# AN ANALYSIS OF HARVESTING COSTS IN EASTERN CANADA

**J. Favreau, F.E. and J.-F. Gingras, F.E.**

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Abstract

This report presents a breakdown of typical wood harvesting costs in eastern Canada using full-tree and cut-to-length systems. Representative costs were calculated on the basis of harvesting under favorable stand and site conditions, and the resultant costs were allocated to various accounting items (e.g., labor vs. machine costs) and to each major work cycle phase. A sensitivity analysis based on terrain and tree size variations was also conducted.

# Authors

*Jean Favreau, F.E., M.Sc.E., is a Senior Researcher in Eastern Division's Wood Harvesting Group. He obtained his Master's degree in Economics in 1991, and he is a member of l'Ordre des ingénieurs forestiers du Québec.*

*Jean-François Gingras, F.E., is the Group Supervisor of Eastern Division's Wood Harvesting Group. He has been a member of l'Ordre des ingénieurs forestiers du Québec since 1982.*

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# Summary

Harvesting costs are an important component of wood costs. To define where efforts to reduce harvesting costs would have the greatest payback and to highlight research priorities, harvesting costs for each phase of the harvesting operation were analyzed.

Using a simulation approach, the analysis involved breaking the total wood harvesting cost into its major components and identifying which phases of the supply chain contributed most to the total cost. Both the full-tree to roadside and cut-to-length harvesting methods were analyzed.

The analysis showed that the full-tree system had the lowest direct wood cost ($13.48/m³). The four phases in the full-tree system contributed roughly equally to total cost, with each representing between 23 and 28% of the total.

Although the cut-to-length system is the simplest in terms of logistics, it leads to a higher cost at roadside ($17.04/m³). The cut-to-length harvester accounts for more than two-thirds of the wood cost because of its high operating cost per hour and its relatively low production levels.

The relative share of the four cost items (ownership, wages, fuel, and repair and maintenance) was similar in both systems. However, each percentage point represented more money in the cut-to-length system, and not all items offered equal potential for cost reductions. For example, wages and ownership costs combined accounted for between 62 and 67% of the total, but cannot be easily reduced because they are driven more by market forces than are the other two cost centers (repair and maintenance and fuel costs). However, because savings in overall harvesting costs can come from either reductions in hourly costs or gains in hourly productivity, increasing productivity could decrease the impact of wages and ownership costs.

Repair and maintenance and fuel costs offer the easiest potential for cost reductions in the short to medium terms. However, reductions in the fuel cost do not produce large benefits because fuel represents less than 11% of the total harvesting cost. Repair and maintenance downtime, which directly affect the machine's utilization rate, represents a major cost component in both systems. For example, a 10% increase in the machine utilization rate would lead to a saving of about $1.40/m³ for the full-tree system and $1.80/m³ for the cut-to-length system.

The processing phase, which includes delimbing, measuring, slashing and topping, accounted for more than 40% of the costs for both systems, and thus holds the most potential for cost reductions. The felling phase was the second largest cost component in both systems. The single-grip harvester, whose work cycle includes all these activities, is a key machine on which to target improvements.

The sensitivity analysis showed that harvesting costs are strongly affected by tree size. A cost reduction of 20% could be achieved if a harvester could handle 1.5 small (0.10-m³) trees in the same time as one 0.15-m³ tree. For extraction machines, a 50-m increase in the extraction distance from 100 to 150 m would lead to an increase of about 2% in total cost; this suggests that an increase in speed or in payload of 50% would be needed to compensate for this increased distance. Difficult terrain can also affect productivity, although the relative proportions of difficult site types may not be equally significant in all regions of eastern Canada. Finally, operator performance can affect the cost by up to 35%, especially with complex machines such as harvesters.

Based on this analysis, the most promising areas for reducing wood harvesting costs are:

- improving single-grip harvester heads by using better, faster, and stronger components;
- developing multi-stem harvester heads or other multi-stem processing systems;
- accelerating boom positioning and movement (e.g., by implementing technologies such as coordinated motion control and machine vision);
- improving machine ability to adapt to steep slopes and developing dedicated or adapted logging systems for rough or steep ground;
- reducing repair and maintenance costs by using improved diagnostic tools, preventive maintenance practices, and failure-prediction systems, as well as by providing maintenance training and encouraging manufacturers to improve hydraulic system design and components;
- improving machine automation through the use of robotics or providing better operator training and thereby reducing the operator's influence on productivity; and
- improving the understanding of human factors in relation to machine performance.

# Introduction

Harvesting costs are an important component of wood costs, which in turn represent a major part of the overall production cost of paper and solid wood products (Price Waterhouse 1990). The *Technology Road Map for Forest Operations in Canada* (FERIC 1996) proposed a review of the costs of the main elements within the harvesting, transportation, and silviculture phases of forest operations (recommendation #15), so as to define where efforts to reduce costs would have the greatest payback and to highlight research priorities. The present report, which was prepared under contract to Industry Canada in 1998, aims to implement part of this recommendation by focusing on the cost components of wood harvesting. Of course, harvesting is only one component of a forestry operation, and efforts to reduce wood costs must also target the overall supply chain, including transportation, mill handling, and organizational parameters.

# Approach

The analysis used a simulation approach to break the total wood harvesting cost into its major components and identify which phases of the supply chain contributed most to the total cost. The analysis covered all the phases that transform standing trees into processed logs delivered at roadside, ready to be loaded onto a truck. A typical full-tree system and a typical shortwood system were simulated to illustrate the potential impacts of reducing the costs of specific phases or cost centers because the majority of the timber in eastern Canada is harvested with these two systems (Godin 1998). Representative costs were calculated on the basis of harvesting under favorable stand and site conditions, although a sensitivity analysis based on terrain and tree size variations was also conducted.

The *Interface* integrated harvesting/silviculture costing software, which was developed by FERIC in 1997, was used to conduct most of the costing simulations. This software bases its calculations on more than 20 years of operational research data collected by FERIC in eastern Canada.

# Working Assumptions: Defining the Base Scenarios

## Site and Stand Conditions

From Manitoba to Newfoundland, eastern Canada is covered by a wide range of site types (based on terrain features, drainage, slope, etc.) and forest types (softwood, mixedwood, and hardwood). The productivities and costs of harvesting systems are strongly affected by these factors. For this study, we chose to use favorable site and stand conditions for the base scenario. A sensitivity analysis, with different operational, stand, and site conditions, is presented later in the report. Appendix 1 presents a description of the base site used for this study.

## Harvesting Systems

Although the *full-tree system* is expected to steadily decrease in popularity in the future, it remains the most widespread harvesting system in eastern Canada, where it accounted for roughly 60% of the harvest in 1997. For the purposes of this analysis, the system comprised a tracked feller-buncher to fell and bunch the trees, a cable skidder to bring the full-tree bunches to roadside, and a stroke delimber to delimb the trees at roadside. A grapple or clambunk skidder could also have been used to extract the wood, but the choice of skidder would not significantly alter the results other than for the cost analysis by work-cycle phase. The full-tree system also included a roadside slasher to slash and pile the logs for subsequent loading onto haul trucks. The slasher was added so that a comparable product would be produced at roadside in the full-tree and cut-to-length systems. More commonly, tree-length stems from full-tree logging operations are brought directly to the mill for slashing.

The two-machine *cut-to-length system* is the simplest in terms of logistics and the number of machines required to do the work. It is expected to increase in use in eastern Canada, and currently accounts for around 25% of the total volume harvested. The system in our analysis comprised a single-grip harvester that felled and delimbed trees and slashed them into logs. A shortwood forwarder then extracted the logs and piled them at roadside for loading onto haul trucks.

## Hourly Cost Assumptions

The direct hourly operating cost of forestry machines includes fixed costs (e.g., financing, insurance, licensing), variable costs (e.g., repair and maintenance, fuel, lubricants) and labor costs (e.g., wages and benefits). Appendix 2 presents the assumptions used to calculate the direct operating costs for the machines covered in this study. These direct costs exclude transportation and supervision costs, as well as profits and other overhead.

# Results

## Cost Breakdown (Base Scenario)

Using the assumptions and descriptions in the previous sections, the *Interface* software calculated values for the following parameters for each machine in both systems, operating under the aforementioned baseline conditions (Table 1):

- the direct operating cost per productive machine hour ($/PMH);
- the average expected productivity under the baseline conditions ($m^3$/PMH);
- the cost of the phase (that is, the direct hourly cost divided by the expected productivity);
- the number of units of equipment required to harvest 150 000 $m^3$/year; and
- the relative contribution of each machine to the total cost of that system (%).

The information in Table 1 can be further broken down to permit an analysis by accounting items (e.g., labor vs. machine costs) and by work-cycle phases for each machine.

## Breakdown of Costs by Machine

The full-tree system provided the lowest direct wood cost ($13.48/$m^3$), although some indirect costs related to residue disposal at roadside (e.g., around $0.80/$m^3$) and site rehabilitation (a variable cost) should also be added for this cost to be fully comparable with that of the cut-to-length system. The phases in the full-tree system contributed roughly equally to total cost, with each representing between 23 and 28% of the total. With the full-tree system, the cost variations are shared between four machines versus two in the cut-to-length system. Moreover, the full-tree system as a whole is less affected by terrain conditions because two of the four phases, delimbing and slashing (which account for 47% of the total cost), are conducted at roadside.

Although the cut-to-length system is the simplest in terms of logistics, it leads to a higher cost at roadside ($17.04/$m^3$). The cut-to-length harvester accounts for more than two-thirds of the wood cost because of its high operating cost per hour and its relatively low production levels; thus, it offers a high potential for cost reductions.

Overall cost reductions can come from either lower hourly costs or greater productivity. Operational research and development has traditionally concentrated on productivity improvements, but reductions in the machine's operating cost would also lower wood costs. Unfortunately, the operating costs of forest machines are not easy to reduce, and further analysis is required to identify the best potential targets for such cost reductions.

## Breakdown of Costs by Accounting Items

In terms of investment, the cut-to-length system would require an investment of $2.9 million to harvest 150 000 $m^3$/year, whereas the full-tree system would require only $2.1 million to harvest an equivalent volume. Therefore, the cut-to-length system represents a riskier investment because more capital is invested in fewer units.

**Table 1. Direct operating costs for each machine in the two systems**

| | Direct hourly cost ($/PMH) | Expected average productivity ($m^3$/PMH) | Cost of the phase ($/$m^3$) | Units required for 150 000 $m^3$/year | Contribution to total cost (%) |
|---|---|---|---|---|---|
| Full-tree system | | | | | |
| Feller-buncher | 110.85 | 33.0 | 3.36 | 1.3 | 25 |
| Cable skidder | 81.92 | 21.6 | 3.79 | 4.1 | 28 |
| Stroke delimber | 99.93 | 30.8 | 3.25 | 1.4 | 24 |
| Slasher | 76.56 | 24.8 | 3.08 | 1.8 | 23 |
| Total | — | — | 13.48 | 8.6 | 100 |
| Cut-to-length system | | | | | |
| Harvester | 130.05 | 10.7 | 12.16 | 4.2 | 71 |
| Forwarder | 87.85 | 18.0 | 4.88 | 2.5 | 29 |
| Total | — | — | 17.04 | 6.7 | 100 |

Figure 1 illustrates the relative contributions of the major cost items to the total system costs. The accounting items include:

- labor costs (wages),
- ownership costs,
- repair and maintenance costs, and
- fuel costs.

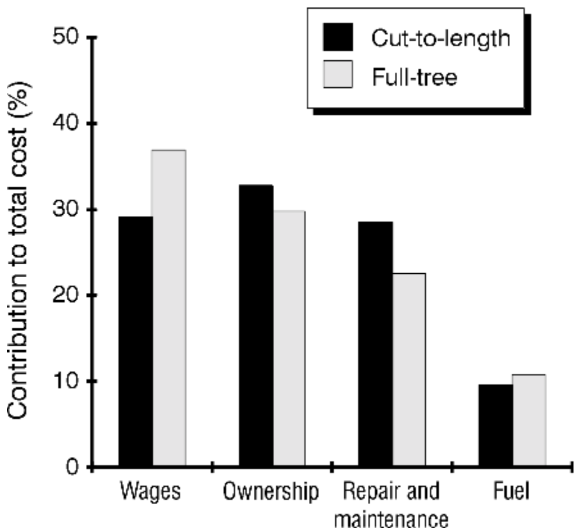


Figure 1. Relative proportions of the major cost accounting components in the full-tree and cut-to-length systems.

The relative share of all cost items is similar in both systems. However, each percentage point represents more money in the cut-to-length system, and not all items offer equal potential for cost reductions. For example, wages and ownership costs combined accounted for between 62 and 67% of the total, but cannot be easily reduced because they are driven more by market forces than are the other two cost centers (repair and maintenance and fuel costs). However, labor costs (when converted to $/m³) could be reduced by increasing productivity through better operating techniques, improving motivation, optimizing shift length, improving training, and so on. Moreover, over the long term, full or partial automation of machine operation could be another way to reduce labor costs. In this context, cut-to-length systems may be more suitable for automation, since only two types of machines would need to be targeted. Conversely, fully automating the full-tree system might be more difficult because four machine types are involved. In both cases, the implementation cost of such technologies should not exceed the current wage expenditures (around $5.00/m³ for both systems).

Although it could be argued that increased research, development, and technology transfer efforts or support of Canadian manufacturers could lead to lower machine costs, these assertions have not been verified. Canadian equipment costs are also influenced by the value of the Canadian dollar and by national monetary policy.

Consequently, repair and maintenance and fuel costs offer the greatest potential for cost reductions in the short to medium terms. However, reductions in the fuel cost do not produce large benefits because fuel represents less than 11% of the total harvesting cost. This means that even a 20% reduction in fuel consumption would only amount to a 2% decrease in total costs. Approximately $1.50 is spent for fuel in each system to produce 1 m³ of wood at roadside.

Repair and maintenance downtime, which directly affects the machine's utilization rate, represent a major cost component in both systems. For example, a 10% increase in the machine utilization rate would lead to a saving of about $1.40/m³ for the full-tree system and $1.80/m³ for the cut-to-length system. This highlights the need for better training for machine operators and mechanics, as well as improved dealer service, technical support, and parts inventories. For example, improved diagnostic tools or failure-prediction tools could reduce diagnostic time and either prevent unnecessary repairs, decrease their cost, or accelerate repairs when they do become necessary. Another example would be the development of improved preventive maintenance practices to increase the mechanical availability of the equipment. As well, many custom-built machines use components that were not originally intended for forestry work; thus, certain design improvements, such as adding more robust oil coolers and higher-capacity hydraulic systems, could improve availability significantly. Newer machines are already beginning to incorporate such improvements.

## Breakdown of Costs by Work-cycle Phases

Each forestry machine has a work cycle that can be broken down into elements such as machine travel, boom positioning, processing, loading, unloading, and so on. We have seen that the cut-to-length harvester presents the single highest cost, whereas the four machines in the full-tree system account for roughly equal costs (i.e., similar proportions of the total). Table 2 and Figure 2 present the costs of the various work-cycle phases based on recent studies conducted by FERIC. The relative magnitude of each phase of the work cycle, and the resulting potential for cost reduction, are also given.

**Table 2. Cost of the various work-cycle phases for the two harvesting systems**

| | Full-tree | | Cut-to-length | |
|---|---|---|---|---|
| | Cost of the phase ($/m³) | % of total cost | Cost of the phase ($/m³) | % of total cost |
| Felling | 2.79 | 21 | 3.28 | 19 |
| Processing (delimbing[a] and slashing) | 6.33 | 47 | 7.42 | 44 |
| Moving with the felling machine | 0.57 | 4 | 1.46 | 8 |
| Load to extract wood | 1.22 | 9 | 2.15 | 13 |
| Travel for extraction (150 m) | 2.20 | 16 | 1.41 | 8 |
| Unload at roadside | 0.37 | 3 | 1.32 | 8 |
| Total | 13.48 | 100 | 17.04 | 100 |

[a] Delimbing was estimated for stems with light average branchiness. The processing cost would increase with increasing branchiness.

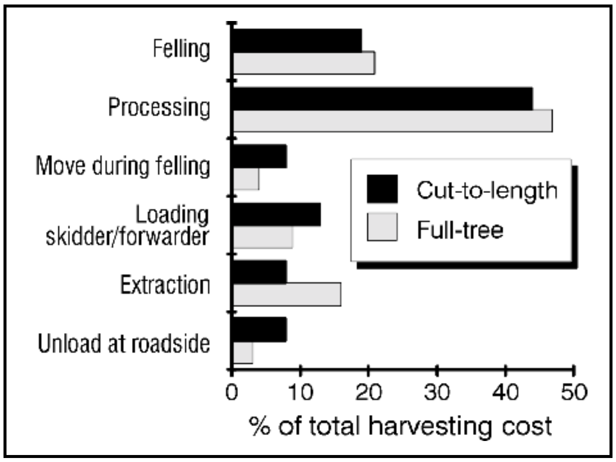


Figure 2. Costs of the various work cycle phases for the two harvesting systems.

The most important cost center was the processing phase (combined delimbing and slashing), which accounted for 47 and 44% of the total wood costs of the full-tree and cut-to-length systems, respectively. This indicates that new technology that would improve processing productivity would have more impacts on total harvesting costs than would improvements in any other work phase. Since processing typically involves treating one stem at a time, any technological development that would allow processing of multiple stems simultaneously would have a significant impact.

The felling phase represented the second most important cost center, and accounted for around 20% of total costs in both systems. Since the actual severing time is quite low with modern feller-buncher and harvester heads, development efforts should focus more on reducing cycle times by accelerating boom positioning and providing multi-stem accumulating devices for harvesters.

The relative importance of the loading, extraction, and unloading phases depends on the extraction distance (in this analysis, 150 m) and on machine configuration. For example, using a grapple or clambunk skidder in the full-tree system would change the cost of each of these three phases, but wouldn't greatly affect the net result. Overall, travel time represented the largest cost component within the skidding cycle, so development efforts should focus on increasing travel speeds without reducing payloads, increasing payloads without reducing travel speeds, or a combination of both. This holds especially true for grapple skidders, which are more sensitive to changes in extraction distance than the other two configurations, which spend proportionally more time in loading. Since increased payload may in turn result in problems related to ground pressure and soil disturbance, it may be more appropriate to focus on speed enhancements.

Conversely, the loading and unloading elements in the cut-to-length system are a more significant component of the wood cost than travel is. Therefore, improvements in boom technology and operator training to improve boom manipulation could affect a portion of wood cost that amounts to around $3.47/m³.

# Sensitivity Analyses

The preceding section provided results using the stand and site conditions in the base scenario (Appendix 1). It is also interesting to assess how the cost of each system responds to changes in the operating conditions. Understanding these responses will help to focus efforts to improve machine productivity and will thus reduce wood costs.

## Effect of Tree Size

Tree size is the variable that most affects the productivity of the majority of forestry machines. Figure 3 indicates that a 33% reduction in average tree size (for example, from 0.15 to 0.10 m³/stem) led to an increase in total costs of about 22% for both systems. Therefore, any technological improvements that could increase productivity levels with small stems (0.10 m³/stem) to match those with 0.15-m³ stems would reduce costs by around 22% in such stands. In the cut-to-length system, an operational or technical improvement that increased harvester productivity with 0.10-m³ trees to the level obtained with 0.15-m³ trees would lead to a saving of around $3.80/m³. Since the productivity curves flatten as tree sizes increase, the potential cost reduction becomes less significant in stands with larger trees. However, it should be noted that the trend is toward harvesting smaller stems than in the past.

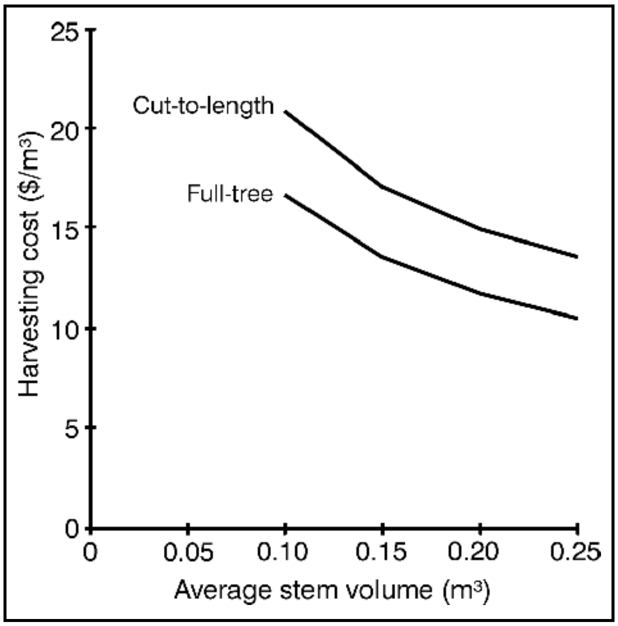


Figure 3. The impact of tree size on harvesting costs.

## Effect of Extraction Distance

Extraction distance is the main variable that affects the productivity of the skidding or forwarding phases because it affects the amount of time spent traveling in and out of the forest. Figure 4 illustrates the effect of extraction distance on the total harvesting cost for the two systems. (Note that the curve shown for the full-tree system applies to cable skidding for illustration purposes. With grapple skidders, the curve is steeper, whereas it is flatter with clambunk skidders.)

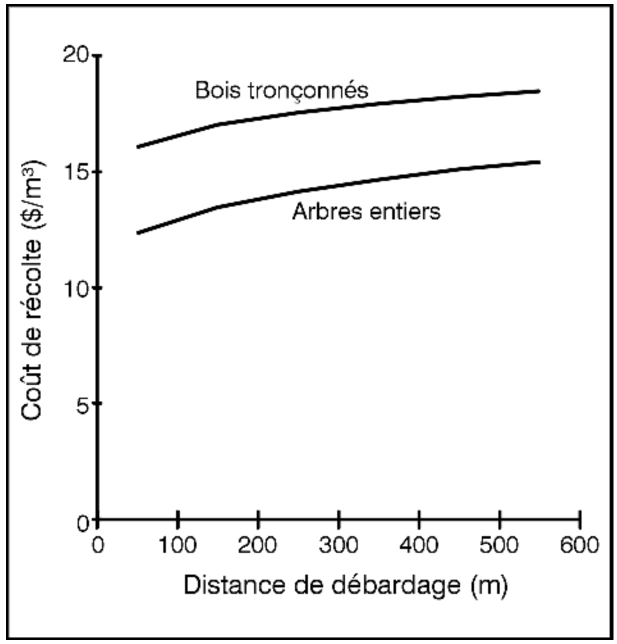


Figure 4. The impact of extraction distance on total harvesting costs.

In the cut-to-length system, technological improvements that provided a 50% speed or payload increase would let extraction productivity at 150 m equal that at 100 m; the resulting savings would amount to only $0.38/m³, or 2% of total costs. However, at longer distances, speed increases provide progressively larger savings. Though still fairly small, the savings would be somewhat greater in the full-tree system because the cost curve is slightly steeper at these distances. It's also important to note that although the direct cost payback is small the indirect effects (i.e., increasing the spacing between haul roads) could be substantial.

## Effect of Terrain Conditions

Harvesting costs increase under more difficult terrain conditions such as soft soil, rough ground, or steep slopes. To illustrate the harvesting cost increase as a result of more difficult terrain conditions, two scenarios were added to our basic scenario. On the first site, the bearing capacity for heavy machines was low when the ground was not frozen (CPPA class 4.1.1), a situation that is typical of the Clay Belt (for example); on the second site, the ground roughness was high and the average slope was greater than 20% (CPPA class 1.4.3), a situation typical of some mixedwood stands. Figure 5 presents the impact on total costs for the two systems on the two sites.

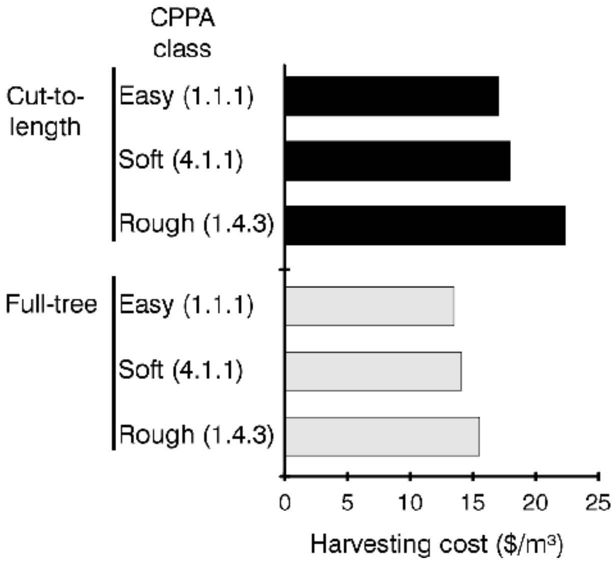


Figure 5. The impact of terrain conditions on total harvesting costs.

In comparison with the easy site, the cost increases on the wet site amounted to 4% in the full-tree system, with two of the four machines operating at roadside. With the cut-to-length system, the forwarder was affected somewhat by working on soils with low-bearing capacity, and the associated cost increase was around 5%. On the rough site, the cut-to-length system was around 31% more costly to operate than on the easy site, again mainly because of the forwarder's sensitivity to rough ground and slopes. Cable skidders are not greatly affected by such conditions, so overall cost increases with the full-tree system were only on the order of 15%.

The difficulty in applying these results over larger areas arises from the fact that little information on ground conditions is available in current forestry databases and maps for eastern Canada, and this information would be necessary to establish the relative importance of the various terrain conditions. Although a site classified as 1.4.3 might have a strong impact on cut-to-length harvesting costs, such sites may only represent a small proportion of the overall terrain conditions encountered in eastern Canada.

For example, Quebec's Crown land inventory data shows that very soft ground (CPPA class 4) covers around 7% of the total forested area, whereas high ground roughness (CPPA class 4 or 5) represents around 2%. However, average slopes of 20 to 30% (CPPA class 3) cover about 18% of the area, a fairly significant proportion of the productive land base.

## Effect of Operator Skills

The operator's skill obviously has a significant influence on machine productivity. For example, harvesters have the most complex work cycle of all machines discussed in this report and their operators must make thousands of decisions each day. As Figure 6 shows, operators may need up to 2 years to reach 100% of their potential productivity on *harvesters*. This learning curve is similar for all forestry machines, although the time required to reach maximum output may be shorter with simpler machines such as skidders.

In Figure 6, the cost difference based on harvester operator experience amounted to a maximum of around 35%. In addition, there is likely a parallel difference in operator ability for similar levels of experience. Of course, operator performance depends not only on experience, but also to a great extent on motivation, dexterity, judgment, aptitude, and depth perception.

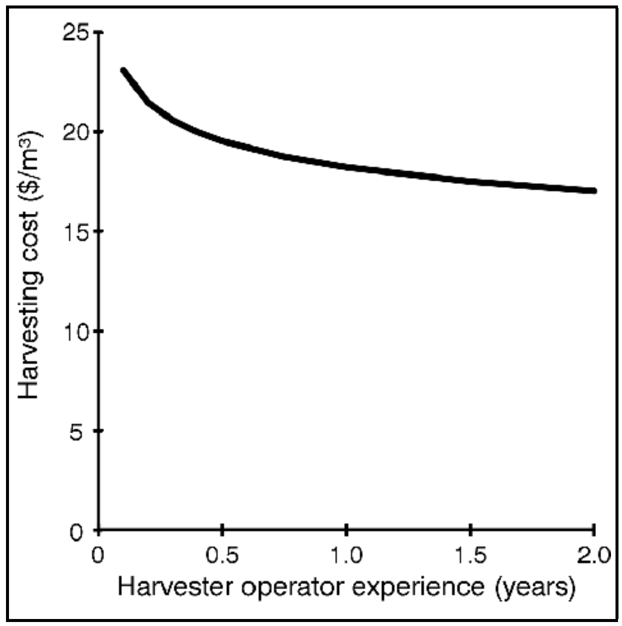


Figure 6. The impact of a single-grip harvester operator's experience on total cut-to-length costs.

Nevertheless, it is clear that improved operator performance can have a big impact on costs because every machine needs an operator, at least for the foreseeable future. Technological developments such as simulators for training, machine-vision systems, and decision-support or robotics tools that can reduce operator stress and fatigue should therefore be considered as priority for improving the competitiveness of the Canadian forest sector. Human aspects such as motivation and work schedules also warrant attention.

# Discussion and Conclusions

Though efforts to reduce wood costs must target the overall supply chain, which includes harvesting, transportation, handling, and organizational parameters, it is still useful to analyze the components of the various phase costs. This report addresses this need by focusing on the wood harvesting cost components.

FERIC's analysis showed that the harvester in a cut-to-length system was the machine with the highest unit costs and is thus perhaps the machine with the highest potential for cost reductions, whereas all the machines in the full-tree system showed approximately equal potential for cost reductions. However, between two and three times as much volume is harvested with full-tree systems as is harvested with cut-to-length systems, despite a trend towards the use of more cut-to-length equipment.

Overall harvesting cost reductions can come from either reductions in hourly costs or gains in hourly productivity. Cost reductions have traditionally concentrated on productivity improvements, since hourly operating costs are more difficult to reduce. Repair and maintenance represents the largest cost item susceptible to cost reductions, and represented 22 and 28% of the full-tree and cut-to-length costs, respectively, in FERIC's analysis. Fuel costs were found to be a less significant item of variable hourly costs. Although wage levels are difficult to reduce, efforts to improve operator performance are important and would have the same effect as reducing labor costs.

The processing phase, which includes delimbing, measuring, slashing, and topping, accounted for more than 40% of the costs for both systems, and thus holds the most potential for cost reductions. The felling phase was the second largest cost component in both systems. The single-grip harvester, whose work cycle includes all these activities, is again the most interesting machine on which to target improvements.

The sensitivity analysis showed that harvesting costs are strongly affected by tree size. A cost reduction of 20% could be achieved if a harvester was able to handle 1.5 small (0.10-$m^3$) trees in the same time as one 0.15-$m^3$ tree. For extraction machines, a 50-m increase in the extraction distance from 100 to 150 m would lead to an increase of about 2% in total cost; this suggests that an increase in speed or in payload of 50% would be needed to compensate for this increased distance. Difficult terrain can also affect productivity, although the relative proportions of difficult site types may not be equally significant in all regions of eastern Canada. Finally, operator performance can affect the cost by up to 35%, especially with complex machines such as harvesters.

Based on this analysis and the estimates of potential cost reductions, the most promising areas for reducing wood harvesting costs are:

- improving single-grip harvester heads by using better, faster, and stronger components;
- developing multi-stem harvester heads or other multi-stem processing systems;
- accelerating boom positioning and movement (e.g., by implementing technologies such as coordinated motion control and machine vision);
- improving machine ability to adapt to steep slopes and developing dedicated or adapted logging systems for rough or steep ground;
- reducing repair and maintenance costs by using improved diagnostic tools, preventive maintenance practices, and failure-prediction systems, as well as by providing maintenance training and encouraging manufacturers to improve hydraulic system design and components;
- improving machine automation through the use of robotics or providing better operator training and thereby reducing the operator's influence on productivity; and
- improving the understanding of human factors in relation to machine performance.

Because of their limited impact on total costs, it would not be cost-effective or warranted to dedicate much R & D effort into reducing energy consumption, increasing machine travel speed or augmenting current extraction payloads.

# References

FERIC. 1996. Technology road map for forest operations in Canada. For. Eng. Res. Inst. Can. (FERIC), Pointe-Claire, Que. Special Rep. SR-117. 15 p.

Godin, A. 1998. Logging equipment database: 1997 update. For. Eng. Res. Inst. Can. (FERIC), Pointe-Claire, Que. Field Note General-64.

Price Waterhouse. 1990. The market pulp industry 1985-1990. Forest Sector Advisory Council. October 1990. Price Waterhouse, Montreal, Que. 83 p.

# Appendix 1
# Site Parameters for the Base Scenario

| | |
|---|---|
| Species composition | 90% black spruce, 10% balsam fir |
| Terrain classification (CPPA) | 1.1.1 |
| - Drainage | good |
| - Roughness | low |
| - Average slope | less than 5% |
| Merchantable trees (stems/ha) | 1000 |
| Merchantable volume ($m^3$/ha) | 150 |
| Merchantable tree size ($m^3$) | 0.15 |
| Branchiness | light |
| Underbrush | low |

# Appendix 2
# Cost Assumptions

## General assumptions

| | |
|---|---|
| Residual value (% of purchase price) | 10 |
| Insurance and license fees (% of purchase price/year) | 5 |
| Interest rate (%) | 10 |
| Utilization (%) | 75 |
| Fuel price ($/L) | 0.45 |
| Operator wages, including fringe benefits ($/SMH) | 25.00 |

## Specific machine assumptions

| | Feller-buncher | Cable skidder | Delimber | Slasher | Single-grip harvester | Forwarder |
|---|---|---|---|---|---|---|
| Machine life (years) | 5 | 7 | 5 | 5 | 5 | 5 |
| Scheduled machine hours (SMH/year) | 4500 | 2250 | 4500 | 4500 | 4500 | 4500 |
| Lifetime repair and maintenance costs (% of purchase price) | 100 | 90 | 100 | 100 | 125 | 100 |
| Purchase price (thousand $) | 420 | 180 | 350 | 200 | 500 | 300 |
| Fuel consumption (L/PMH) | 25 | 14 | 25 | 25 | 20 | 14 |