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Production economics: comparing hybrid tree-length with whole-tree harvesting methods

Harikrishnan Soman[1], Anil Raj Kizha[1,*], Bethany Muñoz Delgado[2], Laura S. Kenefic[2] and Keith Kanoti[3]

[1]*School of Forest Resources, University of Maine, Orono, ME 04469, USA*
[2]*USDA Forest Service, Northern Research Station, Bradley, ME 04411, USA*
[3]*University Forests, University of Maine, Orono, ME 04469, USA*

*Corresponding author Tel: +01 2075 812 851; Fax: +01 2075 812 875; E-mail: anil.kizha@maine.edu

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Felled trees with tops and branches are transported to the landing with a grapple skidder in conventional ground-based whole-tree (WT) harvesting. This method has greater potential to damage advance regeneration than those in which trees are processed at-stump. Hybrid tree-length (Hyb TL) harvesting using an stroke-boom delimber for in-woods processing might be a feasible alternative, but little is known about the production economics of this method. An experimental strip-cutting study was conducted in central Maine, US in the winter of 2018 to: (1) evaluate and compare operational productivity and costs of ground-based Hyb TL and WT methods; (2) identify factors influencing productivity of at-stump and at-landing log processing; and (3) calculate best management practice (BMP) implementation costs in WT harvesting. Time-motion data were recorded for operational phases such as felling, extraction, processing, sorting and loading; machine rates were calculated to determine productivity and costs of operations. Total cost of Hyb TL (US \$17.01 m^{-3}) was lower than that of WT (\$18.38 m^{-3}). Processing cost was lower at-stump than at-landing (\$2.66 and \$2.73 m^{-3} for Hyb TL and WT, respectively). This is likely due to fewer logs handled per cycle at-landing (1.2 logs per turn) compared to the number handled per cycle at-stump (1.4 logs per turn). Sensitivity analysis showed that a 30-m increase in average in-woods distance travelled by the delimber would result in a 41 per cent increase in the processing cost. Cost of BMP implementation in WT was \$2.25 m^{-3} or \$59.2 per productive machine hour. Results suggest that it is feasible to apply Hyb TL method in an industrial harvesting operation, though distance of in-woods delimber movement influences processing costs. Insights from this study will help forest managers and loggers efficiently plan and execute harvesting operations.

Introduction

Timber harvesting methods are crucial to achieve a broad spectrum of forest management objectives, including timber and firewood production, wildlife habitat management, forest protection and aesthetics (Nyland, 2016). The strategy of logging has a strong influence on operational costs, productivity (volume per productive machine hours), revenue generated and economic feasibility; therefore, efficient and cost-effective timber harvesting is vital to commercial forest management.

Industrial-scale timber harvesting utilizes several silvicultural prescriptions, of which clearcutting, an even-aged regeneration practice, is widely practiced in the US and elsewhere. In the state of Maine, however, clearcutting accounted for only 6.8 per cent of total harvested area as of 2017 (MFS, 2018). A silvicultural practice that aims to reduce the impact of clearcutting is strip-cutting, with the retention of unharvested strips between harvested areas (Baker *et al.*, 2015). As per the Maine Forest Service (01-669. Chapter 20. Forest Regeneration and Clearcutting Standards) a Category 1 clearcut (2–8 ha) must be separated from other clearcuts by a 76-m wide separation zone (buffer) of non-clearcut forestland (Maine Forest Service (MFS), 2014). Strip-cutting reduces adverse effects of mechanized logging on wildlife habitat and promotes natural regeneration (Picchio *et al.*, 2018). In mixedwood stands, unharvested strips adjacent to clearcut strips have the potential to modify the species composition of the regenerating stand (Bose *et al.*, 2016). This silvicultural prescription can be executed using whole-tree (WT), cut-to-length (CTL) or tree-length (TL) harvesting methods.

In WT, whole trees are extracted from the stand and processed at the landing. In CTL, trees are processed exclusively at the stump and logs are then transported to the landing. The TL method is intermediate between the CTL and WT methods, wherein logs are delimbed (partially processed) in-woods, then brought to the landing where a final processing (bucking) may be carried out to meet market requirements (Hartsough *et al.*, 2001; Kofman and Kent, 2007). One of the major advantages of TL and CTL over the WT method is that a considerable amount of slash is retained in-woods, and often distributed over the skid trails to protect the soil from adverse effects of machine traffic. Damage to soils may therefore be lower in TL/CTL when compared to the WT method (Han *et al.*, 2009). In mixedwood stands where regeneration relies in part on seedlings established prior to overstory removal, WT has been found to result in greater damage to advance regeneration than other harvesting methods (Waters *et al.*, 2004).

For a conventional WT method in the region, a feller-buncher, skidder, delimber/processor and slasher are commonly used, where the skidder extracts whole trees that are then processed at the landing using a delimber/processor, bucked and loaded by a slasher. In the CTL method, harvesting machinery predominantly consists of a harvester and forwarder. Felling, processing, and bucking are carried out by the harvester at the stump. The forwarder then carries the processed logs to the landing and sorts them to facilitate loading. Harvesting equipment for a conventional TL method usually consists of a chainsaw and a cable skidder. A slasher is also often used at the landing for bucking logs. A traditional TL method is exclusively used for small-scale operations (due to functional impairment) and uses relatively obsolete machinery compared to the CTL method (Ponsse, 2005). Harvesting operations using dilapidated (seasoned) equipment may lower initial capital investment but increase risk of mechanical delays, which ultimately reduces productivity. In contrast, operating newer and advanced machinery is usually associated with higher productivity, but often corresponds to higher initial capital (Regula *et al.*, 2018).

Nordfjell *et al.* (2019) reported CTL, WT and other harvesting methods that accounted for 35, 37 and 29 per cent, respectively, of the global harvest of round wood. In Maine, 80 per cent of recent timber production comes from WT method and TL accounted for about 7 per cent of the production (Leon and Benjamin, 2013). Limited studies have been done on the cost and productivity of the TL harvesting method. Comparisons of TL and WT methods have shown that the extraction cost per cubic meter of timber in WT was almost double that of TL (\$0.32 and \$0.17 m^{-3}, respectively) (Feghi, 1987). Zundel and Lebel (1992) also pointed out that the cost per cubic meter of wood harvested for the WT method was 4 per cent higher than that of TL.

Employing a stroke-boom delimber inside the harvest unit is a unique harvesting method in the northeastern US. Natural regeneration, often present at the time of harvest, is the principal form of stand re-establishment in this region (Brissette, 1996). This harvesting method, generally referred to as hybrid TL method (Hyb TL) ensures less damage to tree regeneration during extraction of the wood compared to WT, and is believed to be more productive than the conventional TL using chainsaws. Unlike the conventional TL method, the Hyb TL method is employed in industrial-level harvesting operations. Studies have shown that shade provided by slash such as that left at the site during Hyb TL favours natural regeneration of softwoods (Rinaldi, 1970; Verme and Johnston, 1986). Productivity of a stroke-boom delimber operating at the landing ranged widely between 10 and 108 m^3 per productive machine hour (PMH^{-1}) (Andersson and Evans, 1996a; Hiesl, 2013; Kizha and Han, 2015). However, production economics of in-woods delimber operations at the stump has rarely been studied.

BMP implementation

A major concern for any mechanized forestry operation is site disturbance that results in degradation of soil and stand quality. Although site disturbances from forestry practices cannot be eliminated, damage can be mitigated through careful implementation of best management practices (BMPs) during forest operations (Han, 2007). Maintaining slash on trails is a common BMP employed throughout the US and elsewhere. Covering the machine trails with slash and ensuring its continuity on the trails has been found to limit the extent of soil disturbance by reducing the probability of soil compaction and rutting (Han *et al.* 2006; Han *et al.* 2009). Previous studies have proposed that BMP implementation can be incorporated into mainstream harvesting operations without considerably affecting harvesting costs (Kelly *et al.*, 2017; Soman *et al.*, 2019).

Production economics of a Hyb TL method has not been scientifically quantified; the data available for the costs and productivity are primarily anecdotal. Hence, there is a need to examine the various operational aspects of the Hyb TL and compare it to other widely practiced harvesting methods. The main objectives of this study were to: (1) evaluate and compare the operational productivity and costs of a hybrid tree-length (Hyb TL) and WT harvesting methods; (2) identify factors influencing the processing (delimbing) costs and productivity at the stump and landing, and (3) calculate the cost of implementing BMPs.

Methods

Study area

The study was conducted in a 21.6-ha stand managed by the U.S. Forest Service at the Penobscot Experimental Forest (PEF) in Bradley, Maine, US (44° 51′ 56.754″ N, 68° 38′ 12.181″ W) (Figure 1). The stand had a gentle slope (<15 percent), with the region experiencing a mean annual temperature of 6.6°C, annual rainfall of 107 cm, and heavy snowfall with an annual average of 168 cm (NOAA, 2019). The elevation of the site was about 200 m above mean sea level. Soil types in the site are of glacial-till and marine sediment parent material. Soil type and drainage of the site varied from the north to south with moderately well-drained Howland loams dominating the northern portion and poorly drained Monarda-Burnham complex, and Scantic silt loams were dominant in the southern portion (Muñoz Delgado *et al.*, 2019). This variation in soil profile and drainage is a crucial factor contributing to the wide variation in species composition throughout the stand. Dominant tree species present in the site were balsam fir (*Abies balsamea* (L.) Mill.), red maple (*Acer rubrum* L.), red spruce (*Picea rubens* Sarg.), black spruce (*Picea mariana* Mill.), eastern white pine (*Pinus strobus* L.), quaking (*Populus tremuloides* Michx.) and big-tooth aspen (*Populus grandidentata* Michx.). Northern white-cedar (*Thuja occidentalis* L.), eastern hemlock (*Tsuga canadensis* (L.) Carrière), red oak (*Quercus rubra* L.), white spruce (*Picea glauca* (Moench) Voss), white ash (*Fraxinus americana* L.), gray birch (*Betula populifolia*

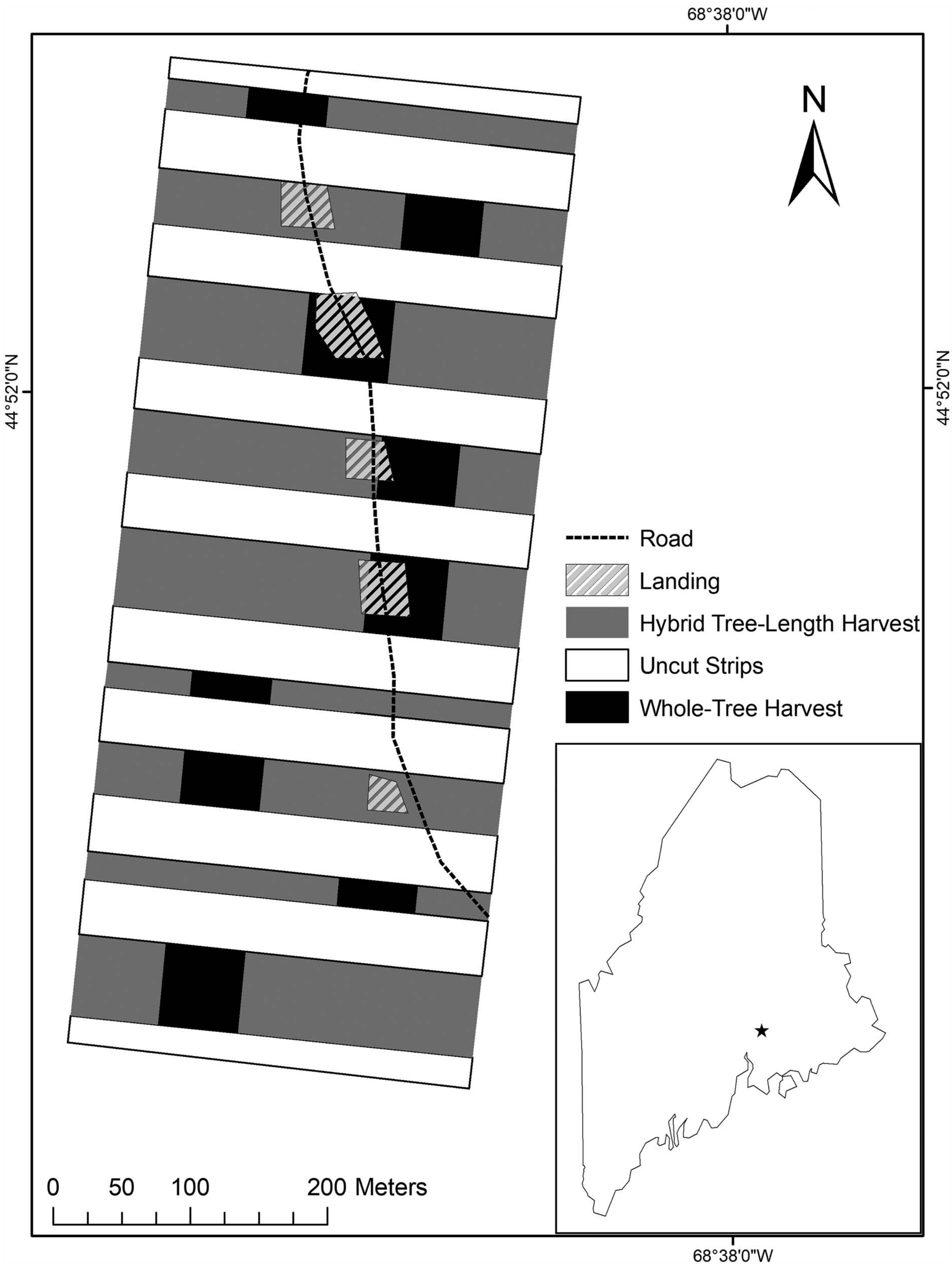

Figure 1 Clearcut strips showing extent of hybrid tree-length and whole-tree harvest treatments.

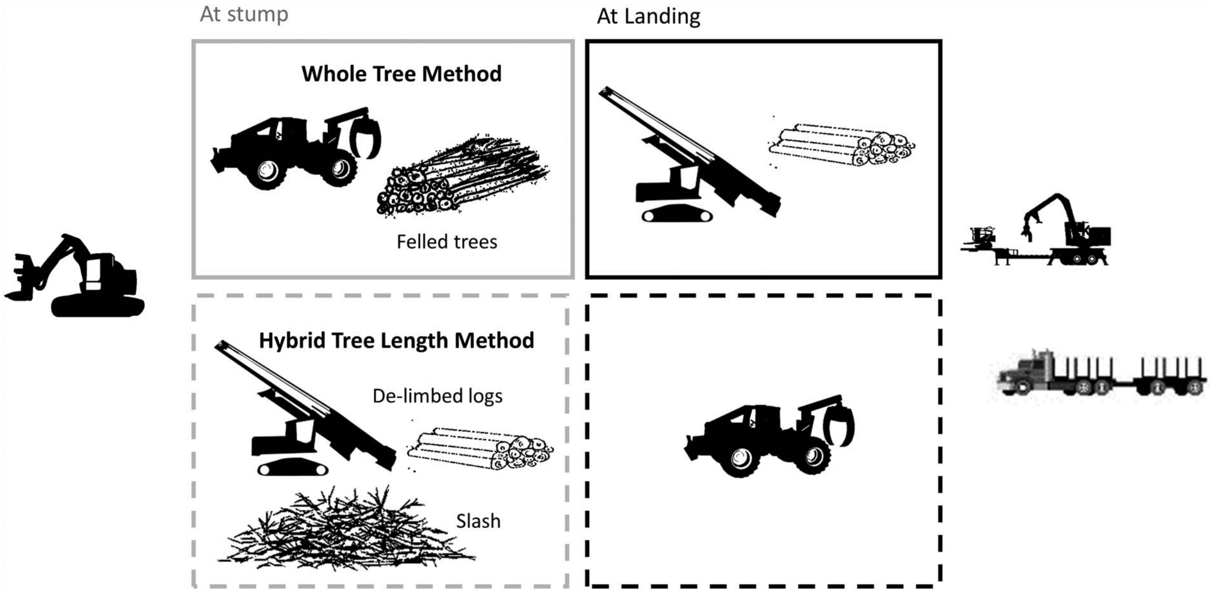

Figure 2 Description of operational components at the stump and landing for the hybrid tree-length (Hyb TL) and whole-tree (WT) treatments. In WT, the skidder brings the unprocessed logs to the landing and processing is done at landing and in Hyb TL, processing is done at the stump and the skidder carries the delimbed logs to the landing.

Marsh.) and paper birch (*Betula papyrifera* Marsh.) were present in minor proportions.

Out of the 21.6, 10.8 ha were harvested as part of this study. Hyb TL harvest was conducted in 8.7 ha and WT treatment accounted for 2.1 ha. There were nine clearcut strips oriented east–west, with the strips at the ends adjacent to 20-m wide buffers and other strips separated by 40-m wide buffers. The width of the strips varied between 20, 40 and 60 m (Muñoz Delgado *et al.*, 2019).

Stand inventory

Before harvesting commenced, each of the strips to be felled had a stand inventory using a total of 19 fixed-area plots with sizes of 0.08 and 0.02 ha in the 10.8-ha study area. Out of the 19 plots, 12 plots (of 0.08 ha each) were in the Hyb TL treatment and 6 plots (of 0.08 ha each) were in the WT. A single plot of 0.02 ha was present in WT treatment. The inventory was conducted at 22 per cent sampling intensity. All trees having diameter at breast height (DBH) $\geq$11.4 cm were inventoried for DBH, tree heights and species type.

Harvesting operation and treatment

The last harvest at this site was a strip clearcut in 1964–1965 using hand-fell operations with chainsaws and a tractor (Bjorkbom and Frank, 1968). The current harvest was done in February and March of 2018, during which there were two snowstorms (45–60 cm of snowfall).

Each portion of the strip was designated either a Hyb TL or WT treatment and followed a similar experimental design pattern to that of the 1964–1965 harvest (Figure 1). The primary difference between the methods was the processing phase. In Hyb TL, at-stump processing was done by deploying a stroke-boom delimber inside the harvest unit and processed wood was extracted using a grapple skidder to the landing. In the case of WT, whole trees were extracted using a skidder and processed at the landing (Figure 2). Another difference was that the slash (i.e. harvest residues such as limbs, offshoots and broken logs) was retained at the site in Hyb TL, whereas for the WT treatment, the harvest residues were taken to the landing. The same machines and crew operated for all the treatments and the experience of the crew ranged from 5 to 25 years.

Data collection

The operational phases included felling, processing, extraction, sorting and loading. Time and motion data were collected for different tasks involved in each of the operational phases (Olsen *et al.*, 1998). The independent variables expected to influence the efficiency of operations were also recorded (Table 1; Sahoo *et al.*, 2018).

Supplementary material

The following supplementary material (pictures of the various machines utilized for the operations) is available at *Forestry* online.

The various operational phases and the variables collected were:

1. *Felling*: The feller-buncher (John Deere 753G) started by laying trails, which involved felling and piling trees on the designated skid trails. Felling operation started from the back of the stand and progressed towards the road. The delay-free cycle time (DFC) for felling was constituted by three cycle elements: (1) travel empty time: began as the machine travelled empty to a tree; (2) cutting time: time required to

Table 1 Cycle elements and independent variables recorded for each operational phase.

Operational phase	Cycle elements	Recorded independent variables
Felling	Travel empty Cutting Bunching Scattering[a] In-woods movement	Trees cut per cycle Tree species Butt-end diameters (cm) Distance between trees (m) Distance to bunch (m)
Processing	Grappling Processing sawlog Decking sawlogs Piling biomass In-woods movement	Distance of in-woods movement (m) Tree species Butt-end diameters (cm) Number of cuts per cycle Number of logs handled per cycle
Extraction	Travel empty Positioning Grappling Re-grappling Travel loaded Dropping grapple Picking slash Handling slash	Distance to the bunch (m) Loaded distance (m) Number of pieces Diameter per piece (cm) Distance travelled for picking up slash (m)
Loading and sorting	Swing empty Grapple Swing loaded Bucking[b] Sorting Loading	Diameter of logs (cm) Number logs handled per cycle

[a]Scattering was done while laying the skid trails during the initial operations of the feller-buncher.
[b]Bucking was done for logs including logs from the Hyb TL and WT treatment.

cut tree/s; and (3) bunching time: the cycle ended as the head of the feller-buncher clutched trees while rotating and stacked into a new or existing pile/bunch. Distance moved by the machine for every cycle element was visually estimated; this was facilitated by setting markers at fixed intervals. The operational phases were decoupled with the feller-buncher operating one week prior to the skidder.

2. *Processing*: A stroke-boom delimber (John Deere 200 CLC) was used for processing. DFC initiated when the processing head swung empty to the pile (swing empty). Swing empty cycle element was followed by grappling the tree (grappling), swinging loaded and processing the tree. The cycle ended when the log was placed in a deck (decking). For the Hyb TL treatment, the delimber had an additional cycle element: in-woods movement, as the machine was mobilized inside the unit. When the delimber was at the landing, it also decked the processed logs brought in by the skidder from the Hyb TL treatment along with logs processed at landing (WT). Processing began prior to the extraction phase in the Hyb TL treatment areas. Independent variables expected to influence the DFC, which include the distance-travelled in-woods, species handled (softwood or hardwood), number of logs handled per cycle, butt end diameter of logs and number of cuts made per cycle, were visually estimated and recorded.
3. *Extraction*: Two grapple skidders (John Deere 748H) were employed for primary transportation, which brought unprocessed trees from the WT treatment stands and delimbed logs from the Hyb TL to the landing (Figure 2). Extraction DFC started when the machine travelled empty from landing to the unit (travel empty). After arriving near the bunch, the skidder positioned itself for grappling the trees/logs (positioning). Grappling initiated as the skidder began grappling the bunch; if a grapple was dropped and then re-picked, it was considered re-grappling. Grappling ended as the machine started skidding the bunch back to the landing (travel loaded). Travel loaded cycle element ended and dropping grapple cycle element started as the skidder dropped the bunch at the landing. Distance travelled, diameter (at butt end) and the number of pieces (trees or logs) skidded during each cycle were recorded based on ocular assessment.

BMP implementation

Following the prescription, slash was only handled in the WT treatment, resulting in two additional cycle components to the DFC of the extraction phase: picking up slash (at landing) and handling slash (within the harvesting unit). As

Table 2 Costs (US$) related to the machinery used for harvesting and skid trail establishment.

Element	Felling	Extraction	Processing	Sorting and loading
Make and model	John Deere 753G, 2008	John Deere 748H, 2011	John Deere 200 LC, 2004	Serco 300, 2008
Purchase price ($)	275 000	320 000	345 000	200 000
Variable and operating cost ($)	37.36	53.10	76.85	28.03
Salvage value ($)	52 250	73 600	34 500	50 000
Labour cost ($ PMH^{-1})	42.86	43.08	35.00	39.75
Fuel use (L PMH^{-1})	18.93	22.71	22.71	22.71
Utilization (%)	70	65	80	80
Machine rate ($ PMH^{-1})	130.49	159.60	175.10	103.40

Fuel cost was set at $0.72 L^{-1} as per the market conditions during harvest time. Machine rates $ PMH^{-1} were calculated based on 2200 SMH/year, 10 per cent interest and 3 per cent insurance (provided by the company that operated and owned the machines). Same machines and operators were employed for both Hyb TL and WT treatments.
These values do not include support vehicles such as fuel trucks and personal vehicles.

the skidder moved back to the unit from the landing, it carried slash generated during the processing phase and placed the slash on skid trails, especially on sensitive spots. BMP implementation time was calculated by summing the time required for each of these additional cycle components.

4. *Sorting and loading*: Sorting and loading were done using a slasher loader (Serco 300) for both harvesting treatments combined. Merchantable products for this study consisted of sawlogs and pulpwood. Sawlogs for each sort were bucked into appropriate market dimensions. Sorting and loading had the same DFC components. The cycle began when the machine swung empty to the deck of logs (swing empty), followed by grappling and swing loaded, then culminated when the log was placed in separate log piles (sorting), or on the log truck (loading). For the cycles with bucking, there was an additional operational component of cutting the logs to market dimensions in between swinging loaded and sorting of logs element.

Machine rate calculation

Average DFC for all operational components was calculated for both treatments. Independent variables expected to affect DFC were also recorded along with time components (Table 1). Mechanical, operational and personal delays were recorded to better understand the factors that affected productivity (Kizha and Han, 2016). The operational costs for the two harvesting treatments were evaluated as cumulative productive machine cost (i.e. adding the operational cost for each machine involved in the harvest) incurred during the performance of the various operational phases (an operational phase was considered as any activity that would change the position or form of the wood).

Owning and operating costs of the machines such as purchase price, salvage value, economic life, utilization rate for the machines, salary and fringe for the logging crew were obtained from the company that owned and operated the machines (Table 2). Fuel price was set at $0.72 L^{-1}, which reflected the market price during the time of operation. Hourly machine costs in US dollars per scheduled machine hour ($ SMH^{-1}) were calculated using standard machine rate calculation methods as per Miyata (1980), which were later used to calculate the cost of $ PMH^{-1}. Scale tickets for the wood products were obtained from the forest management company.

Statistical analysis

A two tailed t-test was performed ($\alpha = 0.05$) to analyze if a significant difference existed in the DBH and stand density among the treatments. Boxplots were created for the feller-buncher, delimber and skidder for both treatments for analyzing trends in DFC. DFC values were analyzed for outliers using a 95 per cent confidence interval. Regression models were developed in IBM SPSS 24 statistical software estimating the influence of the independent variables on the average DFC for each operational phase (Table 1). Dummy variables were used to represent species. Models were selected based on two criteria: fulfilment of the assumption of normality and higher adjusted R^2 values. Multicollinearity was tested using a tolerance value greater than 0.1 and variance inflation factor (VIF) less than 10 (Soman *et al.*, 2019).

Inputs for machine rate calculations were obtained by using standardized variables for the harvesting treatments (Kizha and Han, 2016; Adebayo *et al.*, 2007). In this method, all independent variables for estimating respective DFC for each operational phase were initially regressed, and the DFC values estimated by the regression equations were used for subsequent cost and productivity analysis. Standardized variable comparison helped to illustrate differences in cost and productivity due to the harvesting method (treatment) without accounting for variance in stand and operational conditions (Kizha and Han, 2016). The parameters recorded for log scaling were small-end, large-end diameters (cm) and length (m) of the logs from different decks.

Sensitivity analysis

Sensitivity analysis was conducted to analyze the trends in processing costs with respect to in-woods movement distance of the delimber. The fluctuations of in-woods movement distance had values ranging from 0 to 91 m. Initially, a linear regression model was developed for modeling changes in DFC with in-woods distance. Then, in-woods distance values from 0 to 180 m

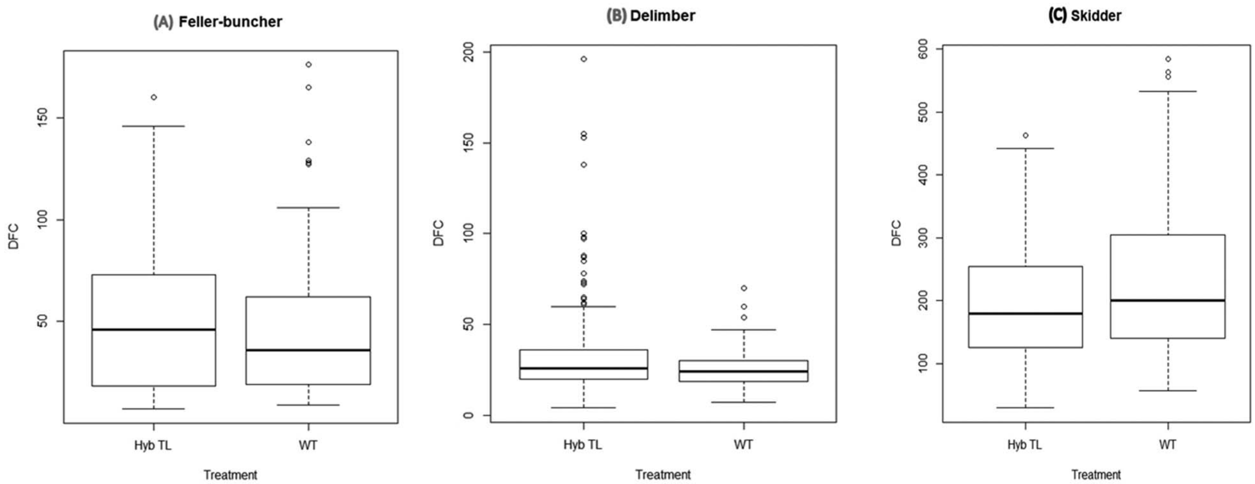

Figure 3 Boxplots comparing the trends in DFC for different machines for Hyb TL and WT treatments: (A) feller-buncher, (B) delimber, and (C) skidder.

Table 3 Stand attributes of areas under Hyb TL and WT harvesting treatments at 22 per cent sampling intensity and considering only trees of diameter at a breast height ≥ 11.4 cm (Stem density and basal area are expressed with standard deviations.)

Stand attributes	Hyb TL	WT
Area (ha)	8.7	2.1
Number of plots	12	7
Stem density (trees ha^{-1})	1069 ± 159	1147 ± 136
Basal area (m^2 ha^{-1})	24.0 ± 5.9	27.1 ± 8.3

Table 4 Summary Statistics of the DFCs in seconds of the different operational phases for Hyb TL and WT harvesting methods.

Operational phase	Prescription	Mean	Standard error
Felling	Laying trails	72.74	5.14
	Hyb TL	53.44	3.76
	WT	45.60	3.40
Processing	Hyb TL	33.65	1.67
	WT	25.10	0.98
Extraction	Hyb TL	193.84	9.69
	WT	247.83	20.01
Sorting	N/A[a]	30.20	1.19
Loading	N/A[a]	60.44	4.41

[a]Not applicable as this operational phase was not treatment specific and was combined for both treatments.

were substituted in the regression equation to understand the DFC sensitivity of the stroke-boom delimber towards in-woods movement distance. Based on the change in DFC, corresponding values of operational costs were estimated to determine the increase in processing cost with respect to in-woods movement.

Results

Stand inventory

Results showed that there was no significant difference between the treatment stands in terms of DBH and stand density ($P = 0.69$ and 0.79, respectively). Stem density and basal area ha^{-1} were calculated for both treatments, separately (Table 3).

Harvesting operation

DFC was calculated for all the operational phases using the standardized regression model and average values of DFC were estimated with standard errors (Figure 3; Table 4).

The total cost of operations from stump to truck was estimated to be \$17.01 and \$18.38 m^{-3} for Hyb TL and WT treatments, respectively (Table 5).

Adjusted R^2 values for the DFCs modelled were between 0.18 and 0.75 (Table 6). According to the scale tickets, a total of 1457 metric tons of wood (1342 metric tons of pulpwood and 115 metric tons of sawlogs) were harvested in total, for both treatments combined. Due to space restriction at the landing, the logs were piled and sorted together, irrespective of treatment, based on their market dimensions.

Felling: A total of 309 DFCs were recorded for the feller-buncher. Felling was the most productive operational phase for both Hyb TL and WT treatments (Table 5). Average DFC was found to be similar for both treatments with a 8-s increase in the Hyb TL. The cost of felling operations for Hyb TL and WT treatments was estimated to be \$2.13 and \$1.65 m^{-3}, respectively. For laying trails, the time taken to scatter slash accounted for the majority of DFC time (43 per cent). The cost of laying trails (\$0.78 m^{-3}) was included in the felling costs for both treatments.

Processing: For accomplishing the second objective, a total of 338 processing cycles were recorded for both treatments. On average in Hyb TL, processing (delimbing) time had the highest contribution to the DFC (33 per cent). In-woods movement time (for Hyb TL) only contributed 9 percent to the DFC (Figure 4).

Table 5 Cost of operating (in US\$ m^{-3}) and productivity (m^3 PMH^{-1}) of the different phases of the operation in Hyb TL and WT treatments.

Operational phase	Cost		Percentage difference in cost[a]	Productivity	
	Hyb TL	WT		Hyb TL	WT
Felling[b]	2.13	1.65	−22.5	264	317
Processing	2.66	2.73	+2.6	66	64
Extraction[c]	10.17	11.96	+17.6	31	26
Sorting	0.96	0.96	N/A[e]	108	108
Loading[d]	1.09	1.09	N/A	95	95
Total	17.01	18.38			

[a]Percentage difference in cost is calculated based on Hyb TL treatment; "+"and "–" indicate higher and lower costs of WT compared to Hyb TL, respectively.
[b]Cost and productivity of laying trails was included to the felling phase for both treatments.
[c]Cost of extraction included cost of operating two skidders.
[d]Loading cost was similar for both treatments as the piles were combined at the landing.
[e]Percentage difference in cost is not applicable for sorting and loading as the operation was combined for both treatments.

Table 6 Regression models developed for predicting DFC in minutes using standardized comparison. All units are in cm for diameter and in m for distance. Dummy variables were used for the species (i.e. hardwood or softwood).

Phases	Prescriptions	Number of DFC	Adjusted R^2	Standardized models predicting DFC
Felling	Laying of trails	99	0.18	[a]Log DFC = 1.247 + 0.008 (distance between trees) + 0.036 (number of trees cut/cycle)
	Hyb TL	104	0.19	[a]Log DFC = 1.053 + 0.127 (species)
	WT	106	0.34	[a]Log DFC = 1.193 + 0.033 (distance between trees) + 0.005 (distance to bunch) + 0.036 (number of trees cut/cycle)
Processing	Hyb TL	238	0.26	DFC = 24.323 + 0.369 (in-woods distance)
	WT	100	0.50	DFC = −10.031 + 1.611 (average diameter/cycle) + 17.882 (number of cuts) + 4.742 (number of logs/cycle)
Extraction	Hyb TL	104	0.75	Log DFC = 1.848 + 0.001 (travel empty distance) + 0.001 (travel loaded distance) + 0.002 (positioning distance)
	WT	53		Model not significant

[a]Log DFC is the log to the base 10 of DFC.

The DFC for the Hyb TL treatment derived from the standardized model was found to be 8 percent higher than that of the WT (28 and 26 sec, respectively). Despite this, the cost for Hyb TL was found to be slightly lower than that of WT (\$2.66 and \$2.73 m^{-3}, respectively). Processing costs accounted for 16 and 15 per cent of the total operational cost in Hyb TL and WT treatments, respectively. Productivity was similar for Hyb TL and WT, which averaged 65 m^3 PMH^{-1}. The linear regression model developed for change in DFC with in-woods movement distance had a slope of $y = 0.38\,x + 30.36$ with an R^2 value of 0.27. A graph was developed based on the values obtained from the equation to show the sensitivity of in-woods distance on DFC.

Extraction: A total of 156 cycles were recorded for both treatments. The final extraction cost included costs for both skidders used. Regression models developed for Hyb TL treatment showed that travel empty, travel loaded, and positioning distance significantly influenced DFC ($P < 0.05$). The models developed for extraction DFC within WT were not found to be statistically significant (adjusted $R^2 < 0.10$, $P > 0.05$). Extraction was the most expensive phase, accounting for 60 and 65 per cent of the total operating costs in Hyb TL and WT treatments, respectively. Volume used to calculate the cost in WT was obtained from the scaling data estimated for merchantable logs, despite the fact that whole trees have higher volume than processed logs. This assumption was based on the idea that harvest residues from the tree, such as branches and tree tops, received a free ride to the landing, as it they were not merchandized.

BMP implementation: On average, time to implement BMPs in the WT stands was estimated to be 95 sec per cycle, costing \$2.25 m^{-3} or \$59.2 PMH^{-1}. Handling slash was the major time component in BMP implementation contributing about 66 percent to the BMP DFC.

Sorting: Sorting was combined for the Hyb TL and WT, with 77 DFCs were recorded. For this reason, regression analysis was not done for the treatments, and the average DFC of 30 sec was used for calculating the operational cost for both treatments.

Loading: Loading data were collected for 62 cycles. Loading cycle had an average DFC of 60 sec, and the average time to load a truck was estimated to be 26 min. Similar to sorting, cost

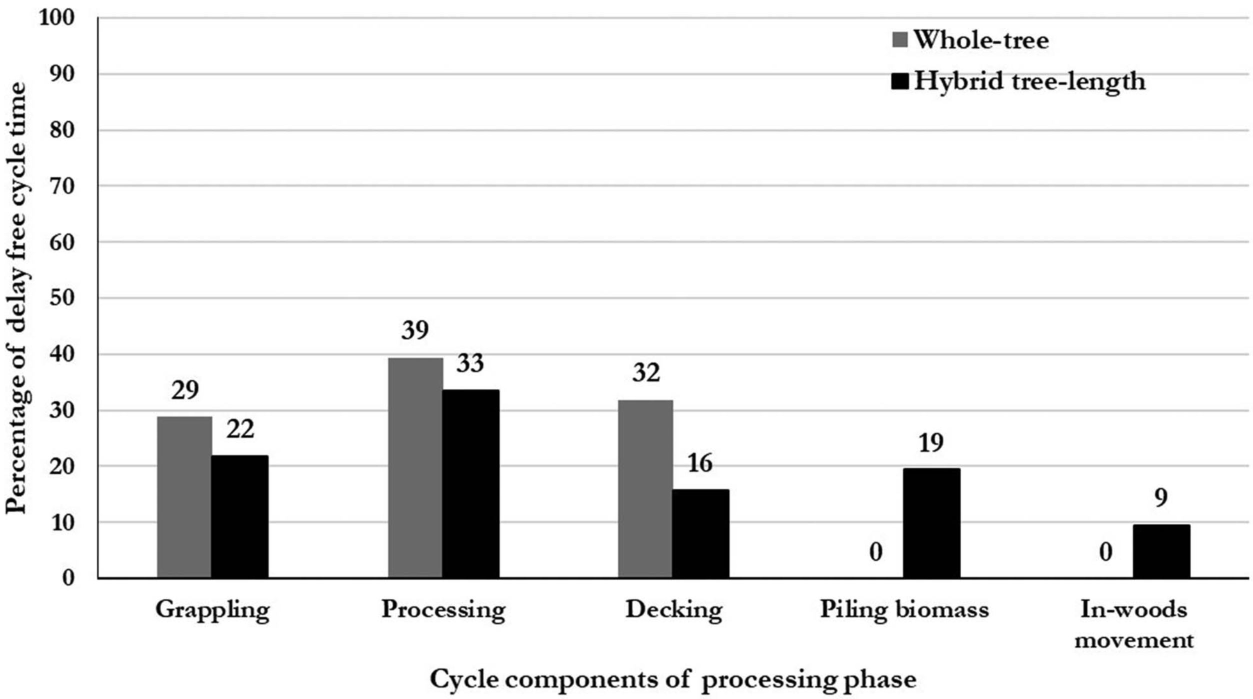

Figure 4 Time taken for cycle components of the delimber expressed as a percentage (%) of the delay DFC for both Hyb TL and WT methods. Where grappling is picking up logs from the feller-buncher sort, processing is delimbing logs, decking logs is placing logs in bunches for facilitating extraction, piling biomass is handling harvest residues and in-woods movement is moving from one bunch (made by the feller-buncher) to another.

and productivity of loading were calculated together for both treatments because the logs from both treatments were piled together at the landing for trucking.

Discussion

During felling, laying of trails had the highest value for mean DFC (72.74 ± 5.14 sec). This coincides with results from an earlier study conducted in the region that had similar results of an increased cycle time, while operating in trails, compared to cutting inside the stands (Hiesl, 2013). Regression models showed that the number of trees cut per cycle was a significant factor influencing feller buncher productivity during the trail laying phase and felling in the WT treatment (Table 6). Distance to bunch and size of trees (average butt-end diameter of trees handled per cycle) were common factors that influence the productivity of felling (Kluender *et al.*, 1998; Li *et al.*, 2006; Kizha and Han, 2016). However, these factors were not found to be significant ($P > 0.05$) in the model of trail laying. This deviation from the general trend could be attributed to the nature of operation as trees were cut and dropped on trails, rather than being bunched for facilitating upcoming tasks. In Hyb TL, species (whether hardwood or softwood) was the only significant factor influencing DFC, which may be due to the contrast in species composition in the stand. Studies have shown that tree-form indicators (such as branching patterns and crown width), which vary between softwoods and hardwoods, influence felling time (Verme and Johnston, 1986; Dodson *et al.*, 2006; Kizha and Han, 2016). Feller-buncher productivity obtained from this study (average 291 m^3 PMH^{-1}) was relatively high compared to other similar studies, which reported values in the range of 22–117 m^3 PMH^{-1} (Andersson and Evans, 1996a; Hiesl, 2013). A possible reason for this variation is that the relatively small harvested area in the present study facilitated better manoeuverability of the feller-buncher between harvest units.

Average productivity of the stroke-boom delimber (65 m^3 PMH^{-1}) found in this study was almost double the productivity for similar studies conducted in Maine (10–30 m^3 PMH^{-1}) (Hiesl, 2013) but was comparable to studies from other regions (48–60 m^3 PMH^{-1}) (Andersson and Evans, 1996a). In Hyb TL, distance moved in-woods was the only significant factor ($P < 0.05$) that influenced DFC, suggesting that the hybrid harvesting method can alter productivity of the processing phase. It was estimated that a 30-m increase of in-woods distance could increase cost of operations by 41 per cent. However, difference in DFC between in-woods and at-landing processing was minimal (2.1 sec). Interestingly, cost of operations for Hyb TL treatment was slightly lower than for WT (\$0.07 m^{-3}), despite average DFC being higher for the former. This anomaly might be due to a higher mean number of logs handled per cycle in Hyb TL (1.4 logs per turn) compared to that of WT (1.2 logs per turn), resulting in a greater volume per turn (0.63 and 0.59 m^{-3}, respectively). A possible reason for the lower volume handled in WT was the intense snowfall (40–65 cm) during the processing phase of that treatment. The snow event was a confounding variable, which might have influenced the cost of operations, because processing in Hyb TL treatment was done prior to the snowfall and WT

Table 7 Studies conducted on costs of forestry BMP in the US.

Study	Geographic region	BMP costs (in US $)
Lickwar *et al.* (1992)	Southeastern states	64 ha^{-1}
Shaffer *et al.* (1998)	Virginia	30–185 ha^{-1}
Sawyers *et al.* (2012)	Virginia	158 ha^{-1}
Wear *et al.* (2013)	Virginia	120/stream crossing
Kelly *et al.* (2017)	Northeastern states	3.88 m^{-3}
Soman *et al.* (2019)	Maine	1.1–3.7 m^{-3} or 10–52 PMH^{-1}

*"ha" corresponds to hectare, "m" corresponds to meter, and PMH corresponds to productive machine hour.

treatment was processed after the snowfall. Nevertheless, these findings suggest that as at-stump processing cost was only 16 per cent of the total operating costs, Hyb TL can be incorporated into a regular harvesting system without considerably affecting the overall cost of operations. However, as a result of in-woods movement, the chances of wear and tear on the tracks of the processor (a significant component influencing the economic life of the machine) would be comparatively higher, thereby increasing the fixed and operating costs (Madden, 2018). That analysis is outside the scope of the present study and warrants further investigation.

Extraction was the decisive factor in determining the overall costs of the operations. The average extraction distance was estimated to be 63 and 44 m for Hyb TL and WT, respectively. Generally, average large-end diameter of trees and average number of pieces handled per cycle, along with the extraction distance, are the factors that influence productivity (Visser *et al.*, 2003). Due to large snow accumulation on the bunch, the operator had difficulty in positioning the skidder to grapple the bunch efficiently, which explains the influence of positioning distance. Potential reasons for these results might be the comparatively lower number of extraction cycles compared to Hyb TL (53 and 103 cycles, respectively), which can be attributed to smaller area harvested in the WT treatment (2.13 ha). Extraction productivity results obtained in this study were comparable to previous studies, which ranged between 6 and 45 m^3 PMH^{-1} (Lanford and Stokes, 1996; Hiesl, 2015).

BMP implementation: Soman *et al.* (2019) reported that the cost of BMP implementation can be a function of the severity and extent of sensitive soil within the harvested stand. As this operation was done on frozen ground with snow cover, these parameters could not be captured. The cost of BMP implementation was found to be around 12 per cent of the total cost of operations for the WT treatment. BMP implementation costs can be reported in different formats including labour cost involved, cost of materials and structure, cost in terms of PMH^{-1}, cost per unit area of harvested stand and as a percentage of unit volume of wood harvested (Table 7). BMP implementation costs reported in the study fall within the range of values reported by similar prior studies.

Management implications: From a managerial viewpoint, a conventional WT harvest is easier to execute than the Hyb TL treatment. In light of the need to move the delimber within the harvest unit, Hyb TL treatment should be carefully executed and demands intense planning such as appropriate skid trail patterns, avoiding areas susceptible to soil disturbance, and proper installation of the landing area. From an operational perspective, at-stump processing can be expected to decrease the machine life of the delimber. However, the Hyb TL harvesting method is likely to minimize residual seedling damage relative to the WT method of harvesting that causes damage to the understory vegetation (Waters *et al.*, 2004; Ranius *et al.*, 2018). In addition, the Hyb TL treatment ensures better retention of deadwood biomass within the stand compared to the WT. In addition to non-timber benefits, slash retention creates cover and low shade that may help established seedlings by moderating microclimatic extremes and reducing competition from non-tree vegetation (Proe *et al.*, 2001). In contrast, the WT method can foster understory vegetation and increase competition experienced by seedlings of desired growing stock (Mann *et al.*, 1988).

In the WT method, the extraction of unprocessed trees to the landing may result in higher site disturbances; this has led to concerns about long-term negative impacts on soil quality and site productivity (Reynolds and Stevens, 1998; Merino *et al.*, 2005; Walmsley *et al.*, 2009). Additionally, it has been observed in the field that extraction in WT could cause damage to the trees being transported, resulting in loss of merchantable volume of wood. Another advantage of Hyb TL over WT is the handling of harvest residue at the stump; this becomes particularly critical in log landings with limited space (Kizha *et al.*, 2016). In the present study, the contractor mentioned he would need to skid back the harvest residues generated during WT processing, in order to keep the landing cleared for bringing in wood, even if it was not prescribed.

Even though the site was poorly drained in the southern portion, no notable soil disturbances were observed. The thick slash layer in the Hyb TL treatment, along with 30–40 cm of snow, shielded the soil and protected it from the impact of the machine passes, which is consistent with the findings from an earlier study (Agherkakli *et al.*, 2014). This would likely help in reducing post-harvest site-preparation costs such as rehabilitation of heavily compacted soils (Han, 2007). Snow, as discussed earlier, could reduce the efficiency of operations, but it might also mitigate soil disturbances. Therefore, winter harvesting can be employed as a feasible strategy for harvesting on poorly drained sites to reduce the risk of post-harvest site-quality deterioration.

Limitations of the study: The study was done on an experimental level rather than on an industrial scale, with a relatively small harvested area (10.8 ha). If the harvesting operation was conducted in a larger area, the trend might have been different for the processing costs due to increase in in-woods distance; this was explored in the present study through sensitivity analysis but not field-tested. Extreme weather conditions, including snowstorms and freezing temperatures, made harvest operation and field data collection difficult. This resulted in relatively fewer cycles being recorded for some of the operational phases (mainly extraction). Future research addressing the influence of climatic factors on harvesting productivity will be increasingly important as a changing climate alters winter conditions in the northern climates.

Conclusion

The overall cost of operations was found to be 7.5 per cent higher for the WT than for the Hyb TL. This was directly related to the extraction cost for WT being 15 per cent higher than that of Hyb TL which may have been influenced by weather conditions during that phase of the operation. The cost of at-stump processing was comparable to the conventional at-landing processing. This suggests that Hyb TL may be a feasible approach in operations where protection of advance regeneration is critical, or where slash is left in the harvest unit for facilitating machine movement in stands with poor drainage and sensitive grounds. Though this practice can help in decreasing the cost for post-harvest soil remediation strategies and favours natural regeneration of the site, in-woods movement distance had a significant impact on the processing cost in Hyb TL. In addition, it is likely that in-woods movement will decrease the machine life of the delimber, resulting in additional cost to the owner over the long term. Outcomes of this study should be tested in industrial-scale operations across a range of harvest sizes and climatic factors before they are adopted in commercial forest operations.

Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

None declared.

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