Effects of Temperature and Moisture Content of Logs on Size Distribution of Black Spruce Chips Produced by a Chipper-canter at Two Cutting Widths

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Four matched groups of black spruce logs were processed with a chipper-canter at temperatures of 20, 0, -10, and -20 °C. Each log was transformed at two moisture contents (MC, green and air-dried) using two cutting widths (CW, 12.7 and 25.4 mm). Mean MC for each CW was assessed from a sample of the obtained chips. Knot characteristics were measured on the cant surfaces after log processing. Chip size was assessed by thickness (Domtar classifier) and width/length (Williams classifier). The results showed that the chip size was significantly affected by the CW and temperature, and in a lesser degree by the chip MC. The weighted mean chip thickness (WCT) increased with the CW. As temperature decreased below 0 °C, WCT and accepts decreased, while proportions of fines and pin chips increased. Chips obtained from green logs were thinner compared to air-dried logs when processed at the coldest temperature (minus 20 °C). The number and size of knots had an important impact on chip size, particularly on WCT. Multiple regressions were developed to predict WCT. Results showed the potential benefits of measuring log temperature and knot features to reduce chip thickness variation during fragmentation and thus improving chip size uniformity.

Keywords: Temperature; Moisture content; Cutting width; Chip size; Chipper-canter; Black spruce

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INTRODUCTION

The forest industry has a major economic importance in Canada. In 2019, this industry contributed about 23.7 billion $CAD to Canada's nominal gross domestic product (NRCAN 2020). The pulp and paper industries are some of the main users of Canada's wood fiber, producing approximatively 25% of the world's northern bleached softwood kraft pulp and 15% of the world's newsprint paper (CIFQ 2014; Murnighan 2018).

In Quebec, sawmills are strongly integrated with the pulp and paper industries. About 61% of the raw material used for pulp production is supplied by sawmills, exclusively in the form of wood chips (Delisle 2019). The quality of chips directly affects their commercialization. Each pulping process has different requirements and specifications regarding chip quality, which is defined by several factors, such as bulk density, moisture content, bark content, wood species mixture, and chip dimensions (mean and distribution) (Bergman 1985). The optimal chip dimensions vary depending on the type of process, the equipment available, and the end-product (Hartler and Stade 1979). Chip thickness appears to be the most important parameter in 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). The chip size uniformity is another key factor that allows for the improvement in the quality of the pulping process (Pulkki 1991). For the purpose of this study, chip quality refers exclusively to the size of chips and their distribution.

Chipper-canters are widely used in eastern Canadian sawmills to transform small and medium diameter logs into cants and chips in a single operation. The most common chipper-canter has a truncated conical-shaped cutterhead fitted with uniformly distributed knife holders, each with a bent knife and a knife clamp. The bent knife has two cutting edges that are joined at an angle; a chipping edge to sever the slice to produce chips and a canting edge to smooth the cant. The performance of the chipper-canter is strongly influenced by the cutting parameters of the machine such as the design of the knife clamp (Hernández and Quirion 1993, 1995), the cutting speed (Hernández and Boulanger 1997), the log infeed position (Kuljich *et al.* 2017), and the inclination angle of the chipping edge (Grubîi *et al.* 2019). In addition, the cutting width (CW), closely associated to the log primary breakdown, is directly related to the resulting chip size. Thus, larger CWs will produce bigger chips (Hernández and Lessard 1997; Cáceres *et al.* 2015).

Wood properties also affect the performance of chipper-canters. The wood density, growth ring characteristics, and mechanical properties of the logs will influence the chip size (Cáceres *et al.* 2015, 2016). The knot features of logs have a large impact on chip dimensions (Cáceres *et al.* 2016, 2017). The log temperature during breakdown also affects the chip size distribution. In general, the logs are stored in the mill yard and have to cope with a variety of weather conditions throughout the year. Among seasons, processing logs during winter is more critical because their liquid water within them freezes and wood becomes stronger at temperatures below 0 °C. The winter historical weather data in the Quebec province reported that the mean temperature ranged between 6 and -30 °C from 1981 to 2010 (Quebec Government 2018). Accordingly, the wood temperature varied about 36 °C from December through March, at variable freezing rates depending on the local climate conditions of each year. Previous studies have reported that the thickness of pulp chips decreases when logs are processed under frozen conditions (Hernández and Boulanger 1997; Hernández and Lessard 1997; Kuljich *et al.* 2017; Grubîi *et al.* 2019). The volume of fines and pin chips can be two times greater when chipping frozen logs compared to unfrozen logs (Hernández and Quirion 1993). This behavior is associated with the variation of mechanical properties of wood as temperature decreases below 0 °C. Hernández *et al.* (2014) found that cleavage and shear strength of black spruce increased 150% and 124%, respectively, when green sapwood temperature decreased from 0 to -20 °C. According to these authors, as the cleavage and shear strength increase with decreasing temperature, a small penetration of knife into the log would start fragmentation and thus thinner chips should be formed.

The moisture content (MC) of wood also has an effect in chip size, especially when processing green frozen logs. The time that logs are stored in the sawmill yards varies depending on the season, region, and log availability. As a result, there could be a great variation in the log MC, and this consequently would affect the size of chips. In general, the seasonal nature of supply can be characterized by the adequacy between the volume of wood delivered to the yard and the mill's consumption. Three seasons can be distinguished, inventory accumulation, inventory outflow, and a balanced season. The accumulation season is the one in which wood deliveries to the yard are greater than the mill's consumption. This season begins from late fall through late winter (Trzcianowska *et al.* 2019). During this period, the MC of the logs gradually decreases with a slow drying rate. For this reason, particular attention should be paid to the effect of MC when chipping frozen logs. Moreover, chip MC should not be lower than 36% on a dry-weight basis, according to sawmill quality standards in the Quebec province. Above the fiber saturation point (FSP), the proportion of frozen water in wood reinforces its strength (Mishiro and Asano 1984; Mishiro 1990; Hernández *et al.* 2014). This reinforcement will be higher when logs are in the green state (high MC), which will thus accentuate the effect of the freezing temperature on the chip size, depending on the amount of ice formed. According to Hernández and Lessard (1997), the high MC difference between heartwood and sapwood in softwoods would affect the chipping process in frozen conditions, depending on the CW. The greater proportion of ice in sapwood when using a small CW (12.7 mm) played an important role in chip size distribution. As a result, sawmills should take into account the MC of logs during machining at temperatures below 0 °C.

A better understanding of the chip size variation due to different log freezing temperatures and moisture contents will give sawmills the proper means to adequately adjust their cutting parameters to maintain chip size uniformity throughout the year. Under this context, this study evaluated the effects of log temperature and MC on size distribution of black spruce chips produced by a chipper-canter at two cutting widths.

EXPERIMENTAL

Materials

Tests were carried out with 60 freshly felled logs of black spruce [*Picea mariana* (Mill.) B.S.P.] from the region of Abitibi-Témiscamingue, in the Quebec province. Black spruce is one of the most important species in Canada and is mainly used for lumber and in a variety of secondary products. With its pale color, low resin content, and long and strong fibers, it is suitable for the manufacture of various types of pulps (Zhang and Koubaa 2008). The logs were crosscut to 2.5 m length and then freshly hand debarked. The crosscutting position was chosen to have a small end diameter of 158.8 mm, which yielded a mean taper of 8 mm/m. The logs were without crook or visible decay. A 50-mm-thick disc was crosscut from each end of the log to measure wood physical properties. The logs and discs were wrapped in plastic films and stored green at -19 °C until testing.

Treatments

Each log was chipped four times: at two moisture contents and two CWs: 12.7 mm and 25.4 mm (Fig. 1).

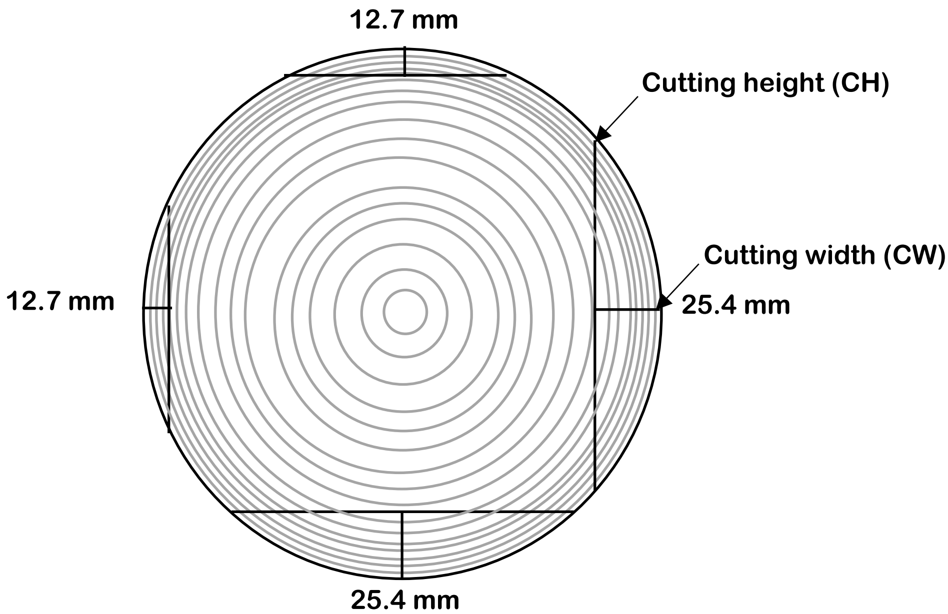

Fig. 1. Positions and dimensions of the CW of each segment in the small end of the log. The cutting height draws the segment area that will be fragmented. The cutting width is directly related to the area of chipping.

The CW positions were selected according to best fitting in terms of log form and knottiness. The CWs were then marked down in both ends of each log and in its corresponding discs. Previous studies reported that mean sapwood thickness in black spruce is about 15 mm (Hernández and Lessard 1997; Kuljich *et al.* 2017; Grubîi *et al.* 2019). Therefore, the smaller cutting width should include only sapwood and the larger one was a combination of both sapwood and heartwood at different proportions, depending on each log diameter.

The first step of fragmentation was carried out with freshly felled logs, considered as the green condition. After that, the logs were coated with a sealer at both ends and at both cut sides to prevent a rapid moisture exchange. Logs were then air-dried during eight days in a conditioning chamber at 20 °C and 60% relative humidity. The second step of fragmentation was performed after air-drying. For these two steps, four temperatures were selected to assess the effect of log temperature on chip size, namely: 20, 0, -10, and -20 °C. Fifteen logs were processed in each case.

Sapwood Thickness, MC, and Basic Density Measurements

Thickness of sapwood was measured at three positions on the four segments of the removed disc, which corresponded to each marked CW (Fig. 1). A cube of 25-mm-wide was then cut from each disc. The cubes were separated into sapwood and heartwood parts to determine MC and basic density (BD) separately. Thickness of these parts varied depending on the sapwood thickness of each log. The MC and BD were determined by the oven-drying method using ASTM D4442-16 (2016) and ASTM D2395-17 (2017), respectively. The sapwood MC was then used as the main criterion to separate the logs into four homogenous groups.

In addition, the MC of chips collected after fragmentation was determined to estimate the mean MC of the removed material from the logs. A sample of 100 g of chips was taken from each cutting condition to determine MC by the oven-drying method. This MC was more appropriate to assess the effect of this variable on the chip size distribution.

Fragmentation Process

Logs were processed with a laboratory prototype chipper-canter equipped with a DK-SPEC cutterhead (DK-SPEC Inc., Quebec, Canada) (Fig. 2). The cutterhead was fitted with eight freshly sharpened bent knives, made from steel A8 MOD, that are joined at an angle; a longer or chipping edge and a smaller or canting edge. The chipping edge had an angle of 30° and a rake angle of 49°. The knife clamp angle was 35° and the distance between the knife clamp edge and the knife edge was 22 mm. The cutterhead was 631 mm in diameter, measured from one knife joint to the opposite one. The cutterhead position (vertical distance from the cutterhead axis to the bedplate) was fixed at 280 mm to obtain a mean attack angle (AA) of 88° (angle between the chipping rake face and the wood grain) (Fig. 2). According to Kuljich *et al.* (2017), this corresponds to the infeed position of the log, which should allow to obtain a chip thickness for unfrozen green logs of 5 mm at a cutting width of 25.4 mm. The chipper-canter was equipped with a hydraulic feed carriage that held the log fixed with five clamps during fragmentation. The linear cutting speed was set at 23.5 m/s at the junction point between the chipping and canting edges of knives. The rotation (718 rpm) and feed (146 m/min) speeds were adjusted to obtain a nominal chip length of 25.4 mm.

As previously indicated, black spruce logs were processed at four temperatures and two CWs (Fig. 1). Because temperature of the chipper-canter laboratory varied between 18 and 22 °C, great care had to be taken to preserve the temperature of the log during testing. Just prior to testing, every log was transferred from the freezing room to the laboratory into a Styrofoam box. The temperature of the log was then measured at two positions and at a depth of either 12.7 or 25.4 mm, depending on the tested CW. This was made using a digital thermometer to the nearest 0.1 °C.

The CW (12.7 and 25.4 mm) was kept constant throughout the log to better assess the effect of this variable on fragmentation (Fig. 1). This minimized the influence of log taper and cutting height (CH) on chipping. The alignment of the CW along the log was made using a laser beam installed over the log carriage and by measuring it every 200 mm along the log until reaching the target CW. To have a similar log infeed position (280 mm) for each CW in the same log (Fig. 1), the width of the previously removed chipped side was replaced by placing a board of the same thickness (12.7 or 25.4 mm) under the log before chipping the next condition. After each fragmentation, all chips produced were collected in plastic bags. Cants were wrapped with polyethylene and stored in a -19 °C freezer along with chip bags for further analysis.

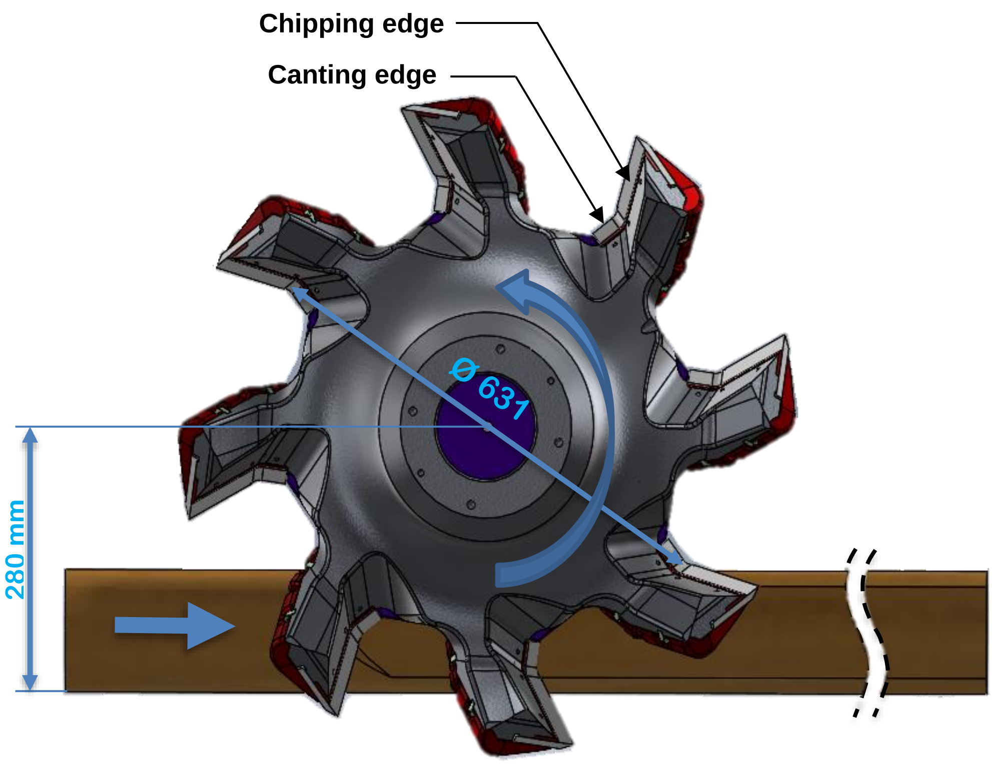

Fig. 2. Back view of DK-SPEC cutterhead provided with eight bent knives, showing the log infeed position used for the tests

High-speed Photography

A high-speed camera was installed below the cutterhead to visualize in real time the cutting action of the chipper-canter. The chip formation mechanism was recorded for 2 logs per cutting condition. Videos were taken with a "MotionPro Y4-S3" camera (Integrated Design Tools (IDT), Tallahassee, FL, USA) fitted with a 35 mm / f1.4 lens (Kowa, Osaka, Japan) at a frequency of 3000 frames/s and an exposure time of 22 µs. The focus was done on the rake face of the knives. The images were acquired with Motion Studio software (IDT, Tallahassee, FL, USA) at a maximum resolution (1024 × 1024 pixels).

Chip Classification

Chips were air-dried indoors for 2 weeks to facilitate their separation. A representative sample of about 2 kg from each cutting condition was taken using a Domtar separator (Fort Mill, SC, USA) when necessary. The chip size distribution was then evaluated by two methods using Domtar and Williams classifiers. The Domtar classifier separates chips according to thickness (into 2 mm classes) and length. Chip categories retained with this classifier were: fines (material that passes a 4.5 mm diameter hole screen); fragile chips (under 2-mm-thick chips, minus fines); accepts (over 2 mm thick by 2 mm classes up to 8 mm); overthicks (over 8 mm thick by 2 mm classes up to 18 mm, over 18 mm), and oversize (the fraction retained on a 45-mm diameter hole screen).

The Williams classifier sorts chips by width and length in the following classes: fines (material that passes a 4.8-mm diameter screen hole); pin chips (material retained in a 4.8 -mm diameter screen hole); 9.5 mm or small chips (material retained in a 9.5-mm diameter screen hole); accept chips (chips retained in screens of 15.9, 22.2, and 28.6 mm of hole diameter); and oversize chips (the fraction retained by the 45-mm diameter screen hole).

The chip classes obtained with both classifiers follow the dimensions required by the Canadian pulp and paper industries. Sawmills aim to maximize the chip volume of the accept class and minimize the volume of the other classes.

Knot Assessment

Knots were assessed on the cant surfaces obtained after log fragmentation. Each surface was scanned with a portable scanner GoScan 50 (Creaform, Lévis, Canada) at a resolution of 0.9 mm. The scanner is based on triangulation of fascicles of white light to capture the surface in full color. The image obtained was processed with VXmodel software to remove the edges and have a 3D image of the cant surface. All knots larger than 2 mm were evaluated. The knot parameters measured with the software included the total knot number on the cant surface (TKN) and the total knot area (TKA) (sum of the area of all knots on the cant surface).

Statistical Analysis

Data were analyzed using Statistical Analysis System (SAS) 9.4 software (SAS Institute Inc., Cary, NC, USA). The experiment followed a split-plot design. The temperature was the source of variation in the main plot. Moisture content and cutting width were the sources of variation in the subplot. The moisture content of chips was nested within the cutting width, since this parameter was specific to each CW. Raw data were first evaluated with the Box-Cox method showing the more fitted transformation if required. For all analyses, knot characteristics and wood physical properties were used as covariates, keeping only those that were significant for each model. First, a mixed model of analysis of covariance (ANCOVA) was used to evaluate the weighted mean chip thickness (WCT). Then, a multivariate analysis of covariance (MANCOVA) was performed using the Aitchison approach of compositional data (Aitchison 1982) for the Domtar and Williams chip class distributions. 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, this compositional data analysis does not allow comparisons of the real values of each class because it works with proportions. Consequently, an ANCOVA of each class was performed individually. Afterwards, a multiple linear stepwise regression was done to determine if the principal sources of variation (temperature, MC, and CW) and the measured covariates were good predictors of WCT. Finally, the normality was verified with Shapiro–Wilk's test, and the homogeneity of variance was verified with the graphical analysis of residuals. Statistical significance was tested at 5 and 1% probability levels.

RESULTS AND DISCUSSION

The mean properties of the four groups of black spruce logs are given in Table 1. The ANOVAs (not shown) revealed that the mean values of MC and BD for sapwood and heartwood, as well as sapwood thickness, and log taper were similar for all groups of logs. Moisture content of freshly felled logs was significantly higher for sapwood (110%) than for heartwood (42%). Similar values of green MC have been reported for black spruce logs from Eastern Canada (Hernández and Quirion 1993; Hernández and Boulanger 1997; Hernández and Lessard 1997; Kuljich *et al.* 2017; Grubîi *et al.* 2019). However, BDs of sapwood (461 kg/m^3) and heartwood (455 kg/m^3) were not statistically different. The mean BD of 458 kg/m^3 was in the highest limit of the BD range (399 to 461 kg/m^3) found in previous studies on this species in Eastern Canada (Hernández and Boulanger 1997; Hernández and Lessard 1997; Hernández *et al.* 2014; Cáceres *et al.* 2016; Kuljich *et al.* 2017; Grubîi *et al.* 2019; Kharrat *et al.* 2021). Density variation can be associated with environmental and genetic factors, including the geographic location, site conditions, and tree age (Miles and Smith 2009). Moreover, knot characteristics depended on the CW. The total knot number increased as CW increased. In fact, a greater CW generated a bigger cant surface resulting a higher number of visible knots. Accordingly, the total knot area also increased with the larger CW. A knot is the base of a branch that has been embedded in the tree stem as the tree grows in diameter (Tong *et al.* 2013). With time, some of the branches die, decay, fall off and become overgrown. These knots will be visible only when the log is sawn or split (Jozsa and Middelton 1994).

Table 1. Characteristics of Black Spruce Logs Used for Each Studied Cutting Condition

Log Characteristics	Temperature (°C)							
	Before Air-drying				After Air-drying			
	1[a] (-20 °C)	2 (-10 °C)	3 (0 °C)	4 (20 °C)	1 (-20 °C)	2 (-10 °C)	3 (0 °C)	4 (20 °C)
Moisture Content (%)								
Sapwood	108 (6)[b]	113 (4)	115 (4)	105 (5)	62 (5)	87 (4)	86 (4)	65 (5)
Heartwood	40 (1)	42 (2)	43 (2)	44 (2)	33 (1)	34 (1)	36 (1)	33 (1)
Sapwood Thickness (mm)								
12.7[c]	16.1 (0.7)	15.6 (0.6)	15.7 (0.7)	16.1 (0.5)	15.4 (0.6)	15.3 (0.7)	15.5 (0.7)	15.4 (0.5)
25.4	16.5 (0.8)	15.6 (0.5)	15.8 (1.0)	15.7 (0.6)	15.1 (0.6)	15.1 (1.0)	15.1 (0.7)	15.9 (0.6)
Total Knot Number [d]								
12.7	13 (2)	15 (1)	12 (1)	15 (1)	15 (2)	14 (1)	17 (1)	16 (2)
25.4	24 (2)	21 (2)	24 (2)	22 (1)	26 (1)	23 (2)	25 (1)	23 (1)
Total Knot Area (mm^2) [d]								
12.7	462 (144)	745 (195)	481 (65)	541 (99)	650 (118)	532 (91)	942 (125)	632 (93)
25.4	1111 (182)	1167 (197)	1458 (144)	1140 (293)	1378 (193)	1137 (241)	1729 (209)	992 (152)

[a] Groups 1 through 4 were tested at two moisture contents before and after air-drying;
[b] Numbers in parentheses are the standard errors of the mean;
[c] Cutting width in mm;
[d] Property measured at each processed cant surface

Chip Formation

High-speed images show the influence of log temperature and cutting width on the formation of chips at green condition (Fig. 3).

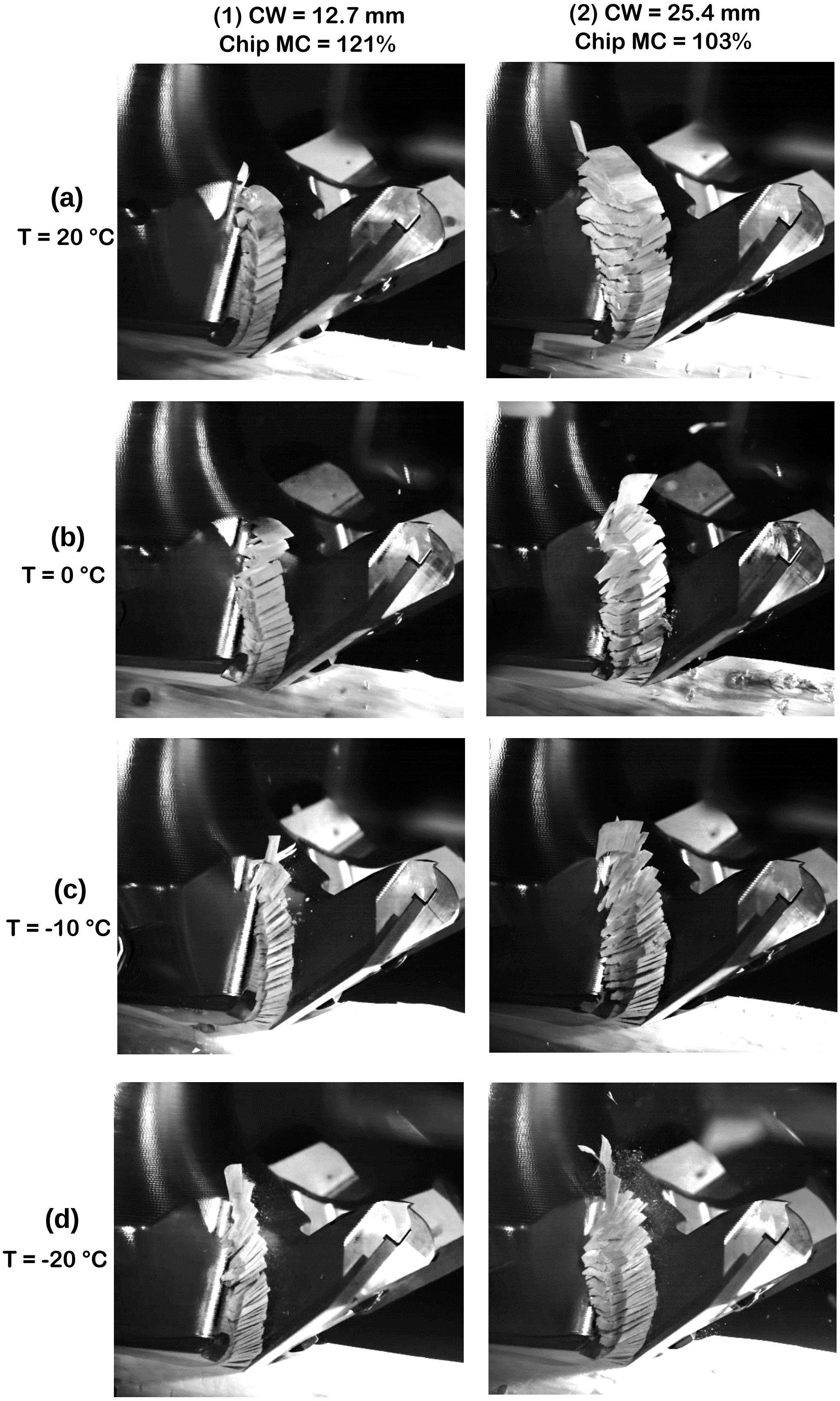

Fig. 3. Progression of the slice fragmentation produced by the chipping edge for two cutting widths (CW) (1) 12.7 mm and (2) 25.4 mm at four wood temperatures (T)

The formation of chips by the chipper-canter has been described in previous works (Kuljich *et al.* 2017; Grubîi *et al.* 2019). The chipping edge cut the wood obliquely to the grain while, simultaneously, the canting edge smoothed the cant surface as it traveled across the grain. Chip formation involved at least two different cutting actions. At the entry point of the knife into the log, the chipping edge compressed the wood obliquely to the grain. The knife then penetrated the log, severing a slice by shearing obliquely to the grain. The feed per knife determines the thickness of the slice, which, after chipping, will correspond to the length of the chips. As the wood slice was formed, it underwent stresses in the parallel and oblique grain directions due to the compression induced by the rake face of the chipping edge. This resulted in a continuous fragmentation of the slice. Accordingly, depending on the attack angle formed between the chipping rake face and the wood grain, chips can be produced by splitting or by shearing parallel to the grain (Kuljich *et al.* 2017). In the present study, chips were mostly produced by splitting, which was desirable because this situation requires less cutting energy.

The high-speed images also showed that as wood temperature decreased from 0 °C to -20 °C, the chip thickness progressively decreased for both CWs, as well as for green logs (Fig. 3) and for air-dried logs. At temperatures below 0 °C, a portion of the MC transforms into ice (free water), while another portion remains in a non-freezing condition (non-freezing bound water) (Li *et al.* 2019). Ordinary ice exhibits brittle behavior under compression at high deformation rates (Schulson 2001; Petrenko and Withworth 2002). Thus, it can be inferred that the presence of ice in green wood during fragmentation increased its brittleness, which means that it would fracture more suddenly with little tendency to deform before rupture. Therefore, chipping by splitting occurred more regularly, resulting in thinner chips. This behavior was amplified as the temperature got colder, which can be associated to the portion of bound water that becomes frozen as higher sub-zero temperatures are reached (freezing bound water) (Telkki *et al.* 2013; Guo *et al.* 2018; Li *et al.* 2019).

In contrast, the cutting width directly affects the wood area in contact with the chipping rake face. As previous studies have reported, a smaller cutting width decreases the split-area in the slice cut by each chipping knife (Fig. 1). Thus, the splitting strength required for chip formation will be more regularly reached, producing thinner chips. In contrast, thicker chips would be obtained with higher cutting widths (Hernández and Lessard 1997; Cáceres *et al.* 2015, 2016, and 2017).

Weighted Mean Chip Thickness

A first analysis of chips sieved by the Domtar classifier can be performed by means of the weighted mean chip thickness (WCT) statistic, which was calculated by using the median value for each 2 mm thickness class separated by the classifier. The expected chip thickness for unfrozen green wood was 5 mm, the median value for the acceptable fraction at a cutting width of 25.4 mm obtained at 88° of attack angle (Kuljich *et al.* 2017). The obtained WCT was 5.10 mm (Table 5), which confirms that this angle is a good alternative to adequately control the thickness of pulp chips.

The ANCOVA showed that WCT was affected by the cutting width and log temperature. The F-values showed that the CW had the greatest effect on the chip thickness (Table 2). Thus, chips were thinner for the smaller CW for all temperatures and moisture contents (Fig. 4). As explained before, the CW directly affects the area of chipping, and therefore the thickness of the chips. This is in agreement with previous studies on the effect of CW on WCT in black spruce logs (Hernández and Lessard 1997; Cáceres *et al.* 2015, 2016, 2017).

Table 2. F-Values Obtained by the Compositional Data ANCOVA of Domtar and Williams Chip Class Distributions and of Weighted Mean Chip Thickness

Source of Variation	Domtar Chip Classes	Williams Chip Classes	Weighted Mean Chip Thickness
Total knot area (TKA)	42.6**	2.9 *	37.9**
Total knot number (TKN)	9.4**	4.8**	13.3**
Sapwood mean thickness (ST)	-	-	7.4**
Temperature (*T*)	71.1**	59.8**	154.5**
Cutting width (CW)	115.2 **	56.1**	392.5**
*T**CW	6.7**	5.5**	1.8 ns
[Moisture content (CW)]	3.5**	3.0**	1.5 ns
*T**MC*CW	1.6*	0.7 ns	3.1**

** Significant at the 1% probability level; * significant at the 5% probability level; ns: not significant

The effect of log temperature on WCT was also important (Table 2). The WCT decreased as log temperature decreased below 0 °C (Fig. 4). In addition, WCT was similar between 20 and 0 °C, which is in agreement with the mechanical behavior of wood (Hernández *et al.* 2014). The decrease of WCT with temperature below 0 °C is associated with changes in the mechanical properties when the wood is frozen. Cáceres *et al.* (2015, 2016, 2017) reported that the modulus of rupture, modulus of elasticity, splitting, and shear strengths are greatly involved in the chipping process. A previous study on black spruce wood at 139% MC, stated that these properties increased as the temperature decreased from 0 to -20 °C, but they showed different sensitivity to the temperature drop (Hernández *et al.* 2014). Accordingly, their combined effect would be different depending on the freezing temperature, resulting in chip size variation. In addition, the presence of ice increased the brittleness of the frozen logs (Koran 1979; Schulson 2001; Petrenko and Withworth 2002; Zhao *et al.* 2015). Thus, as the chipping edge compressed the wood, smaller/thinner chips were generated (Fig. 3d). This behavior would be more pronounced at colder sub-zero temperatures.

The decrease of WCT from 20 °C to -20 °C, obtained at 25.4 mm of CW with logs at green condition, was 1 mm (Table 5). Kuljich *et al.* (2017) also obtained 1 mm of WCT difference using the same cutting parameters, even though the log temperature varied between 18 and -25 °C. It could be expected to obtain a smaller WCT decrease because the sub-zero temperature range was 5 °C lower. However, the similar WCT decrease between these two studies might be attributed to the effect of wood density in chip formation. According to Cáceres *et al.* (2015), higher wood density would result in thinner chips. Mean basic density in the present work was higher (458 kg/m^3) compared to Kuljich *et al.* (2017) (441 kg/m^3), which could account for the similar chip thickness decrease at different ranges of sub-zero log temperatures. This demonstrates that fragmentation is a complex process that can be affected by the wood properties and, therefore, it should be closely monitored to assure a proper chip size consistency.

Moreover, a statistically small but significant three-way interaction affected WCT (Table 2), indicating that the effect of temperature varied depending on the CW and MC. Accordingly, the results showed that at green condition, the difference in WCT between 20 °C and -20 °C was 1.11 mm at 12.7 mm of CW, while it was 1.00 mm at 25.4 mm of CW. For the air-dry condition, this difference was 0.79 mm for the smaller CW and 0.61 mm for the larger CW (Table 5). This behavior is related to the difference in MC between the green and the air-dry conditions at the two studied CWs. Each cutting width had an intrinsic MC represented by the proportions of sapwood and heartwood combined in it. As explained earlier, at 12.7 mm of CW, almost 100% of the slice volume was sapwood. At 25.4 mm of

CW, the slice included a certain volume of heartwood. This resulted in 121% and 79% MC for the smaller CW and 103% and 67% MC for the larger CW, at green and air-dry conditions, respectively. Consequently, a greater effect of temperature on mechanical properties (*i.e.*, splitting) should be found in green wood (Mishiro and Asano 1984; Mishiro 1990; Hernández *et al.* 2014; Zhao *et al.* 2015) compared to air-dried wood, due to the higher amount of ice formed in the logs. Accordingly, Fig. 4 shows that at -20 °C, processing logs with a CW of 12.7 mm, increased WCT from 3.24 to 3.56 when MC decreased from 121% to 79%. Similarly, at -20 °C, processing logs with 25.4 mm of CW resulted in an increase of WCT from 4.10 to 4.38 mm when MC decreased from 103% to 67%. As described earlier, the logs harvested in late fall and in winter will be stored in the log yard for several months before sawing (Trzcianowska *et al.* 2019); therefore a slow log air-drying process is set off. From a practical point of view, it seems that this log storage under colder sub-zero temperatures (≥ -20 °C) during winter could potentially reduce the effect of temperature on WCT.

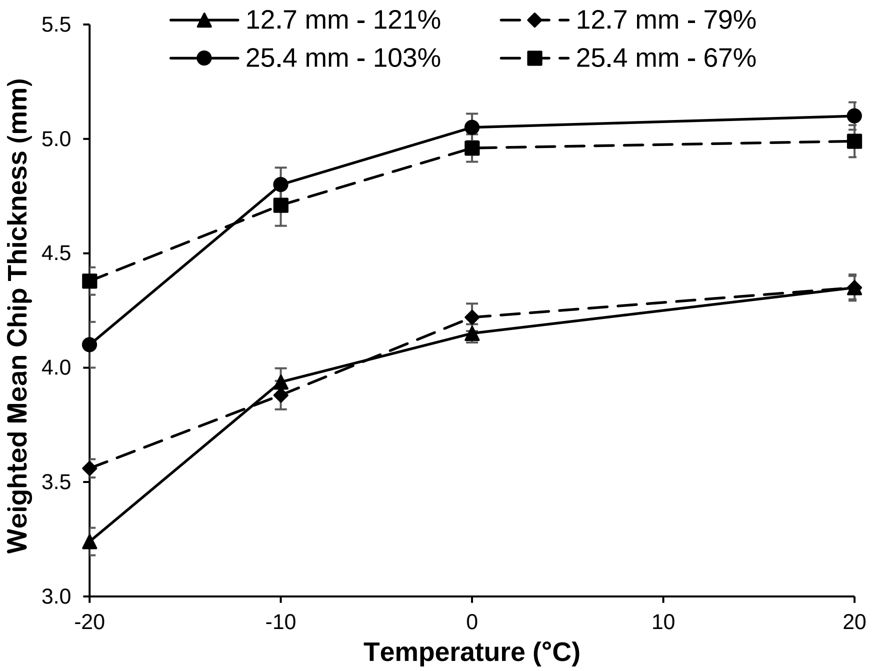

Fig. 4. Weighted mean thickness of black spruce chips as a function of wood temperature for two cutting widths and two chip moisture contents. Bars represent the standard error.

However, the difference in WCT between the two MCs for each CW was not statistically significant when logs were at -10 °C. These results can be partially attributed to the strengthening effect of MC at higher sub-zero temperatures on mechanical properties of green wood (Hernández *et al.* 2014). The splitting strength was estimated for each studied condition using the regression equation developed by Hernández *et al.* (2014) (not shown). The difference in splitting strength between green and air-dried MCs was approximately two times higher at -20 °C compared to -10 °C. This indicates that the difference in mechanical properties generated by the decrease of MC at -10 °C would not suffice to alter the WCT. Moreover, the inherent freezing process of water inside a wood species could also affect its mechanical properties and consequently the WCT. The wood porosity, the difference in the properties of the water in macroscopic and microscopic interstices, the interaction forces between the water and the capillary walls, and the minerals and organic substances dissolved in the water affect the wood freezing process (Torgovnikov 1993). Below the freezing point of bulk water, wood's free water is frozen (MC above FSP, in the cell lumen) (Telkki *et al.* 2013). For bound water (MC below FSP, in the cell wall), there is a portion that remains unfrozen and another one that can be further frozen as higher sub-zero temperatures are reached. This portion will vary with the species because the freezing-point depression is proportional to the pore size (Telkki *et al.* 2013; Gao *et al.* 2015; Li *et al.* 2019). For example, previous studies on *Pinus sylvestris* reported that 17% of bound water can be frozen at -20 °C compared to 5% at -10 °C (Gao *et al.* 2015). Furthermore, the stiffening effect of ice in wood would be stronger as more bound water is frozen within the cell wall (Koran 1979). It would follow that at higher sub-zero temperatures (≥ -20 °C) the proportion of frozen bound water would significantly increase, reinforcing the strength of wood and thus reducing WCT. Seemingly, this would not take place at lower sub-zero temperatures (-10°C). Further studies should be done to fully understand the behavior of WCT in the range of sub-zero temperatures between -10 °C and -20 °C for black spruce wood.

In addition, the covariates that significantly affected WCT were in order of importance (F-value), total knot area (TKA), total knot number (TKN), and sapwood mean thickness (ST) (Table 2). Both TKA and TKN had good correlations with WCT (r = 0.49, r = 0.54, respectively, all data pooled). The weighted mean chip thickness increased as TKA increased (Fig. 5). Thus, as knots covered a larger area of the cant face, thicker chips were produced. A more explicit impact of TKA on WCT can be observed in Fig. 4. For a cutting width of 12.7 mm, TKA was higher at 79% MC (650 mm^2) than at 121% MC (462 mm^2) at -20 °C. This increased the effect of MC on WCT at higher sub-zero temperature, as it was previously explained, producing thicker chips at lower MC. However, TKA was higher in green logs (745 mm^2) compared to air-dried logs (532 mm^2) at -10 °C, which resulted in slightly thicker chips in the former than in the latter. The same behavior was found at a cutting width of 25.4 mm. The number of knots also showed a positive effect on WCT. These results are in agreement with those reported previously by Cáceres *et al.* (2016, 2017) and by Grubîi *et al.* (2019). Overall, this confirms the importance of the knot characteristics on the chip size variation. The sapwood thickness also affected WCT, especially when transforming frozen logs. In fact, a thicker sapwood will promote the formation of thinner chips at sub-zero temperatures. This is in accordance with previous studies of Hernández and Lessard (1997).

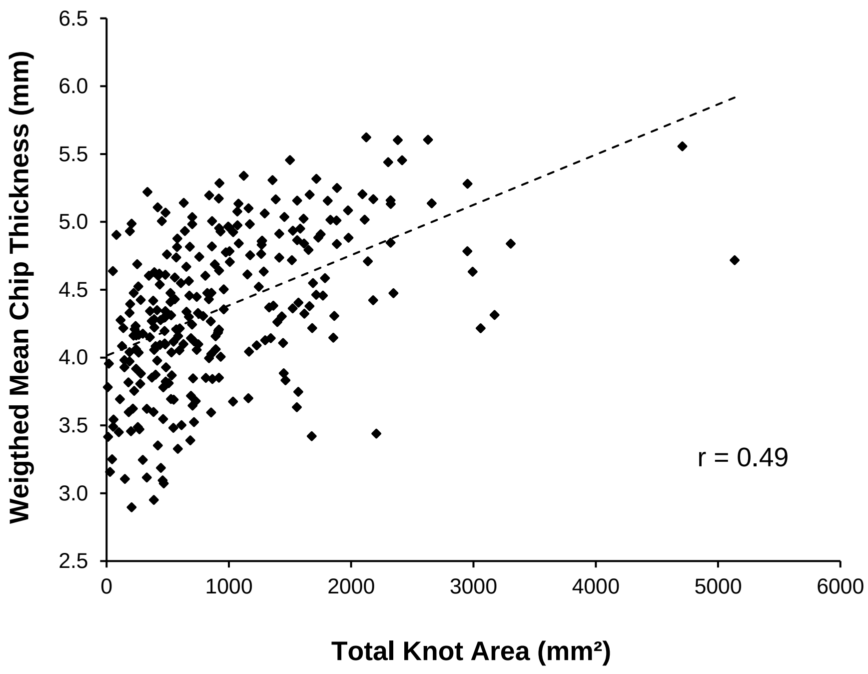

Fig. 5. Relationship between weighted mean chip thickness and total knot area of black spruce chips (all data pooled)

Multiple Linear Regression of WCT

One of the goals of this study was to predict chip thickness for practical applications. Linear regression analyses were performed among WCT and the studied explanatory variables between -20 °C and 0 °C (Fig. 4). The statistical model showed that CW, temperature (*T*), TKA, TKN, and sapwood mean thickness (ST) were significant predictors of WCT (WCT = 3.6 + 0.053 CW + 0.036 *T* + 0.001 TKN + 0.00011 TKA – 0.19 ST). This global fit model gave a coefficient of determination of 84.0% (R^2) and coefficient of variation of 4.9%. The regression showed the combined action of these variables to predict chip thickness. The CW was the most important variable with a positive effect and a contribution to the R^2 of 50.4%, followed by temperature with a contribution to the R^2 of 27.1 %. Moreover, TKN and TKA had positive effects on WCT with contributions to the R^2 of 3.6% and 1.5%, respectively. Finally, ST had a negative effect and a contribution to the R^2 of 0.9%. The high coefficient of determination and the low coefficient of variation confirm that the regression model can be used for predictive purposes. However, at the present time the assessment of TKA and ST just before the log breakdown could represent an important challenge for the industry. Therefore, a second analysis was performed to predict WCT by removing these two parameters. The second model (WCT = 3.27 + 0.056 CW + 0.037 T + 0.016 TKN) explained 81.4% of the WCT variation, with a coefficient of variation of 5.0%. The cutting widths had again the greatest contribution to the R^2 of 52.2%, followed by the temperature and TKN with contributions of 26.2% and 3.1% to the R^2, respectively. This second model remains performant and could be used to effectively predict chip thickness. Accordingly, WCT can be adjusted by using primarily the CW. The technology to measure the other concerned variables before processing the logs has been in the market for several years. An infrared camera could be used to measure the log temperature. In addition, the CT scan technology accurately recognizes knots and is already used in several sawmills to optimize log breakdown. Therefore, sawmills could take advantage of the given knowledge to better control chip thickness during fragmentation and thereby improving chip size uniformity and consistency. However, it is important to indicate that this regression did not use MC to predict WCT because its effect was significant only at -20 °C, which has been already explained. Therefore, the WCT prediction model would be less robust at higher sub-zero temperatures and thus the estimated WCT value would be less accurate.

Domtar and Williams Chip Class Distributions

Multivariate analysis of covariance for Domtar and Williams chip class distributions were performed to study the chip formation process as a whole. They took into account the existing dependences among the chip classes and showed that they were affected differently by CW, temperature, and MC. Table 2 shows that log temperature and CW had the strongest effects (F-values) on the thickness (Domtar) and width/length (Williams) distributions. In addition, the significant effect of their interaction was also well represented in both distributions. However, the effect of MC, which was nested in each CW, and the three-way interaction among temperature, CW, and MC (Table 2) was poorly represented on the individual chip classes and in terms of chip volume (only fines, Table 3). Thus, no further discussion was given on them.

The compositional data approach that was applied did not allow comparisons of the real values of each class because it works with proportions. Therefore, univariate analyses of covariance were performed for each class of Domtar and Williams chip size distributions (Tables 3 and 4). The significant covariates obtained in the MANCOVAs were kept in each class analysis to observe their specific influence on each chip class.

Table 3. F-Values Obtained from the ANCOVAs for each Domtar Chip Classes

Source of Variation	Domtar Chip Classes				
	Fines	Fragile Chips	Accepts	Overthicks	Oversize
TKA	8.2**	0.6 ns	30.3**	119.3**	37.6**
TKN	6.1*	18.5**	2.3 ns	15.4**	0.1 ns
T	103.8**	171.4**	92.7**	39.8**	1.6 ns
CW	12.4**	281.2**	64.9**	133.0**	7.1**
T*CW	3.3*	4.7**	13.8**	3.4*	3.0*
[MC (CW)]	23.0**	0.7 ns	0.1 ns	1.5 ns	2.4 ns
T*MC*CW	3.5**	1.9 ns	1.2 ns	1.5 ns	1.4 ns
** Significant at the 1% probability level; * significant at the 5% probability level; ns: not significant					

Table 4. F-Values Obtained from the ANCOVAs for each Williams Chip Classes

Source of Variation	Williams Chip Classes				
	Fines	Pin Chips	9.5 mm	Accepts	≥ 45 mm
TKA	6.4*	2.9 ns	1.1 ns	0.4 ns	11.1**
TKN	5.8*	9.2*	0.1 ns	2.4 ns	0.4 ns
T	97.7**	96.0**	40.7**	80.3**	3.0*
CW	34.5**	48.0**	63.7**	76.4**	7.2**
T*CW	6.3**	7.9**	1.2 ns	8.2**	2.5 ns
[MC (CW)]	10.8**	1.7 ns	0.2 ns	1.0 ns	0.3 ns
T*MC*CW	1.0 ns	1.6 ns	0.3 ns	0.8 ns	0.7 ns
** Significant at the 1% probability level; * significant at the 5% probability level; ns: not significant					

Domtar and Williams chip class distributions were significantly affected by TKA and TKN as covariates (Table 2). For Domtar distribution, TKA had a significant effect in all classes except for fragile chips. These classes altogether represented around 86% of the total chips (Table 3). The increase of TKA resulted in the increase of thicker chips (accepts, overthick, and oversize) and the decrease of thinner chips (fines). The total knot number had a significant effect on fines, fragile, and overthick classes, which represented 20% of chips (Tables 3 and 5). The effect of TKA on WCT was more relevant to that of TKN. This is in agreement with previous findings that established the importance of the number and size of knots on Domtar chip distribution (Cáceres *et al.* 2015, 2016, 2017). Total knot area and TKN affected in a lesser degree the width and length of chips. For Williams distribution, TKA affected significantly fines and ≥ 45 mm chip classes, which represents 3% of the total volume of chips. The total knot number had an influence on 9.5% of the chip volume coming from fines and pin chips (Tables 4 and 6). Therefore, the chip thickness was more sensitive to the presence and size of knots compared to the chip width/length.

As shown in Tables 3 and 4, all Domtar chip classes and most of the Williams chip classes including fines, pin chips, and accepts, showed a significant interaction of CW and temperature. These results are consistent with the MANCOVAs, showing that chip classes varied differently with temperature and cutting width (Table 2). The F-values showed that this interaction was stronger for the accept chips of both distributions. Figure 6 shows this interaction for the Williams accepts, which decrease as the temperature decreases below 0 °C. The effect of temperature was more pronounced at the smaller CW, which is explained by the higher volume of sapwood transformed into chips.

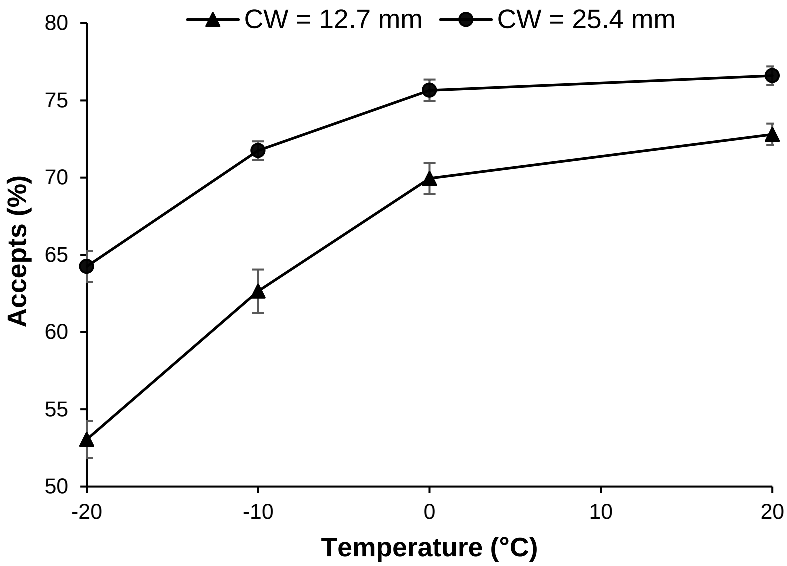

Fig. 6. Proportion of Williams acceptable chips as a function of temperature for two cutting widths (all chip MCs pooled)

Table 5. Mean Values of Domtar Chip Class Proportions and Weighted Mean Chip Thickness Obtained for Each Cutting Condition of Black Spruce

CW (mm)	Chip MC (%)	Temper-ature (°C)	Fines	Fragile Chips	Accepts	Over-thicks	Over-size	WCT (mm)
12.7	121	-20	2.08[a] (0.20)[a,b]	25.3 (1.2)	71.4 (1.3)	1.2 (0.1)	0.03 (0.03)	3.24 (0.06)
		-10	1.54 (0.15)	17.9 (0.8)	77.5 (0.9)	3.1 (0.4)	0.00 (0.00)	3.94 (0.06)
		0	0.92 (0.08)	14.4 (0.4)	81.3 (0.7)	3.4 (0.4)	0.00 (0.00)	4.15 (0.04)
		20	0.49 (0.02)	11.0 (0.5)	84.4 (0.4)	4.0 (0.3)	0.09 (0.07)	4.35 (0.06)
	79	-20	1.57 (0.19)	22.6 (0.9)	73.4 (1.0)	2.3 (0.2)	0.12 (0.06)	3.56 (0.04)
		-10	1.11 (0.16)	18.1 (0.9)	77.9 (1.0)	2.8 (0.3)	0.07 (0.04)	3.88 (0.06)
		0	0.68 (0.08)	14.5 (0.5)	80.7 (0.6)	4.0 (0.4)	0.19 (0.10)	4.22 (0.06)
		20	0.38 (0.02)	11.8 (0.5)	83.7 (0.5)	4.1 (0.3)	0.02 (0.02)	4.35 (0.05)
25.4	103	-20	1.94 (0.21)	15.4 (0.9)	78.2 (0.8)	4.4 (0.6)	0.06 (0.03)	4.10 (0.10)
		-10	0.95 (0.07)	10.6 (0.4)	80.9 (0.7)	7.2 (0.6)	0.30 (0.09)	4.80 (0.07)
		0	0.75 (0.06)	8.5 (0.5)	82.8 (0.7)	7.8 (0.5)	0.08 (0.03)	5.05 (0.06)
		20	0.47 (0.02)	7.0 (0.3)	84.8 (0.9)	7.5 (0.7)	0.21 (0.09)	5.10 (0.06)
	67	-20	0.95 (0.07)	13.6 (0.6)	79.4 (0.6)	5.6 (0.4)	0.42 (0.31)	4.38 (0.06)
		-10	0.79 (0.08)	11.3 (0.5)	80.7 (0.8)	6.9 (0.8)	0.31 (0.12)	4.71 (0.09)
		0	0.55 (0.04)	9.3 (0.3)	82.3 (0.5)	7.5 (0.5)	0.34 (0.13)	4.96 (0.06)
		20	0.37 (0.02)	7.4 (0.3)	84.9 (0.5)	6.8 (0.5)	0.60 (0.19)	4.99 (0.07)

[a] Means of 15 replicates; [b] Numbers in parentheses are the standard errors of the mean

The total volume of removed material at 12.7 mm of CW corresponded to 98% of sapwood, which was reduced to 76% at 25.4 mm of CW. Moreover, the greater amount of ice present in the sapwood compared to the heartwood lead to a higher sensitivity to the temperature decrease below 0 °C for the smaller CW. The weighted mean chip thickness was directly related to the proportion of accepts (Figs. 4 and 6), because it concentrated the highest volume of chips. Therefore, the adjustment of the nominal chip thickness in an adequate manner is essential to avoid an important decrease of the accept chips at temperatures below zero.

The mean values of the Domtar and Williams chip classes by cutting width, moisture content, and temperature are summarized in Tables 5 and 6. Chip classes are expressed as percent weight of the total chips. The temperature affected all Domtar classes, except for oversize chips (about 0.2% of chips total volume). As temperature increased, the proportion of smaller chip classes decreased and, hence the bigger ones increased.

Table 6. Mean Values of Williams Chip Class Proportions Obtained for Each Cutting Condition of Black Spruce

CW (mm)	Chip MC (%)	Temper-ature (°C)	Fines	Pin Chips	9.5 mm	Accepts	≥ 45 mm
12.7	121	-20	5.99[a] (0.69)[b]	12.0 (0.6)	29.8 (0.8)	52.1 (1.8)	0.00 (0.00)
		-10	4.64 (0.45)	9.6 (0.5)	24.1 (1.0)	61.7 (1.9)	0.00 (0.00)
		0	2.72 (0.26)	6.9 (0.3)	20.9 (1.1)	69.5 (1.0)	0.00 (0.00)
		20	1.06 (0.06)	4.8 (0.2)	21.6 (0.8)	72.5 (0.9)	0.06 (0.05)
	79	-20	4.45 (0.52)	11.9 (0.6)	29.6 (0.7)	54.0 (1.6)	0.00 (0.00)
		-10	3.20 (0.48)	8.6 (0.7)	24.7 (1.1)	63.6 (2.1)	0.00 (0.00)
		0	1.90 (0.28)	6.5 (0.6)	21.3 (1.2)	70.4 (1.7)	0.03 (0.03)
		20	0.85 (0.04)	4.2 (0.2)	21.9 (0.9)	73.1 (1.0)	0.00 (0.00)
25.4	103	-20	3.65 (0.44)	8.6 (0.6)	23.5 (0.7)	64.2 (1.6)	0.02 (0.02)
		-10	2.23 (0.15)	6.1 (0.2)	19.1 (0.6)	72.5 (0.7)	0.11 (0.08)
		0	1.41 (0.16)	4.7 (0.4)	17.5 (1.1)	76.3 (1.5)	0.13 (0.06)
		20	1.01 (0.08)	4.6 (0.3)	18.5 (0.7)	75.6 (0.8)	0.35 (0.13)
	67	-20	2.74 (0.35)	8.5 (0.4)	24.4 (0.8)	64.3 (1.3)	0.08 (0.06)
		-10	2.07 (0.22)	6.5 (0.4)	20.3 (0.5)	71.0 (0.9)	0.11 (0.07)
		0	1.48 (0.15)	5.1 (0.2)	18.0 (0.6)	75.0 (0.8)	0.39 (0.11)
		20	0.74 (0.04)	3.7 (0.2)	17.7 (0.8)	77.6 (0.9)	0.32 (0.10)

[a] Means of 15 replicates
[b] Numbers in parentheses are the standard errors of the mean

When transforming logs at the smaller CW, as the temperature increased from -20 °C to 20 °C, the fragile fraction decreased drastically from 23.9 to 11.4% and the accepts increased from 72.4 to 84.1%. Similarly, when transforming logs with the larger CW (25.4 mm), as the temperature increased from -20 °C to 20 °C, the fragile fraction decreased from

14.5 to 7.2% and the accepts increased from 78.8 to 84.9%. These comparisons were done when values of both MCs were pooled. Similar results were found with the Williams chip classes, in which the fines, pin chips, and 9.5 mm classes decreased as temperature increased in contrast to the increase in the accepts and over 45-mm classes. The amount of fines was approximately four times higher at -20 °C than at 20 °C for the cutting width of 12.7 mm and three times higher for the cutting width of 25.4. Pin chips increased from 4.5% to 12.0% at 12.7 mm CW and from 4.2% to 8.6% at 25.4 mm CW, as temperature decreased from 20 to -20 °C. The strong relationships between fines and pin chips with sub-zero temperatures are in agreement with the results reported in previous studies (Wallace *et al.* 1992; Hernández and Quirion 1993; Hernández and Boulanger 1997; Hernández and Lessard 1997).

Even though the fines represent only a little fraction of the total volume of chips, these particles, together with the pin chips, have great impacts in the pulp cooking processes (Hart 2009). Each pulp and paper mill has specific chip quality requirements for its pulping process (mechanical and/or chemical pulping). Domtar and Williams chip class distributions have to fit with these requirements. For example, in a thermomechanical pulp process, a limit of 8 % of rejects of the total chip volume (fines and pin chips) is imposed considering a maximum of 1% of fines (Bélanger and Savard 2016). The authors' results showed that this limit was respected when processing logs at 20 °C and it was exceeded when processing logs at temperatures below 0 °C. A temperature decrease from 20 to -20 °C increased the proportion of rejects from 5.5 to 17.7% and from 5.0 to 11.8% at a cutting width of 12.7 and 25.4 mm, respectively.

Overall, the log temperature should be taken into consideration to adjust the cutting parameters of the chipper-canter to minimize the amount of smaller size chips and thus avoiding the penalties imposed by pulp industries. For instance, Hernández and Boulanger (1997) found that a faster cutting speed for a given chip length produced thinner chips. Under the specific cutting conditions used here, decreasing the cutting speed in winter would increase the WCT and reduce the amount of rejects. Therefore, changing cutting speed as a function of temperature and cutting width can be used to improve chip size uniformity. However, reducing the cutting speed would negatively affect the sawmill productivity. Another possibility could be to use different knives depending on log temperature. Grubîi *et al.* (2019) found that a higher inclination angle of the chipping knife would result in thicker chips. Thus, using this type of knife during winter could again reduce the amount of rejects. The results also indicate that it could be advantageous to keep the logs harvested during fall and stored in the yard for a certain time (up to 62% sapwood MC, Table 1). This air-drying of logs would moderately reduce their MC and thus lessen the negative effect of coldest sub-zero temperatures (≥ -20 °C) on WCT. However, further studies are required to evaluate the effect of air-drying logs for longer periods (sapwood MC ≤ 62%) on chip size distribution, especially at colder sub-zero temperatures.

CONCLUSIONS

1. The cutting width had an important effect on the size distribution of black spruce chips produced by a chipper-canter. Smaller CWs resulted in thinner chips and higher proportions of small particles.
2. Chip size was significantly affected by the temperature and in a slighter degree by the moisture content of the logs. Mean chip thickness and accept chips were generally similar at temperatures between 0 and 20 °C, and significantly decreased as temperature decreased below 0 °C. This effect appeared related to changes in the mechanical properties of wood due to the temperature variation. Moreover, the effect of

temperature on WCT under frozen conditions varied with the moisture content of logs. In general, the storage of logs under harsh cold conditions (-20 °C), enabling their progressive air-drying down to a certain level of sapwood moisture content (≥ 62% MC), could increase WCT and lead to better chip quality.

3. Regression equations were established to predict the chip thickness. These models give useful information to adjust the cutting parameters of chipper-canters working under similar conditions to effectively maintain the target WCT throughout the year.

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