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ORIGINAL PAPER

Lumber recovery and value of dead and sound black spruce trees grown in the North Shore region of Québec

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Abstract

• ***Context*** To increase the wood supply to its industry, the government of Québec has allocated *dead and sound wood* (recently dead merchantable stems, DSW) to the wood supply chain in addition to the annual allowable cut of living trees. However, DSW is often criticized by sawmillers for its perceived poor quality and lower value.

• ***Aims*** The objective of this study was to compare the lumber visual grade yield and value from live and recently dead merchantable trees in three different states of wood decomposition.

• ***Methods*** In total, 162 black spruce trees [*Picea mariana* (Mill.) BSP] were felled from three different sites comprising three different states of wood decomposition and three diameter classes. The state of decomposition of each standing tree was categorized following Hunter's classification (decay stages 1 & 2, 3 and 4) and the DSW classification developed by the Government of Québec.

• ***Results*** Large trees (> 20 cm) of the Hunter 4 class have a lower value as a result of inferior quality.

• ***Conclusion*** Considering the current economic difficulties facing the forest industry and the requirements of ecosystem-based management, we recommend leaving in the forest trees that have reached such a state of deterioration.

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Contribution of the co-authors Julie Barrette was the first author on the manuscript, and carried out the main data analyses. She was principal investigator in the both the design and the implementation of the experiment.
David Pothier was the second author and contributed substantially to the manuscript. He was involved in the experimental design and data analysis, and was the main supervisor for the project.
David Auty helped to revise the manuscript, and contributed to the interpretation and presentation of the statistical results.
Alexis Achim helped to revise the manuscript, and contributed to the interpretation of the statistical results.
Isabelle Duchesne helped revising the manuscript. She was also involved in the design of the experiment and in the supervision of this project.
Nancy Gélinas made valuable comments on the manuscript, and was involved with the design of the experiment.

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1 Introduction

Canada's forest industry has faced a number of challenges over the past few years. Most notably, increased competition from imported low-cost products and the appreciation of the Canadian dollar have had negative repercussions for exports of wood and wood products, particularly to US markets (MacLean, 2007). In the province of Québec, recent successive decreases in the annual allowable cut of 20% in 2005 and an additional 5% the following year (Bureau du Forestier en Chef, 2006) have forced many forestry and wood processing businesses into temporary or sometimes permanent closure.

In response to these new restrictions, the government of Québec decided to allocate *dead and sound wood* (DSW) to the wood supply chain, in addition to the annual allowable cut of living trees (Bureau du Forestier en Chef, 2006). The DSW designation refers to timber that comes from standing trees that have recently died but do not show any apparent signs of decay (MRNFQ, 2005). Unlike the situation that prevails in many jurisdictions, DSW is considered separately from live trees in the public forests of the province. By increasing the supply of timber to sawmills, this special allowance was seen by the government as an effective way to help the industry. However, the use of DSW is sometimes criticized by sawmillers because, even though the stumpage price is the same as that of living trees, it is widely perceived to be of lower quality.

When a tree dies, it undergoes a series of changes that may affect product recovery. Specifically, during the first year after death, the moisture content of both the sapwood and heartwood can decrease rapidly below the fiber saturation point and cause the formation of internal checks (Woo et al., 2005; Lewis and Hartley, 2006). Dead trees are also more prone to invasions by saprophytic fungi and secondary insects, which can lead to an increased incidence of saprot (Snellgrove and Cahill, 1980; Lowell and Parry, 2007). The rate of infestation by decay fungi depends mainly on tree species, moisture content, and temperature (Pischedda, 2004). As the tree dries, the wood also loses plasticity and becomes more brittle (Panshin and C.d. Zeeuw 1980). Such changes do not only have a detrimental impact on the volume recovery at the sawmill (Fahey, 1977; Snellgrove and Cahill, 1980), but have the potential to significantly increase harvesting costs due to an increase in the frequency of stem breakage (Sinclair and Ifju, 1977; Mancini, 1978; Byrne et al., 2005; Nader, 2007). Handling dry logs also complicates sawmilling operations, as debarkers can cause a substantial amount of fibre damage if adjusted to remove the bark of live trees (Mancini, 1978).

The forests in Québec's North Shore region contain a relatively high proportion of DSW compared with other regions of the boreal forest (Lowe et al., 2011). This is mainly attributable to the high proportion of old growth forests, which cover approximately 60% of the unmanaged forest area (Boucher et al., 2003; Côté et al., 2010). The long fire interval that prevails in the area often exceeds the lifespan of individual trees. Thus, the old-growth forest stand dynamics in this part of Québec are mainly driven by small-scale local disturbances (McCarthy, 2001), such as localized windthrow and light-to-moderate outbreaks of spruce budworm (*Choristoneuran fumiferana* (Clemens)). These disturbances, along with those caused by other biotic (e.g., disease, senescence) and abiotic (e.g., acid precipitation, nutrient deficiency) agents, lead to an increase in tree mortality (De Grandpré et al., 2000).

The high incidence of DSW entering the forestry supply chain, coupled with the recent downturn in the global economy, means that it is essential to improve our understanding of how wood degradation affects lumber production. The objective of this study was therefore to compare the lumber visual grade yield and value from live trees with those from dead and sound trees in various states of wood decomposition.

2 Materials and methods

2.1 Study sites

This study was conducted in Québec's North Shore region, which is located in the north-eastern part of the Canadian boreal forest. Due to the long forest fire interval, the region is mainly characterized by old-growth stands with an uneven-aged structure (Côté et al., 2010). The forest stands are dominated by black spruce (*Picea mariana* (Mill.) BSP), with balsam fir (*Abies balsamea* (L.) Mill), white birch (*Betula papyrifera* Marsh.), and trembling aspen (*Populus tremuloides* Michx.) as secondary species (Bouchard et al., 2008). Three study sites (sites 1-3) lying on glacial till with mesic to subhydric drainage, were sampled from these old-growth forests (defined on the ecological maps as stands which are designated as being over 120 years old) in the north of Labrieville, Québec (49° 57' N, 69° 53' W). The study sites were harvesting sites which were designated for clearcutting as part of normal forest operations. They consisted almost entirely of black spruce, except for one of the plots in site 1 which contained one live balsam fir, and one plot in site 2 which contained one live white birch. Basal area of merchantable standing dead and live trees varied among sites from 28 to 44 m^2 ha^{-1}. The proportion of standing dead trees represented 6% of the basal area in site 1, 32% in site 2, and 38% in site 3.

2.2 Data collection

2.2.1 Sample plots

Two temporary plots were established at each site in order to quantify the relative proportions of live and dead trees. A prism of factor 2 was used to identify all standing merchantable stems with a diameter at breast height (DBH) larger than 9.0 cm in the variable radius plots. The DBH of merchantable trees within each plot was then recorded. In addition, information relating to soil type and drainage was recorded to ensure that all study sites were similar.

2.2.2 Sample trees

Tree selection and Hunter's classification At each study site, 54 merchantable standing black spruce trees were selected for destructive sampling in the autumn of 2009. The sample trees were selected according to the classification system for the progressive stages of wood decomposition described by Hunter 1990, which is widely used by forest ecologists. These first stages, or Hunter classes, are: 1) live trees, 2) live but declining trees, 3) recently dead trees and 4) dead trees with loose bark (Fig. 1). In this study, sample trees were assigned into one of three groups according to the following classes: Hunter 1 & 2, Hunter 3 and Hunter 4. Moreover, the sample trees chosen in the Hunter 3 and Hunter 4 classes had to correspond to the specific criteria developed by the government of Québec for DSW classification: i.e., (a) the wood is dry and difficult to crush when pressure is applied, (b) the bark is missing or easy to peel off, and (c) there is no external evidence of wood decay (MRNFQ, 2005).

Within each Hunter class category, the sample trees were selected from three merchantable DBH (over bark) classes (small: 9.1 to 15 cm, medium: 15.1 to 21 cm, and large: >21.1 cm) so that six trees were sampled in each combination of DBH and Hunter class at each site. A total of 162 trees were harvested in the autumn of 2009, but due to operational difficulties four trees had to be left on site, thus decreasing the final sample size to 158 trees.

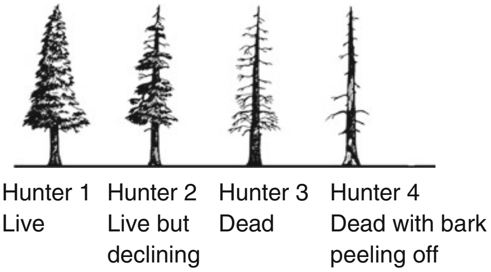


Fig. 1 Illustration of the different states of decomposition by Hunter (1990)

Volume estimations The sample trees were felled by a harvester and cut to 7 cm top-diameter unless the stem was already broken. The timber was then extracted in full-length with a forwarder. Stem diameter from the stump to the top of the tree at 1-m intervals and total tree length were measured to calculate gross stem volume using Smalian's equation (Avery and Burkhart, 2001). Tree stems were then cut into logs measuring 2.8 to 5.0 m in length using a chainsaw, and a sample disk was cut from both ends for the estimation of the volume of decayed wood. Only cavities and advanced decay were considered. The latter was characterized by the disintegration of the fibers when simple pressure was applied with a knife to the affected area (on the cross-section). Sample disks were scanned and decay areas were calculated using the ImageJ freeware (Abramoff et al., 2004). Smalian's equation was then used to calculate the volume of decayed wood in each log. If decay occurred only at one end of the log, we assigned a decay value of zero to one of the two diameters in Smalian's equation. The total volume of decayed wood for a tree was calculated as the sum of decay volumes in each log. The net volume of sound wood per tree was finally calculated by subtracting the volume of decay from the gross volume of the tree.

Sawmill conversion study In the field, both ends of the cut logs were marked in order to identify tree numbers during the sawmill conversion study. A total of 386 logs were transported by truck to a modern sawmill (Boisaco, Sacré-Coeur), which was equipped with a 3D laser scanner. This enabled the sawing pattern to be automatically optimized to extract maximum value from each log. Standard 2-inch-thick (44 mm) lumber and 1-inch-thick (22 mm) boards were produced, ranging in length from 2.8 to 5.0 m. The log reference number was transferred onto each piece of lumber produced to keep track of its provenance. In total, 822 pieces of lumber were produced, of which 8% had nominal dimensions of 1 × 3 inches (22 × 70 mm), 5% of 1 × 4 inches (22 × 95 mm), 1% of 1 × 6 inches (22 × 146 mm), 14% of 2 × 3 inches (44 × 70 mm), 45% of 2 × 4 inches (44 × 95 mm), and 27% of 2 × 6 inches (44 × 146 mm). The boards and lumber pieces were then transported to FPInnovations (Québec City) for kiln drying. They were then dressed at a commercial planer mill (Duchesnay sawmill, Québec) before finally being transported to Laval University's Wood Research Centre for further testing.

Lumber grades and values Lumber pieces were graded green and dry by a qualified inspector according to the NLGA Standard Grading Rules (NLGA, 2008). In Canada, No.2, No.1, and Select grades are usually sold together as 'No.2 and better' (hereafter 'No.2'). Therefore, in this study just four grades were used to classify each piece of lumber (Premium, No.2, No.3 and Economy), while two grades were used to classify each board (Utility and Economy). Although 'Premium' is not an official NLGA grade, it was used in this study because a number of important North American retailers sell lumber of improved visual appearance, designated as 'Premium' grade. This grade uses stricter criteria than the standard NLGA grades and does not allow for decay, stain, insect holes, ring shake and cracks. In addition, wane should not usually exceed 1/4 inch (6 mm). All grading and trimming decisions were aimed at maximizing value recovery, and the causes of downgrade were recorded for each sample.

In order to calculate the lumber value per tree, each piece of lumber was allocated an average dry lumber price using as a reference the prices in the Great Lakes market for specific lumber dimensions and grades, based on a 5-year price index from 2002 to 2007 (Québec Forest Industry 2002 to 2007). In addition, we compared the proportion of board feet generated in each combination of lumber grade, Hunter class and site. This was calculated as the sum of the board feet obtained from a given combination divided by the overall volume of board feet produced.

2.3 Data analysis

Analyses of variance (AOV) were conducted to test the statistical significance of the observed differences between study sites and/or Hunter classes in: 1) stand density and mean DBH of all live and dead trees measured in the sample plots, 2) mean DBH of the sample trees, and 3) average volume of decay, average top diameter, and tree length of different tree sizes. When a significant effect was detected, means were compared using Tukey's honestly significant difference (Tukey HSD) test. Statistical analyses were performed using the R statistical programming software (R Development Core Team, 2011). $P<0.05$ was used as the limit for statistical significance.

Along with the AOV analyses, two separate statistical models were constructed to predict lumber value per tree as a function of Hunter's class and each of two continuous independent variables (tree DBH and tree net volume). After testing several modelling approaches and equations, we found that an exponential function of the form presented in Eq. [1] provided the best fit to the data:

$$y = b_1 x^{b_2} b_3^x \tag{1}$$

where y is the lumber value per tree ($CAD), x is either DBH (mm) or net volume (dm^3) and $b_1 \ldots b_3$ are the model parameters.

However, as it would have been difficult to test the effect of a qualitative factor (*Hunter class*) in the exponential function given by Eq. [1], we linearized this equation by following a log-transformation process as follows:

$$\begin{aligned} &\Rightarrow \ln(y) = \ln\left(b_1 x^{b_2} b_3^x\right) && (2)\\ &\Rightarrow \ln(y) = \ln(b_1) + \ln\left(x^{b_2}\right) + \ln\left(b_3^x\right) \\ &\Rightarrow \ln(y) = \ln(b_1) + b_2 \ln(x) + x \ln(b_3) \\ &\quad\; \ln(y) = b_1' + b_2 \ln(x) + b_3' x \end{aligned}$$

where ln denotes the natural logarithm. Subsequently, Eq. [2] was further adapted to include the qualitative factor *Hunter class,* as given by Eq. [3]:

$$\ln(y) = b_{1,j}' + b_{2,j} \ln(x) + b_{3,j}' x \tag{3}$$

where y is the lumber value per tree ($CAD), x is either DBH (mm) or net volume (dm^3), ln is the natural logarithm, j corresponds to the different Hunter classes and b_1', b_2 and b_3' are the models parameters. b_1' refers to the intercept parameters corresponding to the different Hunter classes (j), b_2 corresponds to the parameter associated with the logarithmic form of the x variable and to its possible interaction with the qualitative factor Hunter classes (j), and b_3' corresponds to the parameter associated with the x variable and to its possible interaction with the qualitative factor Hunter classes (j).

The linearized version of Eq. [3] allowed us to fit linear models using the nlme library in the R statistical programming environment (R Development Core Team, 2011). First, we fitted linear mixed-effects models using the maximum likelihood estimation criterion, in which the variable SITE was treated as a random effect. Secondly, the equations were fitted with the fixed effects only, using the same estimation method, and likelihood ratio tests (LRT) were conducted on the nested models in order to test the statistical significance of the random effects term. Finally, we fitted linear fixed effects models containing all independent variables and their interactions. Hunter class 1 & 2 was used as the reference in all model fits. A correction factor for bias in log-transformed allometric equations (Sprugel, 1983) was applied to both the plotted predicted values and their confidence intervals.

3 Results

3.1 Stand density and mean DBH of living and dead trees from the sample plots

The variation in the mean stand density of living trees and dead trees among the three sites was large, ranging from 454 to 1,449 trees ha^{-1} for live trees and 107 to 840 trees ha^{-1} for dead trees (Table 1). Variation between plots within a site was also large and, consequently, the differences in tree

Table 1 Stand density, basal area, and average DBH of living and dead trees from of each site (± standard deviation: SD)

Site	Stem category	No. of trees/ha	Basal area (m^2/ha)	Average DBH (cm)±SD
1	Dead stems	107	2.0	19.1±9.0
	Live stems	1,449	33.0	19.3±1.1
2	Dead stems	312	9.0	17.4±4.6
	Live stems	454	19.0	24.8±3.8
3	Dead stems	840	17.0	17.0±0.5
	Live stems	916	27.0	21.2±0.6

density between sites were not statistically significant (Site: $F=1.59$, $p=0.28$; Live vs Dead: $F=4.73$, $p=0.07$; Site*Live vs Dead: $F=2.96$ $p=0.13$). The variation in the mean DBH of living trees was from 19.3 to 24.8 cm, and from 17.0 to 19.1 cm for dead standing trees. Differences in mean DBH among sites were not statistically significant (Site: $F=0.23$, $p=0.80$; Live vs Dead: $F=2.47$, $p=0.17$; Site*Live vs Dead: $F=0.57$ $p=0.59$).

3.2 Characteristics of the sample trees

The variation in the average DBH of the sample trees among Hunter classes was relatively small, ranging from 18.4 to 18.7 cm in site 1, from 18.3 to 18.4 cm in site 2 and from 18.1 to 19.2 cm in site 3. Differences among Hunter classes and sites were not statistically significant (Hunter: $F=0.05$, $p=0.95$; Site: $F=0.02$, $p=0.98$; Site*Hunter: $F=0.12$, $p=0.98$). The highest volume of wood decay was observed in large trees (DBH>21.1 cm) of the Hunter 4 class with an average of 48.7 dm^3 (Tables 2 and 3) compared to only 6.1 dm^3 for large live trees. The difference in mean decay volume between Hunter classes of large trees was found to be statistically different (Table 3, $F=6.13$, $p=0.004$). In addition, logs from a significant proportion of large trees in the Hunter 4 class had larger top-diameters than expected

Table 2 Characteristics of the sample trees by site (± standard deviation: SD). Tree length refers to the total height of the tree and was measured once the trees were felled

Site	Hunter classes	Tree DBH class (cm)	*n*	Average DBH (cm)±SD	Average gross volume (dm^3)±SD	Average decay volume (dm^3)±SD	Average net volume (dm^3)±SD	Average tree length (m)±SD	Average top diameter (cm)±SD
1	1 & 2	21.1 +	5	25.0±2.5	414±117	5±11	409±109	15.8±2.5	7.5±1.8
		15.1 to 21	6	17.1±2.0	147±79	3±5	144±78	10.3±2.1	7.4±1.8
		9.1 to 15	5	12.5±1.3	57±23	0.3±0.8	56±23	6.7±0.9	6.8±1.4
	3	21.1 +	6	25.1±2.9	362±94	36±44	326±102	13.0±3.5	11.3±3.5
		15.1 to 21	6	17.8±1.6	153±34	11±10	142±39	8.7±1.7	10.7±2.7
		9.1 to 15	6	13.2±1.4	71±19	10±14	61±21	8.4±1.9	6.8±1.8
	4	21.1 +	6	23.3±2.0	282±96	46±46	236±91	11.2±4.1	11.6±4.3
		15.1 to 21	6	18.0±1.2	155±37	20±16	135±27	9.9±2.0	9.4±1.5
		9.1 to 15	6	13.9±0.9	101±21	13±17	87±29	10.2±1.7	7.1±1.8
2	1 & 2	21.1 +	6	23.8±1.2	385±79	9±20	376±87	14.6±2.1	9.8±1.9
		15.1 to 21	6	18.2±1.4	209±43	0±0	209±43	13.4±0.8	8.5±1.2
		9.1 to 15	6	12.9±1.6	69±26	0.2±0.5	69±25	7.5±1.0	7.1±1.5
	3	21.1 +	6	22.9±1.9	319±79	23±25	296±69	13.5±2.4	9.4±1.4
		15.1 to 21	6	19.3±1.2	186±47	15±23	171±65	10.5±2.7	8.8±1.8
		9.1 to 15	5	12.2±1.6	73±19	1±2	72±19	8.5±1.8	7.1±0.7
	4	21.1 +	5	24.5±2.1	373±64	84±70	289±103	14.0±1.8	10.5±3.5
		15.1 to 21	6	17.8±1.5	160±57	11±11	150±57	10.4±3.6	9.2±2.9
		9.1 to 15	6	13.6±0.8	84±12	7±10	77±15	9.3±1.9	7.5±1.8
3	1 & 2	21.1 +	6	23.8±2.7	388±90	5±11	383±91	15.8±1.5	6.9±0.9
		15.1 to 21	6	17.9±1.0	190±30	1±3	189±32	11.7±1.5	8.0±2.2
		9.1 to 15	6	12.6±1.7	67±22	0±0	67±22	8.3±1.6	7.2±1.8
	3	21.1 +	6	24.7±3.8	365±98	40±26	325±105	13.9±2.2	10.5±3.1
		15.1 to 21	6	18.3±1.5	173±52	17±13	156±58	11.3±3.4	8.1±2.4
		9.1 to 15	6	11.7±1.6	59±27	5±4	54±54	8.2±3.1	5.9±1.2
	4	21.1 +	6	24.7±3.7	331±123	22±17	310±135	12.5±3.1	11.0±3.2
		15.1 to 21	6	19.3±1.6	242±83	27±8	216±85	12.6±3.1	8.9±1.9
		9.1 to 15	6	13.8±0.8	88±21	10±9	78±23	8.1±2.9	8.5±1.6

Table 3 Characteristics of the sample trees in each diameter class across all sites combined. Different letters in the same column and DBH class indicate significant differences between values (Tukey HSD test at *P*<0.05)

Tree DBH class (cm)	Hunter's class	Average volume of decay (dm^3)	Average top diameter (cm)	Average length (m)
Large (21.1 +)	1 & 2	6.1 (a)	8.1 (a)	15.4 (a)
	3	33.0 (b)	10.4 (b)	13.5 (b)
	4	48.7 (b)	11.1 (b)	12.5 (b)
Medium (15.1 to 21)	1 & 2	1.4 (a)	8.0 (a)	11.8 (a)
	3	14.3 (b)	9.2 (a)	10.2 (a)
	4	19.0 (b)	9.2 (a)	11.0 (a)
Small (9.1 to 15)	1 & 2	0.2 (a)	7.0 (ab)	7.5 (a)
	3	5.9 (ab)	6.5 (a)	8.4 (ab)
	4	10.3 (b)	7.7 (b)	9.2 (b)

due to stem-breakage, either as a consequence of natural disturbances or because they were cut to larger top-diameters than trees from other classes due to the increased risk of stem breakage during harvesting. The average top-diameter of large live trees was 8.1 cm compared to 11.1 cm for the Hunter 4 class, which was a statistically significant difference (Table 3, $F=5.29$, $p=0.008$). Consequently, the average length of large trees varied from 15.4 to 12.5 m from the Hunter 1 & 2 to the Hunter 4 classes respectively (Table 3, $F=5.26$, $p=0.008$). Even though the sampling was carried out in order to obtain similar DBH values among Hunter classes, the corresponding net volume averages differed. This was attributable to a decrease in the average stem length and to an increase in decay volume with increasing Hunter class (Tables 2 and 3).

3.3 Visual lumber grade yield for dry lumber

In general, lumber quality decreased with increasing Hunter class. There were important differences in Premium grade recovery of dry lumber among Hunter classes (Fig. 2). The proportions in board feet ranged from 7 to 29%, with Hunter 1 & 2 producing the highest percentage of Premium lumber. For the No.2 grade, we observed the same tendency, but the range of variation was between 32% and 45%. Dead trees of the Hunter 4 class produced the highest volume of No.3 and Economy grades with 36% and 19% respectively.

3.4 Effect of drying

After comparison of the visual lumber grade yields before and after drying for the three decomposition classes, we found that more lumber from the Hunter 1 & 2 category was classified as Premium grade after drying (Fig. 2), and less as No.2 grade, than before drying (Fig. 3). This was probably due to the fact that the lumber was only planed after drying. It appeared that the lumber pieces were mainly misclassified as grade 2 because of wane, which disappeared after planing and trimming. Conversely, the proportion of No.3 grade from the Hunter 1 & 2 category stayed about the same after drying, while around 5% of the No.2 grade pieces were downgraded to Economy, mainly as a result

Fig. 2 Mean (± standard deviation: SD) proportion in board feet, calculated as the sum of the board feet obtained in each lumber grade yield divided by the overall volume of board feet produced in each Hunter's decomposition class after drying

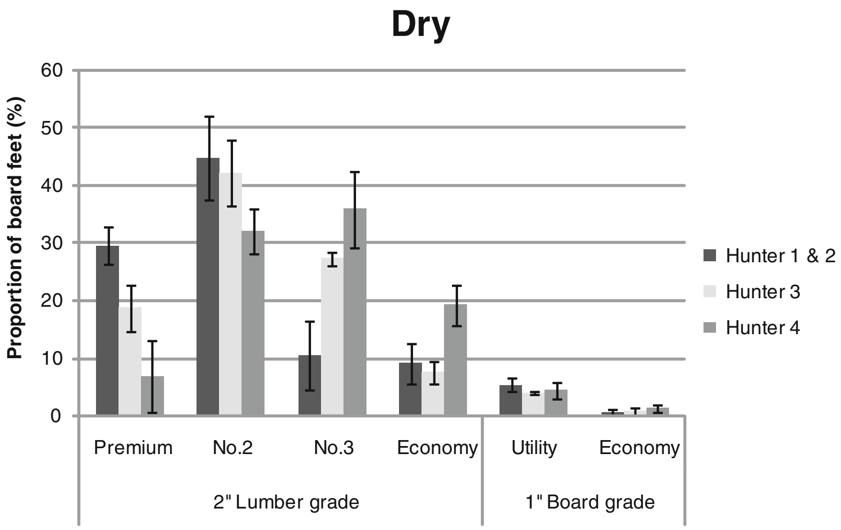
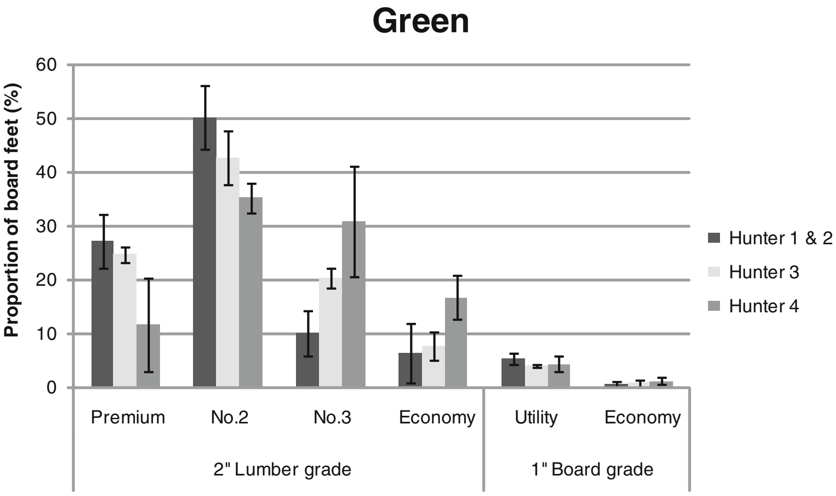


Fig. 3 Mean (± standard deviation: SD) proportion in board feet calculated as the sum of the board feet obtained in each lumber grade yield divided by the overall volume of board feet produced in each Hunter's decomposition class before drying



of wane and twist. When comparing the results before and after drying for the Hunter 3 class only, it can be observed that the proportion of Premium grade pieces decreased by about 6% while the No.3 grade increased by the same proportion. This was mainly due to unnoticed rot during green classification, and to twist and ring shakes that appeared after drying. The proportion of No.2 grade pieces stayed almost constant, and remained the highest proportion of lumber observed after drying, with 42%.

Comparisons of the results before and after drying for the Hunter 4 class show a similar decrease (5%) in Premium-graded lumber to that observed in the Hunter 3 class. The main cause of downgrade was the occurrence of ring shakes. Approximately 3% of the No.2 lumber was downgraded to No.3 and Economy, and this was also due to both unnoticed rot during green classification and to ring shakes. In this case, the highest proportion of lumber after drying was found in the No.3 grade, with 36%.

Table 4 Parameter estimates (± SE) and related statistics of the prediction Eq. [3] fitted with DBH as an explanatory variable

Parameters	Variables	Estimates	*SE*	*P*-value
b_1'	Intercept (Hunter 1 & 2)	−29.4770	3.500	<0.0001
$b_{1,H3}'$	Hunter 3	3.0097	1.3686	0.0294
$b_{1,H4}'$	Hunter 4	3.9780	1.4745	0.0078
b_2	ln (DBH mm)	6.7872	0.8291	<0.0001
$b_{2,H3}$	Hunter 3: ln (DBH mm)	−0.6132	0.2633	0.0212
$b_{2,H4}$	Hunter 4: ln (DBH mm)	−0.8100	0.2835	0.0049
b_3'	DBH	−0.0173	0.0045	0.0002
	n	154		
	R^2	0.8534		
	RSE	0.3598		
	Bias	1.0666		

n is the number of observations used to calculate the parameters, R^2 is the coefficient of determination, RSE is the residual standard error of the model, and Bias is equal to $e^{(\mathrm{RSE}^\wedge 2/2)}$

3.5 Lumber value as a function of DBH

Likelihood ratio tests comparing the linear mixed models revealed that the site-level random effect was not statistically significant, so this was removed in subsequent model fits (p=0.26, AIC with random effect=132.9, AIC without random effect=132.2). Therefore, the final fixed-effects model contained only the variables Hunter class, DBH, the natural logarithm of DBH, and the interaction between Hunter class and the natural logarithm of DBH. This model contained only statistically significant fixed effects (p<0.05), and explained 85% of the variation in lumber value (Table 4). The correlation coefficient between b_1' and b_3' for the reference level Hunter 1 & 2 class was 0.95. Despite this high value, we retained both parameters in the model, as they each had a large influence on the predicted trends. The final model was further used to plot the relationships between DBH and lumber value per tree for the different Hunter classes, along with confidence intervals around predicted values (Fig. 4). To achieve this, we back-transformed the logarithmic parameter estimates from Eq. [3] into arithmetic units according to the process described in Table 5, and corrected for the bias (1.066). In this way, we were able to calculate the values of the parameters in the nonlinear function given by Eq. [1] (Table 6).

From Fig. 4a, it can be seen that, for a given DBH, trees in the Hunter 1 & 2 class produced higher average lumber values per tree than those in the Hunter 3 class. The difference increased with DBH, and became significant at DBH values larger than 20 cm. A similar pattern was observed when comparing Hunter classes 1 & 2 and 4, but with significant differences arising at DBH values just less than 20 cm (Fig. 4b).

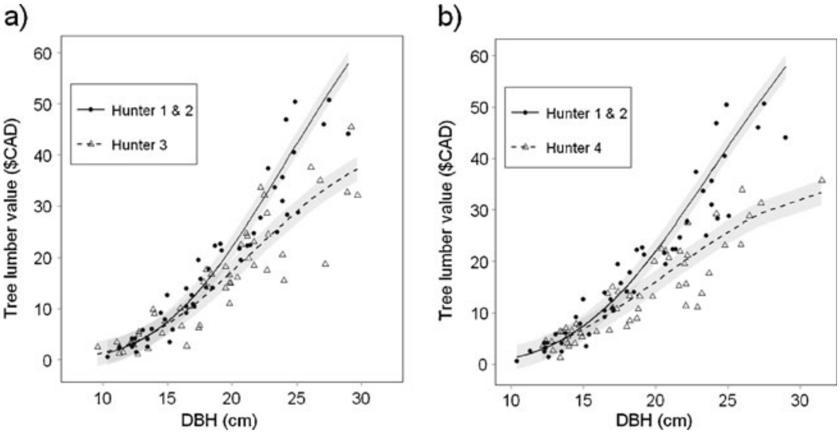


Fig. 4 Predicted lumber value per tree ($CAD) in relation to tree DBH (cm) for **a** Hunter 1 & 2 and Hunter 3 classes, and **b** Hunter 1 & 2 and Hunter 4 classes from Model 1. *Continuous and dashed lines* indicate the regression fit after bias correction; *light grey band* indicates the confidence interval (95%)

3.6 Lumber value as a function of net volume

As for the preceding model, the site-level random effect was found to be non-significant, and was thus ignored in subsequent analyses. The model for net volume contained only fixed-effects variables, i.e., Hunter class, tree net volume, the natural logarithm of tree net volume, and the interaction between Hunter class and the natural logarithm of tree net volume. This model was able to explain 89% of the variation in net lumber value per tree (Table 7). Net lumber value per tree was not significantly different for trees in the Hunter 3 class compared to those in the Hunter 1 & 2 class, although significant differences were found between trees in the Hunter 4 class and those in the Hunter 1 & 2 class (Table 7). Since Hunter class is a qualitative factor and was included in a model interaction term, all parameters were retained in the final model. The correlation coefficient between b'_1 and b'_3 for the reference level Hunter 1 & 2 class was 0.82.

Once again, the logarithmic estimates obtained from Eq. [3] were back-transformed using the same process as described by Table 5 for the previous model (bias=1.047). The obtained parameters (Table 8) were used to plot the relationships between tree net volume and lumber value per tree for each Hunter class, along with the confidence intervals around predicted values (Fig. 5).

According to the resulting model, trees in the Hunter 1 & 2 and the Hunter 3 classes produced relatively similar lumber value for the same net volume (Fig. 5a). However, trees in the Hunter 1 & 2 class produced higher lumber value per tree than those in the Hunter 4 class for the same net volume (Fig. 5b). The difference increased with increasing tree net volume, and became more obvious at values greater than 300 dm^3 or for trees with a DBH greater than 22 cm.

Table 5 Process used in the back-transformation of the logarithmic parameter estimates from Eq. [3] into arithmetic units

Parameters	Hunter 1 & 2	Hunter 3	Hunter 4
b_1	exp (b'_1)	exp ($b'_1+b'_{1,H3}$)	exp ($b'_1+b'_{1,H4}$)
b_2	b_2	$b_2+b_{2,H3}$	$b_2+b_{2,H4}$
b_3	exp (b'_3)	exp (b'_3)	exp (b'_3)

4 Discussion

Hunter's classification proved useful in addressing wood quality changes and their effects on product volume and value recovery of dead and sound trees. Our results show that the lumber value of dead and sound trees is lower than that of live trees, especially when comparisons are made with DBH. The difference in value between Hunter classes was more pronounced when DBH was used as a predictor than with net volume, because net volume of dead and sound trees was corrected for decay, tree length, and tree top diameter, whereas no such corrections were made using DBH. On a DBH comparison basis, larger trees in the Hunter 3 class are worth approximately $CAD 10 less than trees in the Hunter 1 & 2 class, while on a tree net volume basis, tree lumber values are about the same (Fig. 5a). This suggests that the wood volume recovered from trees in the Hunter 3 class was of good quality. This is supported by the relatively large proportion of Premium and No.2 lumber grades that were produced from trees classified as Hunter

Table 6 Parameter estimates of Eq. [1] with DBH as an explanatory variable. Parameters were calculated from the back-transformation of the logarithmic estimates obtained from Eq. [3] into arithmetic units. Numbers in parentheses are the 95% confidence intervals associated with the parameter estimates obtained for the reference level Hunter 1 & 2 class

Parameters	Hunter 1 & 2	Hunter 3	Hunter 4
b_1	1.579e-13 [1.656e-16;1.505e-10]	3.202e-12	8.432e-12
b_2	6.787 [5.162;8.412]	6.174	5.977
b_3	0.983 [0.974;0.992]	0.983	0.983

Table 7 Parameter estimates (± SE) and related statistics of the prediction Eq. [3] with net volume as an explanatory variable

Parameters	Variables	Estimates	*SE*	*P*-value
b_1'	Intercept (Hunter 1 & 2)	−5.2604	0.4879	<0.0001
$b_{1,H3}'$	Hunter 3	0.2063	0.4133	0.6185
$b_{1,H4}'$	Hunter 4	0.9081	0.4486	0.0448
b_2	ln (volume net dm^3)	1.6026	0.1167	<0.0001
$b_{2,H3}$	Hunter 3: ln (volume net dm^3)	−0.0442	0.0811	0.5869
$b_{2,H4}$	Hunter 4: ln (volume net dm^3)	−0.1885	0.0884	0.0348
b_3'	Volume net dm3	−0.0019	0.0006	0.0018
	n	154		
	R^2	0.8956		
	RSE	0.3036		
	Bias	1.047		

n is the number of observations used to calculate the parameters, R^2 is the coefficient of determination, RSE is the residual standard error of the model, and Bias is equal to $e^{(RSE\text{^}2/2)}$

3 (Figs. 2 and 3). The decrease in value was larger in the case of the larger trees in the Hunter 4 class, for which the decrease in value was about $CAD 20 per tree on a DBH comparison basis (Fig. 4b), and $CAD 10 per tree on a net volume comparison basis (Fig. 5b). Hence, trees in a more advanced state of decay tended to produce lumber of a lower average grade than that obtained from live trees.

Our results are in accordance with those of Willits et al. (1990) and Snellgrove and Cahill (1980), who also used a field classification system to compare lumber recovery from dead and live trees in the west coast of the United States after epidemics of mountain pine beetle (*Dendroctonus ponderosae*) and of white pine blister (*Cronartium ribicola*). Snellgrove and Cahill (1980) demonstrated that the average value of lumber produced from western white pine (*Pinus monticola* Dougl. ex D.Don) decreased by about 50% from live to the oldest class of dead trees (no needles and less than 90% percent bark retention in the merchantable bole, which is analogous to the Hunter 4 class). This decrease in value obviously depends on the price list used at the time of the analysis, the type of lumber produced (e.g., boards, shop or dimension lumbers) and on the choice of the independent variables used in the models. In our study, the average differences in value among deterioration classes were not found to be as drastic, especially when comparisons are made on a net volume basis. When examining the lumber values from the price list used (average market prices between 2002 and 2007, see Appendix 1), we realized that differences between Premium and No.2 grades were rather small. As an example, a piece of 2 × 4 × 16 lumber graded as Premium was valued at $CAD 4.44, compared to $CAD 4.31 when it was graded as No.2. While differences among degradation classes appear rather small when based on the lumber value per tree, it is clearly evident that the proportion of high quality-grade lumber decreases substantially with increasing Hunter class (Figs. 2 and 3). Our results also agree with those of Lowell and Parry (2007), who concluded that lumber value decreased significantly with increasing diameter in dead ponderosa pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson) logs, due to the presence of blue stain in lumber that would otherwise have produced higher value of factory grades (e.g., shop, moulding). Although black spruce in the North Shore region of Québec is not affected by blue stain, Lowell and Parry's results were consistent with our observation that the largest trees of the Hunter 4 class had the correspondingly highest losses in net lumber value.

Table 8 Parameters of Eq. [1] with net volume as an explanatory variable. Parameters were calculated from the back-transformation of the logarithmic estimates obtained from Eq. [3] into arithmetic units. Numbers in parentheses are the 95% confidence intervals associated with the parameter estimates obtained for the reference level Hunter 1 & 2 class

Parameter	Hunter 1 & 2	Hunter 3	Hunter 4
b_1	0.005 [0.002;0.014]	0.006	0.013
b_2	1.603 [1.374;1.831]	1.558	1.414
b_3	0.998 [0.997;0.999]	0.998	0.998

According to Lowell et al. (2010), there are two main types of losses in dead trees: 1) volume loss that occurs through defects such as decay, checking, and breakage, and 2) value loss through a reduction in product volume recovery and product quality. In our study, decay and breakage accounted for important volume losses from trees of the Hunter 4 class. Despite the fact that we selected trees on the basis of the DSW criteria, they contained a greater volume of wood decay than live trees. It seems difficult to obtain a precise estimate of the extent of decay based only on a visual inspection of dead standing trees. Even if the tree looks sound at the stem base, it can also contain decay further up the stem, which is much harder to detect. Amongst the sample trees in this study, only six individuals of the Hunter 4 class were not affected by decay, compared to 16 and 41 in the Hunter 3 and Hunter 1 & 2 classes, respectively. According to Lavallée (1965), broken tops are the most common point of entry for insects and decay in black spruce trees. This is even more important on recently dead trees, which are known to be the preferred targets of wood-boring insects (Graham and Knight 1965). Once decay enters the broken tree, it deteriorates the sapwood ahead of insect damage (Lowell et al., 2010).

Approximately 70% of the Hunter 4 trees in this study had broken tops, with 76% of them showing signs of sap rot. In comparison, only 45% of the Hunter 3 trees suffered broken tops, and 57% displayed signs of sap rot. Hence,

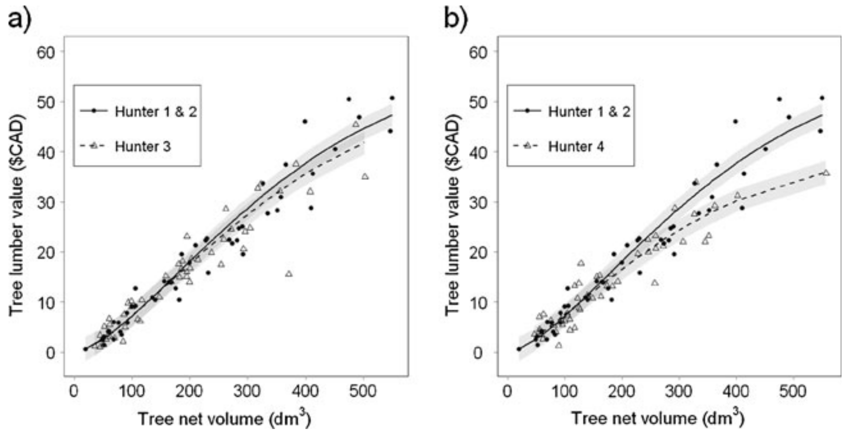


Fig. 5 Predicted lumber value per tree ($CAD) in relation to tree net volume (dm^3) for **a** Hunter 1 & 2 and Hunter 3 classes; and **b** Hunter 1 & 2 and Hunter 4 classes from Model 2. *Continuous and dashed lines* indicate the regression fit after bias correction; *light grey band* indicates the confidence interval (95%)

the more advanced the wood degradation, the larger the observed proportion of stem breakages. This is in agreement with Hunter's classification, which shows an increase in top diameter caused by broken tops with increasing degradation class (Hunter 1990).

Generally, little wood volume is lost to decay and breakage within the first year following tree death (Lowell et al. 1992; Hadfield and Magelssen 2006). According to Hadfield and Magelssen (2006) who studied wood changes in fire-killed trees in Eastern Washington, it is by the second year after death that sap rot becomes an important factor in stem wood deterioration, and by the fourth year after death that tops begin to break, which negatively affects volume recovery. Another study looking at the effect of wood degradation on the mechanical properties of black spruce lumber after windthrow showed an important decrease in the modulus of rupture (MOR) in static bending four years after tree death (Ruel et al. 2010). Even though the trees in the current study did not die as a result of catastrophic disturbances, these previous studies are useful for understanding the processes of wood degradation. However, unlike for salvage operations that are conducted after catastrophic events, time after death is not a factor which can be controlled in old-growth forests, where tree mortality occurs as a slow and gradual process.

In general, there is a very strong relationship between site characteristics (as expressed by soil moisture regime) and stem decay in living black spruce (Basham, 1991). Although the sites selected for this study were at three different locations, it was not our intention to measure the variations among sites. The sites were chosen from old-growth forests with similar soil type, drainage and, slope. Therefore, environmental factors influencing moisture and temperature conditions, which could have hastened or slowed down the rate of deterioration, were very similar among sites. In future studies, it would be interesting to investigate if the Hunter classes are truly independent of site attributes along a gradient of soil moisture and temperature conditions.

In any case, Hunter's classification may be of great interest to forest managers in determining whether to harvest dead and sound trees to increase wood supply. The results of this study suggest that only dead trees of the Hunter 3 class present a good financial opportunity, whereas it might be better to avoid harvesting trees from the Hunter 4 class. Furthermore, the retention of dead standing trees can bring many additional benefits to forest ecosystems, including the provision of habitat for a wide range of decomposer organisms and shelter for a variety of animal species (Franklin et al., 1987) such as cavity-nesting birds (Lowe et al., 2011). Once they fall to the ground, dead trees make an even more important contribution to the enhancement of ecosystem processes. Through the activities of decomposer organisms, they can release nutrients and energy which enrich the soil, a very important aspect of natural seedling establishment (Franklin et al., 1987). New forestry practices in Québec are moving towards an ecosystem-based approach, and the presence of dead standing trees represents one of the most important issues that arises when natural and managed forests are compared.

5 Conclusion

This study showed that the value of lumber sawn from large trees (> 20 cm DBH) of the Hunter 4 class is significantly inferior to that of live trees. Considering the current economic difficulties affecting the forest industry, and the requirements of ecosystem-based management, we recommend leaving these trees in the forest. However, from a strictly financial perspective, trees of the Hunter 3 class could be harvested because the product volume recovery from this category approaches that from live trees.

Our study focused only on the value which may be obtained through visual grades. Future work should investigate the impact of tree deterioration on the mechanical properties of processed lumber. In addition, an important part of the value extracted from black spruce trees from the

Canadian boreal forest is associated with the production of pulp. Further research is needed to explore the detrimental effects of tree death on pulp and paper production processes.

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Appendix 1

Table 9 Average prices between 2002 to 2007 from the Great Lakes market for specific lumber dimensions and grades. MBF is used to express «1,000 board feet». One board foot is equal to the volume of a board with dimensions 12” × 12” × 1”

Lumber dimension (mm × mm × cm)	Average prices between 2002 to 2007 ($CAD/ MBF)					
	Utility board	Economy board	Premium	No. 2	No. 3	Economy
22 × 70 × 183	310	200				
22 × 70 × 213	310	200				
22 × 70 × 244	342	200				
22 × 70 × 274	342	200				
22 × 70 × 305	342	200				
22 × 70 x 366	282	200				
22 x 70 × 427	264	200				
22 × 70 × 488	275	200				
22 × 95 × 183	320	210				
22 × 95 × 213	320	210				
22 × 95 × 244	348	210				
22 × 95 × 274	348	210				
22 × 95 × 305	348	210				
22 × 95 × 366	258	210				
22 × 95 × 427	277	210				
22 × 95 × 488	276	210				
44 × 70 × 122				225	210	200
44 × 70 × 152				225	210	200
44 × 70 × 183			422	294	220	200
44 × 70 × 213			422	288	220	200
44 × 70 × 244			422	317	240	200
44 × 70 × 274			422	317	240	200
44 × 70 × 305			422	309	240	200
44 × 70 × 366			422	341	265	197
44 × 70 × 427			422	356	280	211
44 × 70 × 488			422	382	306	237
44 × 95 × 122				250	240	232
44 × 95 × 152				250	240	232
44 × 95 × 183			417	295	280	232

Table 9 (continued)

Lumber dimension (mm × mm × cm)	Average prices between 2002 to 2007 ($CAD/ MBF)					
	Utility board	Economy board	Premium	No. 2	No. 3	Economy
44 × 95 × 213			417	302	280	232
44 × 95 × 244			417	367	309	232
44 × 95 × 274			417	391	309	232
44 × 95 × 305			417	380	309	232
44 × 95 × 366			417	369	294	225
44 × 95 × 427			417	381	306	237
44 × 95 × 488			417	404	328	260
44 × 146 × 122				340	267	226
44 × 146 × 152				340	267	226
44 × 146 × 183			436	340	267	226
44 × 146 × 213			436	340	267	226
44 × 146 × 244			436	393	267	226
44 × 146 × 274			436	398	267	226
44 × 146 × 305			436	395	267	226
44 × 146 × 366			436	372	259	218
44 × 146 × 427			436	346	233	193
44 × 146 × 488			436	396	284	243

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