et al. 1999), i.e. they are based on flavonoid structure (Mononen 2001). They belong to secondary metabolites of plants and they are most commonly analysed from leaves in connection with stresses, e.g. herbivory and climatical changes (e.g. Tallamy & Raupp 1991, Julkunen-Tiitto et al. 1996, Laitinen et al. 2000). These compounds are also known to take part in the colour changes of ripening fruits (Hillis & Swain 1959), and are supposed to cause loss of brightness in pulp (Hrutfiord et al. 1985).

The solution for keeping birch wood light may be found in some other factors than directly from drying conditions or changes in them. Thus, for example, the growing and felling conditions of trees, as well as the effects of anatomical factors on wood colour, need to be studied, because they may affect the chemical composition of wood.

AIMS OF THE STUDY AND HYPOTHESIS

This thesis consists of a literature part (I) and an experimental part (II-VI). In the literature part information concerning birch in mechanical use is collected to determine the issues needing further research. The main purpose of the experimental part was to investigate the reasons for colour darkening of birch wood during drying in order to suggest how

darkening of birch wood colour during drying could be minimised or even avoided. For this, growing site as an environmental factor, wood location in the trunk as an internal factor, and felling date and log storage as factors related to timber treatment were studied from the standpoint of colour darkening during drying. It was hypothesised that these factors affect changes in wood colour during drying by causing differences in its chemical and/or cell composition.

The specific objectives of the sub-studies were:

1) to compile information on usage of birch wood, properties affecting its usage and the problems encountered in its use as sawn timber and to gather the unwritten knowledge from professionals (Study I),

2) to compare the effects of drying temperatures on the colour and deformations of birch boards and to determine the phases of drying during which colour changes occur. The issues to be taken into account in Studies III-VI were specified on the basis of this study (Study II),

3) to study the effects of drying method, growing site, felling time, log storage and location of wood in the trunk on the colour of birch wood (Study III),

4) to investigate the effects of growing site, felling time, log storage and location of wood in the trunk on proanthocyanidin concentration in wood at different stages of conventional drying and to determine the correlation between colour and proanthocyanidin concentration (Studies IV and V), and

5) to investigate the anatomical characteristics of wood and their relation to wood colour in differently dried birch wood (Study VI).

MATERIALS AND METHODS

Wood material

Sawn birch timber for Study II was provided by the Karjalan Puu sawmill, Rääkkylä, North Karelia, Finland, from its regular production. The boards were sawn into dimensions for parquet billet boards (30 mm x 70 mm in dried condition).

For Studies III, IV, V and VI, silver birches were felled on two growing sites in Ilomantsi, North Karelia, to compare the effect of two very different growing sites on wood darkening during drying. Birches were felled in summer, autumn, winter and spring and two logs were taken from each tree for immediate sawing and for both 5 and 10 weeks storage to be sawn later. During sawing (into dimensions 30 mm x 70 mm in dried condition), the boards cut from the trunk surface, near the pith and in the middle between the surface and the pith were marked for later identification.

Drying

Boards were dried by conventional (II-VI) and vacuum (III-VI) processes in laboratory kilns (Brunner Trockenteknik GMBH). The course of drying was based on the moisture content of wood measured continuously from 12 points on the boards during drying. The conventional drying processes were carried out in Joensuu (Faculty of Forestry, University

of Joensuu), and vacuum drying processes in Mikkeli (YTI-Research Centre, Mikkeli Polytechnic). The conventional schedules (temperature below 100 ˚C) used in Study II were: 1) a schedule with high temperature, 2) a schedule with moderate temperature and 3) a schedule with low temperature; all lots of Studies III-VI were dried using the same conventional and vacuum schedules, which were tried to plan so that darkening would occur.

In addition to kiln-drying processes, to obtain light-coloured dried birch wood, in Studies III-VI room-temperature dryings were performed in laboratory at ca. 20 ˚C and at air humidity of ca. 40-50% on a limited scale.

Measurement of reflectance spectra and presentation of colour as CIEL*a*b* colour coordinates

To determine wood colour, in Studies II and III the reflectance spectra were measured from undried wood after planing the flat side of the boards thinly to make the surface smooth for even reflectance of light and to remove the yellowed surface that developed rapidly on the timber pieces after sawing; the yellowed surface itself was not studied. It was assumed that before drying, wood is the same colour throughout under the yellowed surface, and thus inner and surface woods of undried boards were not measured separately. The changing of the colour of the inner wood of the boards was charted in Studies II and III by sampling two boards at a time and ripping and planing them for spectral measurements several times during conventional dryings. During the same samplings, the surface of the boards was planed thinly to determine the colour of the surface layer. The final colour of the wood at its final moisture content was measured in the same way from both inner and surface wood of boards dried conventionally (II, III), in vacuum (III) and at room temperature (III). Possible knots, pith flecks and other irregularities that affect colour were avoided, and measurements were made on sound wood. On each board, from both surface and inner wood, the spectrum was measured from three points, the average of them being the result for that board.

The reflectance spectra were measured using a Minolta CM-2002 portable spectrophotometer at visible light range (400-700 nm). The spectra were converted to the widely used CIEL*a*b* colour coordinates (e.g. Precise color…1994), in which the coordinate L* stands for lightness, negative and positive values of the coordinate a* for greenness and redness, respectively, and negative and positive values of the coordinate b* stand for blueness and yellowness, respectively. For birch wood the values of the coordinates a* and b* are positive.

The difference in colour between woods from two treatments is presented as ΔE_{ab*}, which corresponds to the distance between two points in the three-dimensional colour coordinate system and is calculated as follows (e.g. Precise color… 1994):

$$\Delta E_{ab*}=[(\Delta L*)^2+(\Delta a*)^2+(\Delta b*)^2]^{1/2} \quad (1)$$

Analysis of proanthocyanidins

Concentration of soluble proanthocyanidins (condensed tannins; phenolic) was measured from wood in Studies II, IV and V with the method of Hagerman (1995; see also Hagerman

2005), based on the method of Porter et al. (1986). According to this method, soluble proanthocyanidins were extracted from milled samples with acetone, and after adding the reagents (butanol+HCl, ferric ammonium sulphate+HCl) the soluble proanthocyanidins were converted to coloured anthocyanidins in a boiling water bath. The amount of anthocyanidins was determined spectrophotometrically (550 nm). The extraction was made twice for every specimen to ensure that most of the soluble proanthocyanidins could be extracted, the sum of the two extractions being the total amount of soluble proanthocyanidins of the specimen.

Wood anatomy

In Study VI, birch wood was observed under a light-microscope to determine the tissue-level factors affecting darkening of the wood. The crosscuts for the measurements were stained with safranin-alcian blue (Fagerstedt et al. 1996) to emphasise the cell structures for measuring. These measurements were carried out for undried and for both conventionally and vacuum-dried wood. The amounts of axial and terminal parenchyma were estimated on a three-step scale (little, average, much).

Phenolic extractives in wood tissue were observed both from $FeSO_4$-fixed (Johansen 1940, Schneider 1980), and unfixed, i.e. unstained, specimens. $FeSO_4$ stains tannins from orange to black (Schneider 1980); but as coloured compounds, they can also be seen without staining.

Analysis of deformations

In Study II, deformations (twist and warp in radial and tangential direction, cupping, casehardening, shrinkage) were measured according to the method of Paukkonen et al. (1999).

Statistical analyses

The statistical analyses in Studies II-VI were performed with SPSS statistical software using GLM procedure, and Pearson and partial correlation procedures as well as non-parametric Kruskall-Wallis analysis of variance and Spearman correlation. The differences in colour and proanthocyanidin results between the compared factors and between the different phases of drying were compared to each other with analysis of variance, while the relation of colour to proanthocyanidin concentration and, on the other hand, its relation to anatomical characteristics were calculated with correlation procedures.

RESULTS

Dependence of wood colour and deformations on drying, growing site, felling date, log storage and location of wood in the trunk

The effect of different drying conditions on wood colour was clear: the higher the drying temperature, the darker was the colour of the inner wood of the boards at the end of drying (II, III). According to calculated colour differences (ΔE_{ab*}), in the moderate- and high-temperature conventional dryings (II) (Table 1) and in conventional drying of Study III (see III), the difference in colour between the inner parts of the boards and the wood located just under the yellowed surface of boards was clear. As well as in vacuum-drying (III), the surface layer also darkened to near the colour of the inner wood when birch wood was dried conventionally in the mildest conditions (lot 3; II) (Table 1). In drying at room temperature, wood remained light-coloured throughout (III).

In both Studies II and III, two critical points in wood colour changes could be observed in conventional drying. After the drying processes started, the wood became lighter in colour until about the moisture content was about 30%, below which to a moisture content of ca. 15-20% the wood darkened. After that, with further drying, the wood lightened clearly again, but remained visibly darker than before drying (Figure 1).

Felling date, length of log storage period, fertility of the growing site, and radial and longitudinal locations of wood in the trunk affected wood colour; and these effects were somewhat different when wood was dried by different methods (III). For example, wood from winter-felled trees was lightest after conventional drying, the difference being statistically significant compared with most of the felling dates, but in vacuum drying, wood from autumn-felled trees remained the lightest. On the other hand, fresh wood was lightest when trees were felled in summer. When storages were compared, wood stored for 10 weeks was least red after conventional and vacuum drying, and after vacuum drying unstored wood was lightest. The colour of wood from different growing sites differed, the wood from the MT site being generally lighter and less red than wood from the VT site. On the other hand, longitudinally on the trunk, colour differences were rare, occurring mainly

Table 1. Comparisons of colours measured in Study II, difference presented as as ΔE_{ab*}. The colour of fresh wood was compared to that of the inner wood of drying 1 and the surface wood of drying 2 because after drying the wood colours in these dryings/locations were the darkest and the lightest, respectively.

Comparison	ΔE_{ab*}
Drying 1, surface - inner wood	6,92
Drying 2, surface - inner wood	7,51
Drying 3, surface - inner wood	1,35
Fresh - inner wood of drying 1	9,64
Fresh - surface wood of drying 2	4,63

in fresh wood: the wood of the top log was lighter and more yellow than that of the butt log, the trend toward yellowing remaining only in conventional drying. Radially in the trunk, there was a clear tendency toward redness: in most cases the wood located near the pith was reddest both before and after drying.

In Study II, the effect of drying schedules on the deformations was limited to differences in case-hardening. Among every three drying lots case-hardening was greatest after drying at moderate temperature and smallest after drying at high temperature.

Dependence of wood colour on the proanthocyanidin concentration of wood

At the final wood moisture content, drying method affected the concentration of soluble proanthocyanidins in birch wood (IV, V). The final average proanthocyanidin concentration of wood was in accordance with the final colour of the wood, the concentration being lowest in the darkest vacuum-dried wood and highest in the lightest room-dried wood. Percentage yields of soluble proanthocyanidins differed between the first and second

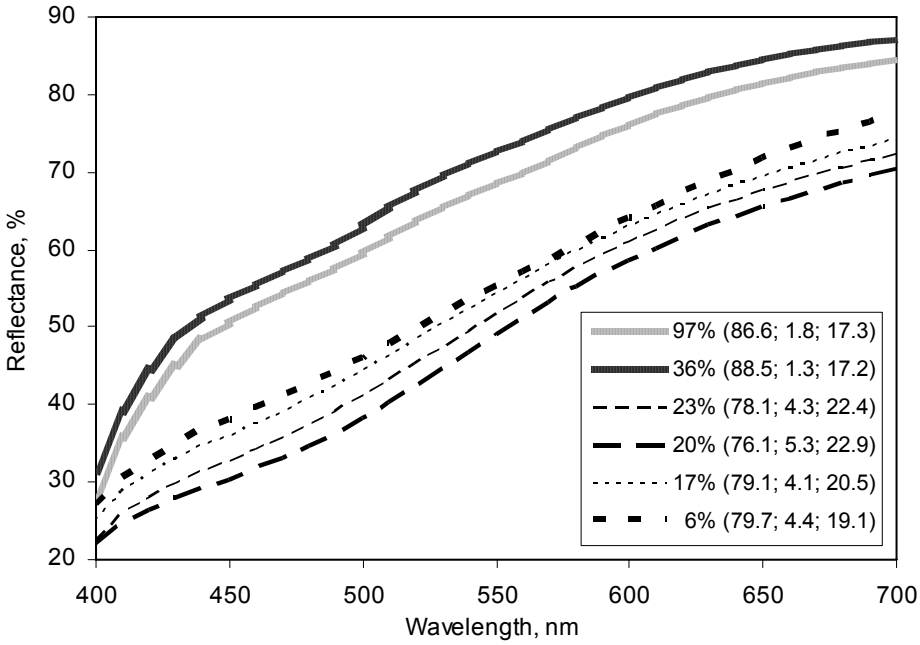

Figure 1. Example (spring-felled, stored 5 weeks) of the average colour of undried birch boards, boards sampled during conventional drying and conventionally dried boards; the moisture content at which the measurements were performed is presented as the name of a spectrum. After the name, L*a*b* colour coordinates are presented in this order. Spectra represent the colour measured from the inner wood of the boards. ΔE_{ab^*}'s were 7.6, 12.4 and 5.3 between 97 and 6%, 97 and 20%, and 20 and 6%, respectively. For moisture contents 97 % and 6 %, the number of measured boards was 31; and for each of the other moisture contents, the number was 2.

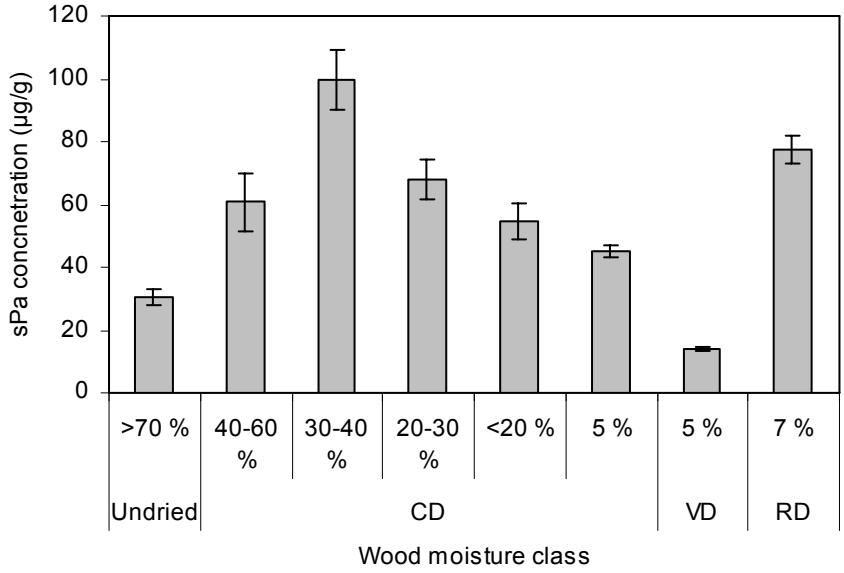

Figure 2. Average concentrations (±SE) of soluble proanthocyanidins (sPa, dry weight basis) in undried wood, during and after conventional drying (CD), in vacuum-dried (VD) wood and in wood dried at room temperature (RD) calculated for the whole material of Studies IV and V.

extraction of the specimens (V). Soluble proanthocyanidins were attached more firmly in wood dried in vacuum than in samples dried in other ways or in undried samples.

The analyses of soluble proanthocyanidins made from specimens of birch wood taken during conventional drying showed that the concentration of proanthocyanidins increased until about 30% of wood moisture content, at which point it started to decrease (IV, V) (Figure 2). Below a moisture content of 30%, the decrease in concentration of soluble proanthocyanidins occurred simultaneously with darkening of the wood. In wood stored for 10 weeks, however, the increase in concentration of soluble proanthocyanidins was smaller than in wood from other storage periods, and the slight increase continued to lower the wood moisture content than in unstored wood or wood stored for 5 weeks (IV). Furthermore, the darkening of wood stored for 10 weeks lasted until the moisture content was lowest, ca. 15%. In general, wood of logs stored for 10 weeks remained least red and least yellow during drying (III). When storage periods were compared, however, the final proanthocyanidin concentrations of similarly dried birch boards were similar.

In fresh wood some differences in proanthocyanidin concentration were observed between sampling dates and at different radial locations in the trunk; but during conventional drying these differences disappeared. On the other hand, after vacuum drying in addition to between sampling dates and radial locations in the trunk, statistical differences in the concentration were also observed between growing sites and storage periods. On this level, however, there was no clear relationship between colour and the proanthocyanidin concentration of wood (IV, V).

Correlation of tissue-level factors with wood colour

In Study VI, the darkening of birch wood was investigated on the cell level. Only small amounts of darkened compounds could be seen in undried and room-dried samples, but more appeared in conventionally and vacuum-dried unstained specimens. The darkening and condensing of the compounds were more evident in vacuum-dried than in conventionally dried specimens. These compounds were located mainly inside the ray parenchyma cells, with small amounts in axial and terminal parenchymas, but not in the cell walls. They stained with $FeSO_4$ in both light-coloured and in darkened specimens, indicating that they were phenolics.

When the anatomical characteristics measured here were correlated with colour coordinates, the clearliest finding was the differences between drying methods in terms of characteristics that correlated with colour coordinates, and the scarcity of such characteristics in undried wood. In both drying methods with raised temperature, the importance of the rays was obvious; however, the effect of the rays differed in the two methods. In conventionally dried wood, the more rays there were, the lighter, less red and less yellow the colour of the wood was; and in vacuum-dried wood, the larger the width of the rays, the darker, redder and yellower the colour of the wood was. In conventionally dried wood, a wide band of latewood caused darkening of wood, while in vacuum drying axial parenchyma also played an important part in colour darkening: the more axial parenchyma there was in a specimen, the darker, redder and yellower its colour was (Figure 3).

DISCUSSION

Effects of drying on colour and proanthocyanidin concentration of wood

In this study, it was confirmed that the most obvious factor affecting the degree of darkening of birch wood during conventional drying is temperature: the higher the temperature, the darker the birch wood was after drying (II, Paukkonen et al. 1999, Stenudd 2002). When drying methods were compared, several results suggested that there was a difference between drying methods in colour darkening; the different temperatures used in conventional and vacuum drying may have also played a part in this. Vacuum drying at lowered air pressure caused redder colour than conventional drying did, different felling times and storages affected the degree of darkening differently in conventionally and vacuum-dried wood (III), and in these two drying methods, the final concentration of soluble proanthocyanidins differed as did the extractability of these compounds (V). In addition, the appearance of the dark compounds inside the ray parenchyma and also the tissue-level characteristics that correlated significantly with colour coordinates differed in different drying methods (VI). Although the ease of vacuum drying in keeping wood colour as light as possible is based on the deficiency of oxygen concentration in kiln as well as on rapidity of drying in lowered vaporisation heat of water, the method does not completely hinder the darkening of wood colour. According to Frey-Wyssling and Bosshard (1959), decrease of non-structural carbohydrates – which was observed in these samples, too

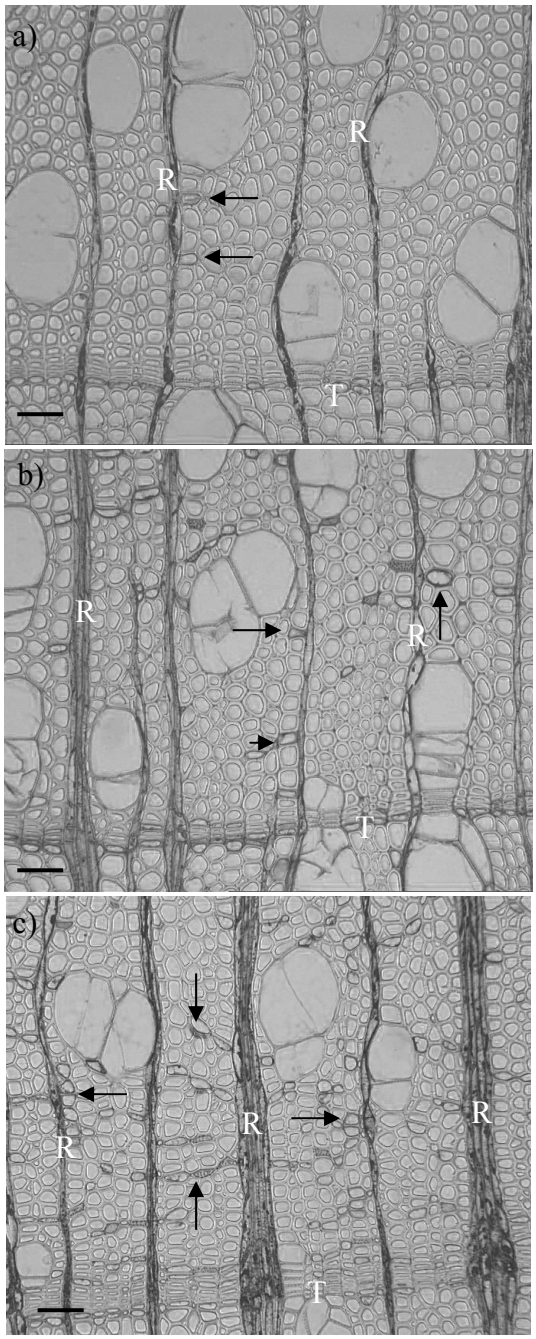

Figure 3. Crosscuts of birch wood with different amounts of axial parenchyma (arrows): a) little, b) average, and c) much. R - ray, T - terminal parenchyma. Bar 0.05 mm. Staining: $FeSO_4$ and safranin-alcian blue.

(Mononen et al. 2001) – raises the redox-potential so that very low concentration of gaseous oxygen is enough for oxidation reactions. The colour differences, measured from the inner wood of the boards, between different dryings in Study II and between drying methods in Study III were clearly visible and would be harmful if boards from different dryings were used for the same product, in writer's opinion. On the other hand, the variation observed in the colour of similarly dried boards was not as great, and similarly dried wood would be acceptable for the same product, assuming that darkened wood would be acceptable at all.

Different drying conditions in conventional drying (II, III) and vacuum drying (III) affected the development of a surface layer that differed in colour from the inner wood of the boards. The surface layer is usually light; but in very mild conditions that do not favour formation of a dry surface layer, like in lot 3 of Study II, the surface wood also darkened. The same conditions emphasise both formation of the light surface layer and case-hardening. In the case of Study II, differences in case-hardening may be due to the fact that the boards of lot 2, with the largest case-hardening and with the largest colour difference between surface and inner wood was frozen when drying was started at quite low temperature. In these kinds of conditions the surface starts to thaw and even dry when inner parts of timber are still frozen. This means that the transport of water towards the surface of boards is limited. Drying of the surface layer is also assumed to block the passage of water out of the wood, which prolongs the hot and wet conditions inside the piece of timber (Paukkonen et al. 1999). In vacuum-drying (III) the observed total darkening of the boards can be explained as being due to decreased possibilities for water to evaporate from the board surfaces at low air pressure, as well as to high temperature. Sugars may have enhanced the darkening of the surface layer because they migrated with water and accumulated on the surface of the boards, and formed clearer gradient in vacuum-dried than in conventionally dried boards (Piispanen & Saranpää 2001). Migration of sugars and nitrogen to the surface of pieces of timber has been observed also earlier in conventional drying (Terziev 1996), but phenolics have not been observed to migrate (Lavisci et al. 1991, see Möttönen & Luostarinen 2005). Thus colour changes occurring in different parts of the timber may be caused by different compounds and reactions. If the surface layer that differs from the inner wood of timber piece due to its colour is very thin, it is removed in planing and does no harm.

The two critical points of drying determined in conventional dryings (ca. 30% and 15-20% moisture content), between which the darkening occurred, suggest that chemical reactions of proanthocyanidins, polymerisation and oxidation, that lead to darkening require oxygen and moisture in addition to raised temperature. On the contrary, the formation of soluble proanthocyanidins, which occurs mainly at higher moisture contents than 30% (although it was possible also below it), do not require high temperatures, as it also occurred in room temperature. When the two results, i.e. that reactions of soluble proanthocyanidins into insoluble form mainly occurred simultaneously with colour darkening and that the final concentration of soluble proanthocyanidins corresponded to the final colour of wood when drying was carried out with different methods, are compared, it becomes clear that chemical reactions of proanthocyanidins take part in darkening of birch wood. It is not, however, possible to predict the final colour based on the concentration of soluble proanthocyanidins in undried wood. For example, the rapidity of drying in the early, capillary phase, which has been observed to help keep birch wood light (Stenudd 2002, Sundqvist 2002), may affect colour by decreasing the formation of proanthocyanidins: in wood of planted silver birch, formation of proanthocyanidins in the

lighter, faster dried surface layer has been observed to be lower than in inner parts of the boards (Möttönen & Luostarinen 2005). As well, the results obtained with planted silver birches (Möttönen & Luostarinen 2005) show that the concentration of soluble proanthocyanidins was lower in undried wood of planted birches than in wood of natural birches here; and although in conventional drying the wood of planted birches remained lighter than that of natural birches, during vacuum drying the wood of planted birches darkened more. Any reason for the lightening of the wood colour at moisture content below 15-20% could not be determined according to this study, but photooxidation (Vano & Németh 1996, Csonka & Németh 1998), temperature having an effect, too (Csonka & Németh 1998), has earlier been observed to destroy the flavonoid structure; breaking down of the structure causes lightening of the colour. From birch wood, two flavonoids, (+)-catechin and (+)-catechin-7-O-β-D-xylopyranoside have been found (Mononen et al. 2001).

Effects of felling season, growing site, log storage and wood location in the trunk on colour and proanthocyanidin concentration of wood

Differences that depended on felling season, growing site, log storage and wood location in the trunk were observed more often in wood colour than in proanthocyanidin concentration; and on this level the colour and proanthocyanidin results were seldom in accordance with each other. This does not, however, exclude the possibility that concentrations of polymerised insoluble and/or oxidised proanthocyanidins (which were not measured) would not correlate with wood colour even on this level. However, other factors, e.g. other extractives, probably also play a role in the colour differences of wood on this level. For example, in birch wood the total concentration of extractives is lowest in autumn and winter (Perilä 1958, Perilä & Toivonen 1958), at which times the colour of birch wood (III) remained lightest during drying. Between sites, water content of the soil in spring causes colour differences in fresh wood (Klumpers et al. 1993), but the colour of oak wood from different sites has been observed to differ also after drying (Charrier et al. 1992). In addition to between-season variation, the chemical composition of birch wood differs between sites (e.g. Mononen et al. 2001).

Furthermore, storage has been observed to cause changes in the extractive composition of birch wood (Assarsson & Croon 1963, Donetzhuber & Swan 1965, Paasonen 1967, Mononen et al. 2001, Piispanen & Saranpää 2001). Other effects of storage are the decrease in moisture content and the death of the parenchyma cells in wood. All of these probably affect slight changes in wood colour during drying. Because the concentration of soluble proanthocyanidins did not rise to as high a level in wood stored for 10 weeks than in unstored wood and wood stored for 5 weeks, the total amount of these compounds, and thus the amount of polymerised and/or oxidised proanthocyanidins, remained lower than in wood in other types of storage. Correspondingly, the colour change in conventional drying to redder was clearer in unstored wood and that stored for 5 weeks than in wood stored for 10 weeks.

In addition, the colour differences observed radially in the trunk – particularly a decrease in the redness from the pith to the surface (III) – were in accordance with other previously observed differences between locations in birch trunks. For example, the proportion of rays decreases from the pith to the surface (Bhat & Kärkkäinen 1981), and mechanical properties are better in the surface wood than in wood near the pith (Heräjärvi 2002).

Concentration of soluble proanthocyanidins showed also a downward trend from the pith to the surface in both undried and dried wood (V).

Although wood colour differed statistically significantly between felling dates, growing sites, storage and location of wood in the trunk, these differences were visually so small that they probably have only slight importance in practice, particularly when drying schedules for producing light-coloured wood are used. However, the best combinations of the factors studied here would be with conventional drying: winter-felling, more fertile growing site, long storage of logs and wood from the surface of the trunks, and with vacuum drying: autumn-felling, more fertile growing site, no storage of logs and wood from the surface or the middle of trunks.

Effects of tissue-level factors on wood colour

In conventionally dried wood, the width of the latewood was important in terms of darkening. This was expected because latewood can be seen as dark bands with naked eye. In addition, dense latewood is a barrier to water movements and may thus prolong wet and hot conditions inside timber pieces. The contribution of the parenchyma, in particular the rays, to wood darkening has also been observed earlier, leading to the conclusion that its effect depends on the compounds inside these cells (McMillen 1975, Koch et al. 2003). The effect of compounds inside parenchyma seemed obvious also here. Thus a surprising result was that the phenolics in the parenchyma of conventionally dried wood would not cause darkening; the darkening effect of the phenolics located in the ray and axial parenchyma was clear only in the vacuum-dried samples. The effect of rays on faster water movements perpendicularly to latewood might have been emphasised in conventional drying. The results of Study VI suggest that differentiation of different types of cells during the whole life of a birch tree affects the colour changing during drying. For example, differences in numbers of parenchyma cells in the xylem have been observed to occur between clones (Rao et al. 2002) and between trees growing in differing environmental conditions (Alves & Angyalossy-Alfonso 2002, Quilhó et al. 2003). Environmental conditions affect the concentration of hormones, of which ethylene, for example, in high concentrations, has been observed to increase the differentiation of parenchyma cells (Yamamoto & Kozlowski 1987, Junghans et al. 2004).

CONCLUSIONS

According to these results, the most obvious factor affecting darkening of birch wood during drying were drying conditions in the drying phase, in which wood moisture content is between ca. 30 and 15-20%. In this phase of drying, darkening of colour and a decrease in the concentration of soluble proanthocyanidins occurred simultaneously. Differences between drying lots in the formation of a light-coloured surface layer suggest that the duration of wood drying may also contribute significantly to darkening. In conclusion, in artificial drying with raised temperature it might be possible to keep birch light in colour, if the wood is dried extremely rapidly. In the case of especially thick sawn timber, this is not possible, at least not with the conventional process. In this case, one solution might be to

dry the wood rapidly until about 30% moisture content, at which moisture content the temperature of the wood should be lowered to a maximum of about 30 °C, rather to a temperature below that. When a moisture content lower than 15-20% is reached, the temperature could be raised again. The difficulty with this is correct timing of the temperature changes, because on-line measuring of the moisture content of wood with adequate accuracy is impossible, and the moisture content in different pieces of timber may differ significantly, particularly in this phase of drying.

Thus the possibilities to affect the concentration of proanthocyanidins in wood and their reactions during artificial drying are limited. Even killing the parenchyma cells before drying is not enough, as formation of proanthocyanidin was observed in wood stored for 10 weeks, in which the cells were most likely dead. Rather, a solution may be found in the breeding, including gene technology, and cultivation of birches on the basis of the anatomical characteristics found to correlate with wood darkening. By controlling the genetic origin and growing conditions, which is possible particularly when the origin of birch seeds for plantlets and sites for birch stands are chosen, it might be possible to affect the cell composition and thus the colour of wood. The possibilities to control colour by manipulating anatomical characteristics need to be studied, also because the drying schedules used here were planned to cause darkening of the wood, not to keep wood light. However, it is improbable that the effects of the tested factors would be totally different if a schedule planned to keep the colour as light as possible were used. Another issue worth further studying is the observed colour lightening at the final stage of drying. In this stage, it might be possible to enhance the lightening so that the final colour of wood would be acceptable from the inner parts to the surface of timber pieces.

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