EFFECTS OF LOG POSITION IN THE STEM AND CUTTING WIDTH ON SIZE DISTRIBUTION OF BLACK SPRUCE CHIPS PRODUCED BY A CHIPPER-CANTER

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Abstract. Fifteen stems of black spruce (*Picea mariana* (Mill.) BSP) coming from the Abitibi-Témiscamingue region in Canada were crosscut into three sections: bottom, middle, and top logs. Logs were fragmented producing three faces with a chipper-canter using three cutting widths (CWs) of 12.7, 19.1, and 25.4 mm. Chip dimensions were assessed by thickness, width, and length (Domtar and Williams classifications). Knot characteristics (total knot number [TKN] and area [TKA]) were assessed in the three cant faces. Growth ring attributes (earlywood density, latewood density [LWD], ring density, earlywood proportion, ring width, and rings per mm [R/mm]), mechanical properties (shear, splitting, modulus of elasticity (MOE), and modulus of rupture (MOR) in bending), and basic density were evaluated on samples obtained within each CW area. The results showed that most of these wood attributes were affected by the log position in the stem and/or CW. Weighted mean chip thickness (WCT) and chip size distributions were significantly affected by log position and CW. WCT increased as CW increased. WCT variation with height could be principally associated with number and size of knots within the stem. However, greater taper in the bottom logs produced thicker chips. Multiple linear regressions showed that CW, TKN, LWD, and TKA were significant predictors of WCT. Also, chip thickness distribution was affected primarily by TKA, cutting height, and LWD, whereas the width and length distribution was mainly affected by R/mm, TKN, and MOE. Chip size variation was to some point determined by knot characteristics, bending properties, growth ring width, and wood density of the raw material. Results showed the potential benefits of classifying logs in wood yards and better controlling the raw material attributes in sawmills. If CW is combined with knowledge of the raw material, chip dimensions can be adjusted using other fragmentation parameters to increase chip size uniformity.

Keywords: Log sampling position in the stem, cutting width, chip size distribution, chipper canter, black spruce.

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INTRODUCTION

In 2013, production in the forest industry contributed $19.8 billion to the Canadian economy, of which the pulp and paper sector accounted for about 36% (NRCAN 2014). Actually, the Quebec Province holds 32% of Canadian production in this sector, taking the lead over the other provinces (MFFP 2014). Furthermore, sawmills are the principal suppliers of wood raw material for the pulp and paper industry (62.5%), providing 51% exclusively in the form of wood chips (MRNF 2013).

Wood chips in sawmills are mostly produced by chipper canters. This machine processes essentially small-diameter softwood logs to produce both lumber and chips in the same operation. These chips come particularly from balsam fir, spruces, jack pine, and larch logs (MRNF 2013). Within these species, black spruce (*Picea mariana* (Mill.) BSP) is suitable for the production of various types of pulps, including mechanical and chemical pulps (Zhang and Koubaa 2009).

In recent years, the development of wood manufacturing optimization systems has been crucial for the forest products industry. To maximize the value from an individual tree, the manufacturing processes should be based on both external stem geometry and internal wood characteristics and properties.

Chips are the principal by-product of sawmill operations that have to meet the quality standards of the pulp and paper industry. Raw material characteristics are crucial for chip quality (McGovern 1979) as for any other wood products. Thus, their variation will considerably affect pulp properties and yield (Svedman et al 1998; Ding et al 2009). Wood density is often used as an indicator of wood quality, and it influences, to a certain extent, the forces produced during fragmentation and chip formation. The within-tree variation in wood density includes radial variation within the stem from pith to bark, intraring variation, and axial variation from the base to the top of the tree (Zobel and van Buijtenen 1989). Ring density (RD) in black spruce decreases in the first year and then increases slowly toward the bark (Alteyrac et al 2005). RD is negatively correlated with ring width (RW), although this effect appears to diminish in mature wood (MW) (Koubaa et al 2000). Furthermore, for a given cambial age, RW and RD characteristics decrease with height in MW. This was associated with the cambium aging process. Tree aging could lower cambium activity, inducing a decreasing fiber yield with time and narrower rings (Alteyrac et al 2005). Conversely, analysis of axial variation in the same calendar years of growth period (same number of rings from the bark) has received little attention. The chipper canter normally cuts the external part of a log. Therefore, the processed volume along the log (or stem) corresponds more with wood that grew during similar calendar years. Jyske et al (2008) found that RW and earlywood proportion (EWP) increased while RD decreased from the base to the top of the stem for the same calendar-year period in Norway spruce. Also, axial and radial variation in a tree will inherently affect the size and number of knots (Lemieux et al 2001). Knots are considered defects for most wood processes and applications, namely timber, veneer, and wood-based products as well as pulp (Buksnowitz et al 2010). Accordingly, it is expected that chip formation in a log will be directly influenced by knot characteristics.

Distribution and uniformity of chip dimensions is one of the main attributes in chip quality. However, dimensions of wood chips produced at sawmills are not inherently homogeneous, leading to material that is not adequate for pulping purposes and is destined for less profitable uses, such as fuel. Consequently, a gain in understanding of wood characteristics at the tree level will contribute to the optimization of chip production by improving chip size distribution.

Chipper canter manufacturing parameters, such as feed speed, cutting speed, cutting angles, types of knives, as well as log temperature and diameter will also affect chip size (Hernández and Quirion 1993; Hernández and Boulanger 1997). Cutting width (CW) also has a considerable effect on chip size. Thus, a decrease in CW would produce a decrease in chip thickness (Hernández and Lessard 1997; Cáceres et al 2015). This behavior could be influenced by variation in wood attributes, such as ring growth, RD, knot characteristics, basic density (BD), as well as the mechanical properties involved in fragmentation, namely static bending, shear, and splitting. The mechanical properties of wood are different in the axial, radial, and tangential planes. Consequently when a chipper knife passes through a log, the forces are not equally transferred in all directions. As a result, chip dimensions (thickness and width) have a distribution around a statistical mean value (Smith and Javid 1992).

The optimal chip dimensions required to obtain homogeneous pulping have been widely studied, differing depending on the pulping process and equipment available (Galloway and Thomas 1972; Hartler and Stade 1979; Christie 1986). There is a trend toward more focus on the thickness measurement of chips. The control of thickness in chips is important in various pulping processes including mechanical pulping (Hoekstra et al 1983), refiner mechanical pulping, chemimechanical pulping (Lönnberg and Robertsén 1986), sulfite pulping (Feiner and Gallay 1962), and Kraft pulping (Hatton and Keays 1973; Olson et al 1980; Tikka et al 1993). In recent years, dimensional consistency of the chips has also become a concern (Wood 1996; Hedenberg 2001; Bjurulf 2005). Broderick et al (1998) suggested that a greater uniformity in chip feed can compensate for chips of inadequate nominal size and that chip geometry (all three dimensions of the chip) could be more significant than a single chip dimension in sulfite pulping. The degree of chip size homogeneity is also an important factor in the thermomechanical pulping process (Brill 1985). Consequently, chip dimension consistency with time could be achieved by taking into account various parameters, namely wood species, provenance, optimization at the tree level, season, and chipping process. In this respect, segregation of raw material has already been suggested as an option for producing pulps for different paper technical specifications (Svedman et al 1998).

In this context, the aim of this study was to relate position of the log within the stem (axial variation) and CW (radial variation) to the variation in size of black spruce chips produced by a chipper canter. More precisely, this work also considered the influence of growth ring and knot characteristics, mechanical properties, and BD on chip formation.

MATERIALS AND METHODS

Study Area and Samples

The material for this study was obtained from the Abitibi-Témiscamingue region of Quebec Province, more specifically in the township of Bacon (49°24′31″ N and 78°39′42″ W). The stand was even-aged ranging from 81 to 90 yr and originated from a forest fire. In the spring of 2012, 15 trees of black spruce were cut down. The selected trees were straight and without obvious decay. Tree diameter at breast height ranged from 181 to 195 mm, and tree height ranged from 16 to 20 m. Three logs approximately 2.5 m long were obtained from each stem by crosscutting it at its bottom (beginning at 0.5 m from the ground), at the middle (3 m into the stem), and at the top (5.5 m into the stem). The smaller end diameter was fixed approximately at 130 mm. Log characteristics are described in Table 1. All logs were debarked at Kruger sawmill in Saint-Roch-de-Mékinac and then stored at −5°C in a freezer until the beginning of the tests.

Fragmentation Process

Fragmentation was made with a DK-SPEC (Quebec, Canada) cutterhead mounted on a laboratory prototype chipper canter. The cutterhead

Table 1. Characteristics of black spruce logs.

	Log position in stem		
Log characteristics	Bottom	Middle	Top
Large end (mm)	216 (5.3)[a]	170 (4.4)	152 (5.8)
Small end (mm)	170 (4.5)	152 (5.5)	132 (7.9)
Taper (mm/m)	19 (15.6)	8 (14.4)	9 (15.1)
Cambial age[b] (number of rings from pith to bark)	86 (3.3)	70 (4.7)	61 (5.7)

[a] The number in parentheses is variation coefficient (%).

[b] Measured at large end of log.

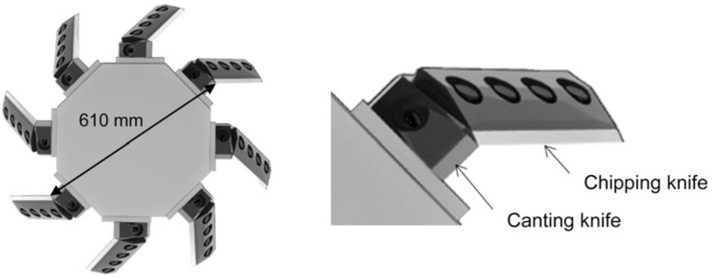

Figure 1. DK-SPEC cutterhead provided with eight sets of double knives.

was fitted with eight sets of double knives that were joined at an angle; the longer, or chipping, knife served to cut the slice to make chips and the smaller, or canting, knife smoothed the surface of the cant. The chipping knife had an angle of 30° and a rake angle of 49°. The cutterhead was 610 mm in diameter, measured from one knife joint to the opposite one (Fig 1). The distance from the cutterhead rotation center to the bedplate was approximately 178 mm.

Fragmentation tests were done with green logs with an average temperature of 15°C. The logs were always fed into the chipper canter by the small end first. The chipper canter makes the primary breakdown of small-diameter logs by chipping the sides with a certain width and producing a cant in the same operation (Hernández and Boulanger 1997; Hernández and Lessard 1997). Thus, three CWs were selected based on the small-end diameter to have three entire segment fragmentations in the log. The CW were 12.7, 19.1, and 25.4 mm (Fig 2a). In contrast to what happens in normal operations of a chipper canter in which the cant width is fixed along the log, in this study, the interest was set in the CW, which is essentially the section of the log that will be transformed into chips. Therefore, CW was kept constant throughout the log to diminish the influence of log taper and cutting height (CH) on chip fragmentation. The alignment of CW along the log was made using a laser beam installed over the log carriage of the chipper canter. It was then adjusted by measuring its actual value every 200 mm along the log until obtaining a mean value corresponding to the selected CW. This allowed CW to be adjusted with the natural form of the log.

Rotation and feed speeds were 726 rpm and 145 m/min, which gave a nominal chip length of 25 mm. Thus, nominal linear cutting speed was 23.2 m/s calculated at 610 mm of cutting diameter. The fragmentation process of each log started at 19.1 mm of CW. Subsequently, the log was turned 90° and fragmented at 12.7 mm of CW and finally at 25.4 mm of CW. To have a similar log infeed of the knife for each CW, the depth of the previously removed chipped segment was replaced by placing a board of the same thickness (19.1 or 12.7 mm) under the log before chipping the next condition. The logs were fixed

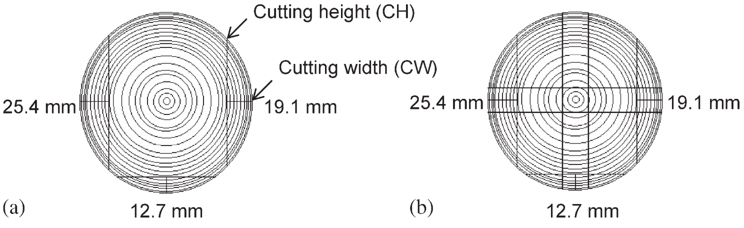

Figure 2. (a) CW and CH at the small end of the log. CH draws the segment area that will be fragmented. (b) Strip positions obtained according to CW at the large and small ends of each log.

in the log carriage with five hydraulic arms ending with picks. The three-sided cant obtained was immediately wrapped in polyethylene to maintain its initial MC. After each fragmentation, all chips were collected and placed in plastic bags and the chipper canter was carefully cleaned.

Chip Screening

The chips and cants obtained were stored at −5°C to keep a constant MC until measurement. Chips were weighed to the nearest 0.001 kg. A chip sample of approximately 2 kg was taken from each cutting condition using a Domtar (Montreal, Canada) chip separator. The chips were then screened using a Domtar chip classifier, which separates chips according to both thickness and length (Lapointe 1979). Several studies have confirmed thickness as the most suitable criterion to evaluate chip size distribution (Hoekstra et al 1983; Tikka et al 1993; Agarwal et al 1994; Tikka and Tähkänen 1994). The Domtar classifier retained the following chip classes: fines (material that passed a 4.5-mm-diameter screen hole), fragile chips (chips less than 2 mm thick, minus fines), accepts chips (chips from 2 to 4, 4 to 6, and 6 to 8 mm thick), overthick chips (chips greater than 8 mm thick by 2 mm classes up to 18 mm), and oversized chips (the fraction retained by the 45-mm-diameter screen hole). This size distribution was used to calculate the weighted mean chip thickness (WCT) statistic (Hernández and Boulanger 1997; Hernández and Lessard 1997). Then, chips were screened with a LabTech (Tampa, FL) classifier (similar to the Williams classifier), which sorts chips by width and length and is more efficient in separating the smallest chip classes. The LabTech classifier retained the following chip classes: fines (material that passed a 4.8-mm-diameter screen hole), pin chips (material retained in a 4.8-mm-diameter screen hole), 9.5-mm chips (chips retained in a 9.5-mm-diameter screen hole), accepts chips (chips retained in screens of 15.9, 22.2, and 28.6 mm of hole diameter), and oversized chips (the fraction retained by the 45-mm-diameter screen hole). This classifier is more often used in the Canadian sawmill industry. The chip classes obtained with both classifiers follow the quality standards required by the pulp and paper industries. Sawmills aim to maximize the chip volume of the accepts class and minimize the volume of the other classes. The overthick class (from Domtar) and the 9.5-mm class (from Williams) have a threshold of 20% of the total chip volume. This threshold may change from one industry to another. The chip size classification used at sawmills is established by the pulp and paper industries and it depends on the pulping process.

Growth Ring Characteristics

Before fragmentation, one 50-mm-thick (L) disk was crosscut from both ends of each log for growth ring measurements. Thus, growth ring properties measured for each log corresponded to an average of the small and large end values of each log. The CW position was carefully marked down in each disk. Disks were dried in a conditioned chamber at constant temperature (21°C) by gradually decreasing the RH (90%, 85%, and 60% RH) until reaching an EMC of about 12%. The disks were then cut following the CW positions into 30-mm-wide sections and finally trimmed into 1.57-mm-thick (L) strips (Fig 2b). The strips were then scanned to analyze the images with WinDendro LA 1600+ software (Regent Instruments Inc., Quebec, Canada). The number and width of the growth rings from pith to bark were recorded. The strips were also scanned from bark to pith with an X-ray densitometer. No extraction was made in the samples before scanning because the extractive content of black spruce wood is known to be low (3.8%; Lohrasebi et al 1999). Measurements were taken at the position corresponding to each CW. The following variables were determined: earlywood density (EWD), latewood density (LWD), RD, EWP, RW, and rings per millimeter (R/mm). Mean values for 12.7, 19.1, and 25.4 mm, measured from the bark toward the pith, were calculated to correspond with the studied CW. Data of growth characteristics could hence be accurately related to the studied CW.

Knot Characterization

Cáceres et al (2015) suggested that knot size could influence chip size distribution. Consequently, knot characterization was done after log fragmentation. All knots greater than 2 mm were counted and measured like an ellipse (larger and smaller diameters) on each face of the three-sided cant. Each side corresponded to the face obtained after chipping at 12.7, 19.1, or 25.4 mm of CW. The total knot number (TKN) and total knot area (TKA) of each cant face were then calculated and associated with each CW.

Mechanical Tests

The three-sided cant was used to obtain samples for the mechanical tests. Each cant was crosscut into three sections to facilitate its handling during sample preparation (Fig 3). Each section was then cut longitudinally at the pith level using a band saw, obtaining three segments from each cant. Samples for mechanical properties were obtained by sawing each segment into three parts, each part corresponding to the preparation of one type of sample (static bending, splitting, and shear samples). Thus, three adjacent samples (a, b, and c) 8 mm thick were obtained as close to the bark as possible. Hence, the results could be associated with each CW studied. For a CW of 12.7 mm, the result of sample a was considered; for 19.1 mm, the result was the mean of samples a and b; and finally for 25.4 mm, the result was the mean of samples a, b, and c (Fig 3). Samples had the growth rings oriented parallel to the tangential surface and were clear of defects. Nine samples from each cant were obtained for each mechanical test, giving a total of 405 samples for static bending, splitting, and shear tests, respectively. All samples were handled carefully to maintain their initial MC and stored at −18°C until the beginning of the mechanical tests.

The mechanical tests were performed on a universal testing machine equipped with a 5-kN load cell, following ASTM (1997). Minor adaptations of the sample dimensions and test speeds were made to relate the mechanical properties to the chipping process. All samples were defrosted over distilled water in a conditioned room 1 da before testing.

The static bending test was performed to calculate MOR and MOE. Specimens had a cross section of 8 (R) × 8 mm (T) and a length of 140 mm (L). Both the upper support, which carried the load, and the two lower supports had a radius of 15 mm. Span length was 112 mm. Load was applied at a crosshead rate of 30 mm/min until complete failure.

The splitting test was performed following the radial–longitudinal failure plane. Specimens had a cross section of 8 (R) × 50 mm (T) and a length of 45 mm (L). To distribute the forces

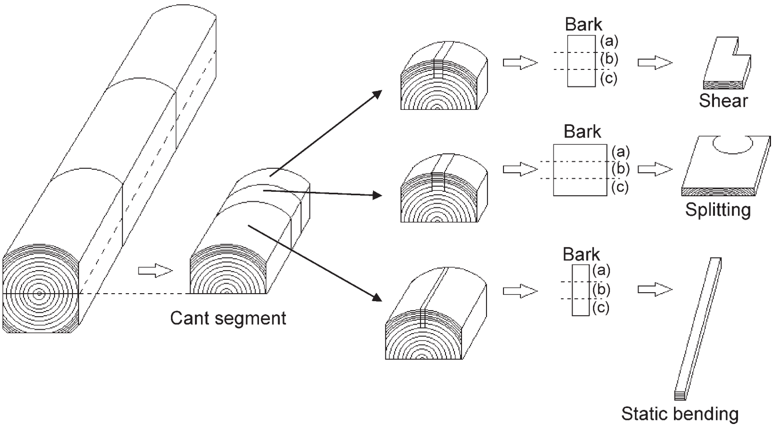

Figure 3. Sample distribution for static bending, splitting, and shear tests.

equally, the samples were fixed in the center of jaws before loading. Load was applied at a rate of 5.0 mm/min until complete failure.

Shear strength test parallel to the grain was carried out in the radial–longitudinal failure plane. Specimens had a cross section of 8 (R) × 25 mm (T) and a length of 35 mm (L). Load was applied at a rate of 5.0 mm/min until complete failure.

Immediately after each mechanical test, green volume of each sample was measured by immersion in water. The samples were then oven-dried at 103°C for 24 h to obtain their oven-dry weight. MC and BD (oven-dry mass divided by green volume) were calculated.

Statistical Analyses

Data were analyzed using the Statistical Analysis System (SAS) 9.3 software (SAS Institute Inc., Cary, NC). Raw data were first evaluated with the Box–Cox method showing the more fitted transformation if required. Data structure followed a split-plot design with log position in the stem (LPS) as the main plot and CW as the subplot. A mixed model of analysis of variance (ANOVA) was used to evaluate the variation in WCT. Growth ring and knot characteristics and mechanical and physical properties were analyzed following the same data structure. Afterward, a stepwise multiple linear regression was performed to determine if the explanatory variables (growth ring and knot characteristics and mechanical and physical properties) were good predictors of WCT. A multivariate analysis of variance (MANOVA) was performed using the Aitchison approach of compositional data (Aitchison 1982) for the Domtar and Williams chip class distributions. Growth ring and knot characteristics and mechanical and physical properties were used as covariates, keeping only the ones that were significant for the model. This approach uses one of the chip classes as a reference and works with the proportion of each of the other classes as a function of the reference. Hence, compositional data analysis takes into account the existing dependence among the classes as they function as a whole, and therefore, when one class increases, another has to decrease to maintain the same whole. However, compositional data analysis does not allow comparison of the real values of each class because it works with proportions. Consequently, an ANOVA of each class was done individually. Finally, the normality was verified with Shapiro–Wilk's test, the homogeneity of variance was verified with the graphical analysis of residuals, and the collinearity was verified with the variance inflation factor and the condition index.

RESULTS AND DISCUSSION

Growth Ring and Knot Characteristics, BD, and Mechanical Properties

The wood characteristics and properties presented in this study were examined with the purpose of better understanding the variation on chip size. As previously explained, CW was measured radially from the bark inward at the ends of each log. This determined the log segment that was transformed into chips (Fig 2). Therefore, the radial increase in CW from 12.7 to 19.1 mm and to 25.4 mm implies that the 19.1-mm CW included the 12.7-mm CW and that the 25.4-mm CW included the 19.1-mm CW. Therefore, the wood characteristics and properties data obtained for the 12.7-mm CW were a subset of the 19.1-mm CW, which was a subset of the 25.4-mm CW. The LPS in terms of height was established at the middle of each log. Therefore, the relative height was 1.8 m for the bottom log, 4.3 m for the middle log, and 6.8 m for the top log.

Growth ring characteristics varied more strongly by height position than by CW. Thus, ANOVAs showed that LWD, EWP, RW, and R/mm were significantly affected by LPS (Table 2). Alteyrac et al (2005) found that growth ring features varied strongly with height in black spruce, although the magnitude of the variation depended on the type of wood: juvenile wood (JW) or MW. The JW/MW transition appeared at about the 20th ring at heights of 2.5 and 5.1 m and even earlier at a height of 7.8 m. On the basis of the criteria previously described, for the largest

Table 2. F-values obtained from ANOVAs of the effects of LPS and CW on the WCT, growth ring and knot characteristics, and wood properties of black spruce logs.

Source of variation	WCT	EWD	LWD	RD	EWP	RW	R/mm	TKN	TKA	BD	Shear	Splitting	MOE	MOR
LPS	3.46*	0.46 ns	3.49*	1.03 ns	39.13**	6.58**	5.92**	4.99*	46.52**	9.65**	7.40**	12.63**	5.32*	5.10*
CW	82.99**	0.15 ns	0.08 ns	1.43 ns	2.05 ns	3.56*	5.19**	19.29**	16.01**	25.76**	1.86 ns	65.73**	5.46**	5.07**
LPS × CW	2.21 ns	0.89 ns	0.89 ns	2.17 ns	2.02 ns	1.12 ns	1.30 ns	0.53 ns	1.62 ns	1.93 ns	2.99*	0.24 ns	2.30 ns	1.81 ns

WCT, weighted mean chip thickness; EWD, earlywood density; LWD, latewood density; RD, ring density; EWP, earlywood proportion; RW, ring width; R/mm, rings per mm; TKN, total knot number; TKA, total knot area; BD, basic density; MOE, modulus of elasticity; MOR, modulus of rupture; LPS, log position in the stem; CW, cutting width; ns, not significant.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

CW (25.4 mm), the average number of rings involved in the fragmentation process reached 34 (number of rings from the bark), which combined with the cambial age (number of rings from pith to bark), established that the fragmented sides, at all heights, belonged to the MW part of the logs (Tables 1 and 3).

In this study, focus was put on the external part of the log, from which chips are produced. Therefore, growth ring characteristics at different heights were not assessed at the same cambial age as is usual in wood quality studies (Alteyrac et al 2005; Xiang et al 2014). For instance, the growth ring data analyzed for the largest CW (25.4 mm) corresponded to the rings between the 54th and the 86th (cambial age) in the bottom log, between the 36th and the 70th in the middle log, and between the 27th and the 61st in the top log. Data for each CW for all LPS corresponded to a comparable calendar-year period (number of rings from the bark). To our knowledge, there are no studies for black spruce using this approach.

According to Table 3, LWD and EWP were significantly different between the bottom and top logs, increasing their values from a relative height of 1.8 m toward 6.8 m. Although LWD increased with sampling height, RD remained similar given that, at the same time, EWP increased. EWD also remained similar for the three sampling heights. As a result, growth rings became more heterogeneous in terms of density as sampling height increased. The LWD/EWD ratio increased from 1.61 to 1.65 as sampling height increased from 1.8 to 6.8 m. Jyske et al (2008) reported similar results in Norway spruce for rings formed during the same calendar-year period. The authors found that EWP increased from the base toward the top of the tree. However, LWD was highly variable between heights; thus, no trend could be established. RW in black spruce showed a negative correlation with LPS. Hence, narrower rings were present toward the top of the stem. Conversely, RW in Norway spruce increased along the stem. This particular information would be very interesting especially for the mechanical pulping processes, for which

Table 3. Growth ring and knot characteristics and wood properties of black spruce by LPS and CW.

Growth ring and knot characteristics and wood properties	LPS[a]			CW[b] (mm)		
	Bottom	Middle	Top	12.7	19.1	25.4
EWD[c] (kg/m^3)	432 A[d]	435 A	436 A	433 A	435 A	435 A
LWD (kg/m^3)	698 B	720 A	717 A	712 A	711 A	712 A
RD (kg/m^3)	552 A	550 A	543 A	546 A	551 A	549 A
EWP (%)	54 C	59 B	61 A	59 A	57 A	58 A
RW (mm)	0.84 A	0.74 B	0.76 B	0.77 B	0.76 B	0.81 A
R/mm	1.31 B	1.46 A	1.41 A	1.47 A	1.40 AB	1.32 B
TKN	27 A	27 A	32 B	24 A	28 B	35 C
TKA (mm^2)	478 A	781 B	1156 C	615 A	756 B	1044 C
BD (kg/m^3)	469 A	454 B	448 B	461 A	459 A	452 B
Shear (MPa)	6.7 A	6.5 AB	6.3 B	6.5 A	6.5 A	6.5 A
Splitting (N/mm)	19.8 A	17.5 B	17.2 B	18.9 A	18.2 B	17.3 C
MOE (MPa)	8157 A	8195 A	7798 B	8111 A	8069 A	7970 B
MOR (MPa)	62.9 A	60.7 B	59.9 B	61.1 B	61.6 A	60.8 B

[a] Log sampling position pooled.

[b] Cutting width pooled.

[c] See footnote of Table 2.

[d] Means within a row followed by the same letter are not significantly different at the 5 percent probability level, for each log position and cutting width separately.

intra-ring density variation and LW/EW proportion are very important, because latewood and earlywood fibers behave differently in the refining process (Rudie et al 1994).

Differences in growth ring characteristics among the three CWs were less noticeable. There was no significant radial variation among RD features. Only RW and R/mm were significantly affected by CW (Table 2). The multiple comparison tests showed that RW significantly increased and R/mm decreased as CW increased (Table 3). This is consistent with other studies (Alteyrac et al 2005; Xiang et al 2014; Cáceres et al 2015) that established that RW increased from bark to pith in black spruce. These results were obtained although growth ring data for 12.7 and 19.1 mm of CW were nested within data for 25.4 mm of CW.

Knot characteristics such as TKN and TKA were significantly affected by LPS and CW (Tables 2 and 3). Actually, the increase in CW (from the bark inward) generated an increase in the cant surface (Fig 2), which increased the number of visible knots in the cant face, as well as their area. Individual knot diameter was about 5 mm, but larger knots could measure up to 30 mm in diameter.

Knots are the internal continuation of branches in a tree. Therefore, their size and distribution in a stem are directly determined by branchiness (Lemieux et al 2001). Colin and Houllier (1991, 1992) studied branchiness in Norway spruce and reported that branch diameter increased from the top of the tree until the maximum lateral extension of the crown and then decreased toward the base of the tree. In fact, in the lower part of the tree, branches belong to the part of the crown where sunlight exposure is very restricted causing their growth to be nearly stopped, and near the ground, the branches are dead. This is in accordance with our results, in which the number and size of knots significantly increased from the base to the top of the stem. Also, the individual knot area (TKA divided by TKN) was about 18 mm^2 in the bottom log, 29 mm^2 in the middle log, and 36 mm^2 in the top log (Table 3).

BD is the single most important physical property of wood because most mechanical properties are closely correlated with this parameter. Wood density varies greatly because of a number of factors, such as location in a tree, geographic location (altitude and latitude), site condition (soil, water, and slope), and genetic source (Shmulsky and Jones 2011). Zhang and Koubaa (2009) summarized average wood density values reported for black spruce grown in North America between 363 and 455 kg/m^3. Previous work on black spruce chip quality reported mean basic densities of 434 (Hernández and Lessard 1997), 430, and 398 kg/m^3 (Cáceres et al 2015). This study showed a mean BD of 457 kg/m^3, indicating that this particular studied material belongs in the higher density range for this species. This variation in BD will have an important effect on the specific wood consumption of a pulp mill. For the same amount of pulp, lower wood consumption will be achieved with a volume of wood chips coming from higher BD wood in comparison with wood chips coming from lower BD wood (Svedman et al 1998). Also, high density variants within a species generally give better pulp quality; although when evaluating pulping potential among species, low density varieties are preferred (Rudie et al 1994). Heger (1974) reported that specific gravity variation along the stem in black spruce trees described a symmetric parabolic pattern, with higher density at the bottom of the tree and then decreasing to its lowest point at the middle of the tree and slowly increasing toward the tree apex. Similar results have been found in this study in which BD significantly decreased from the bottom of the stem upward, until approximately the middle of the tree, namely the top log. This behavior could be associated with the latewood proportion variation with height (Table 3). Thus wood density has been proven to be directly related to latewood proportion in conifers (Zobel and van Buijtenen 1989; Saranpää 2003). Also, BD significantly decreased as CW increased, which is in agreement with the radial variation in BD reported in our previous study (Cáceres et al 2015). Mechanical pulping processes present a great sensitivity to wood species and wood density variation, which has forced mechanical pulp mills to exert significantly more interest and control over their wood supply than the average kraft mills (Rudie et al 1994).

The mechanical properties studied were the ones potentially implicated in chip formation. According to Table 2, LPS and CW had a significant effect on mechanical properties (Table 2). In general, mechanical properties decreased with increase of both CW and sampling height (Table 3). The effect of CW is consistent with the results obtained by Cáceres et al (2015). Axial variation in mechanical properties has been little studied; therefore, comparisons could not be made.

Weighted Mean Chip Thickness

The chip thickness distribution has a form similar to the normal curve, and it can be described by a weighted mean thickness statistic. This factor takes into account all 2-mm-thick groups, and it is a useful tool to describe changes in the chip size distribution as a whole. WCT was calculated for each cutting condition by using the median value for each 2-mm thickness class (from 0 to 18 mm). The desired mean chip thickness was 5 mm, which is the median value of the accepts class, established between 2 and 8 mm.

ANOVA showed that WCT was strongly affected by CW and weakly affected by LPS (Table 2). WCT increased as CW increased. An increase in CW from 12.7 to 19.1 to 25.4 mm increased the mean chip thickness from 4.79 to 5.18 to 5.44 mm, respectively. Thus, the mean chip thickness obtained from each CW remained close to the target value of 5 mm for all LPS (Fig 4a). For a small CW, the thickness of the slice cut by each chipping knife is small as well. Thus, the strength required to chip formation or rupture will be reached more regularly producing thinner chips. Conversely, a greater CW will produce thicker chips. This is consistent with the results of previous studies, which established CW as one of the main parameters to adjust chip thickness (Hernández and Lessard 1997; Cáceres et al 2015). Nevertheless, previous studies have also reported other fragmentation parameters that affect WCT (Hernández and Quirion 1993; Hernández and Boulanger 1997). Although the interaction, LPS × CW, was not statistically significant, Fig 4a shows that WCT variation with CW in the bottom log could be different from the middle and top logs, which both presented similar behavior. This suggests that the log at the bottom had some particularities compared with the rest of the stem. Taper and several growth ring and knot characteristics and wood properties appeared to be different in the bottom log (Tables 1 and 3).

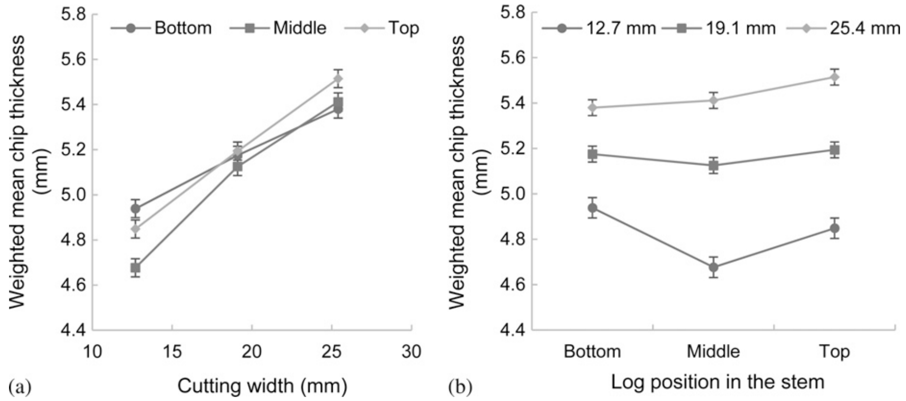

Figure 4. (a) WCT as a function of CW for each position in the stem. (b) WCT as a function of LPS for each CW.

WCT variation with respect to log sampling height was much lower than with CW (Fig 4b). Chips had the same thickness in the bottom and top logs (5.18 and 5.17 mm, respectively, CW pooled) and were thinner in the middle log (5.06 mm, CW pooled). As will be subsequently explained, knot characteristics had a very important role in explaining WCT and chip size distributions (multiple regression analysis; Tables 4 and 5). Chip thickness increase from the middle log toward the top log is associated with the increase of TKN and TKA with height (Table 3). However, it does not explain why the bottom logs produced thicker chips. On the basis of the analysis of the bottom log attributes, their greater taper (Table 1) appeared to positively affect WCT. Taper directly affected the variation in CH between the two ends of the log. Hence, the height from the entrance position of the chipping knife to the bedplate varied between the small and big ends of the log. This height variation was greater in the bottom logs because of their greater taper (30 mm on average compared with 13 mm for the middle and top logs). According to Kuljich et al (2015), WCT increased as this height increased. Therefore, compared with other logs, bottom logs produced thicker chips because they were processed closer to the center of the cutterhead.

Table 4. F-values obtained from compositional data MANOVA of Domtar and Williams chip class distributions.

Source of variation	Domtar chip classes	Williams chip classes
CH[a]	7.02*	ni
LWD	6.14*	6.74*
MOE	8.09*	6.50*
R/mm	ni	8.39*
Shear	ni	11.59*
TKA	10.71*	5.28*
TKN	5.85*	9.10*
LPS	3.48*	1.30 ns
CW	5.12*	17.73*
LPS × CW	2.92*	1.92 ns

ni, not included in the MANOVA; ns, not significant.

[a] See footnote of Table 2; CH, cutting height.

* Significant at the 0.01 probability level.

Also, Fig 4b shows that the taper influence on WCT was more important for the smaller CW (12.7 mm), whereas the effect of knot characteristics was more important for the greater CW (25.4 mm). In real sawmill conditions, the size of the cant is set by the cutting pattern. Therefore, to obtain a cant of uniform dimensions along the log, CW must vary throughout the log. Thus, log taper will determine CW variation between the small and big ends. The bottom log has greater taper and diameter. Therefore, CW will vary more in bottom logs compared with middle and top logs, which have smaller diameter and taper. For instance, if CW is set at 19.1 mm in the small end, for the case of a bottom log, CW will reach 42.1 mm at the big end, and for the case of a middle or top log, it will reach 29.1 mm at the big end (Table 1). Therefore, from a practical point of view, sawmills could adjust other fragmentation parameters, such as rotation speed

Table 5. F-values obtained from ANOVAs for each Domtar and Williams chip class.

Source of variation	Domtar chip classes					Williams chip classes				
	Fines	Fragile chips	Accepts	Overthick	Oversized	Fines	Pin chips	9.5 mm	Accepts	≥45 mm
CH[a]	1.11 ns	0.28 ns	14.99*	11.23*	4.05**	ni	ni	ni	ni	ni
LWD	0.03 ns	1.10 ns	5.12**	5.58**	2.74 ns	0.22 ns	0.38 ns	4.12**	2.03 ns	5.59**
MOE	0.19 ns	2.57 ns	2.05 ns	4.23**	4.25**	1.63 ns	2.85 ns	10.09*	6.61**	3.51 ns
R/mm	ni	ni	ni	ni	ni	6.97**	8.39*	10.10*	5.62**	4.92**
Shear	ni	ni	ni	ni	ni	3.17 ns	9.56*	0.40 ns	9.56*	0.47 ns
TKA	2.41 ns	5.13**	33.65*	24.43*	0.21 ns	4.77**	2.77 ns	2.79 ns	0.01 ns	0.79 ns
TKN	0.93 ns	11.05*	1.77 ns	7.63*	0.37 ns	7.88*	11.56*	9.34*	11.16*	0.11 ns
LPS	3.71**	0.09 ns	12.82*	12.66*	1.59 ns	2.28 ns	1.08 ns	0.91	0.33 ns	0.26 ns
CW	1.20 ns	1.17 ns	11.92*	14.43*	1.99 ns	6.39*	27.91*	63.46*	42.39*	4.13**
LPS × CW	2.04 ns	0.16 ns	3.03**	3.20**	0.70 ns	0.45 ns	2.64 ns	2.30 ns	2.44 ns	1.86 ns

ns, not significant; ni, not included in the ANOVA.

[a] See footnote of Table 2; CH, cutting height.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

and bedplate position, which also affect chip thickness (Hernández and Boulanger 1997; Kuljich et al 2015), to obtain uniform chip dimensions. Conversely, the number and size of knots appeared to have a more important role in the increase of WCT in the middle and top logs, especially at greater CW (Fig 4a, b). In this respect, sawmills could benefit from available log scanning technology to estimate the knottiness in the logs, not only for the optimization of lumber production but also to adjust the fragmentation parameters to obtain uniform chip dimensions.

One of the goals of this study was to describe and predict chip thickness distribution in a suitable manner. The multiple linear regressions found correlations between the studied explanatory variables and WCT, showing if CW and LPS combined with growth ring and knot characteristics and mechanical properties were good predictors of WCT. The bottom log dataset was not included in the multiple regression analysis because of its particular behavior with respect to the other log positions.

As previously described, the stepwise selection procedure was used to obtain significant predictors of chip thickness. Further explanations of this method are given elsewhere (Cáceres et al 2015). The statistical model showed that CW, TKN, LWD, and TKA were significant predictors of WCT ($\mathrm{WCT} = 5.7 + 0.034\ \mathrm{CW} + 0.014\ \mathrm{TKN} - 0.0024\ \mathrm{LWD} + 0.00014\ \mathrm{TKA}$). This global fit model gave a coefficient of determination of 67.2% (R^2) and a coefficient of variation of 3.5%. The regression showed the combined action of all these variables to predict chip thickness. CW was the most important variable with the greatest contribution to the R^2 of 39.2%. It was followed by three variables, namely TKN, LWD, and TKA with contributions to the R^2 of 18.4%, 6.5%, and 3.1%, respectively. The condition index of the model was 2.9, which indicates that collinearity among the independent variables was negligible. This model produced a significant R^2 explaining almost 67% of the variation in WCT, which also indicated that 33% of WCT variation remains unexplained. However, the low coefficient of variation showed that the regression was reasonably consistent.

Overall, WCT can be adjusted using primarily CW. This is in accordance with our previous study, which also established CW as the main variable describing WCT (Cáceres et al 2015). TKN and TKA were also important descriptors of WCT. There were good correlations between WCT and both TKN and TKA (r = 0.68 and 0.66, respectively), as shown in Fig 5 for TKN, which was more important in the WCT model. The number and size of knots within stems are among the most important factors affecting the quality of end products (Buksnowitz et al 2010).

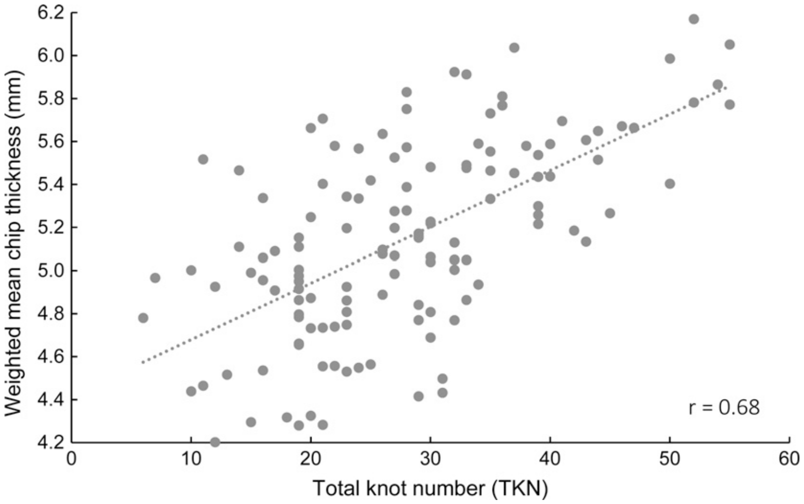

Figure 5. Relationship between WCT and TKN (excluding the bottom log dataset).

This also appears to be applicable in chip production by a chipper canter. The target WCT obtained by setting the CW is positively affected by the number and size of branches in the processed stems. It is known that black spruce trees are poorly self-pruned. The tree normally retains its lower dead branches for years, which is reflected in the considerable number of knots in the bottom and middle logs. Pruning could be an interesting practice to consider in tree plantations, not only because it would increase the volume of the more valuable clear wood but also because it would decrease the number and size of knots in the outer core of the stem (Mäkinen et al 2014). Silvicultural practices that favor pruning in natural forests could also be considered.

In this study, LWD was the most important RD component affecting WCT. Similarly, in a previous study, BD had an important role explaining chip thickness variation (Cáceres et al 2015). Although these are two different wood quality attributes, our results indicated that a density increase was to some extent reflected in a WCT decrease. A study in disk chippers also found wood density to be one of the main variables affecting chip thickness (Twaddle 1997a,b). Thus, the provenance of wood supply enters here into consideration. Black spruce logs coming from northern forests (higher density) produce thinner chips than logs coming from southern forests (lower density) as found by Cáceres et al (2015).

Domtar and Williams Chip Class Distributions

To understand the chip formation process as a whole, a detailed analysis of chip size distribution was performed. The MANOVA for the Domtar chip class distributions showed that CW, LPS (excluding the bottom log dataset), and their interaction significantly affected chip size. In the case of the Williams distribution, only CW had a significant effect (Table 4). These analyses took into account the existent dependence among the chip classes and showed that these classes are affected differently by LPS and CW. The compositional data analysis does not allow comparison of the real values of each class because it deals with proportions. Therefore, an ANOVA for each chip class was done separately for comparison purposes.

The covariates that significantly affected the chip thickness distribution (Domtar) were TKA, MOE, CH, LWD, and TKN (Table 4). These results were consistent with the ones obtained by the multiple regression analysis, which also showed TKA, LWD, and TKN as predictors of the WCT. There were two other variables that significantly affected chip thickness distribution: MOE and CH. MOE was the only mechanical property that affected chip thickness classification. In a previous study on black spruce chip quality, Cáceres et al (2015) reported MOR instead of MOE. Ultimately, the evidence showed that among the studied mechanical properties, the bending properties were more important in the Domtar distribution. The CH significance is most likely caused by the difference between the small- and large-end diameters in each log, as explained previously. Although CW was fixed all along the log, usually there was a difference between both ends of one log. This difference depended on log taper, which varied the height at which the log was fragmented with respect to the center of the cutterhead. When the log was closer to the center of the cutterhead, the resulting chips were thicker (Kuljich et al 2015). However, this effect primarily occurred in the bottom logs and to a lesser extent in the middle and top logs.

The width and length of chip class distribution (Williams) showed more covariates involved, including (in order of importance) shear, TKN, R/mm, LWD, MOE, and TKA (Table 4). These results showed consistency between both chip size distributions, because some of these variables were also significant in the Domtar chip class distribution, namely TKN, LWD, MOE, and TKA. Nevertheless, the relevance of each variable was different between the distributions (Table 4). R/mm was the only growth ring characteristic affecting Williams classification, showing that chip width is more sensitive to growth ring variation. This is in accordance with our previous study on chip quality of black spruce (Cáceres et al 2015). Chip visual assessment showed that chip width was mostly produced by a rupture tangential to the growth ring, in the earlywood zone, which gave evidence of the importance of R/mm in chip width distribution. Knot characteristics were also significant in the Williams chip size distribution. The presence of knots appeared to be more important than the size of the knots on the chip width classification. Observation of the chips supported these results, showing the whole circumference of the knot, in the corresponding width chip face. Among the studied mechanical properties, not only MOE but also shear strength were significant in the chip width classification. Furthermore, LWD was the most important density feature for chips classified by both thickness and width.

Univariate ANOVA were performed for each chip class of Domtar and Williams distributions. The significant covariates obtained in the MANOVA were kept in each class analysis to observe their specific influence on each chip class. According to Table 5, for Domtar chip class distributions, both CW and LPS significantly influenced chip thickness. The interaction LPS × CW was poorly represented among Domtar chip classes. For Williams distribution, only CW significantly affected chip classes, as previously shown by the MANOVA. This showed that chip classes varied differently with height position and CW.

The covariates affected chip classes individually. For Domtar distribution, TKA had a significant effect on fragile, accepts, and overthick classes, which represented 99% of the total chips. CH and LWD significantly affected accepts and overthick classes, which represented 94% of the chips. TKN had a significant effect on fragile and overthick classes, which represented 14% of the chips. MOE significantly affected the overthick class, which represented about 9% of the chips. The fines were not affected by the studied covariates. For Williams distribution, R/mm and TKN were the main covariates affecting all chip classes, almost 100% of the chips. MOE affected 9.5-mm and accepts chip classes, which represented 85% of the chips. Shear significantly affected the pin and accepts chip classes, representing 57% of total chips. LWD affected the 9.5-mm chip class, which represented 40% of the chips. These results showed that chip thickness distribution was affected particularly by the variation of TKA, CH, and LWD, whereas the width and length distribution was affected mainly by R/mm, TKN, and MOE variations. Therefore, chip formation was affected primarily by the CW and LPS, in addition to the effects associated with

Table 6. Domtar and Williams black spruce chip size distributions by CW and LPS.[a]

		Domtar chip classes					Williams chip classes				
		Fines	Fragile	Accepts	Overthick	Oversized	Fines	Pin chips	9.5 mm	Accepts	≥45 mm
		(%)									
CW (mm)	12.7	1.02 (0.03)	6.2 (0.2)	87.1 (0.3)	5.7 (0.4)	0.05 (0.02)	3.2 (0.1)	13.6 (0.4)	46.1 (0.9)	37.1 (1.4)	0.02 (0.01)
	19.1	0.94 (0.03)	5.0 (0.2)	85.1 (0.5)	8.9 (0.6)	0.10 (0.04)	2.9 (0.1)	11.5 (0.4)	40.3 (1.0)	45.3 (1.4)	0.09 (0.04)
	25.4	0.90 (0.02)	4.4 (0.1)	83.4 (0.4)	11.2 (0.4)	0.13 (0.04)	2.8 (0.1)	10.7 (0.4)	34.3 (0.7)	52.1 (0.9)	0.10 (0.03)
LPS	Bottom	0.84 (0.02)	4.9 (0.2)	85.0 (0.4)	9.1 (0.5)	0.05 (0.03)	2.7 (0.1)	11.9 (0.5)	40.4 (1.2)	44.9 (1.6)	0.04 (0.02)
	Middle	0.98 (0.03)	5.3 (0.2)	85.7 (0.5)	8.0 (0.6)	0.10 (0.02)	3.0 (0.1)	12.1 (0.4)	41.4 (1.2)	43.4 (1.6)	0.07 (0.03)
	Top	1.02 (0.02)	5.2 (0.2)	84.7 (0.5)	9.0 (0.6)	0.14 (0.05)	3.1 (0.1)	11.8 (0.4)	38.9 (1.1)	46.1 (1.5)	0.10 (0.04)

CW, cutting width; LPS, log position in the stem.

[a] Numbers in parentheses are standard errors.

the raw material features, such as knot characteristics, growth rate (R/mm), RD (LWD), and bending properties (MOE).

The global results for Domtar and Williams chip class distributions are shown in Table 6. For the Domtar chip classes, the increase in CW from 12.7 to 25.4 mm produced a decrease in the fines, fragile chips, and accepts classes, in contrast to the increase of the overthick and oversized classes (Fig 6a,c). Similar results were found with the Williams chip classes, in which the fines, pin chips, and 9.5-mm classes decreased in contrast to the increase in the accepts and over 45-mm classes (Fig 6b,d). Accordingly, accepts and overthick classes from Domtar were comparable with the 9.5-mm and accepts classes from Williams, respectively. Nevertheless, the magnitude of the proportions between the comparable classes was very different (Fig 6). Overall, the smaller classes decreased and the larger classes increased with the increase in CW. This is consistent with the behavior of WCT (Fig 4a). These results are also in agreement with those reported by Hernández and Lessard (1997) and Cáceres et al (2015).

Furthermore, the effect of LPS showed mixed behavior. For the chip thickness distribution (Domtar), fragile chips and accepts classes increased substantially from the bottom to the middle log and then decreased toward the top log. Conversely, the overthick class decreased from the bottom to the middle log and then increased toward the top log. For Williams distribution, a similar trend was found between comparable classes. For both chip class distributions (Domtar and Williams), the fines and oversized classes increased from the bottom to the top of the stem. In general, the smaller classes tended to increase from the bottom to the middle of the stem and eventually decrease toward the top of the stem, whereas the larger classes presented the opposite behavior. The mean behavior of the chip classes is reflected by the WCT observations (Fig 4b).

The choice of chip dimension assessment in sawmills (Domtar and/or Williams) depends on

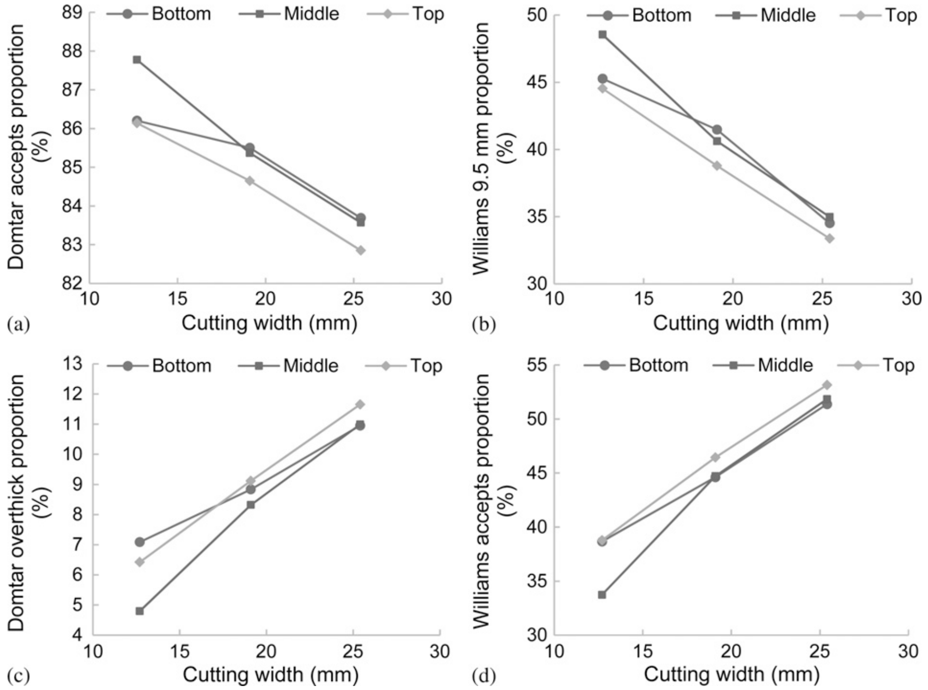

Figure 6. (a) Domtar accepts chip class, (b) Williams 9.5-mm chip class, (c) Domtar overthick chip class, and (d) Williams accepts chip class, by CW for each LPS.

the potential clients for the chips (pulp and paper industries). Based on the pulping process (chemical and/or mechanical), some industries could select the thickness distribution or the width and length distribution. The desirable chip class will vary accordingly. Our results showed that the accepts class of the Domtar distribution almost doubled that of the Williams distribution. However, it is current practice in certain pulp industries to accept up to 20% of the 9.5-mm chip class without penalties to the sawmill.

The results of this study showed the potential benefits of segregating incoming wood in sawmills. In addition to managing the forest properly, sawmills should look into the possibility of adjusting their wood yards to facilitate the segregation of wood raw material. Sawmills could take advantage of the given knowledge of chip dimension variation caused by knottiness, taper, and density to adjust CW or other fragmentation parameters, thereby improving chip size uniformity. The use of advanced log scanners revealing the number and size of superficial knots could improve the assessment of chip quality beforehand because the number and size of knots had a major role in the production of overthick and oversized chips in middle and top logs. It would also be interesting from an economic point of view to classify the logs knowing that bottom logs would produce thicker chips because of their higher taper. Wood segregation would certainly be interesting for the pulp mills, because the better knowledge and control of the raw material would allow them to adjust their pulping processes for different paper technical specifications and maximize pulp yields. Similarly, sawmills could take the lead in innovation and look for other profitable alternatives to wood chips in the near future.

CONCLUSIONS

Dimensions of black spruce chips produced by a chipper canter were significantly affected first by CW and second by LPS. The increase in CW resulted in thicker chips, whereas the variation of the LPS produced thicker chips in the bottom and top logs and thinner chips in the middle log. Variation in knot characteristics up the stem was the main cause of producing thicker chips toward the top of the stem. However, the production of thicker chips from the bottom logs might be attributed to their pronounced taper. The most representative covariates between thickness (Domtar) and width and length (Williams) chip class distributions were different. Knot size appeared to be more important on chip thickness and knot number on chip width in black spruce. Wood density had a predominant role in determining chip thickness, as growth ring size and bending properties had in chip width. Variation in wood density attributes, growth ring characteristics, and bending properties appear to have a considerable role in the chip formation mechanism. Other studies should be conducted to better understand the chip formation process. Ultimately, chip dimensions could be appropriately adjusted to uniform dimensions for a specific industry end use if sawmills had more control and knowledge of their wood raw material–specific attributes (knottiness, taper, density, and provenance).

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REFERENCES

Agarwal N, Gustafson R, Arasakesari S (1994) Modeling the effect of chip size in kraft pulping. Pap Puu Pap Tim 76(6-7):410-416.

Aitchison J (1982) The statistical-analysis of compositional data. J Roy Stat Soc B Met 44(2):139-177.

Alteyrac J, Zhang S, Cloutier A, Ruel JC (2005) Influence of stand density on ring width and wood density at different sampling heights in black spruce (*Picea mariana* (Mill.) B.S.P.). Wood Fiber Sci 37(1):83-94.

ASTM (2007) D143-94 Standard test methods for small clear specimens of timber, American Society for Testing Materials, West Conshohocken, PA.

Bjurulf A (2005) Dimensional consistency of wood chips over time. Nord Pulp Pap Res J 20(1):43-47.

Brill JW (1985) Effects of wood and chip quality on TMP properties. Pages 153-161 *in* Proc. International Mechanical Pulping Conference, May 6-10, 1985, Stockholm, Sweden. TAPPI, Atlanta, GA.

Broderick G, Cacchione E, Heroux Y (1998) The importance of distribution statistics in the characterization of chip quality. Tappi J 81(2):131-142.

Buksnowitz C, Hackspiel C, Hofstetter K, Muller U, Gindl W, Teischinger A, Konnerth J (2010) Knots in trees: Strain distribution in a naturally optimised structure. Wood Sci Technol 44(3):389-398.

Cáceres C, Hernández R, Koubaa A (2015) Effects of the cutting pattern and log provenance on size distribution of black spruce chips produced by a chipper-canter. Eur J Wood Wood Prod 73(3):357-368.

Christie RD (1986) Chip thickness and its effect on pulping needs further study. Pulp Pap Can 87(9):37-43.

Colin F, Houllier F (1991) Branchiness of Norway spruce in north-eastern France: Modeling vertical trends in maximum nodal branch size. Ann Sci For 48(6):679-693.

Colin F, Houllier F (1992) Branchiness of Norway spruce in northeastern France: Predicting the main crown characteristics from usual tree measurements. Ann Sci For 49(5):511-538.

Ding F, Benaoudia M, Bedard P, Lanouette R (2009) Effects of some wood chip properties on pulp quality. Pulp Pap Can 110(6):20-23.

Feiner JH, Gallay W (1962) The effect of chip thickness on sulphite pulp yield and quality. Pulp Pap Can 63(9): T435-T441.

Galloway L, Thomas P (1972) Studies on chip quality from a Chip-N-Saw chipping headrig. Pulp Pap Can 73(8):82-86.

Hartler N, Stade Y (1979) Chip specifications for various pulping processes. Pages 273-301 *in* Hatton JV, eds. Chip quality monograph. Joint Textbook Committee of the Paper Industry, Atlanta, GA.

Hatton JV, Keays JL (1973) Effect of chip geometry and moisture on yield and quality of kraft pulps from western hemlock and black spruce. Pulp Pap Canada 74(1):79-87.

Hedenberg O (2001) Revision of the standardised method for determination of chip size distribution. Pap Puu Pap Tim 83(2):142.

Heger L (1974) Longitudinal variation of specific-gravity in stems of black spruce balsam fir and lodgepole pine. Can J For Res 4(3):321-326.

Hernández RE, Quirion B (1993) Effect of a chipper-canter knife clamp on the quality of chips produced from black spruce. Forest Prod J 43(9):8-14.

Hernández RE, Boulanger J (1997) Effect of the rotation speed on the size distribution of black spruce pulp chips produced by a chipper-canter. Forest Prod J 47(4):43-49.

Hernández RE, Lessard J (1997) Effect of cutting width and cutting height on the size distribution of black spruce pulp chips produced by a chipper-canter. Forest Prod J 47 (3):89-95.

Hoekstra PL, Veal MA, Lee PF, Sinkey JD (1983) The effects of chip size on mechanical pulp properties and energy consumption. Tappi J 66(9):119-122.

Jyske T, Mäkinen H, Saranpää P (2008) Wood density within Norway spruce stems. Silva Fennica 42(3):439-455.

Koubaa A, Zhang S, Isabel N, Beaulieu J, Bousquet J (2000) Phenotypic correlations between juvenile-mature wood density and growth in black spruce. Wood Fiber Sci 32(1):61-71.

Kuljich S, Hernández RE, Blais C (2015) Effects of the cutterhead diameter and log infeed position on the energy requirements of a chipper-canter. Wood Fiber Sci 47(4): 399-409.

Lapointe JA (1979) Domtar classifier accurately measures thickness and length of wood chips. Pap Trade J 8:28-30.

Lemieux H, Beaudoin M, Zhang SY (2001) Characterization and modeling of knots in black spruce (*Picea mariana*) logs. Wood Fiber Sci 33(3):465-475.

Lohrasebi H, Mabee WE, Roy DN (1999) Chemistry and pulping feasibility of compression wood in black spruce. J Wood Chem Technol 19(1-2):13-25.

Lönnberg B, Robertsén L (1986) Significance of chip thickness in CRMP and RMP: A laboratory study with pine chips. Pap Puu Pap Tim 68(1):36-41.

Mäkinen H, Verkasalo E, Tuimala A (2014) Effects of pruning in Norway spruce on tree growth and grading of sawn boards in Finland. Forestry 87(3):417-424.

McGovern JN (1979) Chip specifications for various pulping processes. Pages 91-110 *in* Hatton JV, ed. Chip quality monograph. Joint Textbook Committee of the Paper Industry, Atlanta, GA.

MFFP (2014) L'industrie des produits forestières au Québec. Ministère de Forêts, Faune et Parcs, Government of Quebec, Quebec, Canada. http://www.mffp.gouv.qc.ca/forets/quebec/quebec-regime-gestion-developpement.jsp (23 April 2015).

MRNF (2013) Ressources et industries forestières: Portrait Statistique. Ministère des Ressources Naturelles et de la Faune, Government of Quebec, Quebec, Canada.

NRCAN (2014) Canada's forest industry by the numbers. Natural Resources Canada, Government of Canada. www.nrcan.gc.ca/forests/industry/13311 (23 April 2015).

Olson D, Hatton JV, Hunt K (1980) Effect of chip thickness in kraft-anthraquinone pulping of trembling aspen. Tappi J 63(12):109-110.

Rudie AW, Morra J, Stlaurent JM, Hickey KL (1994) The influence of wood and fiber properties on mechanical pulping. Tappi J 77(6):86-90.

Saranpää P (2003) Wood density and growth. Pages 87-117 *in* JR Barnett and G Jeronimidis, eds. Wood quality and its biological basis. Blackwell, Oxford, United Kingdom.

Shmulsky R, Jones PD (2011) Forest products and wood science: An introduction. Wiley-Blackwell, London, United Kingdom. 478 pp.

Smith DE, Javid SR (1992) New approaches to fines and pins screening. Tappi J 75(1):93-97.

Svedman M, Tikka P, Luhtanen M (1998) Effects of softwood morphology and chip thickness on pulping with a displacement kraft batch process. Tappi J 81(7):157-168.

Tikka P, Kovasin K, Tähkänen H (1993) Chip thickness vs. kraft pulping performance, part 2. Effect of chip thickness screening on cooking, oxygen delignification and bleaching of softwood kraft batch pulp. Pages 833-838 *in* Tappi Proc. Pulping Conference, November 14-18, 1993, Atlanta, GA. Tappi Press, Atlanta, GA.

Tikka P, Tähkänen H (1994) Chip thickness vs. kraft pulping performance, part 3. Effect of new optimized chip quality on continuous cooking, oxygen delignification and bleaching of softwood kraft pulp. Pages 177-182 *in* Tappi Proc. Pulping Conference, November 6-10, 1994, San Diego, CA. Tappi Press, Atlanta, GA.

Twaddle A (1997a) Oversize chip formation and relationship to chip length. Pages 307-315 *in* Tappi Proc. Pulping Conference, October 19-23, 1997, San Francisco, CA. Tappi Press, Atlanta, GA.

Twaddle A (1997b) The influence of species, chip length, and ring orientation on chip thickness. Tappi J 80(6): 123-131.

Wood JR (1996) Chip quality effects in mechanical pulping: A selected review. Pages 491-497 *in* Tappi Proc. Pulping Conference, October 27-31, 1996, Nashville, TN. Tappi Press, Atlanta, GA.

Xiang W, Leitch M, Auty D, Duchateau E, Achim A (2014) Radial trends in black spruce wood density can show an age- and growth-related decline. Ann Sci 71(5): 603-615.

Zhang SY, Koubaa A (2009) Les résineux de l'Est du Canada: Écologie forestière, caractéristiques, transformation et usages. Forintek Canada Corporation, Quebec, Canada. 400 pp.

Zobel BJ, van Buijtenen JP (1989) Wood variation: Its causes and control. Springer-Verlag, Berlin, Germany. 363 pp.