Operational Trials of Cut-To-Length Harvesting of Poplar in a Mixed Wood Stand

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ABSTRACT

Cut-to-length harvesting systems offer an alternative to conventional mechanical systems for thinning mixedwood stands. We evaluated the performance of a single-grip harvester and forwarder in a poplar-dominated mixedwood stand in Southern Ontario to quantify the effect of tree size and tree form on harvester productivity and harvesting cost, and to assess the damage caused by the harvesting operation to advance regeneration and residual trees. A single-tree selection silvicultural system was used. Individual trees were assigned a form index based on their visual estimates of limb size and stem form. The cut-to-length harvester produced 23.1 m^3 per productive machine hour (PMH). Forwarder productivity was 17.2 m^3/PMH. The results indicate a significant and positive relationship between harvester productivity and tree size (dbh) and tree form. Tree size (dbh) has the greatest influence on the unit cost of harvesting. At an average 27 cm dbh and extraction distance of 200 m, the stump-to-landing cost was approximately 10 US$/$m^3$. As tree size increased, the unit cost of wood produced decreased. Damage to residual trees and advance regeneration was minimal. The results suggest that single-grip cut-to-length harvesting systems can be effective in managing poplar-dominated mixedwood stands.

Keywords: *cut-to-length, harvesting, Populus, Canada, forest harvesting, partial cutting, time-motion study, logging damage, cost.*

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INTRODUCTION

The need to manage forests on a sustainable basis and the increasing demand for wood are forcing resource managers to re-examine their approaches to forest management and species utilization. Of particular interest is the long-term management of mixedwood stands dominated by species of the genus *Populus*. “Poplar” species including trembling aspen (*P. tremuloides)*, largetooth aspen (*P. grandidentata)*, and balsam poplar (*P. balsamifera)*, are fast growing with a relatively short life span, moisture loving, generally intolerant of shade, and medium sized trees [3]. Within the Great Lakes St. Lawrence forest region of Canada, where the “poplar” forest type occupies some 20% of the forested area [1], these species are often associated with white birch (*Betula papyrifera)*, eastern white cedar (*Thuja occidentalis)*, balsam fir (*Abies balsamea)*, red maple (*Acer rubrum)*, white ash (*Fraxinus Americana)*, eastern hemlock (*Tsuga Canadensis)*, sugar maple (*Acer sacharum) and* yellow birch (*Betula alleghaniensis)*, among others [9]. Many of these associated species are growing more slowly than poplars, thus requiring more time to attain canopy dominance and commercial size. They are generally more tolerant of shade, and live longer than the poplar species.

While presenting many challenges, the complexity and diversity of these mixedwood stands are recognized increasingly as advantages to be promoted for integrated resource management [22]. Historically in Ontario, poplar in mixed stands was bypassed in favour of more desirable species [28]. However poplar now has a variety of uses including pulp, lumber, waferboard, and oriented strandboard [3]. In poplar-dominated mixedwood forests, an immediate challenge for forest managers is to capture the fibre potential of the fast growing poplar species while maintaining ecological processes, conserving biological diversity, and promoting the longer-term development of associated deciduous and conifer species.

Mixed wood forests are ideally suited to sustainable management techniques such as partial cutting and natural regeneration [22]. Early thinning in mixedwood stands can enrich stand development and maintain the value of stands for wildlife habitat [32]. Forest practices should minimize impacts on soil, water, remaining vegetation, wildlife habitat, and other values. In many situations it can be advantageous for harvesting to emulate natural disturbances. Given these considerations, single-tree or small group selection silvicultural systems are recommended for thinning mixedwood forests [26,27]. The science associated with these silvicultural systems has been well documented [26].

Most conventional harvesting systems employing mechanical full-tree or tree-length felling and skidding are not appropriate for mixedwood management [22]. Injuries to remaining trees from felling or skidding can be vectors for disease resulting in decreased tree vigour, staining or decay [28]. Excessive soil disturbance from skidding can damage the roots of remaining trees and destroy advance regeneration [5, 25, 31].

Cut-to-length (CTL) harvesting systems provide an alternative to conventional mechanical systems for thinning mixedwood stands and offer several advantages over conventional mechanical systems, including perceived softer impact on the environment, reduced destruction of advance regeneration, and increased fibre recovery [30,31]. In Ontario, mechanical CTL systems are most often associated with thinning in conifer plantations. However, these systems are becoming more prevalent in harvesting natural forests elsewhere in North America [14, 30].

With CTL systems, the delimbing, topping and bucking occur in the stand rather than at the landing area; logs are carried, rather than dragged, during extraction; and the log trucks are configured to haul shorter log lengths [7]. Two main types of CTL systems are being used in Canada and elsewhere. The most popular system uses harvesters to cut, delimb, measure and buck the stems [14]. In the second system, feller-bunchers fell and bunch or windrow the stems. Thereafter, processors delimb, measure and buck them. Both systems use forwarders to transport the shortwood to roadside [7]. In Southern Ontario, several independent harvesting contractors are using single-grip harvesters and forwarders for thinning conifer plantations. In the fall of 2001, one of these contractors, Conifer Farms Ltd., agreed to participate in a harvesting trial to assess the use of CTL systems for thinning poplar-dominated mixedwood stands.

The objectives of this study were to: assess harvester performance in a mixedwood stand, quantify the effect of tree size on harvester productivity, and evaluate the damage of the harvesting on advance regeneration and residual trees. In this study, poplar pulpwood, a relatively low-value product was being harvested. Therefore the cost of the harvesting operations was also of great interest.

SITE AND SYSTEM DESCRIPTION

The harvesting trial was conducted in a 23.1 ha woodlot near the town of Jackson's Point, in Southern Ontario. The woodlot is situated on a sand plain in the Lake Simcoe Lowlands physiographic unit [8]. The area is within Site Region 6E of the Great Lakes-St. Lawrence forest region of Ontario [11]. Soils on the study site are classified as Tecumseth sandy loams [15]. Water percolates quickly through the soil but surface run-off is low. The topography is flat to gently sloping.

The ground surface is characterized by pit-and-mound features, suggesting that the site was not cleared for agriculture when the area was settled in the mid 1800's. Rather, the evidence suggests that the present forest was established following a natural disturbance such as a catastrophic wind event some 60 years ago. Stand and harvest information for the study site is provided in Table 1.

The single-tree selection silvicultural system was used to remove approximately 30% of the basal area in the stand resulting in a residual basal area of 23 m^2/ha. The silvicultural prescription called for the removal of overmature or suppressed trees and trees with major defects as defined in the Ontario Tree Marking Guide [26]. In this thinning, an effort was made to target the aspen for removal while retaining and releasing final crop trees of other species. Trees to be removed were marked with yellow paint by certified tree markers. Snags (dead standing trees) and trees with cavities were retained as wildlife habitat in accordance with provincial guidelines [26]. The tree markers regularly checked the accuracy of their marking by employing a variable radius plot sampling technique using a basal area factor 2 wedge prism. The marked trees were numbered to facilitate volume estimation following the harvesting and to estimate the relationship between tree volume and diameter at breast height (dbh). The numbering of marked trees was part of the research methodology for this study and is not part of conventional silvicultural marking methodology.

The harvester was a four-wheeled Rocan Enviro. This machine is built in Canada, using an original Canadian design and Scandinavian components. It is a purpose-built thinning harvester, with a very compact design and a limited overall weight. The machine can be fitted with either a Logmax 828 head or a Logmax 3000. The machine used for the trial carried the larger 3000 model (Table 2). Rocan harvesters have been the subject of previous harvester trials involving commercial thinning elsewhere in Canada [7, 24].

The harvester followed pre-marked forwarding trails spaced 20 m apart. Usually the harvester cut a trail from a primary access road to the back of the block and continued in a loop, thinning along the adjacent trail back to the access road. The operator created "ghost trails," generally 4 to 6 m in length, to remove marked trees that could not be reached from the forwarding trails. Logs were piled along both sides of the trail. Sorting was not required as

Table 1. Stand and harvest information for the study site.

Total area (ha)	23.1	
Ecosite [21]	Dry-Fresh Poplar- Deciduous Forest Type FOD3-1	
Terrain classification [12]	2.3.1 G	
Age (yr.)	59	
Pre-treatment species composition % by basal area	Largetooth aspen	50%
	White ash	20%
	White birch	10%
	Sugar maple	10%
	Black cherry, Eastern white cedar, Eastern hemlock, Red maple	10%
Height (m.)	20-23	
Initial density (stems/ha)	555	
Initial basal area (m^2/ha)	33.0	
Initial avg. dbh (cm.)	Largetooth aspen – 27; Other species - 20	
Initial range of dbh (cm.)	10 - 50	
Area harvested during the study (ha)	3.4	
Trees harvested (stems/ha)	118	
Basal area harvested (m^2/ha)	10.4	
Avg. volume per harvested tree (m^3)	0.46	

Table 2. Manufacturers specifications - Rocan Enviro harvester.

Carrier	Rocan Enviro
Type	4 x 4 wheeled unit
Weight (kg)	8040
Engine	IVECO 7450
Power (kW)	88 @ 2100 rpm
Width (m)	2.0
Length (m)	4.18
Height (m)	3.19
Ground clearance (m)	0.62
Boom	Mowi 465
Max. Reach (m)	6.1
Head	Logmax 3000
Max. diam. cut (cm)	50
Weight (kg)	525
Rotator	Indexator GV-6

all of the logs were destined for a pulp mill.

A Rotobec F2000B forwarder extracted the logs, entering the stand one day after the harvester. The F2000B is a hydrostatic drive, 4x4 compact forwarder, especially designed for thinning operations (Table 3). Given the relatively small size of the woodlot, the forwarder operated on short distances. The forwarder operator usually drove in reverse to the end of the trail, then loaded the machine enroute to the access road. All wood was taken to two landings, built along the primary access road.

Both machines were run by experienced, highly motivated operators, who also performed all maintenance and most minor repairs. The operator of the harvester, who is also the owner of the firm, has over 20 years experience operating mechanical harvesters including three years experience operating the Rocan Enviro harvester used in this study. The forwarder operator has two years experience operating the Rotobec F2000B forwarder. Both operators had a clear understanding of the goals that the treatment was to achieve.

Table 3. Manufacturers specifications - Rotobec F2000B forwarder.

Model	Rotobec F2000B
Type	4 x 4 wheeled unit
Weight (kg)	8865
Engine	Cummins 4 BTA3.9
Power (kW)	87
Width (m)	2.62
Length (m)	7.64
Height (m)	5.26 to top of boom when cradled
Max payload (kg)	5000
Loader	Rotobec 40F
Max. Horiz. Reach (m)	5.64

RESEARCH METHODS

The pre- and post-harvest stand conditions were sampled using 100 m^2 fixed-area (5.64 m radius) inventory plots distributed throughout the study site. All trees of 10 cm dbh or greater were measured. Tree heights were measured using a clinometer. The average age of the stand was determined from increment cores. The information gathered during the pre-harvest inventory was used to develop the silvicultural prescription for the study site.

A total of 6.9 ha was harvested within the 23.1 ha stand. This included 3.4 ha on the study site and another 3.5 ha that were harvested immediately prior to the study period. Post-harvesting damage was assessed across the entire 6.9 ha harvested area using 10 m x 100 m transects distributed systematically throughout the study site using an 80 m (distance between transect lines) x 40 m (distance between 100 m transect segments) grid pattern. All trees within the transects were inspected for stem abrasions, broken limbs, damaged or dislodged roots, and trees bent over using provincial standards for unacceptable logging damage [27]. The type of damage was noted and the information was subsequently used to estimate the percentage of the remaining trees that exhibited each type of damage. Only damage that was caused by the harvesting operations was assessed. Some trees did exhibit signs of old damage such as stem abrasions and broken limbs. New damage was readily discernable by the freshness of the abrasions and lack of scar tissue.

The study was carried out on October 29-30, 2001. Daytime temperatures when the harvesting was in progress varied from 3^0C to 5^0C. Overnight temperature fell to -3^0C on October 29. Although overnight temperatures were below freezing, operating conditions could be described as “unfrozen” indicating that the ground surface was still susceptible to disturbance and the trees did not exhibit characteristics often associated with frozen wood such as the limbs shattering and breaking upon contact with the ground during felling.

A time-motion study was carried out in order to evaluate machine productivity and to identify those variables that are most likely to affect machine performance. Cycle times were split into a number of time elements considered as typical of the working process. Time elements were recorded with a Husky Hunter 2 hand-held field computer, equipped with Siwork3 timestudy software.

Volume output for the harvester was estimated by numbering and scaling all of the logs produced from each tree. Log length was measured using a tape measure and log diameter was measured at mid-length with calipers. Volumes were calculated by the Huber method [2, p.30]. Individual trees were assigned a form index based on a visual estimate of limb size and stem form. Discrete form coefficients have been used in other studies of CTL harvesters [4,10]. A research assistant recorded the tree and log numbers as they were collected by the forwarder. This was accomplished without disrupting the forwarding operation. Volume output for the forwarder was based on cumulative scaled volume of the trees forwarded.

RESULTS AND DISCUSSION

Although the duration of the study was short, the statistical results suggest that the number of observations (394) was adequate for obtaining meaningful mathematic relationships and for achieving the other study objectives such as post-harvest stand damage assessment.

A summary of the study is shown in Table 4. The difference between total observation time and productive cycle time includes machine downtime and all study and organizational delays. Data collection for the forwarder was not as extensive as initially planned due to the limited time available for the study and the realization that forwarder cycles were simpler and showed less overall variability than harvester cycles.

Overall, 394 trees were marked and removed for the trial, for a total harvest of 174 m^3. Largetooth aspen accounted for 88% of the total volume removed. White ash and white birch represented another 4% each while sugar maple, black cherry *(Prunus serotina)*, basswood *(Tilia Americana)*, and eastern hemlock constituted the remaining 4% of the volume harvested.

Table 4. Study summary.

Machine	Harvester	Forwarder
Study duration - days	2	1
Total observation time – hrs.	11.1	2.5
Productive cycle time – hrs.	7.9	1.8
Valid observations – number of cycles	394	5
Volume harvested - m^3	174	32

Volume-Diameter at Breast Height Relationship and Tree Form Index

The relationship between tree volume and diameter at breast height was estimated for 376 trees observed in the study (Figure 1). The equation is significant at the 0.0001 level. Individual trees were assigned a form index based on visual estimates of limb size and stem form (Table 5). Overall, the trees were relatively straight and lightly branched.

Harvester and Forwarder Performance

A description of the cycle time elements for both machines is given in Table 6. The results of the detailed timing of the harvester and forwarder are shown in Tables 7 and 8 respectively.

LeDoux and Huyler [20] have demonstrated the effects of machine utilization rate on direct harvesting costs and the break-even average tree size that a given harvester can operate in. A machine utilization rate of 65% was assumed for both machines [6], and is consistent with the contractor's experience to date. The machine utilization rate of 65% is lower than the 69% - 80% used for other trials of CTL harvesters [7,14]. However the contractor, who is also the harvester operator, must also attend to other aspects of managing the business with the result that the harvester is occasionally idle for lack of an operator.

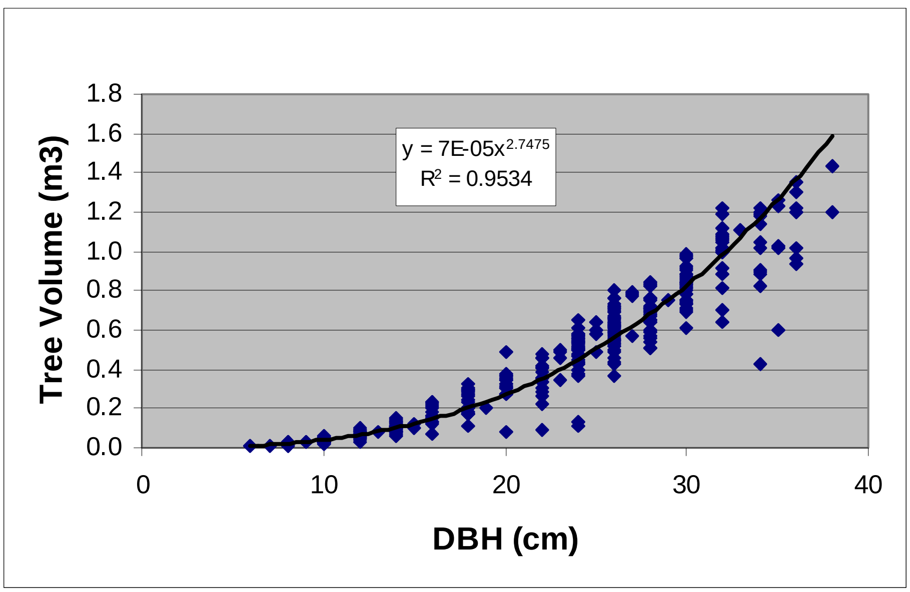

Figure 1. Relationship between tree volume and diameter at breast height.

Table 5. Tree form index.

Form Index	Branch Density	Max. branch diam. (at the trunk)	Bole Form	Frequency (% of 394 trees)
1	light	< 5 cm	straight	42.4
2	dense	< 5 cm	straight	25.1
3	light	> 5 cm	straight or moderate crook	18.5
4	dense	> 5 cm	straight or moderate crook	5.8
5	malformed		heavy crook or forked	8.1

Table 6. Description of machine cycle time elements.

Harvester Time Elements	Forwarder Time Elements
Move: any time when the harvester wheels are turning **Brush:** removal of undergrowth and unmerchantable trees **Position:** time from when the wheels stop (or brushing ends) to when the bottom saw begins cutting **Fell:** time from when the felling saw begins advancing to when it is totally retracted in its casing **Handle:** any movement of the boom while the head holds a cut tree, provided the machine is not doing any other job (e.g., delimbing) **Limb:** total time that the cut tree is being propelled through the delimbing knives **Crosscut:** any time the saw is being operated to crosscut **Pile slash:** piling limbs and tops **Other:** any other productive time, mostly re-handling, ejecting tops and locating next marked tree	**Travel unloaded**: time for the empty forwarder to drive from the landing to the first loading spot **Load:** time for the loader to pick up the logs and place them in the bunks **Move while load**: time moving between loading spots **Travel loaded**: time required for the loaded forwarder to drive to the landing **Unload**: the forwarder arrives at the landing, positions for unloading, and unloads the logs **Maneuver:** the forwarder maneuvers around obstacles, generally at the end of the loading routine **Other:** any other productive time

Table 7. Productivity of the Rocan Enviro Logmax 3000 harvester.

Time Element	Mean	Std. Dev.	Proportion of cycle (%)
Move (cmin)	30.5	41.5	25.4
Brush (cmin)	11.8	23.3	9.8
Position (cmin)	11.8	7.1	9.7
Fell (cmin)	4.1	3.2	3.4
Handle (cmin)	26.7	30.9	22.2
Limb (cmin)	19.3	13.9	16.0
Crosscut (cmin)	9.5	5.9	7.9
Pile slash (cmin)	5.7	6.9	4.8
Other (cmin)	0.9	6.1	0.8
Total cycle time (cmin)	120.3		100.0
Logs/Cycle	5.7		
Volume/cycle (m^3)	0.463		
Trees/PMH	49.9		
Trees/SMH	32.4		
m^3/PMH	23.1		
m^3/SMH	15.0		

Table 8. Productivity of the Rotobec F2000B Forwarder.

Time Element	Mean	Std Dev.	Proportion of cycle (%)
Distance (m)	121	48.4	
Travel unloaded (cmin)	127.0	51.9	6.4
Load (cmin)	978.0	283.5	48.9
Move w. load (cmin)	174.0	43.5	8.7
Travel loaded (cmin)	219.4	66.9	11.0
Unload (cmin)	365.2	95.0	18.3
Manoeuvre (cmin)	85.6	69.5	4.3
Other (cmin)	50.4	51.7	2.5
Total cycle time (cmin)	1999.6		100.0
Logs/Cycle (n)	60.8		
Volume/cycle (m^3)	5.74		
Trips/PMH	3.0		
Trips/SMH	1.9		
m^3/PMH	17.2		
m^3/SMH	11.2		

Among others, Huyler and LeDoux [14], LeDoux and Huyler [20] and Kellogg et al. [17] have found that harvester productivity is generally closely related to tree size. Harvester productivity may be affected by operator skill and motivation, branch size, and undergrowth density [18,23,29]. Data from the harvester study was used to generate relationships between time consumption and tree diameter at breast height and form index for the various elements in the harvesting cycle. For the delimbing and crosscutting functions, including the number of logs in the regression equations increased the accuracy of the predictions. Another equation was estimated to predict the number of logs obtained from a tree as a function of its diameter at breast height.

The productivity relationships obtained for the harvester are shown in Table 9. All the terms in the equations are highly significant ($p<.0001$). A constant

Table 9. Harvester productivity relationships.

Time (cmin)	Regression	R^2	No. obs.
Move =	30.5	-	394
Brush =	11.8	-	394
Position =	$5.6 + 0.280$ dbh	.099	376
Fell =	$1.7 + 0.00234\ dbh^2 + 0.00089\ dbh^2$ * form index	.367	376
Handle =	$3.5 + 0.0172\ dbh^2$ * form index	.642	376
Delimbing =	$-2.0 + 0.00533\ dbh^2$ * form index + 2.44* logs per tree	.715	376
Crosscut =	$-0.4 + 0.00209\ dbh^2$ * form index + 1.22* logs per tree	.728	376
Pile slash =	$4.6 + 0.00084\ dbh^2$ * form index	.029	376
Other =	0.9	-	394
Logs per tree =	$-7.80 + 10.43\ Log_{10}$ dbh	.665	376

value was assumed for those time elements that did not occur every cycle and/or did not affect any of the independent time elements.

The high move and brush times reflect the use of the single-tree selection silvicultural system and the management objectives for the operation, which targeted a substantial number of low-quality trees for removal while minimizing damage to residual trees and advance regeneration. Position time is somewhat related to tree size, as larger trees require more accurate positioning of the harvester head.

The quadratic relationship between felling time and dbh underlines the fact that the chainsaw cuts through a cross-sectional area. Here, the additional interaction between dbh^2 and form reflects the combined effect of tree size and tree form on the stability of the harvester during felling. Tree handling is also related to the interaction of tree size (dbh^2) and form. Large trees with a poor form are more difficult to handle and they often need to be released and grabbed again several times during processing.

Delimbing is logically related to the same variables and the number of logs produced because the head has to stop and restart with each log in order to make the crosscut. Stopping involves a loss of momentum that slows down the delimbing process. Delimbing is also expected to be easier during the winter months when the trees are frozen. For example, the limbs of many deciduous species, including *Populus* species, often shatter and fall off the bole of the tree when the tree makes contact with the ground during felling. Daytime temperatures were above freezing during the study and consequently all of the limbs had to be removed by the harvester.

Diameter and form also affect crosscutting time, but here the quadratic relationship to diameter at breast height is easily interpreted, as it simply represents a relative measure of the cross-sectional area cut at each point. Form index also affects crosscutting time because extra cuts were often required when dealing with heavy branches and forks. Finally, slash piling time shows a weak yet significant relationship with tree size. The relationship is probably weak because the operator would pile the slash from multiple trees at the same time, thus confounding the effect of individual tree size. However, it is logical that larger trees produce more slash and result in a longer slash piling time.

Tree size is the most important measurable variable that affects harvester productivity [14,30]. Single-grip harvesters are very sensitive to tree size because they generally handle only one stem at a time. The observed productivity of the Rocan harvester as a function of tree size and tree form is presented in Figure 2. The average cycle time for the harvester was 1.20 minutes. Average net productivity was 49.9 trees/PMH, equal to 23.1 m^3/PMH. Forwarder productivity was 17.2 m^3/PMH. The forwarder averaged 5.74 m^3 per load.

The productivity of the harvester is consistent with productivity levels for single-grip harvesters reported elsewhere [4,13,14,20,24,30]. For example, Huyler and LeDoux [14] reported an average productivity of 14.8 m^3/PMH (523 ft^3/PMH) and approximately 47.5 trees/PMH using a tracked CTL harvester in mixed hardwoods. In their study, the average volume per tree was 0.379 m^3 (13.4 ft^3); slightly smaller than the 0.463 m^3/tree (16.3 ft^3/tree) in our study. Forwarder productivity is within the range reported by Bulley [7] and others [19, 30] for forwarders of various sizes and under a range of site and stand conditions.

The most time-consuming elements for the forwarder were loading (48.9% of cycle time) and unloading (18.3% of cycle time). These results are consistent with those from other studies of forwarders on CTL operations [7, 30]. Other factors affecting forwarder productivity such as travel speed and load size, will vary between operations and within the same operation [7]. Forwarder travel speed is expected to vary with terrain conditions, the quality of the forwarding trails, and load weight [7]. Load size is also expected to vary with the size and weight characteristics of the wood being harvested. However, the data pool for the forwarder was not large enough to undertake a detailed statistical analysis. For this machine, we developed a mechanistic model assuming constant speed and load size. Although very basic, such a model allows estimating machine productivity as a function of extraction distance (Figure 3). Cycle time was calculated with the following equation:

Cycle time (cmin) = 1653 + 2.871 * Extraction distance (m)

Total Harvesting and Extraction Cost

Machine cost was calculated following the Forest Engineering Research Institute of Canada standard machine costing worksheet from data on machine utilization and fuel consumption gathered by the contractor over the life-to-date of both machines (10 months for the Rocan harvester and 17 months for the Rotobec forwarder) and using prices and wages in effect at the time of the study (Table 10). Combining these cost figures with the productivity estimates, and assuming an average extraction distance of 200 m, harvesting and extraction cost can be estimated as a function of tree size and tree form (Figure 4). Tree size has the greatest influence on harvesting and extraction cost (Figure 4). As tree size increases, the unit

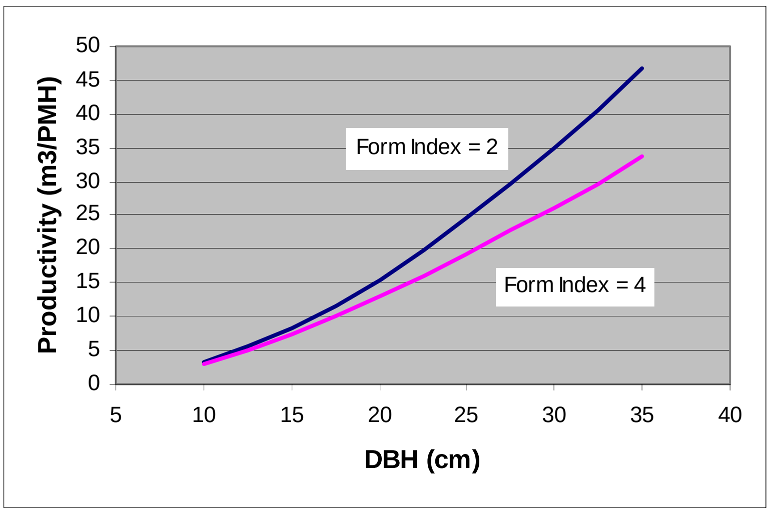

Figure 2. Harvester productivity vs. tree size and tree form.

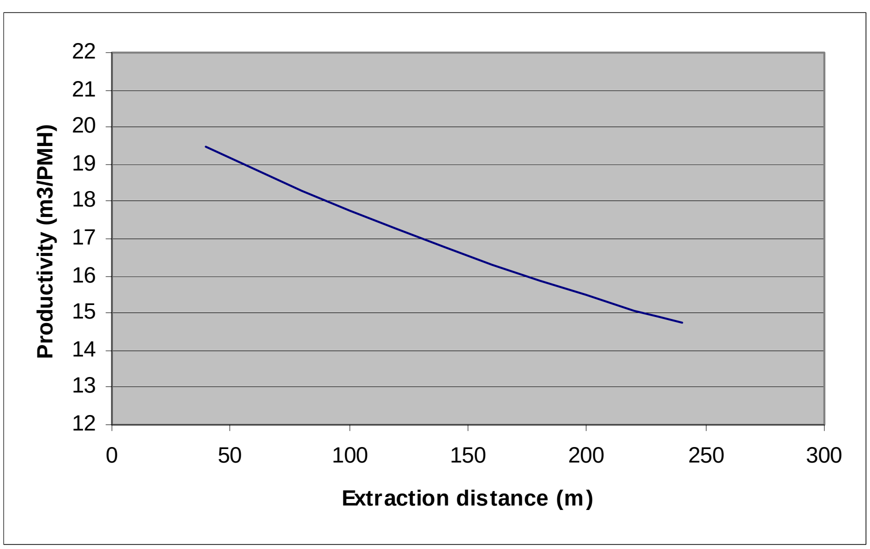

Figure 3. Forwarder productivity vs. extraction distance.

cost of wood produced decreases. The impact of form on the combined harvesting and extraction cost is identical in Figure 4 and Figure 2, in the sense that the productivities displayed in Figure 2 are those used in developing Figure 4. However, the productivity figures show up in the denominators of the costs per unit volume, so high productivities result in low unit costs and vice versa. The cost per cubic meter = Harvester $/PMH / Harvester m^3/PMH + the (assumed constant) forwarding cost. The constant forwarding cost dilutes not only the effect of form, but also of tree size. These results are intuitive and are consistent with the findings reported in other studies involving single-grip harvesters and forwarders [7,14,16]. At an average 27 cm dbh and extraction distance of 200 m, the stump-to-landing cost was approximately 10 US$/$m^3$. The contractor received approximately 13 US$/$m^3$ for the hardwood pulpwood at roadside.

Table 10. Machine costing.

	Harvester	Forwarder
Purchase price – US$	220,000	88,000
Service Life – yrs.	5	5
Annual workload – SMH/yr	1,500	1,800
Utilization rate – PMH/SMH (%)	65	65
Fuel consumption – L/hr	11	7
Fuel price – US$/L	0.315	0.315
Operator wage – US$/SMH	22.00	13.81
Hourly cost – US$/SMH	95.45	42.07

Harvesting Damage Assessment

Post-harvesting damage was assessed across the 6.9 ha area that was harvested immediately before and during the study. Other studies suggest that the CTL system causes fewer root and stem wounds than conventional harvesting systems [14]. The post-harvest assessment on our site reveals that damage to residual trees and advance regeneration was minimal (Table 11). Residual trees were grouped according to size categories as regeneration (< 10 cm dbh), polewood (10-24 cm dbh), and small sawlog (26-40 cm dbh). There were no trees greater than 40 cm dbh in the post-harvest assessment plots. Each tree was assessed for stem abrasions (> 20 cm^2 in size), broken or damaged crowns, roots, and stem and whether the tree appeared to have been bent or uprooted during the operation. If a tree exhibited multiple forms of damage, the most severe damage was recorded in order to avoid double counting. Of the 599 trees assessed, 65 (10.8%) exhibited some form of harvesting damage. Damage to advance regeneration was the most severe with 13.3% of the regeneration receiving some form of damage. Damage to polewood and small sawlog trees was minimal. The level of damage is considered acceptable for the stand and operating conditions and the single-tree selection silvicultural system used [27].

CONCLUSIONS

The CTL harvesting system is receiving considerable attention for managing mixedwood forests in Ontario. The advantages of CTL systems include softer impact on the environment, reduced damage of advance regeneration and residual trees, and increased fibre recovery. The availability of compact, maneuverable harvesting systems will be crucial to implementing cost effective and efficient thinning regimes in mixedwood forests. Although such machines are already used for thinning conifer plantations, many questions have been raised about their ability to treat hardwood stands, and on their economic efficiency in general.

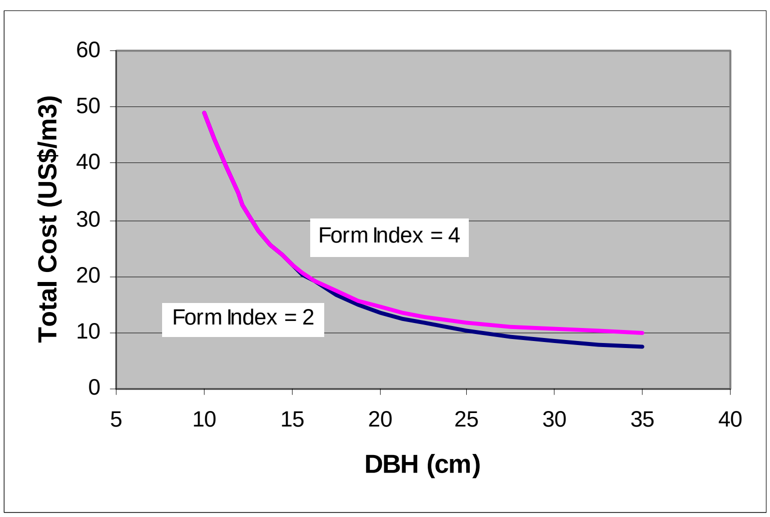

Figure 4. Total harvesting and extraction cost vs. tree size and tree form.

Table 11. Post-harvest damage assessment.

	Regeneration (< 10 cm dbh)	Polewood (10-24 cm dbh)	Small sawlog (26-40 cm dbh)	Total	Damage percent of total trees
Total no. of trees assessed	384	135	80	599	
Stem abrasion (>20cm^2 in size)	8	5	5	18	3.0
Crown damage		4		4	0.6
Root damage	3			3	0.5
Stem broken	11			11	1.8
Tree bent over	29			29	4.8
Damage percent of trees in size class	13.3	0.7	0.6	10.8	

This study demonstrates that a light harvester can be used to effectively treat the larger hardwood trees found in these stands. The form of many of the hardwoods on the study site did affect the productivity of the harvester, as shown by the strong effect of the form index in many of productivity equations. A CTL harvester is a sophisticated, expensive machine. Therefore, maintaining high productivity is crucial for cost-effective thinning. Productivity increases with tree size, and harvesting cost decreases accordingly. The contractor who participated in the study felt that the cost of the harvesting was acceptable for the range of tree sizes and operating conditions experienced on the study site. Finally, the study confirms the limited site impact of CTL systems, as the residual stand exhibited very low damage levels.

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ACKNOWLEDGEMENTS

The authors wish to thank John Houston, Mike Mitchell, and Ed Beatty, Conifer Farms Limited for their assistance during the course of the study. Special thanks are also due to Chris Gynan, Silv-Econ Ltd. for his invaluable help with both data collection and data processing. We also acknowledge the helpful comments and suggestions from the anonymous referees.