Stem form variations in the natural stands of major commercial softwoods in eastern Canada

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1. Introduction

The lumber industry in Canada plays an important role in the whole value chain of wood processing and utilization. Lumber recovery (e.g., lumber volume, value and grade) is one of the most important measures to appraise the performance of the industry. Over the past four decades, sawmilling research and development of technologies have contributed to a significant improvement in the overall lumber recovery in Canada. It is well-known that lumber recovery depends highly upon resource characteristics. Of different resource characteristics, stem geometry or form (e.g., stem taper and deformations) is of critical importance to lumber recovery (Zhang et al., 1997, 2005). To maximize product recovery and economic value of the forest resource, it is important to understand the variability of these stem quality attributes in major commercial species.

Various studies indicated that stem form is affected by site quality and stand density (Ballard and Long, 1988; Birk, 1991), container design (Rune, 2003), regeneration method (Karkkainen and Uusvaa, 1982), initial spacing (Tong and Zhang, 2005) and external forces (Leaphart et al., 1972). In addition, stem form is genetically controllable (Vidakovic and Ahsan, 1970; Shelbourne and Stonecypher, 1971), and different species have different stem forms. Many have reported that stem taper and deformations like sweep and crook have significant effects on tree value, product recovery and lumber properties (Brown and Miller, 1975; Dobie and Middleton, 1980; Cown et al., 1984; Cahill and Cegelka, 1989; Heneka, 1993; Monserud et al., 2004). While numerous models and taper equations have been developed to describe stem diameter profile and taper for various species, limited information...
has been documented on stem deformations. Embry and Gottfried (1971) presented an overstorey inventory data analysis for Arizona mixed conifers showing the frequency of stem quality features including sweep, crook, lean and forks. A curve sawing study based on seven sawmills investigated stem deformations including sweep and crook in spruce-pine-fir (Corneau, 1989) and alpine fir (Middleton and Munroe, 1984). However, no single study has been conducted on the variability of stem form in a relatively large wood supply region like eastern Canada.

The objective of this study was to quantify the variations in stem form for major commercial softwood species from different regions in eastern Canada. A better understanding of the stem form variations in major commercial species will help not only the industry optimize wood processing to maximize the value from the highly variable fibre resource, but also forest managers choose appropriate silvicultural regimes.

2. Data

Data used in this study were from a stem bank established by FPInnovations - Forintek Division. The stem bank contains detailed three-dimensional (3-D) geometric information and stem-level characteristics for each stem. The 3-D geometrical data include cross-sectional coordinates in 3-D and diameters at both x- and y-axes collected at 5–20 cm intervals along the stem from butt to top using a portable scanner (C1-Scan&Snap-Scan, COMACT Optimization). Fig. 1 illustrates a visualized image of such 3-D geometric data of a stem. Stem-level characteristics include diameter at breast height (DBH) class, species and provenance (region from which the stem originated).

Information associated with major commercial softwood species in eastern Canada, namely jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana*), white spruce (*Picea glauca*), red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*), was extracted from the stem bank. Logs bucked from tree-lengths were not used. Stems were originated from 31 sawmills scattered in three regions (Fig. 2) representing typical species distributions in the spruce-pine-fir group in eastern Canada (Bédard, 2001). In region A, overall species composition was 76% spruce, 9% balsam fir and 15% jack pine; in region B, 75% spruce and 25% balsam fir; and in region C, 40% spruce and 60% balsam fir.

Several sawmill studies have been carried out in each sawmill over years. In each sawmill study, stems were randomly selected from the mill yard to cover the whole diameter range without considering exterior characteristics. The 3-D geometric data were used to determine large end diameter (DLE), small end diameter (DSE), stem length, taper, sweep, eccentricity and stem volume. Inside-bark DBH for each stem was calculated by averaging two-axis diameters at a 1.15 m height from the butt of the stem (stump height 15 cm). Based on the calculated DBH, total tree height was estimated using Chapman–Richards’ three-parameter diameter–height model (Richards, 1959; Chapman, 1961) for boreal forest species in Ontario (Peng et al., 2001).

Sweep in this study was defined as a gradual curvature of the longitudinal axis of a stem. It was measured as the maximum deviation from a straight line running from end to end over the total stem length. Overall stem taper was measured as the diameter difference between stem ends over the whole stem length, while stem taper and volume were determined based on the stem length up to a 9 cm diameter top, or alternatively total stem length if the DSE was larger than 9 cm. Eccentricity in this study was estimated as the ratio of the small axis diameter to the large axis diameter at breast height. As butt log is generally the most valuable part in a tree-length, basal sweep and butt taper were also determined for the first 8-foot-long (2.54 m) log from butt for each stem.

Analysis of variance was performed for taper, sweep and eccentricity grouped by DBH class, species and region. SAS software (SAS Institute Inc., 1999) was used for most tests in this
study. SPSS (SPSS Inc., 2005) was used to perform post hoc tests when variances in groups were not equal.

3. Results

It was obvious that the majority of the stems (78%) had a DBH ranging from 10 to 32 cm, while only a small proportion of the stems (3%) had a DBH over 40 cm (Fig. 3). The DBH in black spruce and balsam fir was mainly distributed between the 10 and 26 cm classes. As these two species accounted for 75% of the total number of the stems, the shape of the DBH class distribution curve was skewed (Fig. 3).

Total tree height ranged from 7 to 28 m for all stems (Table 1). The majority of the stems (80%) had a total height ranging from 10 to 20 m. Average merchantable stem length was 10.6 m with a DSE ranging from 9 to 26.9 cm. Large values for DSE, such as 26.9 cm, probably resulted from the transportation limitations for the stem length. Merchantable volume ranged from 0 to 3148.4 dm$^3$, with an average of 295.7 dm$^3$.

As the available number of stems falling within the DBH classes of 50 cm and larger was not sufficient for statistical analysis, these stems were not included. For the same reason, stems of the 6 cm DBH class were also excluded. Totally 7018 stems were used for analysis including 1182 jack pine, 4143 black spruce, 464 white spruce, 46 red spruce and 1183 balsam fir stems.

3.1. Stem taper

The average overall taper was 1.15 cm/m, and the average stem taper was 1.0 cm/m, which fits the general assumption for stem taper. There was a 0.15 cm/m difference between the overall and merchantable tapers, which indicated a larger taper on the top of stem than through its length. Of 7018 stems, 10.1% had a taper larger than 1.5 cm/m, 15.5% between 1.2 and 1.5 cm/m, and 74.4% under 1.2 cm/m. The coefficients of variance (CV) by DBH class, species and region of origin were computed for stem taper to examine the consistency of stem taper within each group. Except for the smallest DBH classes (8 and 10 cm), the CVs for all DBH

### Table 1

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<th>Number of stems</th>
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<th>DSE$^b$ (cm)</th>
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$^a$ Large end diameter.  
$^b$ Small end diameter.  
$^c$ Standard deviation.
classes were not over 30% (Table 2), indicating that within each DBH class, stem taper varied over a relatively narrow range. The CV values for all species, except for white spruce, and for all regions were over 30% (Table 2).

With increasing DBH from 10 to 48 cm, stem taper increased steadily from 0.78 to 1.75 cm/m (Table 4). The Levene’s test showed that the null assumption for equality of taper variances was violated (Table 3). The Welch analysis indicated that the differences in stem taper were significant at $p < 0.0001$ among DBH classes and among species. The Dunnett’s C multiple comparison was then performed to compare the difference between each possible pair of DBH classes and of species. With a couple of exceptions, each DBH class, up to 32 cm, had a significantly smaller taper than the larger DBH classes (Table 4).

### Table 2

<table>
<thead>
<tr>
<th>DBH class (cm)</th>
<th>Number of stems</th>
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<td>Probability</td>
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| Stem taper | DBH class | 11.17 | <0.0001 | 338.5 | <0.0001*
| Species  | 17.83 | <0.0001 | 183.66 | <0.0001*
| Region   | 23.85 | <0.0001 | 2.5 | 0.0824*
| Butt taper | DBH class | 36.80 | <0.0001 | 391.90 | <0.0001*
| Species  | 34.07 | <0.0001 | 97.35 | <0.0001*
| Region   | 22.13 | <0.0001 | 22.53 | <0.0001*
| Stem sweep | DBH class | 1.09 | 0.3495 | 1.73 | 0.0231
| Species  | 8.52 | <0.0001 | 44.87 | <0.0001*
| Region   | 9.48 | <0.0001 | 74.33 | <0.0001*
| Basal sweep | DBH class | 2.91 | <0.0001 | 1.39 | 0.1182*
| Species  | 2.09 | <0.0001 | 10.35 | <0.0001*
| Region   | 9.42 | <0.0001 | 4.0 | 0.0187*
| Eccentricity | DBH class | 1.37 | 0.1238 | 1.90 | 0.0091
| Species  | 4.63 | 0.0010 | 4.45 | 0.0016*
| Region   | 10.77 | <0.0001 | 5.3 | 0.0052*

* Welch’s ANOVA.
terms of species, white spruce appeared to have the largest taper, followed by jack pine and balsam fir, while black spruce had the smallest taper. The region of origin did not show a statistically significant effect ($p = 0.0824$) on stem taper (Table 3).

### 3.2. Butt taper

Butt logs had an average taper of 1.83 cm/m, which is much larger than the overall stem taper. With increasing DBH from 8 to 48 cm, butt taper increased steadily from 0.74 to 4.23 cm/m. The paired $t$-test indicated that butt taper was significantly larger than stem taper grouped by either DBH class ($p < 0.0001$), species ($p = 0.0050$), region ($p = 0.0070$) or individual ($p = 0.0000$). Butt taper also appeared to be more inconsistent than stem taper within each DBH class, species and region (Table 2).

Similar to stem taper, the assumptions of equal butt taper variances and means in groups under each group name were rejected ($p < 0.0001$) (Table 3). The Dunnett’s $C$ test demonstrated a similar pattern of difference for butt taper to that seen for stem taper grouped by DBH class. Though butt taper for red spruce was not significantly different from that of either white spruce or jack pine, generally butt taper followed the following descending order: white spruce (2.99 cm/m), red spruce (2.39 cm/m), jack pine (1.86 cm/m), black spruce (1.73 cm/m) and balsam fir (1.63 cm/m). Region C seemed to produce smaller-tapered butt logs than did regions A and B.

### 3.3. Eccentricity

The average eccentricity was 0.96 with a standard deviation of 0.03. Only 3.1% of the stems had an eccentricity of less than 0.9, of which only 2.1% were under 0.8. However, more than 75% of the stems had an eccentricity over 0.95. The small CV values ($<4.0\%$) (Table 2) indicated a high consistency of the eccentricity data. The Tukey test showed that only the difference between 44 and 8 cm DBH classes were significant. The differences were significant between species ($p < 0.0016$) and between regions ($p = 0.0052$) (Table 3). The Dunnett’s $C$ test further indicated that jack pine (0.961) had a slightly but significantly less round cross-section than both balsam fir (0.966) and black spruce (0.964). No significant differences could be observed between other pairs of species. Stems from region C had a more round cross-section than those from regions A and B.

### 3.4. Stem sweep

Sweep reflects the straightness of a log or a stem. Overall sweep based on the 7018 stems averaged 0.87 cm/m. The maximum, minimum and standard deviations were 7.28, 0.12, and 0.5375 cm/m, respectively. These statistics suggest that stem sweep varied over a wide range, and that some stems were seriously curved. The 10 most extremely curved stems were black spruce, each having a sweep over 5 cm/m. Severe sweep not only reduces lumber recovery (Monserud et al., 2004; Dobie and Middleton, 1980), but lowers productivity and operability during conversion, and weakens mechanical properties. However, seriously curved stems (sweep $>3.0$ cm/m) accounted for only 0.77%, while 96.2% had a sweep less than 2.0 cm/m, within which 73.2% were not over 1.0 cm/m (Fig. 4). Jack pine and black spruce had a similar proportion of stems with intermediate ($<2.0$ cm/m) and small sweep ($<1.0$ cm/m). Black spruce stems with severe sweep ($>2.0$ cm/m) accounted for a slightly higher proportion (4.7%) than jack pine (1.8%), however, this had caused a significantly ($p < 0.0001$) higher average sweep for black spruce (0.91 cm/m) than for jack pine (0.86 cm/m).

The overall CV of 61.5% (Table 2) indicated highly varied sweep data. Sweep was also highly variable within DBH classes, especially within the 12, 18 and 46 cm DBH classes. Within-species and within-region consistencies were similar to that of within-DBH class. The Levene’s test demonstrated an equal sweep variance

![Fig. 4. Stem sweep distributions for white spruce, black spruce, red spruce, jack pine and balsam fir.](image-url)
between DBH classes but not between species or between regions. ANOVA indicated significantly different sweeps between DBH classes \( (p = 0.0231) \) (Table 3), however, the difference appeared significant only between the 46 and 16 cm DBH classes based on the least significant difference test, while no difference between any possible pair of DBH classes was detected by other tests such as Tukey–Kramer or Student–Newman–Kel. While black spruce had a larger sweep than jack pine, balsam fir had the smallest sweep. Region C produced stems with a smaller sweep than did regions A and B.

3.5. Basal sweep

The average basal sweep was 0.95 cm/m. Butt logs had a more acute maximum sweep (9.85 cm/m) than the whole stems (7.28 cm/m). The 10 most curved butt logs had an average basal sweep of 7.7 cm/m and 6 of which were black spruce. Of the 7108 stems, 1.2% had a basal sweep larger than 3.0 cm/m, 28.5% fell between 1.0 and 2.0 cm/m, and 66.2% were less than 1.0 cm/m. The paired \( t \)-test further confirmed that butt logs were more seriously deformed than the whole stems \( (p < 0.0001) \). Jack pine had a higher proportion of intermediate sweep (1.0–2.0 cm/m) butt logs, but a lower proportion of small \(<1.0 \text{ cm/m}\) and severe sweep \( (>2.0 \text{ cm/m}) \) butt logs than the other species (Fig. 5).

Like stem sweep, basal sweep varied over a wide range (Table 2). The most extreme variations occurred in the DBH classes of 44 and 46 cm with CV values of 104% and 131%, respectively. The Levene’s tests showed significantly disparate variances between DBH classes and between regions (Table 3). No significant differences in basal sweep were detected between DBH classes \( (p = 0.1182) \). However, region B produced more seriously deformed butt logs than did region C, while neither region was different from region A. Balsam fir produced significantly straighter butt logs than did all other species, while red spruce had the most seriously curved butt logs. No significant differences in basal sweep could be detected among jack pine \((0.98 \text{ cm/m})\), black spruce \((0.95 \text{ cm/m})\) and white spruce \((1.02 \text{ cm/m})\).

4. Discussion

Stem form is one of the most important external stem quality parameters, often used as log assortment criterion. Inferior stem form, such as larger taper, sweep or crookedness, is usually related to low lumber recovery, poor mechanical property and high processing cost.

Stem taper had statistically significant effects on lumber recovery (Heneka, 1993), bending stiffness and strength (Haartveit and Flate, 2002). It is widely accepted that there is a strong correlation between tree size and stem taper, and a larger taper for a given tree size is associated to a large extent with a wider tree spacing or a lower stand density. This study showed that stem taper increased steadily with increasing tree diameter (Table 4). A similar trend has been observed in natural jack pine (Zhang et al., 2006), plantation-grown jack pine (Tong and Zhang, 2005) and plantation-grown black spruce (Zhang and Chauret, 2001).

Stem straightness (e.g., sweep and crook) is closely associated with deviations in grain angle and the formation of compression wood. An increased grain angle leads to increased drying distortion and warp as well as a reduction in lumber stiffness and strength (Zobel and Haught, 1962). Compared with normal wood, compression wood has a shorter tracheid length, a greater microfibril angle and a higher lignin content (Zobel and Haught, 1962; Brändström, 2004). These characteristics of compression wood may result in a failure under bending and in longitudinal shrinkage (Green et al., 1999; Gindi, 2002), lumber deformation (Warendsjo and Lundgren, 1998), and a conspicuous decrease in the yield of chemical pulping (Timell, 1986). Sweep and crook may cause a higher logging and transportation cost by occupying a larger space, decrease operability in debarking and lumber conversion, while reducing lumber recovery (Brown and Miller, 1975; Dobie and Middleton, 1980; Cown et al., 1984; Monsrud et al., 2004) and weakening mechanical performance if conventional sawing is applied (Taylor and Wagner, 1996). This study revealed that, although stem sweep is a frequently occurred defect in the commercial softwood species grown in eastern Canada, 73% of the stems from the natural stands had a very small sweep \(<1.0 \text{ cm/m}\), and only a very small proportion had a sweep over 3.0 cm/m. Generally, effects of sweep and crook on lumber recovery may be diminished to a large extent during lumber conversion by jump cutting and optimized bucking. Modern sawmill technologies like curve sawing may also improve lumber recovery, lumber stiffness and strength from sweepy logs (Taylor and Wagner, 1996).

Jack pine is known to have an inferior stem form, especially plantation-grown trees (Tong and Zhang, 2005). In this study, jack pine had a smaller overall stem sweep than black spruce. This seems to contrast with the general perception that jack pine is less straight than black spruce. However, the basal sweep was slightly higher in jack pine than in black spruce though the difference was not statistically significant. The difference \((0.12 \text{ cm/m})\) between basal sweep and stem sweep in jack pine was relatively large compared to that in black spruce \((0.03 \text{ cm/m})\). Moreover, when stems were bucked into 8-foot-long logs, jack pine had a considerably more severe log sweep \((0.91 \text{ cm/m})\) than black spruce \((0.76 \text{ cm/m})\) and other species \((0.61–0.72 \text{ cm/m})\). This suggests that sinuosity may occur more frequently in jack pine than in other species.

Butt logs are larger in size hence have greater potential to produce higher-valued products. As accelerated diameter growth due to stand density management tends to weaken with increasing stem height (Zarnovican and Laberge, 1996; Koga et al., 2002), stem taper is not constant along the stem, as evidenced by the significantly larger butt taper. Basal sweep is strongly correlated to compression wood content in young trees (Rune, 2003), and is one of the most frequently occurred stem form defects in some species, such as Douglas fir (Sundström and Keane, 1999) and maritime pine (Auberlinder, 1983). This study showed that butt logs had a larger taper and more severe sweep than whole stems, but badly deformed butt logs accounted for only a small proportion \(<2.0\%\) (Fig. 5).

The average eccentricity value \((0.96)\) was close to 1.0, suggesting that the difference between the \(x\)- and \(y\)-axis diameters at breast height was small. This value was somewhat larger than
that reported for coastal western hemlock (0.92) (Kellogg and Barber, 1981). The small CV values (<4.0%) (Table 2) indicate that stem eccentricity was distributed over a narrow range. However, eccentricity in this study measured only the roundness of stem cross-section at breast height rather than the eccentric distance between the geometric center and pith, therefore it revealed only the cross-sectional shape rather than the presence of compression wood.

As species compositions were different among the three regions (Fig. 2), the regions having a higher proportion of better stem form species appeared to have a better stem form. Therefore, the differences in stem form between the regions may be explained by the differences in species composition. As discussed above, stem taper and sweep have negative effects on wood and lumber quality and product recovery. Stem form is affected by stand density management and regeneration method, and is also genetically controllable. Therefore, it is possible to define for each species an appropriate stand density management regime and regeneration method, and to establish effective tree breeding programs to improve stem form. A special attention should be paid to jack pine, which has an inferior stem form to other species.

It should be noted that the stems were destined for sawmills. Although the stems were randomly selected and covered the whole diameter range in each sawmill study, there still may exist a potential of bias in the data, namely the data might not include trees with bad stem forms which might have been left in situ at harvesting. Nevertheless, this study provides valuable information on stem form and its variations in the natural stands of the major commercial softwood species in eastern Canada. This information will not only help the lumber industry optimize wood processing to maximize the value from the highly variable fibre resources, but also enable forest managers to manage forests effectively to improve stem form and economic value.

5. Summary

The analysis of 2018 stems from the natural stands of five species showed that the five species had a DBH ranging from 10 to 32 cm and total height between 10 to 20 m. Stem taper and butt taper increased steadily with DBH. DBH had little effect on stem taper and sweep have negative effects on wood and lumber quality. Differences in diameters of different axes at breast height were generally small. Balsam fir and jack pine had the best and worst stem forms, respectively, while black spruce had the in-between. Region C produced stems with smaller butt taper, sweep. Butt logs were most seriously curved in red spruce and most tapered in white spruce. It is possible to define for each species appropriate stand density management regimes and regeneration method, and effective tree breeding programs to improve stem form. A special attention should be paid to jack pine, which has an inferior stem form to other species.

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