Comparative effects of full-tree and tree-length shelterwood harvesting on residual tree damage and coarse woody debris volume in the Great Lakes – St. Lawrence forest

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ABSTRACT

Residual stand damage and coarse woody debris loads were evaluated in 15 hardwood and white pine uniform shelterwood harvest blocks, in the Great Lakes – St. Lawrence Forest Region, using tree-length (TL) and full-tree (FT) harvesting techniques. Stand-level damage rates to residual stems in both the TL and FT harvest operations were below Ontario's allowable "major" damage limits of 15% to all residual trees and 10% to acceptable growing stock (AGS) trees. No significant differences in damage rates were observed between the TL and FT harvest systems and were comparable to past assessments in TL and FT harvested blocks. Despite efforts to increase utilization of material from these study sites, no significant differences were observed in coarse woody debris (CWD) volume or the distribution of that volume across decay classes.

Key words: full-tree harvesting, hardwoods, white pine, shelterwood silviculture, coarse woody debris, logging damage

RÉSUMÉ

On a évalué les blessures aux arbres résiduels et la quantité de débris ligneux grossiers dans 15 blocs de coupes progressives uniformes de feuillus et de pin blanc situés dans la région forestière des Grands Lacs et du Saint-Laurent utilisant les techniques de récolte par arbres en longueur (TL) et par arbres entiers (AE). Les taux de blessures aux arbres résiduels dans l'ensemble du peuplement, tant dans les opérations de TL que d'AE, se situaient sous les limites permises en Ontario pour les blessures « importantes » soit 15 % pour tous les arbres résiduels et de 10 % pour les arbres formant le stock sur pied acceptable (SPA). Aucune différence significative dans les taux de blessures n'a été observée entre les systèmes de récolte par TL et par AE et ces taux étaient comparables aux évaluations antérieures pour des blocs récoltes par TL et par AE. Malgré des efforts pour accroître l'utilisation de la matière ligneuse tirée de ces sites d'étude, aucune différence significative n'a été observée dans le volume de débris ligneux grossiers et dans sa répartition parmi les classes de décomposition.

Mots clés : récolte par arbres entiers, pin blanc, sylviculture par coupes progressives, débris ligneux grossiers, blessure d'exploitation

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Introduction

The Great Lakes – St Lawrence (GLSL) forests of central Ontario have had a long history of management and manipulation. Past anthropogenic activities and natural disturbances have significantly influenced the species composition, stand structural attributes, and health of the current forest. Prior to the development and enforcement of the Crown Forest Sustainability Act (Statutes of Ontario 1995) many of the forests in southern and central Ontario were selectively harvested, with a preference for the biggest and best trees of the desired species. More often than not, the remaining forest was severely damaged by logging operations, stocked with unhealthy trees and left to regenerate to species that were less

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well suited to the sites they occupied. In the 1980s and 90s, many stands were harvested using the selection silviculture system because it was viewed as the most ecologically sustainable solution for managing hardwood forests even when site productivity, species composition, and forest structure were not suited to this approach. The prevalence of small canopy gap disturbances associated with selection harvesting led to a persistence of shade-tolerant hardwoods within the GLSL region (Jackson *et al.* 2000). The continued loss of mid-tolerant species, such as yellow birch (*Betula allegheniensis* Britt.), white pine (*Pinus strobus* L.), and red oak (*Quercus rubra* L.), resulted in decreased species diversity (Schwartz *et al.* 2005, Neuendorff *et al.* 2007, Webster and Jensen 2007).

The net result was that large areas of the forest were degraded and in need of species rejuvenation and quality improvement. The current tool for regenerating mid-tolerant species and restoring damaged stands to healthier and more productive forest is the shelterwood silviculture system. However, regenerating mid-tolerant species in these stands is challenging, often requiring heavy investment in site preparation, planting, and repeated tending treatments. To achieve the desired outcome, both careful logging and post-harvest silviculture activities are usually required. Even with these large investments, successful regeneration of some species, red oak for example, is often not very successful.

From an economic perspective, damage to residual trees during the harvest operation or subsequent silviculture treatments is a major concern because it can lead to loss of product volume and reduced value (Rice 1994, Vasiliauskas 2001). From an ecological perspective, damage to residuals can increase mortality rates (Caspersen 2006) as well as reduce tree- (Jones and Thomas 2004) and stand-level growth rates if tree health is compromised as a result of the harvest (Bedard and Majcen 2001, Forget *et al.* 2007). Cline *et al.* (1991) and Fajvan *et al.* (2002) indicated that logging damage is most common on boles, with less injury to roots and crowns. In a study of whole-tree harvesting by Kelly (1983), up to 80% of the damage occurred on the stems. This damage is the result of trees being extracted from where they are felled and traffic on skid trails. Crown damage can be controlled with careful felling practices and root damage can be minimized by limiting trail coverage and soil compaction and rutting.

To offset the cost of achieving silvicultural and ecological objectives in shelterwoods, some combination of three economic drivers must occur during harvest. First, the harvest must recover and markets must be found for large quantities of small-diameter and low-quality material. Second, sufficient volume of higher-value, defect-free material is needed to increase the value per unit volume recovered from the harvest block. Third, increased efficiencies in per-unit volume harvest and transport costs must offset the fixed costs of fibre acquisition. One way to increase volume per unit area is to increase the utilization of material recovered. Full-tree harvesting both increases recovery of material and potentially reduces harvest cost per unit area. In addition, it may reduce the cost of site preparation through slash removal and substrate scarification via skidding during harvesting. Full-tree harvesting, during the limbing phase of operations, also offers a safer and more productive work environment for processing tree tops; these are important considerations for controlling costs and for worker safety. However, in Ontario's current sil-

viculture guidelines for shelterwood (and selection) management systems, full-tree harvesting is "not recommended" due to potential for damage when skidding tops and limbs (OMNR 1998a,b). Skidding of large limbed trees could (1) damage more residual trees, (2) disturb a greater proportion of the advanced regeneration both within and beyond skid trails, and (3) increase disturbance of the soil surface. Moreover, concerns have been expressed about the effect of full-tree logging on productivity of the stand for future harvests and coarse woody debris (CWD) loads, and the effect of reduced CWD on wildlife habitat and species diversity (Berch *et al.* 2011, Puddister *et al.* 2011).

To address some of these concerns, several provincial, national, and international studies have been initiated to evaluate the effects of full-tree harvesting and increased utilization harvests on stand productivity in clearcut systems (Hornbeck *et al.* 1990, Tenhagen *et al.* 1996, Morris and Duckert 1999, Duckert and Morris 2008, Morris 2009, Fleming 2011). In addition, the Ontario Ministry of Natural Resources (OMNR) and partners have begun a series of harvesting experiments in the GLSL forest to investigate the effects and benefits of full-tree logging. The intent is to document the effects of increased utilization harvests (including full-tree harvests) on soil nutrient availability, substrate disturbance, woody debris loads, as well as damage to advanced regeneration. These studies provide intensive plot-based measures of harvest effects at the stand level but do not capture variation among harvest blocks. To quantify harvest block-level effects, more extensive cruising data and comparisons among multiple blocks are required. Since 2004, surveys of damage to residual trees have been carried out on a relatively small scale on two central Ontario management units as part of required monitoring for full-tree harvesting trial areas, referred to as *exceptions monitoring*. However, to be useful, these surveys need to cover a broader scope of conditions and results compared to those from tree-length harvesting.

The study reported here was designed to complement the data collected as part of previous exceptions monitoring in full-tree (FT) and tree-length (TL) logging operations between 2004 and 2010. We evaluate two uniform shelterwood harvest block-level questions as follows: Relative to TL harvesting, (1) does FT harvesting increase damage to residual trees, and (2) does FT harvesting deplete CWD?

Methods

Study sites

We evaluated residual tree damage and CWD volume on 11 different hardwood and four white pine uniform shelterwood harvest blocks from three Sustainable Forest Licences (SFL) in the GLSL forest region of Central Ontario (Fig. 1). Dominant species in the region include sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), yellow birch, eastern white pine, red oak, white birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca* [Moench] Voss), and red pine (*Pinus resinosa* Ait.), as well as largetooth (*Populus grandidentata* Michx.) and trembling (*Populus tremuloides* Michx.) aspen.

Stands included in the study were all harvested at the regeneration cut stage of the shelterwood silvicultural system. All harvest blocks were prescribed as uniform shelterwood regeneration cut due to stand structure, species composition

Fig. 1. Locations of the Northshore, Nipissing, and French–Severn Forests within the Great Lakes – St. Lawrence Forest Region of Ontario.

and health criteria within the SFL management plans. All blocks were harvested prior to the inception of this study; however, no post-harvest site preparation or tending treatments had been undertaken in the harvest blocks and the harvests had all occurred after 2009. In addition, all of the sites were harvested using mechanized logging with feller bunchers and grapple skidders. The number, size and composition of the harvest blocks used in the study were constrained by the availability of harvest blocks that met the criteria for inclusion within the GLSL forest region of central Ontario. The decision to harvest as FT in five of the 15 blocks harvested was not based on pre-harvest forests structure or tree spacing but rather based on the need to operationally test the feasibility of FT harvesting on “typical” uniform shelterwood regeneration cuts. In total, 10 sites (harvest blocks) were chosen from Nipissing Forest (NP), three from Northshore Forest (NS) and two from French–Severn Forest (FS). Of those harvest blocks, two white pine and three hardwood harvest blocks were harvested using FT harvesting methods.

Sampling design

Each harvest block was sampled systematically using a predefined grid of sample points. To accomplish this, geographic information system (GIS) data and harvest block records were obtained from the SFLs and a 75-m to 150-m grid was established uniformly over the entire harvest area. Grid size was determined based on the size of the harvest block. Harvest blocks under 50 ha were sampled at 75 m, blocks between

50 ha and 75 ha were sampled at 100-m spacing and blocks over 75 ha were sampled at 150-m spacing. Our goal was to obtain between 20 and 50 plots per harvest area to fairly represent the average stand condition across the entire area. During field sampling, plots were excluded if they occurred within 10 m of roads, landings, or areas of concern (AOC) and harvest boundaries.

Field measurements

To assess residual basal area, a basal area factor 2 prism (BAF 2) sweep was conducted at each plot centre. Each tree identified as within the prism plot was evaluated for pre-harvest health status, ignoring any wounds that occurred during recent harvest operations. Trees were determined to be healthy and acceptable growing stock (AGS) or unhealthy and unacceptable growing stock (UGS) using criteria described in Ontario’s tree marking guide (OMNR 2004). Trees were also evaluated visually for logging damage to the bole, crown, and roots. Trees with greater than 20% to 30% projected losses in crown or root volumes, due to breakage or shearing, as well as any trees that were snapped off or tipping up, was also considered to have major damage. Trees with bole damage greater than 900 cm² were assessed as having major wounds; those with less than 900 cm² bole damage were considered to have minor wounds. Furthermore, any tree with a wound greater in width than the diameter of the tree was considered to have major damage. These definitions of major damage are a simplified yet slightly more stringent

version of the major damage criteria described in Ontario's silviculture guides (OMNR 1998a,b), providing a conservative estimate of whether these harvesting methods result in stands that meet the standards for Crown land. We chose these more stringent criteria because setting a fixed wound size for all trees was easier to determine on a consistent basis than the methods described in the silviculture guides (OMNR 1998a,b), and could be rapidly assessed. The lower criteria for crown and root damage were more biologically meaningful with respect to potential for reduced growth and future health risk.

At each plot centre, two 20-m perpendicular CWD transects were established; one in a North–South direction and another in an East–West direction. Diameters of CWD that intersected the transects were measured at the point of intersection. Each piece of CWD was identified to species based on residual bark and/or branch morphology. Species of highly decayed CWD were recorded as unknown. Each piece of CWD was also assigned one of five decay classes using criteria first described by Maser *et al.* (1979). The volume of CWD was calculated at the harvest block level using the line intersect method described in Marshall *et al.* (2000).

Historic data

In addition to the residual stem damage data collected as part of this study, data were compiled from an additional 34 recent FT harvest blocks as well as 25 TL harvest blocks. These data were collected by different individuals from three different SFLs. The sample intensity and design were non-standard within and between treatments and harvest blocks and as a result the data were adequate for validation of the current study results but could not be added to the current studies data for direct comparison. For these historic data sets, the total residual basal area, proportion of basal area (BA) with major damage, and the proportion of major damage to AGS trees were recorded. Criteria for major damage were those set out in the provincial silviculture guides, i.e., bole wounds greater than 1000 cm² on trees greater than 31 cm in diameter and any wound greater than or equal to the square of the tree's diameter for trees under 31 cm diameter at breast height (DBH) were considered major. Crown damage >33% and root damage >25% were also considered major (OMNR 1998a,b).

Data analyses

The total tree damage rate (%) was calculated as the total basal area of trees damaged in the harvest block divided by the total basal area of trees sampled in the block. Similarly, the percent of basal area with major

damage was calculated as the basal area of trees with major damage divided by total basal area of trees sampled. The percent of AGS stems with major damage was also calculated as the proportion of AGS basal area that showed evidence of major damage. An analysis of variance (SAS v9.2) was used to test for differences in harvest block-level residual basal areas, volumes, and damage rates as well as differences in CWD volumes between the FT and TL harvest treatments. The experimental unit for analysis was the harvest block, which resulted in a total sample size of 15. To test for differences in CWD volume by decay class, a two-way ANOVA was employed. A separate ANOVA was run on the historic data sets due to the differences in criteria used to assess damage and the large differences in sample size between the two data sources. No direct statistical comparison was made between the current and historic datasets.

Results

Residual stand structure

In total we sampled 510 plots across 15 harvest blocks in three different forests. Plot-level variability in residual basal area within a harvest block was high, ranging from 2 m² ha⁻¹ to 32 m² ha⁻¹ (Fig. 2). Average residual basal areas were also highly variable, with a nearly two fold difference among harvest blocks, ranging from 8.4 m² ha⁻¹ to 14.7 m² ha⁻¹ (Table 1). Because of this variability, no significant difference ($P = 0.294$) in average block-level residual BA was apparent between the FT and TL treatments (Table 1).

Fig. 2. Plot-level residual basal areas distribution within the full-tree and tree-length harvest blocks in central Ontario. Boxes represent the 25th and 75th percentile; bars represent the 10th and 90th percentile. Plots below the 10th percentile and above the 90th percentile of residual basal area are represented by dots.

Table 1. Post-harvest residual damage and coarse woody debris (CWD) volumes from recent full-tree and tree-length harvests in central Ontario forests

			Damage (% BA)						CWD volume (m ³ ha ⁻¹)
Harvest type/ Block name	SFL ^a	Forest Type	Number of Plots	Total BA ^b (m ² ha ⁻¹)	Total AGS ^c BA (m ² ha ⁻¹)	Total	Major all	Major AGS ^c	
Full-tree									
NP-183	Nipissing	Hardwood	43	14.7	8.7	7.5	2.5	4.3	56.4
NP-196	Nipissing	Hardwood	49	14.2	7.9	9.7	6.9	12.4	50.3
NP-227	Nipissing	Hardwood	23	9.7	5.7	17.9	6.3	10.6	47.4
NS-400	Northshore	White pine	22	12.4	10.8	8.1	2.9	3.4	63.3
NS-551	Northshore	White pine	19	12.0	9.9	12.2	2.6	3.4	68.4
Mean ± SE				12.6±0.9	8.6±0.9	11.1±1.9	4.3±1.0	6.8±2.0	57.2±3.9
Tree-length									
FS-N1	French-Severn	Hardwood	30	11.5	9.6	9.8	3.4	4.1	50.9
FS-BT1	French-Severn	Hardwood	11	12.9	10.9	8.5	2.8	3.3	67.8
FS-FT1	French-Severn	Hardwood	48	14.3	12.7	5.6	3.2	3.5	90.8
NP-109	Nipissing	Hardwood	37	12.4	6.8	20.0	9.1	16.8	60.2
NP-172	Nipissing	Hardwood	31	10.0	5.0	20.6	8.3	16.9	52.7
NP-183	Nipissing	Hardwood	49	12.2	6.7	8.0	4.3	8.0	38.7
NP-197	Nipissing	Hardwood	30	11.8	9.7	11.9	9.6	11.7	36.3
NP-228	Nipissing	Hardwood	36	10.6	4.0	34.0	6.8	18.1	68.4
NP-333	Nipissing	White pine	34	8.4	8.2	13.4	4.9	5.0	41.9
NP-999	Nipissing	White pine	48	11.5	11.1	13.4	9.3	9.8	46.2
Mean ± SE				11.6±0.5	8.5±0.9	14.5±2.6	6.2±0.9	9.7±1.9	55.4±5.3
ANOVA				<i>F</i> = 1.20 <i>P</i> = 0.294 <i>n</i> = 15	<i>F</i> = 0.01 <i>P</i> = 0.927 <i>n</i> = 15	<i>F</i> = 0.71 <i>P</i> = 0.416 <i>n</i> = 15	<i>F</i> = 1.92 <i>P</i> = 0.190 <i>n</i> = 15	<i>F</i> = 0.98 <i>P</i> = 0.341 <i>n</i> = 15	<i>F</i> = 0.05 <i>P</i> = 0.830 <i>n</i> = 15

^aSFL = Sustainable Forest License^bBA = Basal area^cAGS = Acceptable growing stock

Damage to residual trees

Of the 3082 trees inspected for damage, 389 or 12.6% had evidence of damage that resulted from felling and skidding operations. Only 175 or 5.7% had wounds that were considered major damage. Full-tree skidding resulted in damage (both major and minor) to 11.1±1.9% and TL operations resulted in damage to 14.5±2.6% of the total trees sampled (Table 1). The rate of tree damage between the FT and TL harvest systems did not differ significantly (*P* = 0.416). Of the trees damaged in the FT operations, only 4.3±1.0% had major damage. This low rate of damage did not differ significantly (*P* = 0.190) from the 6.2±0.9% of trees with major damage following the TL operation (Table 1, Fig. 3). Although average damage rates were low for both types of harvesting operations, large differences in damage rates were observed among harvest blocks. Major damage in the FT harvest blocks ranged from 2.5% to 6.9%, while in the TL blocks it ranged from 2.8% to 9.6%.

The proportion of trees deemed AGS varied among harvest blocks, ranging from 37% to 98%. Stands with higher proportions of conifer had a greater proportion of stems in the AGS category. Across all harvest blocks, 72% of the residual stems were deemed AGS. Although major damage to AGS trees did occur, the rate of damage was variable and no significant differences (*P* = 0.341) in damage rate were observed between the FT (6.8±2.0%) and TL (9.7±1.9%) operations (Table 1, Fig. 3). However, the proportion of damage to AGS

depends on the ratio of AGS trees to all trees. Thus, a high proportion of AGS damage may, in some cases, be more reflective of limited AGS trees in the stand than actual damage rates.

Historic (collected between 2004 and 2010) exceptions monitoring data shows similar trends of no significant difference (*P* = 0.589) in major damage to total BA. Trees in the 34 FT harvest blocks (18 white pine and 16 hardwood) averaged 7.6±0.7% major damage compared to 8.1±0.6% for those in TL harvest blocks. Major damage to AGS BA in the FT (7.3±0.6%) harvest blocks also did not differ significantly (*P* = 0.372) from that in the TL (8.1±0.5%) harvest blocks (Table 2, Fig. 3).

Coarse woody debris volumes

Coarse woody debris volumes in the TL harvesting block ranged from 38.7 m³ ha⁻¹ to 90.8 m³ ha⁻¹, with a mean of 55.4±5.3 m³ ha⁻¹. These volumes did not differ statistically (*P* = 0.830) from those in the FT harvest blocks, which ranged from 47.4 m³ ha⁻¹ to 68.7 m³ ha⁻¹, with a mean of 57.2±3.9 m³ ha⁻¹ (Table 1, Fig. 4). The distribution of CWD among decay classes did not differ statistically between harvesting treatments (Fig. 5). New CWD in decay class I and II made up 36.9% and 35.5% of the total volume in the FT and TL harvest treatments, respectively. Individual CWD diameters increased with increasing decay class whereby CWD in decay

Fig. 3. Box plot of percent major damage to total and acceptable growing stock (AGS) of residual basal area in both recent and historic full-tree and tree-length harvest blocks. Boxes represent the 25th and 75th percentile; bars represent the 10th and 90th percentile. Plots below the 10th percentile and above the 90th percentile of residual basal area are represented by dots. Dashed horizontal lines show the standard for acceptable levels of major damage to both total (15%) and AGS (10%) residual basal area.

classes IV and V was significantly larger than that in decay classes I and II (data not shown). No significant difference in piece size was apparent between harvest treatments.

Discussion

The concern over FT logging in partial harvest systems is that coarse-branched species like most hardwoods and large white pines will result in increased damage to residuals due to wider and longer loads during the skidding phase of harvest operations. Requirements for careful logging practices and maximum damage standards for partial harvesting operations on Crown land in Ontario are in place to help minimize damage to forest stands harvested using shelter wood and selection systems (OMNR 1998a,b). Under these standards, major damage must affect <15% of total basal area and <10% of AGS basal area. Using the more stringent definition of major damage applied in this study, both FT and TL logging operations were, on average, under the 10% standard for major damage to AGS basal area (Fig. 4). Unfortunately not all of the harvest blocks evaluated were below the 10% standard. In the current study, two of five (40%) FT harvest blocks and four of 10 (40%) TL harvest blocks had excessive damage to AGS stems. The historic exceptions monitoring blocks, for which less

stringent definitions of major damage were applied, were also, on average, within the standard for major damage to AGS. Six of the 34 (17.6%) FT blocks matched or exceeded the 10% major damage to AGS standard compared to three of 25 (12%) TL harvest blocks. Overall damage levels, however, may be a better reflection of careful logging success since AGS damage levels are highly sensitive to the proportion of AGS trees in a stand. These rates of damage from FT (and TL) operations are comparable to findings by Cline *et al.* (1991) that average block-level damage frequency was <10% during whole-tree (= FT) harvesting in hardwood and mixed forests in the eastern United States. However, examples of damage levels exceeding 30% as a result of FT harvesting do exist (e.g., Nichols *et al.* 1994).

The fact that there were no statistical differences in damage between harvest methods suggests that skidding with or without limbs is not a factor in residual tree damage for shelterwood regeneration cuts when careful logging methods are used. The extent of logging damage can be explained by several other factors, but these can vary: density and arrangement of skid trails, proportion of timber harvested, density of residual stems, season of operation, operator experience, and terrain (e.g., Cline *et al.* 1991, Nichols *et al.* 1994). All these factors can be controlled with the use of careful logging practices and effective planning and layout of trails and landings. In addition, the regeneration phase of a uniform shelterwood harvest requires that the stand be thinned from below and that the largest and healthiest crowns of desirable species are retained as seed source for natural regeneration. The trees to be removed are typically smaller-diameter trees with relatively small and flexible tops and branches. It is likely that the additional material in FT logging was not too much greater in width and length than the TL system and that the extra material was thin and flexible enough not to damage residual trees excessively if contact during skidding were to occur.

Aside from concerns related to potential damage to residual trees during FT harvest, concerns have been raised about potential effects on nutrient balances and recruitment of CWD, regardless of silvicultural system (Berch *et al.* 2011, Puddister *et al.* 2011). Retention of coarse woody material is an important part of sustaining forest productivity and biodiversity (Spies 1998, Shields *et al.* 2007, Vanderwel *et al.* 2009, OMNR 2010), though quantities vary considerably (Fig. 4). Published volumes for CWD in northern hardwood and mixed forests of eastern North America show values ranging from 10.8 m³ ha⁻¹ to 136.7 m³ ha⁻¹, and averaging 60.5 m³ ha⁻¹ (Fig. 4). Typically, mature second-growth and old-growth forests had greater volumes of CWD than managed forests (Fig. 4). The CWD volumes measured in our study ranged from 36.3 m³ ha⁻¹ to 90.8 m³ ha⁻¹ and were comparable to the range of values for managed and unmanaged forests elsewhere (Fig. 4). Moreover, the FT and TL harvest systems did not differ in terms of total volume or the distribution of that volume across decay classes (Fig. 5). The majority of the post-harvest volumes of CWD in both FT and TL systems were in the later decay stages and likely pre-dated the harvest (Fig. 5). Addition of new CWD, those in decay class I and II were low in both systems and were not significantly different between FT and TL harvests. Although FT harvesting will likely result in lower residual “slash” volumes in the short term, we do not necessarily expect to see reductions in CWD, i.e., pieces larger

Table 2. Historic post-harvest residual damage documented following full-tree and tree-length harvesting in central Ontario forests

Block name	SFL	Forest type	Number of plots	Total BA ^a (m ² ha ⁻¹)	Total AGS ^b BA (m ² ha ⁻¹)	Total BA (m ² ha ⁻¹)	Damage (% BA)	
							Major all	Major AGS ^b
Full-tree								
Cloutier 126 FT	Nipissing	White pine	5	8.0	7.2	8.0	0.0	0.0
Cloutier 129 FT	Nipissing	White pine	66	10.0	9.0	10.0	4.0	3.0
Grant 14	Nipissing	White pine	37	11.9	9.1	11.9	7.7	7.7
Grant 17	Nipissing	White pine	27	6.7	5.6	6.7	2.2	2.6
Mad 123 FT	Nipissing	White pine	95	12.1	10.5	12.1	6.8	6.8
N'bisissing 34	Nipissing	White pine	17	11.3	8.2	11.3	9.4	12.9
Tem 107A	Nipissing	White pine	46	11.8	10.3	11.8	2.6	2.5
Tem 107B	Nipissing	White pine	55	10.2	8.6	10.2	3.9	3.8
108	Northshore	White pine	60	7.8	6.3	7.8	7.2	7.4
54 PW	Northshore	White pine	10	7.8	6.4	7.8	2.6	3.1
72 PWUS	Northshore	White pine	10	14.2	13.4	14.2	7.0	7.5
551	Northshore	White pine	10	12.2	10.6	12.2	11.5	9.4
333	Northshore	White pine	10	10.8	10.0	10.8	9.3	10
459 & 385	Northshore	White pine	10	9.8	9.2	9.8	6.1	6.5
182	Northshore	White pine	30	7.8	6.3	7.8	9.4	9.5
72 PW MIX	Northshore	White pine	7	12.3	9.4	12.3	2.3	3.0
416B	Northshore	White pine	5	12.0	9.6	12.0	13.3	8.3
416	Northshore	White pine	7	10.9	9.7	10.9	13.2	8.8
Behnke 67	Nipissing	Hardwood	11	16.7	8.7	16.7	7.6	12.5
175	Northshore	Hardwood	30	7.9	5.1	7.9	6.7	5.2
179	Northshore	Hardwood	30	8.4	5.7	8.4	4.8	7.1
302	Northshore	Hardwood	43	9.5	7.1	9.5	4.4	3.3
600	Northshore	Hardwood	30	4.7	1.7	4.7	14.3	15.4
54 HWD	Northshore	Hardwood	10	10.6	4.4	10.6	9.4	13.6
560	Northshore	Hardwood	10	10.4	4.6	10.4	0.0	0.0
828, 2009	Northshore	Hardwood	5	13.6	5.2	13.6	8.8	7.7
828, 2008_1	Northshore	Hardwood	10	11.4	6.6	11.4	10.5	9.1
828, 2008_2	Northshore	Hardwood	10	15.4	7.8	15.4	11.7	7.7
822	Northshore	Hardwood	10	15.0	7.6	15.0	12.0	7.9
857_1	Northshore	Hardwood	10	14.4	8.2	14.4	11.1	9.8
857_2	Northshore	Hardwood	10	9.4	5.0	9.4	12.8	8
885	Northshore	Hardwood	10	9.0	5.2	9.0	8.9	7.7
409_1	Northshore	Hardwood	10	10.4	8.8	10.4	5.8	6.8
409_2	Northshore	Hardwood	10	8.2	4.4	8.2	12.2	13.6
Mean ± SE				10.7 ± 0.5	7.5 ± 0.4	10.7 ± 0.5	7.6 ± 0.7	7.3 ± 0.6
Tree-length								
Goulard 10 TL	Nipissing	White pine	53	9.9	7.5	9.9	4.2	5.6
Tem 105 TL	Nipissing	White pine	20	11.3	9.5	11.3	9.7	9.5
Cloutier 126 TL	Nipissing	White pine	6	9.3	8.0	9.3	3.6	4.2
Cloutier 129 TL	Nipissing	White pine	22	10.3	8.9	10.3	7.1	7.1
Mad 123 TL	Nipissing	White pine	36	11.6	9.7	11.6	4.3	2.9
824	Northshore	White pine	12	10.2	9.8	10.2	13.1	11.9
841	Northshore	White pine	10	11.6	8.6	11.6	6.9	9.3
880	Northshore	White pine	7	12.0	12.0	12.0	4.8	4.8
884	Northshore	White pine	22	12.2	11.5	12.2	6.7	5.5
885	Northshore	White pine	10	13.2	12.2	13.2	7.6	8.2
898	Northshore	White pine	44	13.0	12.6	13.0	9.8	9.0
902	Northshore	White pine	10	14.8	12.2	14.8	13.5	9.8
5420	Northshore	White pine	5	10.4	10.0	10.4	3.8	4.0
5930	Northshore	White pine	10	10.0	9.0	10.0	10.0	8.9
6731	Northshore	White pine	10	8.6	7.0	8.6	7.0	8.6
6847	Northshore	White pine	10	11.0	11.0	11.0	9.1	9.1
7151	Northshore	White pine	10	10.8	10.4	10.8	9.3	9.6
9638	Northshore	White pine	10	9.0	8.8	9.0	13.3	13.6
1416, 1468	Northshore	White pine	10	10.8	9.6	10.8	9.3	8.3
43, 161	Northshore	White pine	10	10.8	10.0	10.8	9.3	10.0
5420, 5930	Northshore	White pine	10	10.8	10.0	10.8	7.4	8.0
9734-A	Northshore	White pine	7	8.3	8.0	8.3	10.3	10.7
6109	Northshore	Hardwood	10	9.4	7.4	9.4	6.4	8.1
7819	Northshore	Hardwood	27	8.7	6.1	8.7	10.2	7.3
228	Nipissing	Hardwood	36	10.6	4	10.6	6.8	8.3
Mean ± SE				10.7 ± 0.3	9.4 ± 0.4	10.7 ± 0.3	8.1 ± 0.6	8.1 ± 0.5
ANOVA				<i>F</i> = 0.02 <i>P</i> = 0.902 <i>n</i> = 59	<i>F</i> = 9.55 <i>P</i> = 0.003 <i>n</i> = 59	<i>F</i> = 0.02 <i>P</i> = 0.902 <i>n</i> = 59	<i>F</i> = 0.29 <i>P</i> = 0.589 <i>n</i> = 59	<i>F</i> = 0.81 <i>P</i> = 0.372 <i>n</i> = 59

^a BA = Basal area; ^b AGS = Acceptable growing stock

Fig. 4. Comparison of coarse woody debris (CWD) volumes, from old growth, unmanaged second growth and managed forest, reported in the literature, to those from full-tree and tree-length harvest blocks in this study. Boxes represent the 25th and 75th percentile; bars represent the 10th and 90th percentile. Data below the 10th percentile and above the 90th percentile of CWD volumes appear as dots.

than 10 cm in diameter. Residual biofibre (tree tops, cull trees, unmerchantable trees, and salvaged trees) from partial harvests tends to be tops, branches, and unmerchantable species left post-harvest. The difference in biofibre loads between the two harvest systems is therefore primarily due to the removal of tops and branches during FT harvesting.

In Ontario, those implementing current TL harvest systems are required to adhere to the utilization standards set out in the provincial scaling manual (OMNR 2007) whereby conifers, poplar, and birch should be topped to a diameter of 14 cm and other hardwoods should be topped at 18 cm. In many operations in the GLSL, utilization standards for top diameter are already being exceeded through the recovery of large branches and additional non-merchantable top material that is of sufficient size for use as fuelwood or pulp. For the most part, the tops and branches are smaller in diameter than the criteria used to define CWD and are not captured in CWD surveys. However, CWD loads are dynamic, current volumes are a reflection of past disturbance processes, and future volumes will depend not only on rates of depletion and decay but also on the rate of input from residual standing trees. *Direction from the Forest Biofibre – Allocation and Use* (OMNR 2008) policy states that available material for harvest includes only “tree tops, cull trees or portions of trees, individual and stands of unmerchantable and unmarketable trees, and trees that may be salvaged as a result of a natural disturbance”, and that stumps, below-ground biomass, and CWD must be retained on site (OMNR 2010). Furthermore, current provincial guidelines for the retention of standing trees state that at least 25 trees per hectare be retained in all harvested stands, regardless of silvicultural system (OMNR 2010). These residual trees are meant to maintain structural diversity at the stand scale and provide habitat and future CWD as well as seed sources for natural regeneration into the future. The so-called “wildlife trees” can include any combination of standing healthy, dead, or dying trees, and should include

Fig. 5. Proportion of total coarse woody debris volume, by decay class for full-tree and tree-length harvest blocks on 10 sites in central Ontario. Decay class I is freshly dead with branches attached and intact bark and wood; II has intact to partly decaying wood with bark intact to partly missing; III is generally partly decayed with traces of bark; IV is well decayed with bark usually absent and branch stubs will pull out; V is highly decayed with no bark and branch stubs easily pull out (Maser *et al.* 1979).

trees with cavities, mast producers, scattered conifers in hardwood stands, and veteran trees. Following these practices will help to ensure that woody material remaining on harvested sites is comparable to what would occur in natural stands.

Management implications

Based on our findings, FT harvesting can be done in such a way as to maintain the stand within acceptable damage levels; however, this management approach may not be appropriate in all cases. During the shelterwood regeneration cut stage that we studied little or no regeneration is typically present. The objective at this stage of management is to create a partially shaded understory condition and remove competition to facilitate establishment of a new cohort. Mineral soil exposure may also be desired to establish some species from seed, e.g., white pine and yellow birch (OMNR 1998a,b). Such conditions are created by “thinning from below”, removing small suppressed trees and some dominant or co-dominant trees, but mainly those with smaller crowns. Spacing among residual trees also needs to be fairly wide (8 m to 14 m depending on crown closure targets and crown geometry). For these reasons, FT harvesting is possible without causing excessive damage, and helps create favourable (“clean”) conditions for establishing a new cohort of desirable regeneration. Other stages of management and silvicultural systems, however, present additional challenges. At the preparatory cut stage of shelterwood management tree spacing is much tighter, and careful extraction of full trees is difficult. At the removal cut stage, the added risk of damage to established regeneration results from skidding tree tops and limbs; machine traffic can kill saplings and reduce seedling regeneration (Nichols *et al.* 1994). The selection system has similar challenges with close spacing of residual trees and the need to protect abundant seedlings and saplings. Therefore, while FT harvesting is advantageous for the shelterwood regeneration cut stage, it is

probably not appropriate for other stages of shelterwood management nor for selection harvesting.

While our results show that damage levels from FT harvesting are similar to those for TL harvesting, excessive damage can occur regardless of logging method, if harvesting is not done carefully. The skill and care of loggers and effective planning of extraction trails and landings are paramount. Extension activities designed to transfer knowledge gained from the operational best management practices developed during initial FT harvest trials may assist in minimizing damage in future FT harvesting operations.

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Appendix A. List of literature sources and CWD volumes used in Fig. 5: comparing management effects on CWD volumes.

Source	Location	Forest type	Management approach/ stand type	Volume (m ³ ha ⁻¹)
Angers <i>et al.</i> 2005	Quebec	Northern hardwood	Selection	72.7
Angers <i>et al.</i> 2005	Quebec	Northern hardwood	Diameter limit	41.6
Angers <i>et al.</i> 2005	Quebec	Northern hardwood	Old growth	78.4
Bolton 2011	Minnesota	Hardwood	Unmanaged second growth	77.8
D'Amato <i>et al.</i> 2008	Massachusetts	Hemlock-hardwood	Second growth	33.2
D'Amato <i>et al.</i> 2008	Massachusetts	Hemlock-hardwood	Old growth	135.2
Doyon <i>et al.</i> 2005	Quebec	Northern hardwood	Strip cut	46.8
Doyon <i>et al.</i> 2005	Quebec	Northern hardwood	Selection	60.7
Doyon <i>et al.</i> 2005	Quebec	Northern hardwood	Unmanaged second growth	36.2
Forrester and Runkle 2000	Ohio	Hardwood	Old growth	80.2
Goebel and Hix 1996	Ohio	Northern hardwood	Second growth	13.5
Goebel and Hix 1996	Ohio	Northern hardwood	Old growth	29.8
Goodburn and Lorimer 1998	Wisconsin/Michigan	Northern hardwood	Selection	61.3
Goodburn and Lorimer 1998	Wisconsin/Michigan	Northern hardwood	Even-aged	24.6
Goodburn and Lorimer 1998	Wisconsin/Michigan	Hemlock-hardwood	Selection	56.0
Goodburn and Lorimer 1998	Wisconsin/Michigan	Northern hardwood	Old growth	102.2
Goodburn and Lorimer 1998	Wisconsin/Michigan	Hemlock-hardwood	Old growth	93.9
Hale <i>et al.</i> 1999	Minnesota	Northern hardwood	Old growth	88.0
Hale <i>et al.</i> 1999	Minnesota	Oak hardwood	Old growth	75.0
Hale <i>et al.</i> 1999	Minnesota	Northern hardwood	Mature second growth	49.0
Hale <i>et al.</i> 1999	Minnesota	Oak hardwood	Mature second growth	46.0
Hardt and Swank 1997	North Carolina	Northern hardwood	Old growth	86.0
Hura and Crow 2004	Michigan	Northern hardwood	Second growth	46.5
Hura and Crow 2004	Michigan	Northern hardwood	Thinned uneven-aged	84.1
Hura and Crow 2004	Michigan	Northern hardwood	Thinned even-aged	47.4
Hura and Crow 2004	Michigan	Northern hardwood	Old growth	120.5
Jenkins <i>et al.</i> 2004	Indiana	Hardwood	Managed	22.4
Jenkins <i>et al.</i> 2004	Indiana	Hardwood	Managed	19.0
Jenkins <i>et al.</i> 2004	Indiana	Hardwood	Managed	10.8
Keeton 2006	Vermont	Northern hardwood	Selection	49.0
McGee <i>et al.</i> 1999	New York	Northern hardwood	Partial cut	59.9
McGee <i>et al.</i> 1999	New York	Northern hardwood	Maturing even aged	59.0
McGee <i>et al.</i> 1999	New York	Northern hardwood	Old growth	136.7
Muller and Yan 1991	Kentucky	Oak hardwood	Old growth	47.8
Orwig <i>et al.</i> 2001	Massachusetts	Mixed hardwood	Old growth	34.2
Orwig <i>et al.</i> 2001	Massachusetts	Mixed hardwood	Old growth	14.5
Orwig <i>et al.</i> 2001	Massachusetts	Mixed hardwood	Old growth	19.9
Orwig <i>et al.</i> 2001	Massachusetts	Mixed hardwood	Old growth	32.2
Roovers and Shifley 1997	Illinois	Oak hardwood	Old growth	81.2
Rubino and McCarthy 2003	Ohio	Oak hardwood	Unmanaged second growth	42.5
Spetich <i>et al.</i> 1999	Midwest, USA	Hardwood	Second growth	20.0
Spetich <i>et al.</i> 1999	Midwest, USA	Hardwood	Old growth	60.0
Stewart <i>et al.</i> 2003	Nova Scotia	Mixed hardwood	Old growth	58.0
Stewart <i>et al.</i> 2003	Nova Scotia	Mixed hardwood	Old growth	45.0
Stewart <i>et al.</i> 2003	Nova Scotia	Mixed hardwood	Old growth	71.0
Stewart <i>et al.</i> 2003	Nova Scotia	Mixed hardwood	Old growth	91.0
Tyrell and Crow 1994	Michigan\Wisconsin	Hemlock-hardwood	Old growth	54.8
Tyrell and Crow 1994	Michigan\Wisconsin	Hemlock-hardwood	Unmanaged second growth	54.0
Vanderwel <i>et al.</i> 2008	Ontario	Northern hardwood	Selection	45.5
Vanderwel <i>et al.</i> 2008	Ontario	Northern hardwood	Selection	43.6
Vanderwel <i>et al.</i> 2008	New York	Northern hardwood	Unmanaged second growth	58.5
Webster and Jenkins 2005	Kentucky	Mixed hardwood	Managed	85.6
Webster and Jenkins 2005	Kentucky	Mixed hardwood	Unmanaged second growth	134.3
Ziegler 2000	New York	Hemlock-hardwood	Old growth	126.0
Ziegler 2000	New York	Hemlock-hardwood	Unmanaged second growth	63.0