Sources of Variation in the Net Value of Sugar Maple Trees: Implications for Tree Selection and Operations Management

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Abstract

The net value of hardwood trees (dollars per tree) is thought to increase with stem size for three reasons. First, large trees yield a greater volume (cubic meters) of logs, which tend to be larger than logs from small trees; second, large logs are more valuable (dollars per cubic meter) than small logs; and, third, large logs cost less (dollars per cubic meter) to process than small logs. Yet few studies have assessed both the cost of processing hardwood trees and the value of their products. In this article, we examine how the net value of sugar maple trees (*Acer saccharum*) varies with tree size and the presence of defects, such as fungi and seams. We quantify the gross value of firewood, lumber, and residues as well as the costs of harvesting and sawmilling. For each tree, we also calculate its net value to an integrated forestry company by subtracting costs from gross values. Our results confirm that large trees are more profitable than small trees but challenge current assumptions as to why. As expected, the volume and value of products are reduced by defects, while costs (dollars per cubic meter) are lower for larger trees. However, we found that gross value (dollars per cubic meter) does not vary with tree size, indicating that large trees yield more but not necessarily better products. The results of this study provide insight into how loggers can improve value recovery while limiting processing costs. These results also challenge the rationale behind silvicultural prescriptions that retain large trees based on the assumption that they produce greater volumes of higher-quality wood.

Temperate hardwoods are known to exhibit greater variation in quality and size than most softwoods (Miller et al. 1978, Shmulsky and Jones 2011). Hardwood trees vary in quality because they are susceptible to a wide range of biotic and abiotic defects, such as fungi, frost cracks, and stain, many of which reduce the quality and value of lumber (Shigo 1984, Carpenter et al. 1989). They also vary widely in size because hardwood stands are typically managed using uneven-aged silvicultural methods, such as single-tree selection, which aim to release future crop trees by felling trees from a full range of size classes (Nyland 1998, Ohara 2002).

This variation in quality and size is both well known and well documented (Cutter et al. 2004), so one would expect the attendant variation in tree value to be documented as well. However, few studies have explicitly examined how the value of products recovered from hardwood trees varies as a function of both tree size and quality (Lussier 2009). Thus, it is difficult for loggers to assess the financial consequences of operational decisions, such as whether to skid a low-quality tree or whether to sort logs as firewood or sawlogs. Without knowing how size or defects affect product values and processing expenses, harvesting activities may accrue excessive costs without increasing value recovery. Furthermore, foresters may pursue silvicultural objectives, such as the retention of large trees, that do not contribute to profitability.

Previous studies suggest that the gross value of hardwood products (dollars per cubic meter) increases with tree size because large trees yield larger sawlogs with fewer defects (Fortin et al. 2009). In turn, large sawlogs are thought to yield higher-grade lumber than small sawlogs because lumber grading rules place a premium on long and wide boards (Hanks 1976, Drouin et al. 2010). However, these studies do not consider the recovery of low-quality logs

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(firewood and pulp) or sawmill by-products (chips, sawdust, and bark), which usually exceed the volume of lumber recovered from any given tree (Hanks 1977, Alderman 1998). As a result of overlooking these products, the value of small trees may be underestimated.

Whereas gross value (dollars per cubic meter) is believed to increase with tree size, time-motion studies have shown that harvesting costs (dollars per cubic meter) decrease with tree size (Ashe 1916, LeDoux and Baumgras 1989, Wang et al. 2004). Sawmilling costs per unit of lumber are also known to decrease with sawlog diameter and length (Kirkland 1943, Foster 1972, Lin et al. 2011). Thus, it is often assumed that the net value of hardwood products (dollars per cubic meter) increases with tree size for two reasons. First, large trees yield better wood and, second, that wood comes at a lower cost. However, we are not aware of studies that have assessed both the cost of processing hardwood trees and the value of the recovered products, including firewood and sawmill residues (Cole et al. 2003). Such a comprehensive evaluation is necessary to understand the sources of variation in the net value of hardwood trees.

In this article, we use product recovery and time-motion studies to quantify the net value (dollars per tree) of sugar maple trees (*Acer saccharum*) and their products (dollars per cubic meter), the most common hardwood species in the Great Lakes–St. Lawrence forest region (Ontario Ministry of Natural Resources [OMNR] 1998). For each tree, we assessed diameter at breast height (DBH) and quality (based on the presence of defects) and then measured the volume and value of all products and calculated harvesting and processing costs (OMNR 2004). The objective of this study was to assess the effects of tree size and defects on the volume, quality, and value of logs and sawmill products as well as the harvesting and processing costs.

Methods

Study area

The study was conducted at Haliburton Forest and Wildlife Reserve, a privately owned multiuse forest in Haliburton County, Ontario. Approximately 70 percent of the 1,000 ha harvested annually at Haliburton Forest is managed under a single-tree selection regime. A general prescription is used by their tree markers, who evaluate every tree in each harvest area and use paint to indicate which stems should be felled by loggers. This prescription prioritizes the removal of trees with major defects, favors intolerant and midtolerant species, and aims to reduce the basal area of stands dominated by sugar maple to 16 m^2/ha, with a maximum diameter of 60 cm for most hardwoods. Haliburton Forest has been certified by the Forest Stewardship Council since 1997.

For this study, three harvest stands in Haliburton Forest were selected and harvested between July 2010 and August 2012: Stand 1 (131 trees), Stand 2 (251 trees), and Stand 3 (152 trees). The preharvest basal areas of the stands ranged from 18 to 24 m^2/ha. Stands 2 and 3 had been harvested approximately 20 years earlier, whereas Stand 1 had not been harvested for at least 40 years. Like much of the Great Lakes–St. Lawrence forest region, every stand was defined by shallow, well-drained soil and granite bedrock. The stands were dominated by sugar maple (~50% of basal area), red maple (*Acer rubrum*; ~15%), American beech (*Fagus grandifolia*; ~15%), and yellow birch (*Betula alleghaniensis*; ~10%). Typical of central Ontario, the stands showed evidence of past high grading in which the best trees were harvested with little regard for silvicultural objectives.

Operator equipment

The three stands were marked by the same certified tree marker prior to harvesting (OMNR 2004). The equipment used during harvesting operations varied between the stands. A John Deere 540 G-III cable skidder was used for skidding trees out of the forest at Stand 1 and Stand 3, while two Belgian horses skidded trees at Stand 2. For bucking trees into logs, a Franklin 632 Bogie Forwarder with a Hultdins SuperSaw 550S mounted on the grapple was used at Stand 1 and Stand 2, while a Timrick Serco 270 mobile loader slasher was used at Stand 3. The operators responsible for bucking had been trained at the Haliburton Forest sawmill and had at least 3 years of bucking experience. Two different loggers (one at Stands 1 and 3 and a different one at Stand 2) harvested the trees. At every stand, the logger felled and limbed trees with a Stihl MS 441 chainsaw.

Haliburton Forest has owned and operated a sawmill since 2009. Its setup is typical for midsized hardwood sawmills in the region, with a 640 MoreBark debarker and a 40-inch Helle headsaw for opening logs. It has a homemade bandsaw for resawing and an 8-inch Sherman bull-edger in addition to two Truway trimsaws. Chips and sawdust are processed through a 58-inch Forano six-knife chipper. Seventeen Lesson electric motors, ranging from 200 to 7.5 horsepower, power the mill. Daily lumber production is 17 Mfbm for an annual capacity of 3,500 Mfbm. Approximately 60 percent of lumber produced is sugar maple. The sawmill focuses on recovering value from low-grade logs harvested during single-tree selection operations in Haliburton Forest, resulting in an average log-to-lumber conversion rate of <35 percent.

Product recovery methods

After tree marking but prior to harvesting, numerous characteristics were assessed on each tree marked for removal, including DBH and the presence of defects. Calipers, a tape measure, and a GPS were used. Trees were sorted into eight groups based on their size (four size classes according to DBH) and quality (two defect classes based on the presence or absence of fungi, seams, and other defects; Arbogast 1957, Leak et al. 1987, OMNR 1998). The size classes included pole (<24.1 cm DBH), small (24.1 to 36), medium (36.1 to 48), and large (>48). The defect classes included acceptable growing stock (AGS) and unacceptable growing stock (UGS) (Table 1; OMNR 2004). Each of the eight size and defect classes included at least 50 trees except pole AGS (43 trees) and large AGS (28 trees).

Prior to being felled, every tree was painted with a unique code indicating its size and defect class. At each stand, after trees were felled and skidded to the landing, they were bucked into logs that were sorted as either firewood or sawlogs. The unique code that was painted on each tree was also painted on every log cut from the tree during the bucking process. After trees were harvested and bucked, we recorded the length and both butt diameters of all firewood logs and sawlogs using calipers and a tape measure, noting which tree each log had been cut from.

Sawlogs were scaled using the Ontario Log Rule scaling system in order to determine defect-related scaling deduc-

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Table 1.—Classification scheme used to assess tree quality based on the presence and severity of defects (Ontario Ministry of Natural Resources 2004).

Defect class	Description	Defects
Acceptable growing stock	Low-risk and healthy with relatively few defects Expected to maintain/ improve quality over the rotation	Burls and lumps Crooks and minor sweeps Epicormic branching Whiteface scars
Unacceptable growing stock	High risk and generally unhealthy with major defects Expected to decline and lose quality over the rotation	All of the above All fungi and cankers Darkface scar (>900 cm^2) Severe sugar maple borer wound Spiral seams and weeping seams Sweeps and leans >10°

tions, grade, heart size, and volume (Ontario Woodlot Association 2000). Before being processed in the sawmill, each sawlog was painted with a code indicating the size and defect class of the tree from which it was cut. The sawlogs were grouped by size and defect class and processed in the sawmill. The code that was on each sawlog was then written on each board of lumber as it exited the sawmill. The lumber was measured and graded according to hardwood lumber grading rules (National Hardwood Lumber Association [NHLA] 2011). In this way, it was possible to know what kind of tree (i.e., size and defect class) each graded board was cut from.

Time-motion methods

Harvesting costs were estimated for 334 trees at Stand 3 using standard time-motion costing procedures (Rickards and Savage 1983) and guidelines for the assessment of direct costs (Duerr 1993). Processes involved in logging and bucking trees were divided into discrete cycles and then elements, similar to those defined by Wang et al. (2004). A stopwatch was used to measure the time per element and cycle for each tree.

Sawmilling costs were assessed using data collected during a time-motion study of 395 sugar maple sawlogs at Haliburton Forest's sawmill. The sawlogs were measured and scaled and then arranged into one of 12 categories according to small-end diameter (three classes) and scaling deduction (four classes). The logs were painted with a code indicating size and scaling deduction. Similar to Lin et al. (2011) and conforming to standard methods (Rickards and Savage 1983), each process in the sawmill was measured depending on how costs are accrued (e.g., dollars per board, cubic meter, and hour). For example, the cost of loading logs onto the debarker deck is a function of the volume of logs (cubic meter) because the loader is limited by volume, while the process of edging accrues costs per board because all boards require the same effort regardless of size or quality.

Volume and value calculations

The volume of all logs and sawmill products was calculated throughout the supply chain. Smalian's formula was used to calculate the volume of firewood logs and sawlogs, using diameter and length measurements collected on the landing and at the sawmill. Lumber volume was calculated with standard measurement rules (NHLA 2011) and converted to metric measurements using a ratio of 423 fbm to 1 m^3 of lumber. The volume of sawmill residues recovered from each tree—chips, bark, and sawdust—was calculated by subtracting the volume of lumber yielded by a tree's sawlogs from the total volume of its sawlogs. The relative volume of each residue was calculated using proportions provided by the sawmill manager (58% chips, 14% sawdust, and 28% bark) based on the respective volumes sold the previous year.

The value of firewood logs was calculated for each tree by multiplying the volume of firewood logs by the average price paid at the landing in central Ontario, approximately $16/m^3$. The value of lumber was calculated in three steps. First, we compiled the volume of each lumber grade for each size and defect class of trees processed in the sawmill. Second, we allocated a portion of the compiled lumber volume to each tree based on the scaled value of its sawlogs. For example, if a pole AGS tree's sawlogs accounted for 10 percent of the scaled value of the pole AGS group, that tree would be assigned 10 percent of the lumber produced by that group. Third, the volume of each lumber grade recovered from each tree was multiplied by the prices received by the mill (Table 2). Figured lumber (e.g., birdseye maple) was graded and valued as conventional lumber, even though it can earn a premium in specialized markets. The value of each residue was calculated in the same manner. To calculate the lumber conversion rate, or the percentage of a sawlog's volume becoming lumber, we divided the volume of lumber recovered from each sawlog by its total volume. Some trees were felled but left in the forest because it was unlikely that they would produce even a single merchantable log; these stems were assumed to have no product value.

Cost calculations

Harvesting costs per machine per man-hour were calculated using the FPInnovations ProVue machine productivity database for manual felling, cable skidding,

Table 2.—Free-on-board mill gate prices used to calculate the value of firewood at the landing in the forest as well as sawmill residues and rough/green lumber at the sawmill.[a]

Product	Price ($)
Firewood (m^3)	
Logs	16.00
Lumber (Mfbm)	
Select	1,250.00
1 Common	800.00
2 Common	660.00
3a and 3b	660.00
Cants	400.00
Pallet	330.00
Residues (m^3)	
Chips	48.00
Sawdust	12.80
Bark	8.00

[a] Prices were provided by Haliburton Forest forestry and sawmill staff in October 2013.

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and mobile bucking. The cost per machine per man-hour was multiplied by each element's time to calculate the cost of performing a particular task for each tree (e.g., felling, skidding, or bucking). The cost of transporting sawlogs to the sawmill was calculated as a function of the amount that trucking contractors are paid per load ($300), the average volume of each load (50 m^3), and the volume of each tree's sawlogs.

Sawmilling costs were calculated by multiplying the direct cost per unit by the number of units produced by each sawlog milled during a time-motion study of 395 sawlogs at Haliburton Forest's sawmill. The cost per sawlog was averaged for each size and scaling deduction class. Then the cost of processing each type of sawlog was multiplied by the number of each type of sawlog produced by each tree in the product recovery studies. Finally, the cost of milling each tree's sawlogs was summed and then added to the harvesting, bucking, and transport costs to calculate each tree's milled cost.

Net value calculations

In order to calculate volume-based values and costs (dollars per cubic meter) for statistical analysis, we added together the gross value of all the products from each tree and then divided the total by the volume of each tree's firewood and sawlogs. We also combined the direct costs of harvesting, bucking, and milling each tree and then divided the sum by the combined volume of firewood and sawlogs. Thus, unless otherwise noted, gross value and cost are expressed on a volumetric basis (dollars per cubic meter). We then subtracted the cost from the gross value to calculate each tree's net value. Net value has been called ''conversion surplus'' in past research (e.g., Duerr et al. 1956). It is a measure of a product's potential to yield value in excess of the direct cost of production in a given operational context. Finally, to quantify the variation in net value among trees, we calculated the mean net value of each tree size and defect class.

Statistical analysis

To assess the sources of variation in net value, we conducted a separate regression analysis for each step in the supply chain (Table 3). Analysis was conducted with the R statistical package (R Development Core Team 2008). We used logistic and beta regression as well as analysis of covariance and analysis focused on trees that yielded at least one sawlog. The goal of the regression analysis was to determine whether tree size and the presence of defects have a significant effect on product volume, gross value, direct cost, or net value. Product volume was log transformed prior to analysis to improve the normality of residuals. Significance was tested by assessing P values at a 95 percent confidence interval. Included in the analysis was a random stand term (i.e., individual trees nested within stands) with a normal error distribution to account for any unmeasured variances associated with nested data (Pinheiro and Bates 2013).

Results

Across the stands, 8 percent of the trees were felled but left in the forest rather than skidded to the landing. Whether a tree was skidded out of the forest was not significantly related to size or defect class (Table 3). Among trees that were skidded, the volume of firewood and sawlogs increased with DBH and was higher for AGS trees (Fig. 1). Larger trees (>36.1 cm) were also more likely to yield at least one sawlog (Fig. 2). Among trees that yielded at least one sawlog, the proportion of each tree's volume sorted as sawlogs (rather than firewood) increased with size but was not related to defect class (Table 4). Larger trees produced significantly more overall sawlog volume than smaller trees (<36 cm; Table 4). For example, among milled trees, an average of 0.10 m^3 of sawlogs was recovered from trees in the pole size class compared with 1.03 m^3 from large trees.

AGS trees were more likely than UGS trees to yield at least one sawlog (Fig. 2). They also yielded more sawlogs, and their sawlogs had fewer deductions for rot, sweep, and other defects (Table 4). Thus, the lumber conversion rate of sawlogs (the ratio of sawlog volume to lumber volume) was higher for AGS trees compared with UGS trees. However, neither the average scaling deduction of sawlogs nor the lumber conversion rate varied with DBH. Furthermore, while the proportional area of stained wood at the end of each sawlog increased with DBH, the mix of lumber grades recovered from sawlogs did not vary according to the size or defect class of the original tree. Thus, the gross value (dollars per cubic meter) of milled trees did not vary with DBH, although AGS trees were more valuable than UGS

Table 3.—Regression models specifying recovery as a function of tree size and/or the presence of defects.[a]

Error distribution	Dependent variable	Independent variable	Coefficient	Intercept [constant]
Normal	Probability of being skidded			[92%]
Bernoulli	Probability of skidded trees producing a sawlog	DBH[b]	0.07547	−0.89539
		Defect	−0.73236	
Beta	Proportion of a skidded tree's volume sorted as sawlogs	DBH	0.009333	0.60832
Lognormal	Volume of milled trees	DBH	0.039139	−1.767704
		Defect	−0.108597	
	Volume of firewood trees	DBH	0.049285	−2.323213
		Defect	0.013284	
Normal	Gross value/m^3 of milled trees	Defect	−19.769	85.461
	Gross value/m^3 of firewood trees			[$16.00]
	Cost/m^3 of milled trees	DBH	−0.33648	52.97338
	Cost/m^3 of firewood trees	DBH	−0.5937	39.164
	Cost/stem of nonskidded trees	DBH	0.052494	−0.357014

[a] In cases where the regression was nonsignificant, the mean value of the dependent variable is reported (constant in brackets) in lieu of coefficients.
[b] DBH = diameter at breast height.

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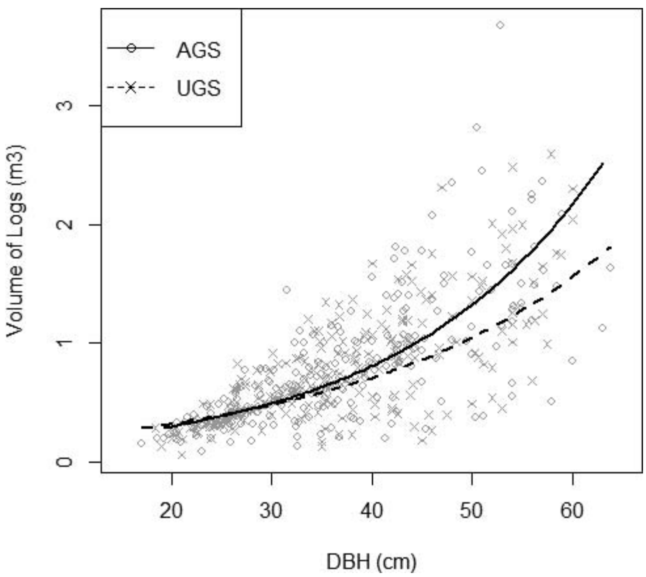

Figure 1.—Volume of logs, including firewood and sawlogs, for all skidded trees. AGS = acceptable growing stock; UGS = unacceptable growing stock; DBH = diameter at breast height.

trees owing to the superior lumber conversion rate of their sawlogs (Fig. 3).

In contrast, AGS and UGS trees incurred the same costs (dollars per cubic meter), but the cost of harvesting and processing trees decreased with tree size (Fig. 4; Table 2). For example, it was 80 percent more expensive to harvest, skid, and buck trees smaller than 36 cm DBH (\$16.38/m^3) compared with larger trees (\$9.17/m^3). The same trend was evident at the sawmill and generally throughout the supply chain. As a result, the mean milled cost of larger trees was \$37.73/m^3 compared with \$47.20/m^3 for smaller trees.

Table 4.—Sawlog characteristics for each tree size and defect class.[a]

Size class	Defect class	Sawlog volume (m^3)	Heart proportion (%)	Scaling deduction (%)	Lumber conversion (%)
Pole	AGS	0.25	18	54	28
	UGS	0.22	21	59	24
Small	AGS	0.20	32	47	28
	UGS	0.24	19	56	28
Medium	AGS	0.39	26	47	30
	UGS	0.31	33	50	24
Large	AGS	0.47	36	44	30
	UGS	0.44	34	51	23

[a] Values represent the average of all sawlogs cut from each group of trees. AGS = acceptable growing stock; UGS = unacceptable growing stock.

In summary, among milled trees, net value (dollars per cubic meter and tree) was higher if a tree was AGS, and it increased with DBH (Figs. 5 and 6). Furthermore, among all trees that were skidded out of the forest, large AGS trees yielded the greatest net value (\$79.04/tree and \$47.05/m^3), while pole UGS trees earned the least (\$0.72/tree and \$7.58/m^3).

Discussion

Tree size

It has long been known that harvesting and sawmilling costs per cubic meter are inversely related to the size of trees and sawlogs, and our results confirm past research (Ashe 1916, Kirkland 1943, Wang et al. 2004). Costs per cubic meter tend to decrease with size because larger trees contain more merchantable products but incur comparable costs to smaller trees. For example, if a tree in the large size class is skidded, the effort will produce approximately 10-fold the sawlog volume than a tree in the pole size class. Yet the skidding cost for these stems is essentially the same

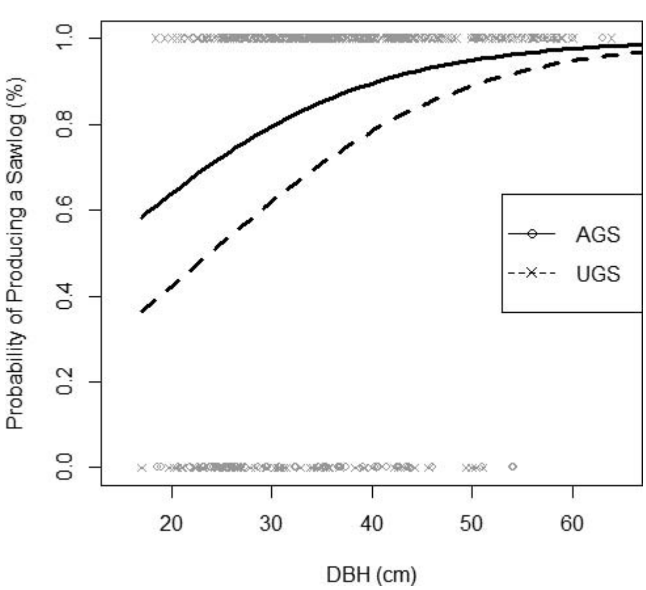

Figure 2.—Probability of a tree that was skidded yielding at least one sawlog. Trees that did not yield any sawlogs were sorted entirely as firewood. AGS = acceptable growing stock; UGS = unacceptable growing stock; DBH = diameter at breast height.

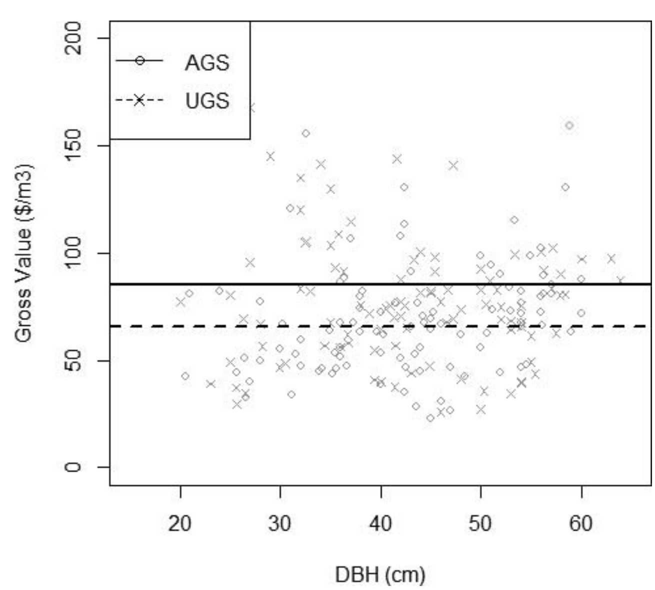

Figure 3.—Gross value per cubic meter for milled trees. This reflects the value of lumber, residues, and firewood recovered from these trees divided by the volume of their sawlogs and firewood logs. AGS = acceptable growing stock; UGS = unacceptable growing stock; DBH = diameter at breast height.

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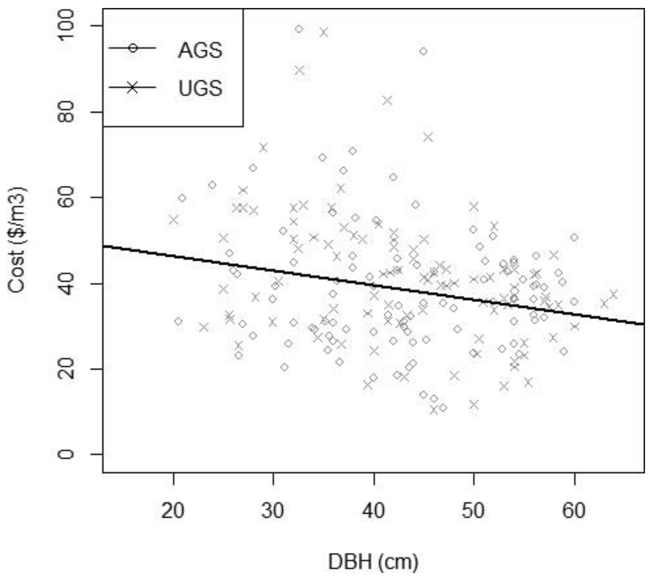

Figure 4.—Cost per cubic meter for milled trees. Harvesting, slashing, transport, and sawmilling costs were added together and divided by the combined volume of their sawlogs and firewood logs. AGS = acceptable growing stock; UGS = unacceptable growing stock; DBH = diameter at breast height.

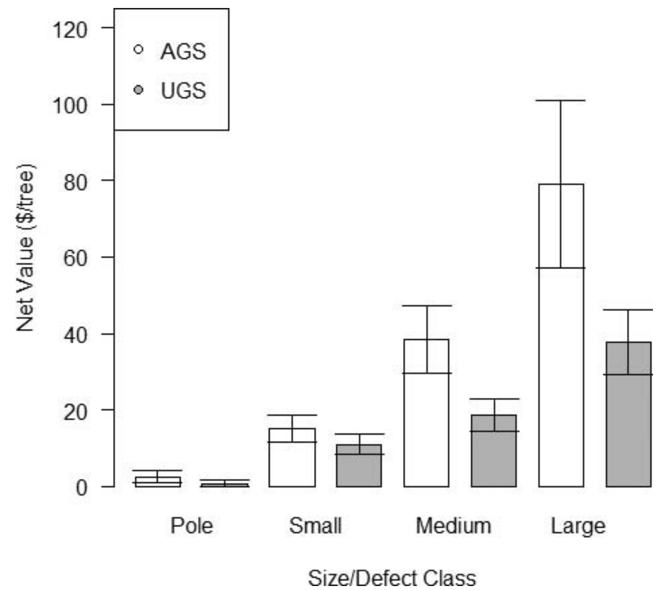

Figure 6.—Net value per tree for all trees, including trees that were felled but left in the forest. Error bars show two standard errors. AGS = acceptable growing stock; UGS = unacceptable growing stock.

because each tree takes an entire choker on the cable skidder. The large tree has a cost per stem equal to the pole but a greater product volume, resulting in lower costs per cubic meter of sawlogs or lumber. This cost efficiency is more or less repeated throughout the supply chain and is the major reason that large trees are more profitable than small trees.

It is also commonly assumed that large trees are more profitable for an integrated forestry company because the gross value of sawlogs increases with tree size (Arbogast 1957, Lin et al. 2011). For example, researchers in Quebec concluded that the likelihood of recovering high-grade sawlogs increases with DBH among sugar maple trees of the same defect class (Fortin et al. 2009). Others have suggested that larger sawlogs, which were recovered from larger trees, yield superior lumber in other deciduous species, such as paper birch (*Betula papyrifera*; Yaussy 1987, Drouin et al. 2010). Accordingly, these researchers suggest that gross value increases with tree size for two reasons. First, larger trees produce a greater volume of logs, and second, timber quality increases with tree size.

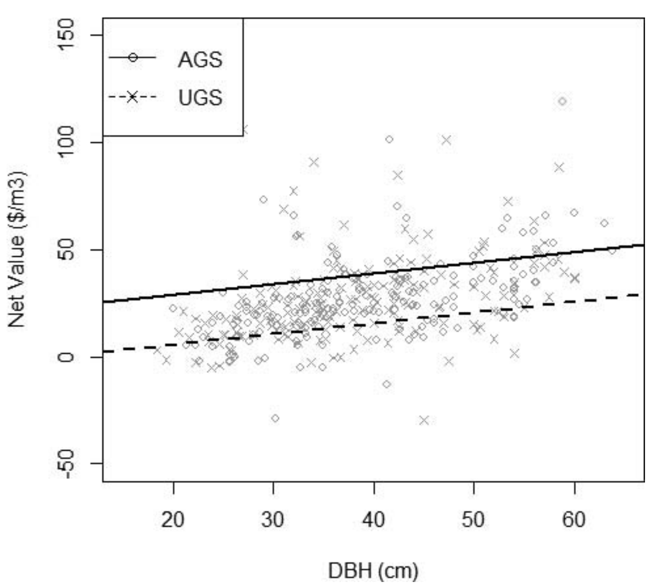

Figure 5.—Net value per cubic meter for milled trees. AGS = acceptable growing stock; UGS = unacceptable growing stock; DBH = diameter at breast height.

The first point—that volume and hence gross value increase with DBH—is supported by this study. Larger trees yield significantly more volume, and a greater proportion of this volume meets sawlog specifications. Smaller trees are less likely to yield sawlogs because their logs are below the minimum sawlog diameter (~24 cm) or their defects are too substantial for sawlog recovery. The gross value of firewood is approximately 20 percent that of sawlogs, so the tendency of smaller trees to be sorted mostly or entirely as firewood reduces the gross value of smaller trees relative to larger trees, which yield proportionally more sawlogs. In summary, our results confirm the notion that gross value per tree increases with size because bigger trees yield more products.

But our findings diverge on the second point—that log and lumber value increase with size. We found that trees in the same defect class that yield at least one sawlog are worth approximately the same per cubic meter regardless of tree size. Sawlogs recovered from large trees do not exhibit fewer defects than sawlogs from smaller trees, so lumber recovery rates do not vary by tree size. It is indeed easier to cut longer and wider boards from large sawlogs, which facilitates high-grade lumber recovery. But sawlogs from large trees have a greater proportion of stained wood, which tends to produce low-grade lumber in most hardwood species (including sugar maple and paper birch; Table 4). As a result, the lumber grade mix recovered from sawlogs does not vary according to original tree DBH, and the value of sawlogs (dollars per cubic meter) is not higher for larger

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trees. This indicates that bigger trees are more valuable to the forestry sector simply because they yield more wood at a lower cost rather than better wood at a lower cost. In this way, our findings contradict previous assertions about the relationship between tree size and product value.

Defect class

The quality of a tree, as measured by the two defect classes (OMNR 2004) or similar systems from Quebec (Boulet 2007), is believed to be a good predictor of mortality and growth (Hartmann et al. 2008). There is also thought to be a relationship between defect class and value (Leak et al. 1987, OMNR 2004). The results of this study also show that the gross value of UGS trees, which have major defects, is consistently lower than comparably sized AGS trees. Thus, this study confirms that defect classification schemes can be fairly accurate predictors of tree value by virtue of assessing the presence of defects that affect the volume and quality of wood products as well as future growth potential (Fortin et al. 2009). To the best of our knowledge, this study is the first to test this defect classification scheme in this way.

The silvicultural implications of this finding are significant because the consideration of defects and, by extension, anticipation of financial gains and losses are critical parts of the tree selection decisions made by tree markers. For example, tree markers have long been instructed to prioritize the removal of stems with defects that reduce tree health to facilitate the future growth of more valuable stems (OMNR 1998). More recently, tree-marking prescriptions have been refined to capture the current value of trees at risk of decline, that is, trees with recent defects that are yet to affect its value (Pothier et al. 2013). This may prove difficult to achieve because most defects are believed to affect tree value soon after they are apparent to tree markers, if not before (Shigo 1984). Nonetheless, the inclusion of estimates of the dual nature of defects, which affect tree health as well as quality, in tree-marking guidelines has been a positive development in this relatively new practice. Also including estimates of economic worth, such as those presented in this article, will allow tree markers to base their decisions on a combination of tree health, quality, and net value.

Limitations

The utility of this study is limited in two ways. First, the conditions, equipment, and personnel involved in harvesting and sawmilling operations vary within any forest region. For example, this study is based on the use of chainsaws and skidders, a harvesting system that is currently common but may eventually be displaced by mechanized operations. Furthermore, operators at Haliburton Forest are instructed to aim for 75 percent sawlog recovery, while loggers at other companies would typically sort 50 percent of harvested hardwood volume as sawlogs. This means that Haliburton Forest's sawmill receives an unusually large volume of low-quality sawlogs. As a result, additional product values as well as costs may be accrued by low-quality trees that produce marginally profitable sawlogs. Nonetheless, this study aims to assess the basic relationship between size, defects, and net value, not provide universally applicable figures for all hardwood species. We expect that the commonness of the measurement systems used makes these results generally applicable to sugar maple trees in the Great Lakes–St. Lawrence forest region.

The second noteworthy limitation is that for ease of analysis and implementation, we assessed tree quality using a binary classification scheme. Defects can range from being barely noticeable to severe, and the consequent range in tree quality is not accounted for in our assessment, even though it is closely related to both tree health and past management practices (Shigo and Larson 1969, Keys and McGrath 2002). Future research may do well to analyze the impact of particular defects on gross product value and processing costs. Such research could also explain the high levels of variance that exist in assessments of tree value. However, we concur with Pothier et al. (2013), who noted that reducing defect assessments to discrete classes is justified by ease of analysis and implementation.

Operational relevance

Accurately evaluating standing timber can improve the efficiency of harvest planning by indicating the recoverable volume and value of a forest (Mendel et al. 1976). It can be used to prevent uneconomical silvicultural activities, such as building roads to access stands with insufficient timber to cover infrastructure costs. These results will be particularly useful in the Great Lakes–St. Lawrence forest region, where many stands are held by small, nonindustrial, private landowners who can afford to be selective about when, where, and how to conduct harvests (DeBald and Mendel 1976). With a method for interpreting the cost and value implications of forest inventory data, it is easier to strike an efficient balance between silvicultural and financial objectives.

In stands that have been selected for harvest, it is important that operators seek the optimal balance between product recovery (value) and production effort (cost). Some trees earn a negative net value because harvesting and processing costs exceed product values. For example, in this study, due to inefficient/poor log sorting, some smaller trees were worth only slightly more if they were AGS (Fig. 6). This is likely because the operator sorting logs was deceived by the sound appearance of these trees—he believed that sufficient lumber could be recovered from them, even though these trees end up mostly as chips when they are milled. The operator sorted the logs as sawlogs instead of firewood, so the small sawlogs from these trees incurred excessive costs at the sawmill but failed to yield enough products to cover the additional processing costs. A better understanding of the relationship between tree size, tree quality, value recovery, and cost accrual could prevent such inefficiencies, for example, by discouraging the sorting of small logs as sawlogs in the first place.

Further work

This study explains why operators should want to harvest larger trees: their gross value (dollars per cubic meter) is the same as smaller trees, but their harvesting and processing costs (dollars per cubic meter) are lower. However, this does not imply that it is as economically viable to grow large trees as it is to harvest them. The cost efficiency of larger trees, which benefits primarily operators and integrated forestry companies like Haliburton Forest, does not come free to landowners, who carry the cost of waiting for a tree to grow and are exposed to the risks of tree mortality or

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quality loss due to defect development. From a landowner's perspective, for example, a tree should be retained for future harvest only if the additional value and cost savings derived from its rate of growth exceed the risk of mortality and decline. This trade-off is fundamental to forest management, but the financial and silvicultural implications are poorly understood.

Analyzing the characteristics that affect the net value of individual trees is an initial step toward developing guidelines for tree selection that maximize the long-term value growth of forests (Lussier 2009). To calculate how tree value changes over time, the net value functions identified here can be adjusted by rates at which trees grow in terms of DBH, develop or accrue defects and transition from AGS to UGS, or die. Such estimates of value change can assist foresters in selecting an appropriate alternative rate of return for managed hardwood stands (Canham 1986) and thereby calculate financial maturity, the point at which a tree's rate of value growth fails to exceed an alternative rate of return (Duerr et al. 1956). Choosing stands and even individual trees on the basis of net value in the short term and financial maturity in the long term would improve the economic viability of hardwood silviculture in the Great Lakes–St. Lawrence forest region and beyond.

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