VARIABILITY OF WOOD COLOR IN PAPER BIRCH IN QUÉBEC

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(Received March 2009)

Abstract. Color variability of paper birch (*Betula papyrifera* Marsh.) wood at the tree level was examined in this article. Tree age, dimension, and vigor were expected to influence the proportion of discolored wood in paper birch boards; older, larger, and less vigorous trees were assumed to produce boards with higher proportions of discolored wood. The color analysis was performed on approximately 2250 boards produced from 168 paper birch trees harvested in two different stands from which only logs of sawing quality were used. An industrial scanner was used to digitize the boards and obtain colorimetric information. Results show that tree diameter and vigor significantly influenced the proportion of discolored wood in boards, whereas the effect of tree age did not have a significant influence in the model. An average area of 32.4% of discolored wood was obtained when considering all boards. Less vigorous trees showed a mean area of 45.32%, whereas middle-vigor and most-vigorous trees had mean areas of 30.78 and 15.47%, respectively. The colorimetric values were mainly affected by tree age and diameter, but these effects were variable for every colorimetric parameter. The analysis of the random effects demonstrated that most of the total random variance of the dependent factors came from the between-board, between-tree, and, to a lesser extent, between-log variation. These findings suggest that favoring shorter rotations would help produce trees with lower proportions of discolored wood.

Keywords: *Betula papyrifera* Marsh., sapwood, discolored wood, colorimetry, color scanner.

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Wood and Fiber Science, 41(4), 2009, pp. 333–345

INTRODUCTION

Paper birch (*Betula papyrifera* Marsh.) is an interesting alternative to the high-value species traditionally used by the Québec hardwood sawmilling industry. It is broadly distributed in large volumes across Canada and has appealing physical and appearance characteristics. In the manufacture of appearance products, wood color is undeniably an important attribute influencing the value of wood. The color of paper birch wood has a broad range of shades creating a number of design possibilities. Its light-colored sapwood is suitable for many appearance products, but it comes with a contrasting darker, brown–reddish discolored wood, also called red heart. This difference in coloration is not appreciated by the wood appearance products industry in which homogeneously colored products are desired. In particular, the simultaneous presence of sapwood and discolored wood on boards makes it more challenging to match components and apply finishes.

The brown–reddish discoloration found in paper birch wood has been given different names in the literature: red heart, discolored wood, affected wood, pathological heartwood, stained wood, traumatic heartwood, wetwood, etc (Campbell and Davidson 1941; Siegle 1967; Shigo 1967, 1986; Shigo and Larson 1969; Shigo and Hillis 1973; Basham 1991; Allen 1996; Hallaksela and Niemisto 1998; Boulet 2005). Most of these authors advance the theory that discolored wood, or red heart in paper birch, is not normal heartwood but is of traumatic origin. Although in many tree species, normal heartwood is linked to aging processes, traumatic heartwood results from processes associated with tree injuries and microorganisms.

Shigo and colleagues suggested a pattern for discoloration and decay in living hardwood trees of North America that explains the presence of red heart in paper birch (Shigo 1967; Shigo and Larson 1969, 1986; Shigo and Hillis 1973). Broken branches, stem wounds, or any other tree injury would be the triggering factors for wood discoloration. At this wound stage, an initial discoloration may appear because of the production of phenolic compounds by the tree to create a protective barrier. Thereafter, the wounded area may be invaded by bacteria and nondecay fungi leading to more discoloration. Finally, wood-degrading (or decay) fungi may further increase the extent of wood discoloration. Different stages of discoloration may be present in a paper birch tree through time and in different locations of the tree. Some research has tried to explain how the presence of microorganisms can induce discoloration in trees. An association between white birch red heart and a nondecay fungus, *Torula ligniperda*, was found suggesting that it could be one of the causes of red heart (Campbell and Davidson 1941). Without confirming the association of *Torula ligniperda* and red heart, Siegle (1967) nevertheless showed that red heart is the result of an enzymatic oxidation caused by fungi entering the tree after a mechanical injury. Campbell and Davidson (1941) noted that red heart was often present in trees having decay, suggesting that this discoloration is formed at the early stage of the decay process, a hypothesis also advanced by Siegle (1967).

Many authors agree that this discoloration is an important character mark affecting paper birch wood for various uses. From a sample of 936 trees, based on a provincewide survey in Ontario, discoloration represented 70% by volume of the defects in white birch (Basham 1991). Tree age appeared to be an important factor influencing the presence of red heart. Basham (1991) demonstrated that the volume of stain and decay increases with age, whereas Campbell and Davidson (1941) reported considerable discoloration in trees older than 70 yr. The latter authors also noted that most trees over 50 yr contained some discolored wood regardless of stand conditions. In a study on the occurrence, proportion, and distribution of paper birch heartwood (Giroud et al 2008), the presence of red heart was also positively correlated with tree age at stump height. Of the 150 birch trees, 27% contained discolored wood at breast height. On a smaller sample of 18 birch trees, the volume of wood occupied by red heart was 13%. Belleville et al (2008) studied the distribution and sources of initiation of red heart in paper birch. In more than 77% of the logs analyzed, the discoloration was initiated from an external defect, which supports the traumatic cause of red heart. Their results also support the idea that red heart spreads downward in the stem; every new wound creates more discoloration that is added to the central column. The study concluded that the presence of branch scars, dead branches, forks, and callus on standing trees could help to predict the presence of red heart inside the trees.

Hallaksela and Niemisto (1998) investigated the discoloration of stem wood in planted silver birch (*Betula pendula* Roth). Tree age was found to have an effect on the proportion of discolored wood; the average volume of discoloration in all sampled birches (18 – 65 yr old) was $1.6 \times 10^{-3}/m^3$, whereas it was $3.2 \times 10^{-3}/m^3$ for the older trees (42 – 65 yr old). Moreover, as the trees increased in age, there was an increase in diameter of the discolored column around the pith. These authors also mentioned that broken (or dead) branches and invasions of microorganisms were the most common reasons for the presence of discoloration in birch trees. In 83% of the sampled birches, discoloration was associated with microbial colonization.

The color and color uniformity variation in Scots pine wood was evaluated (Grekin 2007) with significant differences in the wood colorimetric parameters, CIE L*a*b*, between trees and sites. Wood lightness was greatest in the northern stands. The colorimetric coordinates of sapwood and heartwood areas of the boards were also compared, and significant differences between the two zones were found for the three variables. Heartwood had lower luminosity (L*) and higher colorimetric values (a* and b*) meaning a darker, redder, and more yellow wood than sapwood. The sources of variations affecting the total random variance of the L*, a*, and b* values were presented by Grekin comparing the between-stand, between-tree, and residual covariance parameters. In all cases, the residual variation (between-samples) was the highest source followed generally by the between-tree and the between-stand variations.

In light of these findings, the present study addresses the following hypotheses. According to the theory of the traumatic nature of red heart, tree age and diameter are assumed to have an influence on the proportion of discolored wood; older and larger diameter paper birch are expected to produce more discoloration in the boards. Furthermore, less vigorous trees that show more external defects are expected to produce boards with higher proportions of discolored wood. The main objective of this study is to verify these hypotheses to better understand the sources of the variability of color in paper birch wood keeping in mind its potential use as a raw material for appearance products. The specific objectives are to assess the expression of the discolored wood, to objectively characterize the color of its sapwood and discolored wood, and to analyze the effects of three explicative variables—tree age, tree diameter at breast height (DBH), and tree vigor—on the variability of these colorimetric parameters.

MATERIALS AND METHODS

Stand Selection and Tree Classification

In the winter of 2005, 100 paper birch stems were selected in an overmature mixed stand located in the north of the Laurentian region (N 47°, W 74°) of the province of Québec, Canada. Stems were selected using the current classification system for tree vigor in Quebec to source an adequate number of trees in different vigor classes. Tree vigor is determined by the MSCR classification established by the Québec Ministry of Natural Resources and Wildlife (Boulet 2005) based on external tree defects. Trees classified M (mourir), nongrowing stock, and trees classified S (survie), poor growing stock, correspond to the less vigorous trees. Classes C (conserver), acceptable growing stock, and R (réserve), premium growing stock, are assigned to the most vigorous trees and correspond to the growing forest capital.

They include healthier trees with fewer wounds and defects. The trees were classified as M (32%), S (26%), C (22%), and R (20%). Harvesting occurred at the end of March 2005 and trees were left in the forest with branches intact until June 2005. No end stains from oxidative reactions were observed on the birch stems. At the beginning of June, trees were cut into logs after an optimized slashing based on Petro and Calvert (1976) rules for log quality. A total of 261 logs were produced of which 130 were of sawlog quality (F1, F2, F3, and short logs [F4]) and 131 logs were pulpwood. The sawlogs originated from 68 trees and only those logs were retained for the present study. They were sawn into boards at a hardwood sawmill using a sawing-around pattern in June 2005. The central cants were resawn into boards on a "WoodMizer" portable sawmill shortly thereafter. These sawing operations produced more than 1400 boards.

In the fall of 2007, the same procedure was repeated on a younger stand (Stand 2) located less than 1 km from the first and on the same ecological site type (MJ22: Bétulaie jaune à sapin sur dépôt de texture moyenne mésique [yellow birch–fir forest on loamy or midtexture and well-drained soil]) (Gosselin 2002). On Stand 2, 68 paper birch trees were selected. Following the same optimized slashing method (Petro and Calvert 1976), 85 sawlogs (F1, F2, F3, F4) were obtained (from 54 birch trees) with the remaining 101 logs being pulpwood. The logs were sawn at the beginning of November of the same year and more than 800 boards were produced. These boards, in addition to the boards from Stand 1, constitute the research material used in this study; a total of 2284 boards were analyzed.

The age of the selected trees ranged 46 – 154 yr with a mean of 101 yr. The age distribution showed two age subdistributions. Most of the trees coming from Stand 1 were older than 100 yr with an average of 122 yr, whereas trees from Stand 2 were younger than 100 yr with an average of 74 yr. DBH ranged 24 – 66 cm with an average of 33 cm including both stands. Again, larger trees were found primarily in Stand 1, whereas smaller ones were in Stand 2 with some overlap in the stand distributions. Tree growth rate ranged 2 – 7.2 mm/yr with an average of 3.7 mm/yr (3.1 mm/yr for Stand 1 and 4.4 mm/yr for Stand 2). In summary, Stand 1 contained older and larger trees but had slower growth rates than Stand 2. Stand 1 also had a greater number of less vigorous trees.

The board dimensions ranged 1.2 – 3.7-m long and 76 – 330-mm wide. All boards were dried in a conventional kiln in the month after sawing for both stands. A mild schedule with a maximum 60°C dry-bulb was used to limit color change and checks (Normand 2004). Boards were planed with a molder (Weinig Unimat 23 EL) on both faces to get a fresh and clean surface just before scanning for wood color.

Colorimetric Analysis of Paper Birch Boards

The colorimetric analysis was performed on board images acquired by an industrial scanner, BorealScan, developed by the Center de recherche industrielle du Québec (CRIQ) for wood furniture industry applications (Caron 2005). For each board, digital images were recorded for both faces. Defects were automatically identified by the scanner. Image processing software, CRIQTraitement, developed for the scanner, was used to view and process images and collect colorimetric information. The software first permitted segmentation of the board images into two different zones representing sapwood and discolored wood based on the pixel color intensity. The limits between these two zones were established by taking many color intensity measurements in each zone of coloration. The values were graphed and a threshold set based on a change in slope between the zones. Finally, manual iterations helped determine the optimal threshold within this slope-changing section. A median filter of 80 × 80 pixels was used to classify the different zones (image segmentation). After this segmentation, software was used to measure the proportion of every board surface belonging to sapwood and discolored wood. Figure 1 illustrates an example

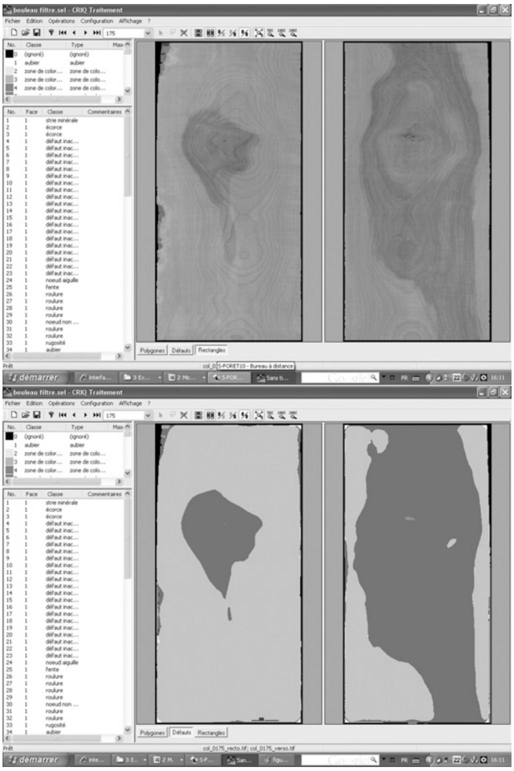

Figure 1. Example of an image segmentation operated by the software CRIQTraitement. Discolored wood and sapwood regions were created based on the pixel color intensity.

of image segmentation performed by the image analysis software.

For most of the boards, the segmentation method produced accurate results where the lines of the created zones followed the geometry of the colored zones on boards. However, in the case of boards not having abrupt color transitions, the use of automatic image detection yielded less accurate results. This weakness of the method, however, did not significantly affect the accuracy of the results; the fraction of board area not correctly classified was very low in comparison with the total surface area analyzed.

The mean color of each board, and each sapwood/discolored wood region, was determined using software based on the CIE L*a*b* color system. In this three-dimensional colorimetric space, the L* coordinate indicates the luminosity of the color on a scale from 0 (black) to 100 (white). The a* and b* coordinates are chromatic values indicating the position of a pixel on the red–green axis (a*), from −100 (green) to +100 (red), and on the blue–yellow axis (b*), from −100 (blue) to +100 (yellow). Wood character mark areas (eg knots, bark) detected by the scanner were excluded from the colorimetric analysis. However, the average color per board included those character marks.

The colorimetric values (L*a*b*) and the proportion of sapwood/discolored wood were analyzed statistically using SAS software version 9.1 for Windows (SAS 2003). Multiple regressions were used to simultaneously test and model the effects of three tree variables (tree age, diameter, and vigor) on wood color parameters. The effect of tree growth rate was also considered but not included in the statistical model because of the strong correlation with tree age. A mixed-model procedure was used to take into consideration the random effects associated with the hierarchical model, ie board, log, tree, and stand associations. The threshold used to determine the significant variables was $\alpha = 0.05$. The statistical model used transformed data only for the proportion of discolored wood variable. For these data, an arcsin square root transformation was used to normalize data.

RESULTS

Proportion of Discolored Wood

Overall, 32.4% of boards were discolored with a standard deviation of 33.3%. The latter was indicative of the high variability in color of the material evaluated. Boards were sawn as completely sapwood, completely discolored wood, or including both types in variable proportions. From the 122 trees that produced sawlogs, only 12 had little discoloration. Therefore, the presence of discolored wood in these stands is important because it occurred in almost every tree analyzed. However, the proportion of discoloration within trees and within boards was highly variable and there was a majority of boards with the desired light color.

The statistical analysis showed that tree diameter and vigor (MSCR) had a significant effect on the proportion of discolored wood on board surfaces, but not tree age ($p = 0.0972$). Concerning tree vigor, the less vigorous trees (M class) with more external defects had a greater area of discolored wood (45.32%). Middle classes S and C had mean discolored areas of 30.41 and 31.15%, respectively. In contrast, the area of discolored wood in the most vigorous trees (R class) was only15.47% (Fig 2). A statistically significant difference was found between all the vigor classes except between trees of the S and C classes. Tree diameter had a statistically significant effect on the proportion of discolored wood in boards (Fig 3). Results indicated that boards from large-diameter trees had higher proportions of discolored wood. As previously mentioned, tree age did not have a significant effect on discoloration.

When tree growth rates were plotted against age, a linear negative relationship was observed; older trees had lower growth rates (Fig 4). Moreover, Fig 4 suggests that tree vigor has an influence on the distribution of growth rates. Less vigorous trees (M) tended to have lower growth rates (more dots present on the lower right part of the graph), whereas the most vigorous trees (R) tended to have higher growth rates (more dots on the upper left side of the graph).

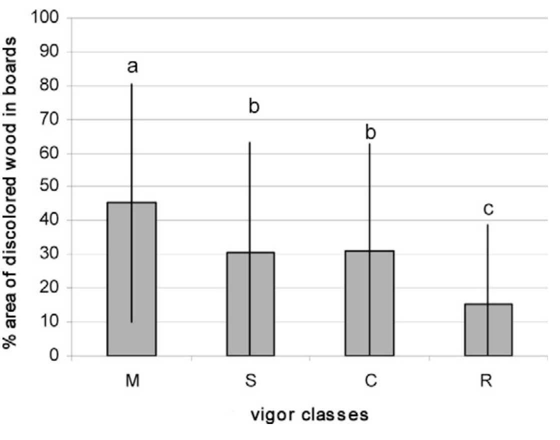

Figure 2. Areas of discolored wood in boards in relation to tree vigor classes (average and standard deviation). Different letters indicate significant differences between vigor classes.

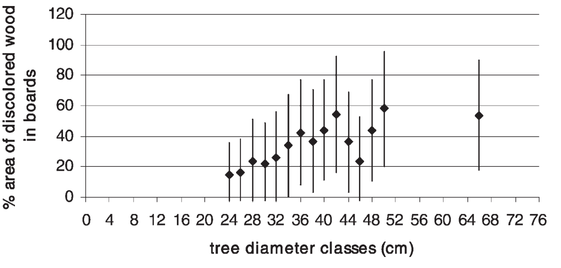

Figure 3. Areas of discolored wood in boards in relation to tree diameter (DBH) (average and standard deviation).

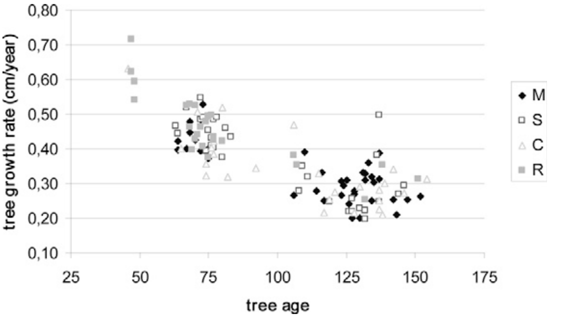

Figure 4. Tree growth rate in relation to tree age and vigor classes.

Colorimetric Analysis in the Sapwood and Discolored Regions

Colorimetric values for all boards in the study are presented in Table 1. The mean L*a*b* values are presented separately for sapwood and discolored wood regions. When comparing the colorimetric values of these zones, the transition is more abrupt for luminosity values than for chromatic values a* and b*. A difference of approximately 10 units can be observed between the mean luminosities of sapwood and discolored wood, although the chromatic values a* and b* have differences of fewer than 2 units.

The mean colorimetric values associated with sapwood and discolored wood zones were compared using paired-sample t-tests (Table 1). For every L*, a*, and b* value, the results show a significant difference between these zones.

Table 1 shows mean colorimetric values for whole boards. These results have to be viewed with caution. When boards are homogeneous in

Table 1. *Comparison of the mean colorimetric values for the different board sections.*

Sections	L*	a*	b*
Whole board	71.21 (4.03)[a]	3.59 (0.92)	19.38 (1.00)
Sapwood	73.89 a[b] (2.13)	3.09 a (0.56)	19.09 a (1.04)
Discolored wood	64.43 b (5.32)	4.59 b (1.02)	20.97 b (2.56)

[a]Standard deviation.
[b]Different letters indicate that from a paired-sample t-test, the value differs significantly at p = 0001.

Table 2. *Effects of the three independent variables on the colorimetric parameters (Pr > F).*

Variable	L* sapwood	a* sapwood	b* sapwood	L* discolored wood	a* discolored wood	b* discolored wood
Tree age	0.3121	0.0004[a]	0.0023[a]	0.0015[a]	0.0825	<0.0001[a]
Tree diameter	0.0040[a]	0.0003[a]	<0.0001[a]	0.3344	<0.0001[a]	0.0854
Tree vigor	0.3178	0.5062	0.4819	0.2909	0.7568	0.2375

[a]$p < 0.05$.

color, the mean color value accurately represents what can be seen visually. However, when boards are heterogeneous, with variable proportions and distribution of sapwood and discolored wood, the mean color value for the entire board becomes more of an index of coloration than a true image.

The mean colorimetric values of sapwood and discolored wood were analyzed in relation to tree age, diameter, and vigor to evaluate the potential influence of these parameters on the variability of paper birch wood color. The colorimetric variables, L*, a*, and b*, were analyzed separately in different multiple regression models and the results are presented in Table 2.

Sapwood luminosity was significantly influenced by tree diameter. Larger diameter trees had lower luminosity meaning that sapwood was darker. Tree age and diameter had significant effects on the red color (a*) of sapwood, both positively, indicating that older and larger trees have redder sapwood. The yellowness (b*) of sapwood was also significantly influenced by tree age (negatively) and by tree diameter (positively) meaning that older trees have less yellow sapwood, whereas larger trees have more yellow sapwood. The luminosity of discolored wood significantly increased with age indicating that older trees have paler discolored wood. Tree diameter did not influence luminosity. In accordance with the results for sapwood, the red color (a*) of discolored wood was positively influenced by tree diameter with larger trees having redder sapwood. In this case, tree age did not influence the red color of discolored wood. Finally, the b* values were significantly influenced only by tree age. Older trees had a discolored wood that was less yellow (Figs 5 – 6).

In summary, this study shows that wood color in the paper birch boards varies according to tree age and diameter, but not for all L*a*b* values and not constantly. Moreover, this variation is sometimes different for sapwood and discolored wood zones.

Analysis of Random Sources of Variation

The linear mixed model used to analyze data made it possible to identify not only the effect of the fixed (tree) factors on paper birch wood color, but also to assess the influence of the random effects associated with the hierarchical structure of the data (stand, tree, log, and board associations). The relative influence of these random effects was measured by SAS statistical software using the covariance parameters information (Tables 3 and 4). These independent factors were regarded as random effects because only few levels of their variation were considered in the study.

For all variables evaluated (proportion of discoloration per board and L*a*b* sapwood and discolored wood values) stands did not play a significant role in variation. The precision of their variance was too weak to induce a significant influence because only two stands were in the study. On the other hand, tree effects were important and had significant effects on all the

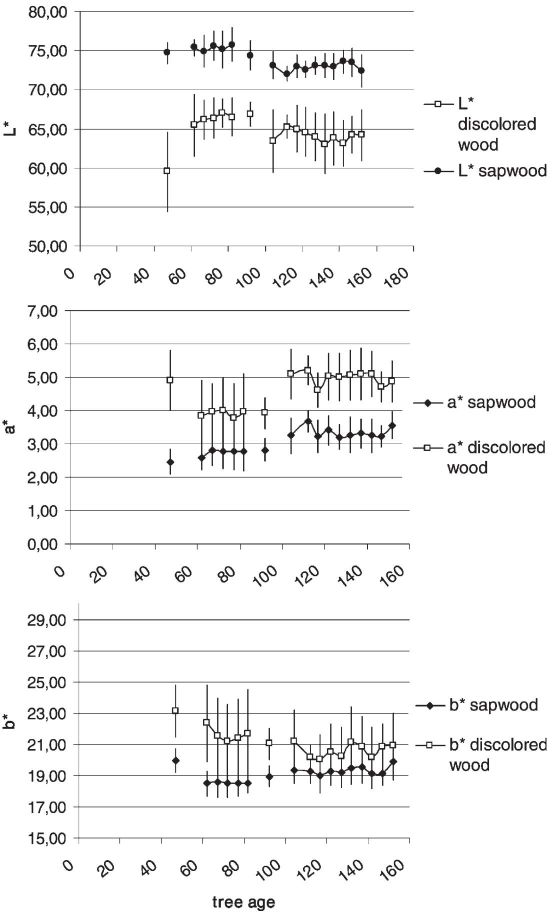

Figure 5. L*, a*, and b* color parameter in relation to tree age (average and standard deviation) for sapwood and discolored wood regions.

variables evaluated. The log effect was not as strong as the tree effect, but the results demonstrated that it was significant for some variables. Nevertheless, when the total random variability was considered, the between-boards variation (residual parameter) always had the highest score, a result that indicates there is less variation in board color between the different logs, trees, or stands compared with the variation between boards.

DISCUSSION

The results concerning the proportion of discolored wood in paper birch stems partly meet the initial hypothesis. As expected, tree diameter and tree vigor (MSCR) had a significant influence on this proportion, but tree age on the other hand was not strong enough to have a significant influence in the model.

Considering tree vigor, the higher proportion of discolored wood obtained in less vigorous trees is coherent with the theory of the traumatic

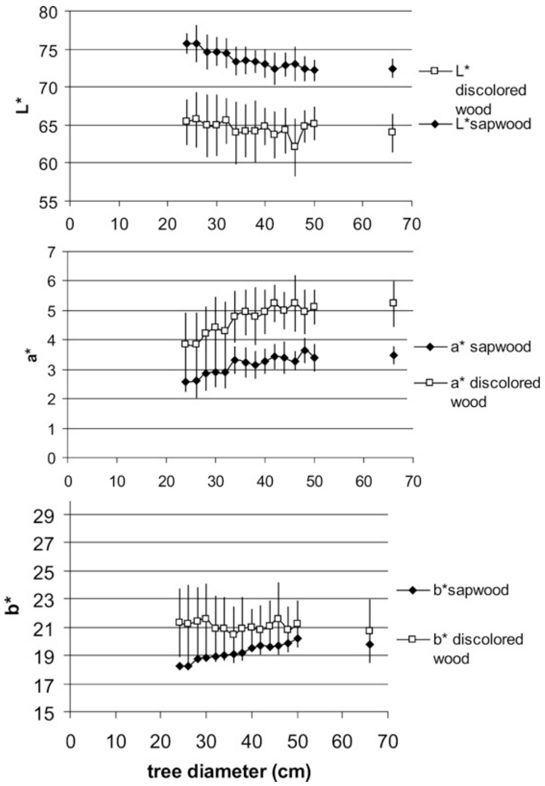

Figure 6. L*, a*, and b* color parameter function of tree diameter (average and standard deviation) for sapwood and discolored wood regions.

Table 3. *Covariance parameter estimates for the percentage of discolored wood per board.*

	Percentage of discolored wood		
Covariance parameters	Estimate	Percent	Pr > Z
Stand	0.008926	5.78	0.2731
Tree	0.02493	16.14	<0.0001[a]
Log	0	0	—
Residual	0.1206	78.08	<0.0001[a]

[a] $p < 0.05$.

Table 4. *Covariance parameter estimates for sapwood and discolored wood colorimetric values.*

	L* sapwood			a* sapwood			b* sapwood		
Covariance parameters	Estimate	Percent	Pr > Z	Estimate	Percent	Pr > Z	Estimate	Percent	Pr > Z
Stand	0.9868	24.24	0.2543	0	0	—	0.6329	43.75	0.2441
Tree	1.3830	33.98	<0.0001[a]	0.1154	46.36	<0.0001[a]	0.1824	12.61	<0.0001[a]
Log	0.0810	1.99	0.0148	0.001803	0.73	0.1949	0.1229	8.49	<0.0001[a]
Residual	1.6197	39.79	<0.0001[a]	0.1317	52.91	<0.0001[a]	0.5086	35.15	<0.0001[a]
	L* discolored wood			a* discolored wood			b* discolored wood		
	Estimate	Percent	Pr > Z	Estimate	Percent	Pr > Z	Estimate	Percent	Pr > Z
Stand	12.7113	55.81	0.2422	0.5866	46.27	0.2418	0.2064	4.15	0.2738
Tree	2.4269	10.66	<0.0001[a]	0.06393	5.04	<0.0001[a]	0.4651	9.34	<0.0001[a]
Log	0.4262	1.87	0.0060[a]	0.01885	1.49	0.0376[a]	0.02638	0.53	0.3207[a]
Residual	7.2113	31.66	<0.0001[a]	0.5983	47.20	<0.0001[a]	4.2794	85.98	<0.0001[a]

[a] $p < 0.05$.

origin of paper birch heartwood. The MSCR classification is based on the presence of external defects on the tree. Less vigorous trees show more external defects that provide a way for pathogenic organisms to colonize wood and create discoloration. Our findings support the same hypothesis that discoloration of paper birch is caused by microorganisms. As illustrated in Fig 7, the discolored board areas are usually linked to knots or wounds. Because the provincial silvicultural strategy has a priority in harvesting the less vigorous hardwood trees (M and S) to improve stand quality, it is expected that important proportions of discolored wood will prevail in the hardwood supply for the coming few decades until the overall hardwood quality improves in the stands of the province.

The pioneering and relatively short-lived nature of the paper birch species can help to explain the high frequency of discolored wood. In short-lived species, discoloration and decaying processes may be more rapid than that of long-lived species, and these trees are possibly more sensitive to wounding events and further attacks by microorganisms. Although broken branches are generally considered the main route for microbial colonization and discoloration, other stem wounds such as mechanical damage are also associated with discoloration in the stem. In this study, paper birch came from mixed stands, where conifers had been harvested in the past, leaving the birch. Mechanized partial-harvest operations may have inflicted wounds on the birch boles and led to discoloration. Therefore, special care to protect the residual trees during harvesting operations and other silvicultural treatments should be taken to limit the presence of discoloration in the ensuing boards.

The analysis of the effect of tree diameter on the proportion of discolored wood in boards determined that larger trees had more discoloration. As the tree diameter increases, so do the branches. Therefore, they constitute larger openings that are longer and more difficult for the tree to close and more easily penetrated by air and microorganisms. It can be hypothesized that growing conditions (eg high stand density) that increase self-pruning in young paper birch trees could be a solution to reduce the presence of discoloration in trees. If branches die when relatively small, processes inducing discoloration might be limited (Toole 1961; Eisner et al 2002).

Tree age did not have a significant effect on the proportion of red heart in paper birch boards. One could assume that because tree diameter had a significant influence, so would tree age. Moreover, the chance that trees are exposed to a wound stress causing discoloration would be greater as the trees age, but no such significant influence was demonstrated using this statistical model. However, the probability value is almost significant, and, when the proportion of discoloration per board is plotted against tree age in a simple regression, there is a clear significant

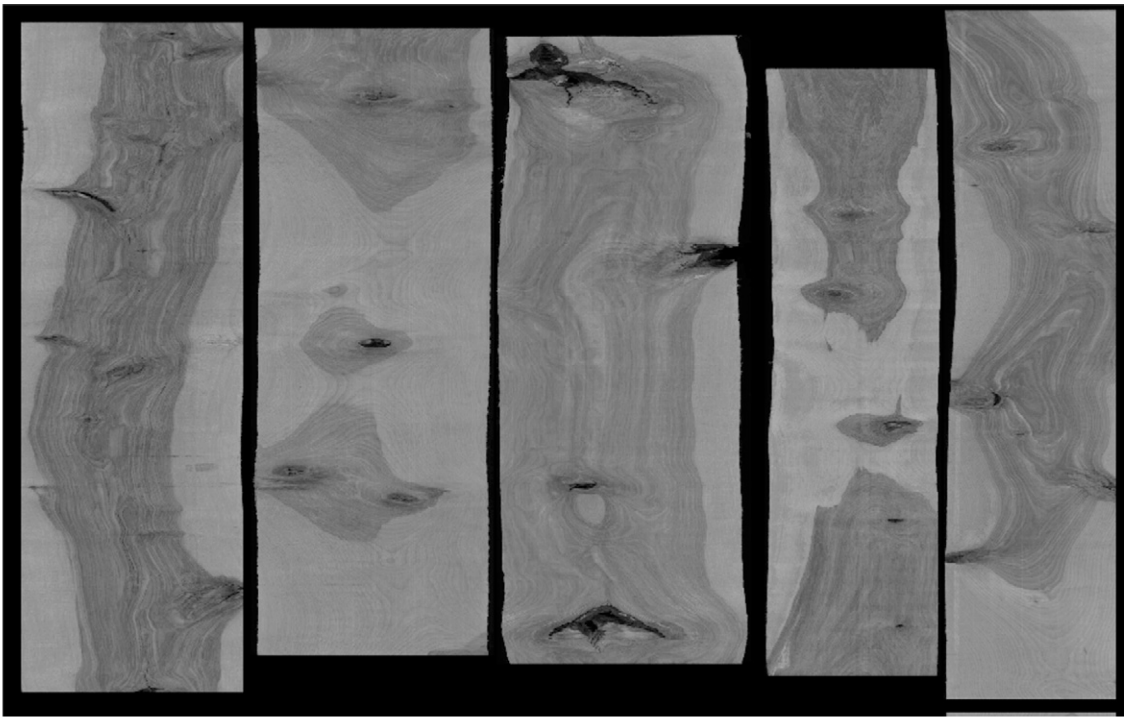

Figure 7. Digital images of boards showing the relationships between discolored wood and character marks where most of the time, knots and wounds are found in discolored wood regions.

effect of tree age on the proportion of discoloration ($p = 0.0001$) (Fig 8). This suggests that tree age has an indirect effect on the proportion of discolored wood in paper birch boards. The significant effect of tree age in simple regression is no longer significant in multiple regression, in which the model corrects the variance for the presence of tree diameter. In other words, tree age has an indirect effect on the proportion of discolored wood in boards through tree diameter. The correlation between tree age and diameter was assessed by a multicollinearity test (Belsey et al 1980) and these two variables were not found to be too highly correlated to be analyzed together in a mixed model.

In the literature, tree age is often mentioned as an important parameter influencing the proportion of discolored wood in trees (Campbell and Davidson 1941; Basham 1991; Hallaksela and Niemisto 1998; Giroud et al 2008).The fact that the present study considered both parameters

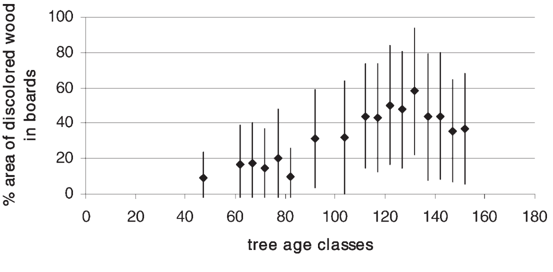

Figure 8. Percentage areas of discolored wood in boards in relation to tree age (average and standard deviation).

(age and diameter) in a multiple regression using a mixed model might explain the divergence in the results. Nevertheless, tree age can be considered a noteworthy factor influencing the proportion of red heart in trees.

Our findings that tree diameter and, to a lesser extent, tree age influenced the proportion of discolored wood in boards suggests that harvesting trees at a younger age or in shorter rotations will produce more homogeneously colored wood. In addition, the negative relationship between tree diametral growth rates and age, in which older trees tend to have smaller growth rates (Fig 4), is an important argument in favor of harvesting trees earlier to maintain good stand productivity.

Significant differences were found between L*, a*, and b* values of the sapwood and discolored wood zones (Table 1). Similar results were found for Scots pine wood by Grekin (2007) in which there were also significant differences in color parameters between sapwood and heartwood, although heartwood is not traumatic in this species.

The greater difference of luminosity (L*) between sapwood and discolored wood zones compared with the differences obtained for the chromatic values (a* and b*) highlight the importance of luminosity when characterizing the color of paper birch wood. The L* values give a fair and quick representation of the different possible colorations that can be seen on the boards. The a* and b* values on the other hand vary little between the different color zones and therefore are much less indicative of color changes. Consequently, this outcome can be useful for machine vision systems for wood. In applications in which it is important to discern sapwood and discolored wood zones, luminosity appears to be an interesting colorimetric parameter to use for paper birch wood.

In Table 1, the standard deviation of the colorimetric values was larger for discolored wood zones compared with sapwood zones. This can be explained in that paper birch sapwood is usually pale and homogeneous in color, whereas its discolored wood shows a more heterogeneous coloration with a higher variation in color and in the spatial distribution of these different shades (Fig 9).

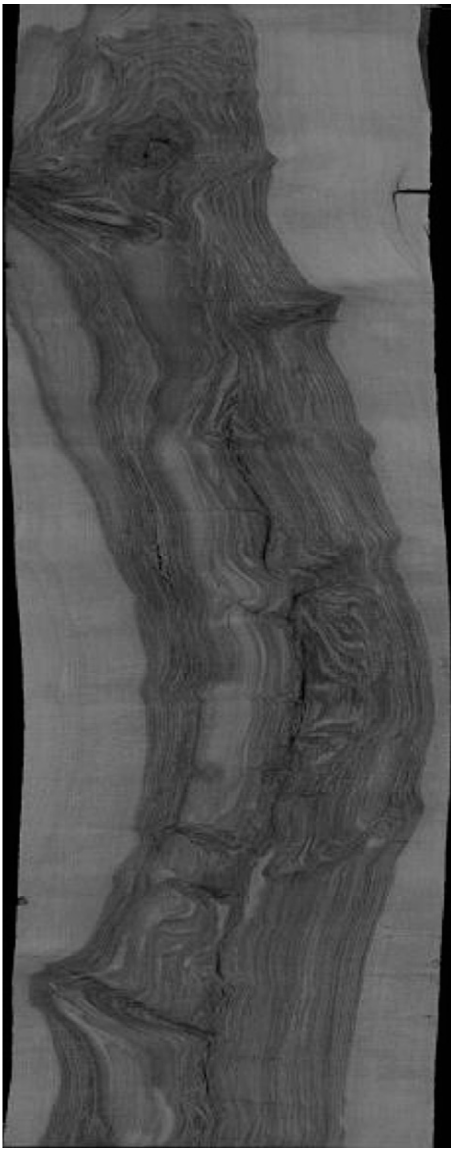

Figure 9. Example of a difference in color homogeneity between sapwood and discolored wood regions. Although sapwood is homogeneous in color, discolored wood presents different shades and creates a visual marble effect.

Overall, the most important variables affecting the colorimetric parameters were tree age and diameter. Tree vigor had no significant effect on any of the wood color parameters. In other words, a tree with more external defects might have more discolored wood, but the color of its sapwood and discolored wood would not be different from that of trees with fewer defects. On the other hand, tree age and diameter significantly affected wood color. However, as mentioned, the effect of tree age and tree diameter is not the same for every L*a*b* value. Alteration with time of the chemical compounds responsible for wood color could explain the effect of tree age on wood colorimetric parameters.

Finally, results regarding the variables considered as random factors in the statistical models are similar to what was proposed by Grekin (2007) for Scots pine wood color. In that study, the residual variation (between boards) was always the most important parameter followed by between-tree and between-stand variation (Grekin 2007). In the present study, the residual variation was also responsible for the highest proportion of the total random variation. The between-tree variation was, like with Scots pine, the second most important variable. Finally, contrary to Grekin's findings, stand did not induce significant effects on any of the variables considered for paper birch material. This difference can be explained by the number of sites considered. For the Scots pine study, a total of 60 sites were sampled compared with only two sites for the present study. Therefore, the uncertainty was too great to draw any conclusion on site effect.

CONCLUSIONS

This study shows that for the sawing-quality paper birch wood obtained from two stands in Québec, discolored wood had a considerable presence, although sapwood remained as a higher proportion of the board area (67.6%). Tree age and diameter had a significant influence on the colorimetric parameters L*a*b* of sapwood and discolored wood zones of paper birch wood, but their effect was variable among all those parameters. Tree diameter also influenced the proportion of discolored wood in the boards in addition to tree vigor (MSCR), whereas tree age did not. When considering the total random variation, the main source of variation in this hierarchical data came from the residual term, meaning that between-board color variation was always the greatest source of variation. The between-tree variation was significant for all dependent variables considered and between-log variation had a significant influence on some of these dependent variables to a lesser extent.

The present study gives a general picture of paper birch wood color. Greater knowledge of the sources of variation of its coloration will help develop control strategies. Silvicultural treatments that favor shorter rotations and self-pruning at young ages appear to be possible paths to limit the presence of discoloration in paper birch stems. On the other hand, the poor vigor of the hardwood forests and the current provincial MSCR selection system applied to improve stand quality will continue to cause a relatively high percentage of discolored wood for some time.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of Canada Economic Development (CED), Natural Sciences and Engineering Research Council of Canada (NSERC), Le Fonds de Recherche sur la Nature et les Technologies Québec (FQRNT), and FPInnovations–Forintek Division and Québec Ministry of Natural Resources and Wildlife. Thanks are extended to Centre de Recherche Industrielle du Québec (CRIQ) for their technical support and to Mr. Gaétan Daigle for statistical guidance.

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