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MECHANIZED SELECTION CUTTING IN HARDWOODS WITH A TIMBCO T-445

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Abstract

Qualified fellers with experience in selection cutting of tolerant hardwoods are increasingly difficult to find. This represents a potential wood supply problem that could be alleviated through mechanized harvesting. In the present study, FERIC evaluated the degree of protection of the residual stand and the costs of hardwood selection harvesting with a Timbco T-445 feller-buncher and cable skidders. The influence of various work methods and of various terrain or stand conditions on these factors was also analyzed.

Introduction

Selection cutting in uneven-aged hardwood forests has always been done manually. This can be explained primarily by the difficulty of mechanizing the felling and delimbing of large hardwood stems. Since 1990, the need to develop mechanized approaches to harvesting has become increasingly evident because of a growing shortage of qualified workers. The working conditions for fellers are physically demanding, and the risks of injury are high. In addition, forests harvested by manual selection cutting increasingly present unfavorable conditions for high productivity and quality work: low harvest volumes compared with clearcutting, low stand density, increasing proportions of pulpwood to recover, more stringent standards for protection of the residual stand, and so on.

In the face of these constraints, H. Leggett et fils inc. (Namur, Que.) decided to acquire a feller-buncher and to evaluate its suitability for selection cutting in hardwood stands. The harvesting occurred primarily on Crown land, in maple stands with a basswood or yellow birch component, with a prescription to remove 30% of the basal area. The selection criteria for the trees to be felled and the criteria for evaluating the quality of the residual stand were those established by Quebec's Ministry of Natural Resources (MRNQ 1995).

The current study was performed in cooperation with H. Leggett et fils and Groupe forestier Intech inc. (consultants from Lachute, Quebec), within a project funded by the Canadian Forest Service's "Testing, experimenting and technological transfer in forestry" program. FERIC's work, conducted in the summer and fall of 1995 and in the winter of 1996, was intended to:

- estimate the harvesting costs and the effect of tree volume and terrain conditions on productivity;
- evaluate the effects of harvesting on the residual stand and the soil;
- assess the efficiency of working at night with the feller-buncher;

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- optimize felling and skidding activities; and
- determine the delimbing capability of the equipment.

The full-tree harvesting system in the study used a Timbco T-445 feller-buncher equipped with a continuous-rotation Quadco saw head with a 55-cm capacity (Figure 1). Delimbing was done mainly with chain saws. Tree Farmer C6D and John Deere 640 cable skidders extracted the delimbed stems to the landings.

Figure 1. The Timbco T-445 feller-buncher, equipped with a Quadco saw head.

Description of the Study Blocks

Four sites that differed in terms of terrain conditions or stand structure were selected for the trials in this study. The soils were generally well drained and had a good bearing capacity. However, there were some difficult areas with high ground roughness (e.g., the presence of boulders) and steep terrain (Table 1).

- Site 1 was on a hillside, and presented uneven ground with many boulders (50 to 100 cm).
- Site 2 presented more favorable terrain, but had smaller-diameter wood in an even-aged stand.
- Site 3 presented favorable terrain (slightly uneven) and stand conditions.
- Site 4 was characterized by steep slopes (33 to 50%).

Table 1 presents the stand conditions before and after the selection cut. The treatment objectives were generally met for the study sites, with removal levels ranging from 24 to 31% of the basal area. A detailed analysis by the company and by Groupe forestier Intech (who compiled the cruise results) confirmed the ability of mechanized felling to meet provincial regulations that apply to selection cutting in hardwoods (Anon. 1996).

Table 1. Description of terrain conditions and stand parameters for the sites in the study before and after selection cutting

		Site 1	Site 2	Site 3	Site 4
Ground strength[a]		good	good	good	good
Ground roughness[a]		uneven	slightly uneven	slightly uneven	very rough
Slope[a]		gentle to steep	gentle	gentle	steep
Density (stems/ha)	Before	453	620	492	574
	After	299	507	324	453
	Diff. (%)	-34	-18	-34	-21
Basal area (m^2/ha)	Before	19.2	27.7	25.0	25.6
	After	13.7	19.0	18.3	19.4
	Diff. (%)	-29	-31	-27	-24
Volume (m^3/ha)	Before	155	226	209	204
	After	113	144	157	148
	Diff. (%)	-27	-36	-25	-27

Work Methods

Distribution of Trails on the Cutover

In selection cutting, the feller-buncher's work is affected by the manner in which the machine travels in the forest, fells the marked trees, and arranges the felled trees for delimbing and skidding. Figures 2 and 3 illustrate the two trail layouts that were evaluated during the study. These layouts were intended to account for three factors: the feller-buncher's productivity, the skidder's productivity, and protection of the residual trees. For the layout illustrated in Figure 2, the trails were spaced at 13 m, about twice the effective reach of the boom, as is done in clearcutting of softwoods. This approach favors the productivity of the feller-buncher because its travel follows a straight path; as well, the trees are individually placed at the edge of the trail after felling, with no particular effort made to bunch them.

The second layout used main trails spaced at 33 m (Figure 3) and the operator bunched the felled trees. In this approach, the operator moves the feller-buncher towards the back of the block while felling all the trees in its path. During its return to the landing, the machine moves up to 10 m off the trail to reach any marked trees that were beyond its initial reach; the trees that are then bunched at the side of the trail so as to facilitate loading by the skidder operator. Repositioning of cut trees was easily done by the feller-buncher, which was able to carry the trees in a vertical position. This helped the operator control the direction in which the trees fell and thereby minimize damage to the residual trees.

Table 2 presents a theoretical calculation of the differences in the area covered by the trails used in the two harvesting methods. The method with trails spaced 13 m apart required the least travel by the feller-buncher; however, skid trails covered nearly one-third of the site. The creation of so many trails can lead to felling considerable numbers of unmarked stems, and more of the residual trees are exposed to damage from the skidding operations. This increases the risk of failing to meet the prescription's quality objectives.

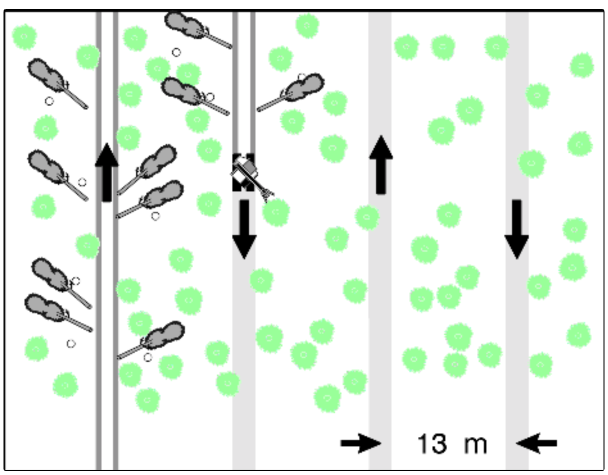

Figure 2. The layout with skidding trails spaced 13 m apart.

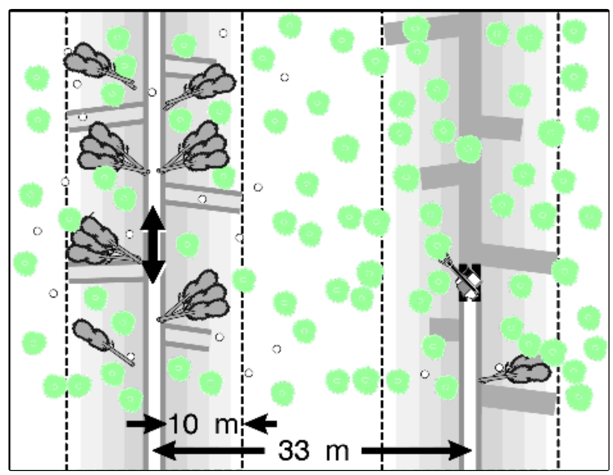

Figure 3. The layout with skidding trails spaced 33 m apart.

Table 2. Extent of the coverage of the site by skid trails at two trail spacings

	Trail spacing	
	13 m	33 m
Theoretical total distance traveled by the feller-buncher (linear m/ha)	789[a]	1406[a]
Extent of coverage by skid trails (% of total area)	30	12
Length of the skid trails (linear m/ha)	769	303

[a] Includes travel required for bunching and moving between skid trails.

The layout with trails spaced 33 m apart increased the distance traveled by the feller-buncher by nearly 78%, but significantly decreased coverage of the site by skid trails. This work pattern was used wherever the terrain conditions permitted and was adopted as the *standard pattern* for most of the work performed during the current study.

Partial Delimbing by the Feller-buncher

Manual delimbing with chain saws is tedious and dangerous, particularly in the context of selection cuts. During the study, FERIC evaluated the feller-buncher's ability to partially delimb the trees. With the saw head, the operator was able to cut about half the branches in the tree crowns of one or more trees lying on the ground (Figure 4). The skidder operator could then choke these stems and pull them out of the delimbing debris before completing delimbing by removing the remaining branches and any overly large branch stubs. This method reduced the amount of work to be done with chain saws and permitted integration of this task with the skidding operation.

Figure 4. Trees felled and partially delimbed by the feller-buncher.

Study Methods

Table 3 presents the work scenarios studied on each site. For the purposes of the study, FERIC studied three different scenarios for the method with trails spaced 33 m apart on Site 3; the scenarios were based on the stand conditions described in Table 1. The first (3a) involved manual delimbing on favorable terrain. The second (3b) involved partially mechanized delimbing on favorable terrain. The third (3c) used the same techniques as 3a, but on the roughest parts of Site 3.

The feller-buncher's productivity was determined via detailed time studies using FERIC's standard methods. The feller-buncher's work cycle comprised the following elements: travel, brushing, felling, bunching, and delimbing (if applicable). Operational delays related to operation of the machine or to planning were included in the total productive time if they were shorter than 15 minutes. The worker who performed the delimbing was evaluated similarly by timing his travel and chain saw work. The work of the skidders was also evaluated via time studies for three different scenarios.

Table 3. Work scenarios on the study sites

	Delimbing	Terrain[a]
Trails spaced 13 m apart		
Site 1	Manual	Moderately favorable
Trails spaced 33 m apart		
Site 2	Manual	Favorable
Site 3a	Manual	Favorable
Site 3b	Partially mechanized	Favorable
Site 3c	Manual	Moderately favorable
Site 4	Manual	Unfavorable

[a] See the conditions listed in Table 1.

A post-harvest survey evaluated the impact of harvesting on the residual stand and on the soils. The information collected for each tree in the sample plots included the presence of trunk, crown, or root damage, the probable cause of the damage (felling or skidding), and the dimensions (in cm^2) of the wound (the area occupied by a broken branch stub or the area of bark torn from the trunk or a root, with a minimum of 1 cm^2). Each tree was also assigned to a quality class. The frequency of wounds that would lead to downgrading of the highest-quality trees was determined using the wound severity criteria in Appendix 1.

The soil condition after harvesting was evaluated using a network of 4-m^2 sample plots systematically established in each of the sub-blocks. The area in each plot of each of the disturbance classes in Appendix 2 was estimated with a precision of 5%. The classes in which no modification of the soil was apparent (U and ND) were considered to represent insignificant disturbance. The classes in which inversion of the humus or exposure of surface mineral soil (HD, MSD, SMSE, and MIX) was present were considered to represent moderate disturbance, since they involved breakage of the fine roots of the residual trees but also provided good sites for seed germination. Deep ruts (DMSE) were the only severe disturbance.

Results and Discussion

Productivity of the Timbco T-445 Feller-buncher

Effect of Average Stem Volume on Productivity

The method with trails spaced 33 m apart and manual delimbing was evaluated during eight distinct studies on sites 2 and 3, where the average volumes harvested ranged from 0.45 to 1.04 m^3/stem. The overall productivity of the feller-buncher in this method reached 35.3 m^3/PMH (about 43 stems/PMH) with an average volume of 0.81 m^3 per stem. Figure 5 illustrates the relationship between the volume per stem and the feller-buncher's productivity. Feller-buncher productivity increased in direct proportion to the increase in average stem volume.

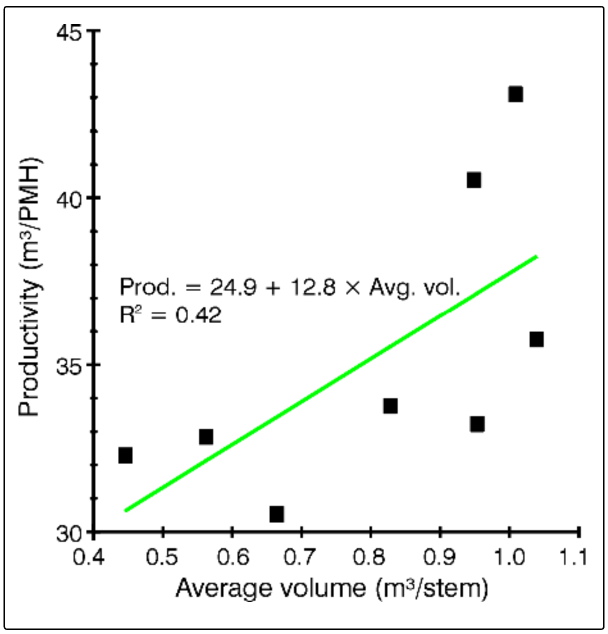

Figure 5. The relationship between the feller-buncher's productivity and the average volume per stem for the method with trails spaced 33 m apart (sites 2 and 3a).

In comparison with the results reported by Howard (1988), it appears that the average stem volume influenced the productivity of mechanized felling more than the productivity of a feller equipped with a chain saw. Several other aspects of the operation affected the feller-buncher's productivity, including human and environmental factors (e.g., weather, terrain conditions), stand factors (e.g., visibility, understory vegetation, stem quality), and the silvicultural prescription defined by the tree marking.

Figure 6 illustrates the influence of average stem volume on the various elements of the feller-buncher's work cycle. In contrast with what is observed in softwood stands, travel represented a significant part of the work cycle (47%), whereas felling itself represented only 15% of cycle time. The average volume per stem mainly affected the travel and bunching times, as indicated by the more pronounced slopes of the lines in Figure 6.

In general, it became more difficult to optimize bunch size for skidding with decreasing stem volumes, even though the bunches were easier to form along the trails. Modifications to the work methods or improvements to the equipment should be considered so as to facilitate travel and bunching in stands with low average stem volumes. For example, modern felling heads can typically be equipped with an optional device that permits a side tilt of 180° or more, and this would facilitate bunching by reducing the amount of travel required.

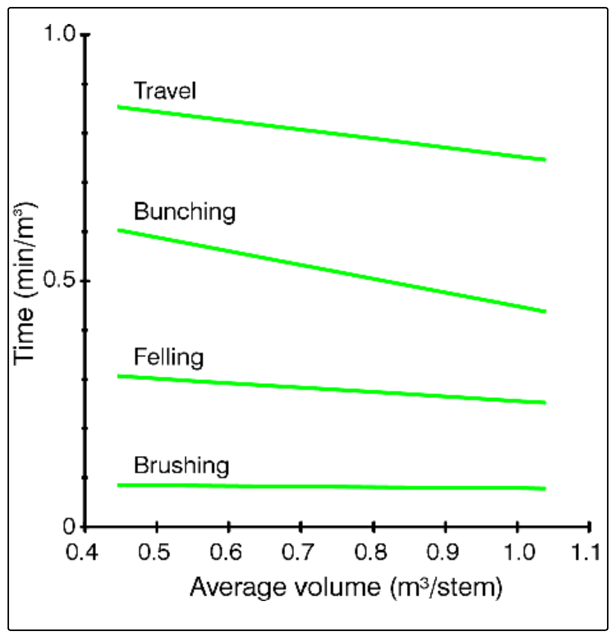

Figure 6. The effect of average stem volume on the feller-buncher's work cycle (sites 2 and 3a).

The work technique used by the operator in the system with trails spaced 33 m apart did not favor travel times. The feller-buncher moved towards the back of the block while preparing the trail, and felled the trees marked for removal while returning to roadside so that the felled timber would not interfere with the feller-buncher's movements away from the main trail. This was not an optimal approach. If the stems are properly bunched, it should be possible to cut both the trail and the trees to each side in a single pass. This approach would let the operator fell all the stems allocated to a given trail while moving toward the back of the block, and begin a new trail while returning to the landing.

Effect of the Work Method and the Terrain Conditions

Table 4 presents the results of the productivity studies for the feller-buncher in the various work scenarios. The terrain conditions on Site 1 (13-m trail spacing) were similar to those on sites 2 and 3a (where the observations of the standard method, at 33-m spacing, were performed), thus permitting a productivity comparison for the two trail networks. The productivity difference of 6.1 m³/PMH can be attributed mainly to the effect of the average volume per stem rather than to the different work methods, since the productivities were comparable in terms of stems/PMH. The productivity with the trails spaced 13 m apart should not be significantly different from this average given the magnitude of the variation observed.

The productivity observed while the feller-buncher performed felling and partial delimbing was 25.7 m³/PMH (Site 3b), which is about 10 m³/PMH less than when the feller-buncher only performed felling. This productivity difference can be attributed largely to the additional work required by delimbing.

Less-favorable terrain conditions also decreased productivity. On uneven ground, with small valleys and several short sections with short, abrupt slopes, the feller-buncher's productivity was 26.9 m³/PMH (Site 3c). A steep but even slope (Site 4) appeared to cause fewer problems, since productivity remained relatively high (32.4 m³/PMH).

Figure 7 illustrates how each work scenario influenced the feller-buncher's productivity. The feller-buncher was more productive with trails spaced 13 m apart than with the network of trails spaced 33 m apart because it spent less time per cubic metre in felling and bunching. The differences between the two approaches in terms of travel and bunching times are not as large as those suggested by the layouts presented in the "Work methods" section of the report. The volume per hectare to be harvested on Site 1 was much lower than on sites 2 and 3a, and this difference masks the travel advantages of the method with trails spaced 13 m apart. The lower productivity of the method with partially mechanized delimbing was attributable to an overall increase in travel, bunching, and delimbing times.

Table 4. Results of the studies of feller-buncher productivity for the various work scenarios

	Scenario	Site	Volume/stem (m³)	Productivity (m³/PMH)
Trails spaced 13 m apart	Favorable, manual delimbing	1	1.00	41.4
Trails spaced 33 m apart	Favorable, manual delimbing[a]	2 and 3a	0.81	35.3
	Favorable, partially mechanized delimbing	3b	0.78	25.7
	Irregular site, manual delimbing	3c	0.87	26.9
	Steep slope, manual delimbing	4	0.89	32.4

[a] An average of eight distinct studies with variable average diameters, weighted based on the duration of the studies.

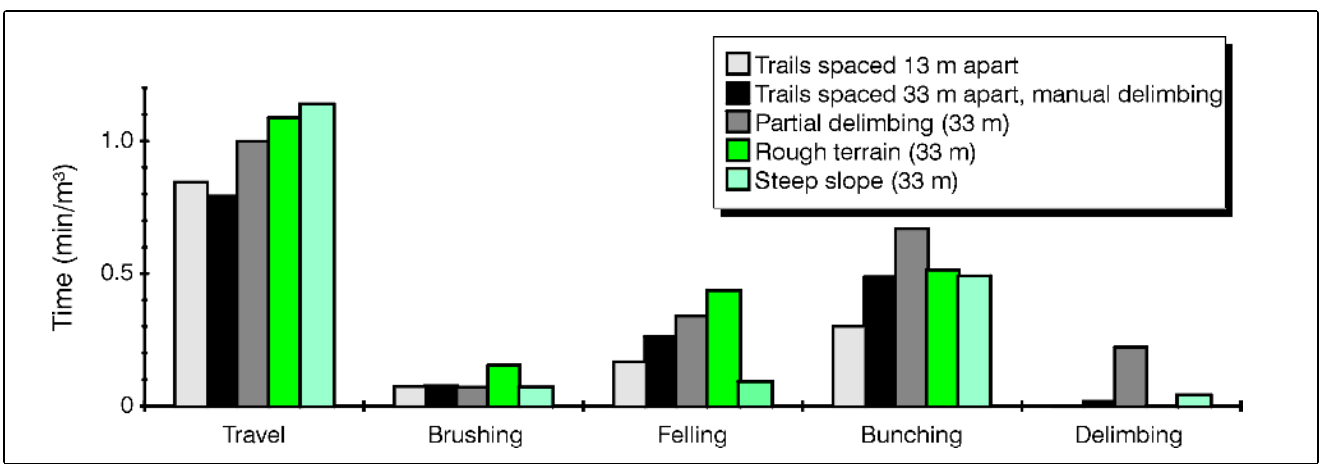

Figure 7. Standardized times for the feller-buncher's work cycle in the various scenarios in the study.

When terrain conditions were more difficult, the increased travel time was the main cause of decreased productivity. The felling time on steep slopes was shorter than in the other scenarios, and this reflects the care the operator took in positioning and stabilizing the feller-buncher before felling. On slopes, the operator also transported stems vertically less often, and performed bunching by dragging the trees. Rough terrain was more of a constraint than steep slopes. The feller-buncher's travel on slopes of more than 40%, with 40 cm of snow on the ground, was not severely hampered, whereas terrain with less of a slope but with more "stair steps" required additional maneuvering.

Productivity of Manual Delimbing

The productivity of the worker who performed the delimbing depended more on the dispersion of the felled trees along the trails than on the number of stems per bunch. Working with small bunches of trees reduced the amount of travel required compared with single trees, but the tangled tops posed a new difficulty. Manual delimbing remains difficult and dangerous, and many factors can affect productivity (e.g., the shape of the crowns, the proximity of the skidding operation, weather conditions). Many of the branches to be removed were under tension. Delimbing productivity reached 25 stems per productive hour at an average volume of around 1 m^3 per stem.

Skidding Productivity

Table 5 presents the skidding productivities for three felling and delimbing scenarios. The average extraction distance was 300 m, a typical distance for comparable operations in the region. The arrangement of the felled trees in the approach with trails spaced 13 m apart prevented the operator from maximizing the skidder's payload. The slope was favorable for skidding on this site, but the number of stems skidded was lower. The scenario with trails spaced 13 m apart also led to a longer cycle time, particularly for the time elements related to loading: choking and winching, travel during loading, and delays related to finding the trees to be skidded. The method with trails spaced 33 m apart favored skidding productivity by grouping the stems.

Even though the wood was smaller on the site with partially mechanized delimbing, it was possible to pick up more stems and thus more easily obtain a full load. In the method with partial delimbing, the skidder operator had to devote 1.05 min/m^3 to completing the delimbing that the feller-buncher had started. This work also required some planning on the part of the operator, who did not want to needlessly clutter his trail with the delimbing debris.

Table 5. Skidding productivity for three felling and delimbing scenarios (over an average distance of 300 m)

	Trails spaced 13 m apart	Trails spaced 33 m apart	Trails spaced 33 m apart, with partially mechanized delimbing
Average volume (m^3)			
per trip	5.4	7.4	7.1
per stem	1.00	0.94	0.82
Productivity			
stems/PMH	11.4	16.4	14.1
m^3/PMH	11.4	15.4	11.6
Cycle time elements (min/m^3)			
Travel empty	0.86	0.59	0.57
Maneuvers	0.29	0.26	0.20
Choking and winching	1.66	1.06	1.20
Travel during loading	0.32	0.14	0.19
Travel loaded	0.73	0.77	0.82
Unhooking	1.04	0.88	0.92
Operational delays (finding trees)	0.38	0.09	0.24
Delimbing	0.00[a]	0.10[a]	1.05
Total	5.28	3.89	5.17

[a] Delimbing was done manually, independent of the skidding operation.

Night Work

Qualitative results from this study suggested that night operations are unlikely to be productive, produce high-quality work, or have an acceptable cost. Since much of the work conducted by this equipment consists of navigating within the stand and finding the trees to be felled, good visibility is essential. In the current study, well-established regeneration in the understory already reduced daytime visibility considerably, and made the feller-buncher's lighting system ineffective at night. Winter conditions tend to facilitate the night work, but the trials demonstrated the need to improve tree marking by using a large amount of reflective paint. One of FERIC's current projects is researching this aspect of night work, particularly in terms of discovering the best paint compositions. FERIC is also working on the use of GPS-assisted navigation, in which the trees are mapped in advance of the operation so the operator of the feller-buncher can use an onboard computer to locate the trees to be felled during the night shift.

Where the conditions permit night operations, only sites with good terrain and with medium-sized trees should be harvested at night. Larger trees (dbh >40 cm) have wide crowns that are difficult to fell directionally in the darkness without risking serious damage to the residual trees. If the infrastructure permits, night work should be restricted to the felling of trees on the road right-of-ways and in areas to be clearcut, or to work in those parts of the stand most conducive to selection cutting.

Impact of Harvesting

An evaluation of the extent of damage to residual stems and of soil disturbance was conducted on sites 1 and 3. Anon. (1996) discusses the degree of conformity of the work with MRNQ regulations in more detail. Overall, mechanized harvesting met the prescribed quality objectives.

Damage to Residual Trees

Table 6 describes the damage to residual trees after felling and skidding in the two areas that were surveyed. For all wound classes taken together, 42% of the residual trees on Site 1 (trails spaced 13 m apart) were affected, whereas on Site 3 (trails spaced 33 m apart), the comparable figure was only 12%. On the first site, the conditions were dry at the time of harvesting, but the trees were flushing, which made them more susceptible to wounding.

For those wounds that were considered significant based on the MRNQ guidelines (Appendix 1), the proportions of wounded stems were 26 and 7% on sites 1 and 3, respectively. This represents an interesting result given the values (18 and 29%) reported by Thompson et al. (1995) for manual felling with cable skidding on two cutovers in Wisconsin.

For the two sites in the present study, 3 and 4% of the stems in the stand would have been in quality class 1 had they not received large wounds. These stems represented 5 and 6% of the total basal area, respectively; thus, it was the largest trees that were affected, and their potential ability to provide quality logs during the next harvest may have been decreased.

Soil Disturbance During Harvesting

The results presented in Table 7 show similar levels of soil disturbance in the two blocks, and that nearly 70% of the soil surface remained intact. The low proportion of severely disturbed soil gives a clear indication that mechanized felling did not lead to unduly negative consequences. The most severe disturbances generally occurred on trails near the landing, where the number of passes by the skidder is greatest, and this finding is typical of many skidding operations.

Table 6. Extent of stem damage after felling and skidding

	% of residual stems	
	Site 1 (trails spaced 13 m apart)	Site 3 (trails spaced 33 m apart)
Stems with wounds (all sizes)	42	12
Stems with significant wounds[a]	26	7
Stems of quality level 1	27	51
Stems of quality level 1 with significant wounds	3	4

[a] See Appendix 1 for definitions.

Table 7. Results of the soil disturbance survey

	Soil disturbance (% of area)	
	Site 1 (trails spaced 13 m apart)	Site 3 (trails spaced 33 m apart)
Regrouped disturbance classes[a]		
Insignificant disturbance (U+ND)	68	73
Moderate disturbance (HD+MSD+SMSE+MIX)	31	25
Severe disturbance (DMSE)	1	2
Total	100	100

[a] See Appendix 2 for definitions.

Hourly Rate and Harvesting Costs

The harvesting costs for the various methods and scenarios in the study were determined by dividing the direct hourly cost of the equipment by its observed productivity. The hourly cost was calculated using FERIC's standard methodology and the assumptions presented in Appendix 3. These operating costs are hypothetical, but are considered realistic in the context of hardwood selection cutting. They do not include indirect costs such as transportation, supervision, profits, etc. When two different skidders were used within the same method, a weighted average rate was calculated. In evaluating the approach in which the wood was partially delimbed by the feller-buncher, the skidder's hourly rate was calculated as a weighted average of its "waiting" and "operating" rates.

A machine's total scheduled hours per year is a key element in calculating its hourly cost. To ensure that these calculations produced realistic costs, regional utilization patterns were considered. For the feller-buncher, no regional historical data was available for the number of hours worked per year. This type of equipment typically works two or three shifts per day in softwood clearcutting operations, and easily accumulates 3600 to 4000 SMH per year. For the purposes of this study, the analysis considered only the operating hours between sunrise and sunset as being suitable for selection cutting; this translates into about 2000 SMH/year.

Table 8 presents the total costs of the system for the various approaches that were studied. It is important to note that the average stem volume differed slightly between methods as well as between the activities in each method. The impact of this variation on the results has been discussed in previous sections of this report.

The differences between the total costs of the work methods (Table 8) were low and not significant. However, the methods in the study provided different "service" and different effects on the residual stand. With partial delimbing by the feller-buncher, management of the workforce is simpler since the delimber's job is eliminated. A work method in which the feller-buncher takes the time to do part of the delimbing is thus worth evaluating further. The development of tools to facilitate this work should also be undertaken.

Table 8. Costs of the various methods observed[a]

	Cost ($/m³)		
	Trails spaced 13 m apart	Trails spaced 33 m apart	Trails spaced 33 m apart, with partially mechanized delimbing
Felling @ $119.04/PMH	2.87	3.37	4.63
Delimbing @ $30.00/PMH	1.20	1.20	0.00
Skidding[b]	5.60	4.75	5.19
Total	9.67	9.32	9.82

[a] The average volume per stem varied between the methods and between the activities for each method.
[b] Variable rate: Trails spaced 13 m apart, Tree Farmer C6D @ $64.44/PMH.
Trails spaced 33 m apart, weighted rate for the Tree Farmer C6D and John Deere 640 @ $73.21/PMH.
With partially mechanized delimbing, the weighted average for the Tree Farmer C6D working and waiting was $59.70/PMH.

A study by Groupe forestier Intech (Anon. 1996) on the costs of harvesting in the Ottawa valley showed that the costs of systems based on manual felling are greater than those in the present study. The companies paid their contractors an average price of $13.90/m³. By way of comparison, this study estimated a cost of $11.72/m³ for the wood produced with mechanized felling and trails spaced 33 m apart; these costs are based on the data in Table 8, but include a reasonable profit margin, additional transport costs, supervision costs, and other overhead.

Conclusions

The results of the study demonstrated that mechanized felling with a feller-buncher was a viable replacement for traditional manual felling methods in hardwood selection cutting. On each of the study sites, the felling operation was productive and efficient, and it adapted well to variations in terrain conditions and stand structure. The success of this approach nonetheless relies on the use of an appropriate feller-buncher. The Timbco T-445, for example, has several attractive characteristics: cab leveling, no rear overhang, a fast and powerful drive system, a boom with good lifting capacity, etc. Another important factor is the operator's skill. Contractors who change to a mechanized harvesting system must pay considerable attention to personnel management factors such as training.

The use of a feller-buncher in selection cutting can be easily implemented without adding an additional phase or any special infrastructure, since the products (tree-lengths) remain the same. Tree marking is done in essentially the same way as in traditional operations, and assigning the feller-buncher to the most difficult parts of the cutover (assuming day operations) will also improve morale for the manual felling teams. The other equipment in the operation remains the same, and this makes the system easily adaptable to other situations.

The study showed that the economics of mechanization were favorable, though night work is unlikely to be viable. The ability to meet quality criteria was similar to that in more typical operations, and protection of the residual stand and of the soil was particularly effective. Changes in the tree marking technique could eventually account for the required trail layout in the context of mechanized felling, and this would improve the results.

The use of the feller-buncher permitted increased spacing between skid trails and facilitated the task of loading the skidders. However, the trials of mechanized delimbing revealed the need to modify the felling head so as to increase its maneuverability, thereby facilitating the production of tree-lengths.

Acknowledgments

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Disclaimer

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Appendix 1
Defining Criteria for Significant Wounds[a]

Criteria		
Trunk	Crown	Roots
Wound whose width is larger than the radius of the stem at the height of the wound or Area of exposed sapwood greater than: 50 cm² if 10 < dbh < 20 150 cm² if 20 < dbh < 30 300 cm² if dbh > 30 cm	1/3 of the crown destroyed	1/3 of the root system destroyed (deep rut)

[a] Based on MRNQ (1995).

Appendix 2
Soil Disturbance Classes

Undisturbed soil (U): No apparent modification of the soil surface, or light disturbance of the vegetation, or light movement of the litter without damaging the humus.

Humus disturbed (HD): Any physical modification to the humus layer, including compression of the LFH layers, exposure of the H and F layers, and removal of the LFH and/or of the moss, with or without inverting the layer, but excluding any mineral-soil exposure.

Mineral soil deposits (MSD): Includes deposits at the edge of ruts or following wheel slippage.

Shallow mineral-soil exposure (SMSE): Exposure of the upper mineral-soil horizon, in which 90% of the roots of the trees that form the stand are found (up to a 15-cm depth).

Mix of mineral soil and organic matter (MIX): Deposit of mixed material (mineral, humus or litter) in which the structure is loose or unstable.

Deep mineral-soil exposure (DMSE): Exposure of mineral soil beneath the rooting zone.

Mud (M): Mixture of mineral soil or organic matter with water, caused by the passage of a machine; evaluated in the dry or wet state.

Signs of erosion (E): Creation of erosion channels, leaching, or sedimentation.

Not capable of disturbance (ND): Stumps, stones, or boulders.

No evaluation possible (NE): Soil surface is concealed by the presence of harvesting debris, interfering with the evaluation.

Appendix 3
Assumptions Used to Calculate the Hourly Cost of the Equipment

	Timbco T-445 feller-buncher	Tree Farmer C6D skidder	Tree Farmer C6D skidder (waiting)	John Deere 640 skidder
Assumptions				
Economic life (years)	10	5	5	5
Scheduled Machine Hours (SMH)/year	2 000	2 000	2 000	2 000
Purchase price ($)	450 000	114 200	114 200	165 000
Residual value ($)	45 000	11 400	11 400	16 500
License cost ($/year)	500	500	500	500
Insurance ($/year)	13 500	3 500	3 500	4 950
Interest rate (%)	10	10	10	10
Utilization rate (%)	85	90	0	90
Lifetime repair costs ($)	450 000	97 061	0	148 500
Fuel consumption (L/PMH)	25	16	0	16
Fuel cost ($/L)	0.50	0.50	0.50	0.50
Oils and lubricants ($/PMH)	1.00	0.00	0.00	0.00
Operator wages ($/SMH)	25.00	25.00	25.00	25.00
Total cost				
Grand total per year ($)	202 361.88	115 990.27	82 178.11	140 373.93
Grand total per PMH ($)	119.04	64.44	n.a.	77.99
Grand total per SMH ($)	101.18	58.00	41.09	70.19