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ECONOMIC FEASIBILITY OF TIMBER HARVESTING IN LOWLANDS

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Abstract: *Northern white-cedar (Thuja occidentalis L.) is an important commercial tree species in the New England and Great Lakes regions of the USA and adjacent Canada, yet cedar-dominated stands are comparatively less harvested. This is mainly attributed to the operational challenges associated with fragile and poorly drained soils in lowlands where the species is commonly found. In terms of forest operations, such conditions can pose safety hazards for both crew and machines and harvesting might not be economically viable. The objectives of this study were to 1) estimate cost and productivity of timber harvesting operations in a sensitive-soil stand relative to those of an operation on sturdy ground, 2) understand the effects of stand variables on productivity as expressed by delay-free cycle (DFC) times. The study was conducted in Maine, USA using cut-to-length (CTL) harvesting during the winter of 2019. Stands selected for the treatments were lowland cedar-dominated (>80% cedar, with fragile soils) and non-cedar-dominated (~10% cedar, with a sturdy soil profile). DFC times and predictor variables were recorded for the harvester and forwarder using detailed time-motion study techniques. Harvested wood timber volume was estimated from scaling data and scale tickets. Machine rate calculations to determine hourly production cost were performed utilizing information from the forest management company. The cost of the operation was found to be higher for the cedar stand (USD 31.93 m^{-3}) than the adjacent non-cedar stand (USD 24.27 m^{-3}). Cost of extraction was reduced by 34–41% when the landing was shifted to stand boundary. Apportioning methods showed that the cost of felling and processing cedar (USD 6.35 m^{-3}) was higher than hardwoods (USD 6.09 m^{-3}) and other softwoods (USD 5.66 m^{-3}). Sensitivity analysis showed that increases in predictor variables such as butt-end diameter, distance between the trees, and number of cuts per cycle increased the DFC time of the harvester. In the case of the forwarder, length and diameter of the log were inversely proportional to the DFC time, whereas an increase in forwarding distance and number of pieces increased the DFC time. Though few, if any direct effects of soils were found on winter harvesting productivity and costs, tree species composition was an influential factor and is itself related to soils. This work will allow foresters and timberland managers to make more informed decisions regarding cost-effective and sustainable forest management in lowlands.*

Keywords: cedar, cut-to-length, forest operations, sensitivity analysis, winter harvest.

1. Introduction

Northern white-cedar (*Thuja occidentalis* L.) is a commercially important tree species in the northeastern United States and southeastern Canada, seen both in pure stands and as a minor species in mixed stands (Boulfroy et al., 2012). In 2017, cedar sawlogs worth USD 5 million were harvested within the state of Maine (MFS, 2018a; MFS, 2018b). The volume of cedar growing stock has decreased over the past few years in some parts of its range (Huff and McWilliams, 2016; Kenefic et al., 2017), mainly due to the challenges in managing cedar sustainably.

In the northeastern United States, about 75% of cedar forests are on lowlands, of these, 54% and 21% are on flatwoods and swamp or bogs, respectively (Boulfroy et al., 2012). Pure cedar stands are typically associated with "cedar swamps" characterized by deep, organic, poorly drained soils (Larson et al., 1993; Frohn, 2017). These are comparatively under-managed due to challenges associated with the fragile ecosystem where the species grows (Kenefic, 2013). In terms of forest operations, trafficability constraints such as accessibility to the stand, lack of solidity, and terrain roughness, as well as soil fragility constraints such as high-water table and high probability of erosion, rutting, and scalping can pose safety hazards to logging equipment and the ecosystem. The economic viability of the operation is also a constraint (Boulfroy et al., 2012). Above-mentioned conditions, along with the compressed length of logging seasons – a consequence of climate change – likely contribute to the 47% decline in cedar harvest in Maine since the year 2000 (Woodall et al., 2019; Berry et al., 2019).

Based on the silvics of lowland cedar, the selection or irregular shelterwood method (partial harvest) is suggested for regenerating stands with a component of cedar (Boulfroy et al., 2012; Kenefic, 2013) to retain and release well-established cedar in the stands and expedite cedar regeneration. Moreover, partial harvesting has been observed to have the smallest detrimental effect on logging sites (Jiang, 2016). To sustainably manage a healthy growing stock of lowland cedar, care should be taken to minimize residual stand damage; operations should be conducted during frozen periods of the year to avoid excessive soil compaction, rutting, root damage, windthrow (Boulfroy et al., 2012) and the chances of machine sinking. Winter harvest would be the best fit for sensitive grounds (EPA, 2005) because frozen soil during winter harvesting can ensure low soil disturbances and operational safety (Dubé et al., 1995; Dahlman and Rossman, 2010; Russell et al., 2018; West Fraser, nd; Timber harvesting, nd). It could also reduce damage to trees and thereby lessen the likelihood of spreading disease (Schira, 2013)

Conventional harvesting using full-tree or tree-length methods that employ mechanical felling and skidding are not suitable for sensitive sites (Puttock et al., 2005); cut-to-length (CTL) harvesting method is preferred (Jiang, 2016). Reasons include less impact on the environment, reduced disturbance to advance regeneration, and increased fiber recovery (Sauder, 1993; Richardson and Makkonem, 1994; Puttock et al., 2005; Cudzik et al., 2017). In CTL, 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 (Bulley, 1999). This harvest method reduces the number of machine entries to the stand and enables on-site slash retention. From an operational viewpoint, retaining slash will help to safely and efficiently operate equipment on sensitive site and minimize potential soil disturbances (Dahlman and Rossman, 2010).

An appropriate and economically feasible timber harvesting system is essential to successfully meet management objectives (Bennett, 2010). To determine the economic feasibility of lowland cedar harvest, the experiment was carried out with specific objectives: 1. Estimate the cost and productivity of a CTL harvesting operation in a lowland cedar stand, 2. Compare the cost-effectiveness of forest operations in lowland cedar to operations on sturdy ground, 3. Understand the effect of predictor variables on the DFC time for each harvesting components.

2. Methods

2.1 Study area

Detailed time-motion study data were collected from an operational-scale experiment conducted at the Penobscot Experimental Forest (PEF) in Bradley and Eddington, Maine (44°49'56" N, 68°36' 26" W) (Figure 1) in the northeastern United States during the winter (February to March) of 2019. The study consisted of two stands, a cedar-dominated lowland with an area of 4.4 ha and a non-cedar stand on sturdy ground with an area of 12.5 ha. The temperature during the harvesting operation ranged between 1.5°C and

-20.5°C with an average of -7.4°C. The average snow depth recorded within the stands during the experiment was 16 cm, with a maximum and minimum of 21 cm and 11 cm respectively. The soil of the cedar stand was Bucksport and Wonsqueak muck with a slope ranging from 0–2%; in the non-cedar, soils of the Becket-Skerry complex and Peru-Colonel-Tunbridge association dominated with a slope ranging from 2–15% (Soil Survey Staff, 2019).

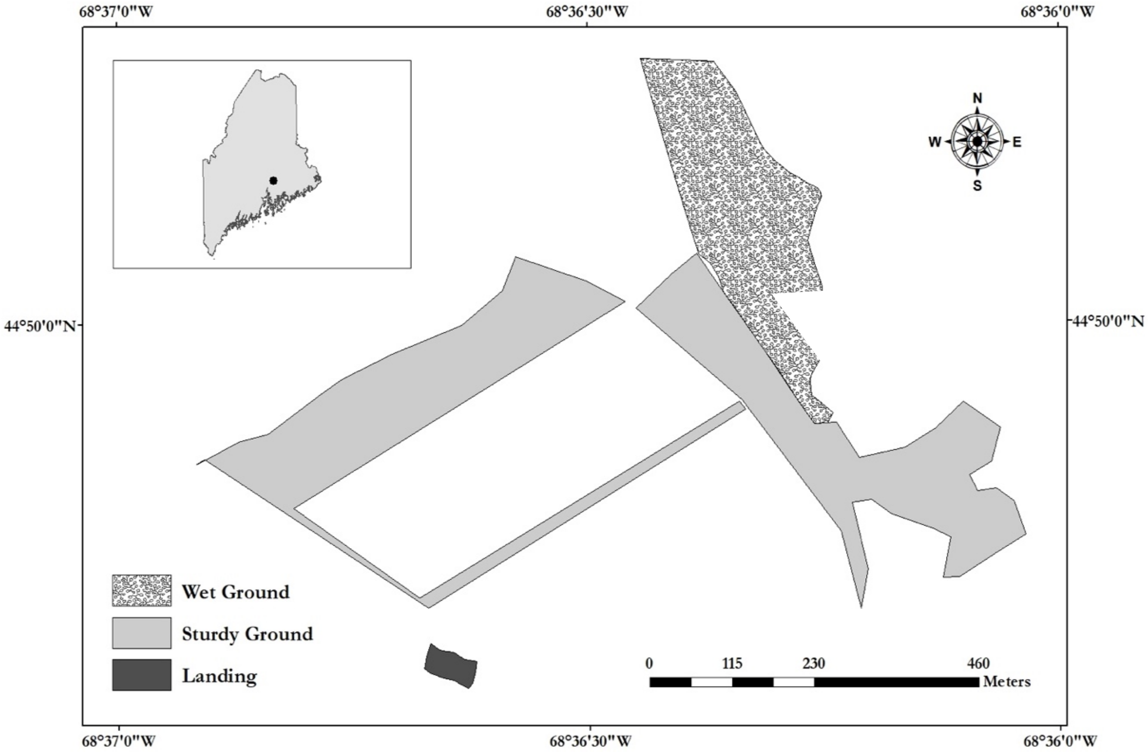

Figure 1. Map of study site showing the harvested lowland cedar and non-cedar stand

2.2 Stand Inventory

As the lowland cedar stand is a permanent experimental plot, the stand was inventoried using permanent circular plots laid out in nested plot design (Kenefic et al., 2017). A total of 9 fixed-radius plots of 0.08 ha were selected to measure diameter at breast height (DBH), tree height, height to base of the crown (bole height), species, and the spatial location of trees ≥ 15.2 cm DBH. Since the non-cedar stand constituted an industrial timberlands operation, the stand was inventoried using 24 variable-radius plots with a 20 Basal Area Factor (BAF) prism. The sample plots were measured for DBH, tree height, bole height, and species (Kanoti, 2018). Differences in stand inventory techniques was a constraint in this study. As the stands were managed by two different organizations, the preferred inventory method varied. The stand inventory was carried out by the respective managing organizations. One was research-oriented, so used permanent fixed-area plots to generate large amounts of information which can be traced back and used for future experiments. On the other hand, the variable-radius inventory method was preferred for commercial forest management as it is cost and time-efficient, in part because more time is spent measuring sawtimber-size trees.

2.3 Silvicultural prescription

2.3.1 Lowland cedar stand

The stand was partially harvested to establish and release cedar regeneration through the creation of small canopy gaps and to favor the growth of the residual pole and small sawtimber cedar though crop tree release between gaps. Removal outside the gap areas was limited to 20% of relative density, with 100% removal in gaps and trails. The irregular shelterwood treatment was prescribed to remove a BA of 20 m^2 ha^{-1} (40% of total BA, ≥15.2 cm DBH) (Kenefic et al., 2017). The lower level of merchantability was 15.2cm DBH. The stand was not actively managed before this operation. Logging residues were placed in the machine trails during harvesting to minimize site damage. Other species found in the stand were spruce (*Picea spp*.), larch (*Larix laricina* (Du Roi) K. Koch.), balsam fir (*Abies balsamea* (L.) P. Mill.), and eastern white pine (*Pinus strobus* L.).

2.3.2 Non-cedar stand

The stand was found to have species such as eastern hemlock (*Tsuga canadensis* (L.) Carr.), red maple (*Acer rubrum* L.), eastern white pine, spruce, quaking aspen (*Populus termuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), balsam fir, and cedar. Irregular shelterwood and pine shelterwood establishment cuts were prescribed for the non-cedar stand. The irregular shelterwood establishment cut was meant to establish an understory of tolerant conifers and release advance regeneration. In areas dominated by hemlock that lack desirable regeneration (hemlock, spruce, or white pine) overstory BA was reduced to 23 m^2 ha^{-1}, retaining a uniform overstory of the best quality hemlock, white pine, spruce, and tolerant hardwoods. Also, quality growing stock intermediate crown class stems of any species and uncommon species such as brown ash (*Fraxinus nigra* Marsh.) and basswood (*Tilia americana* L.) were retained. There were a few patches of overstory white pine in this stand; in these areas, openings 21 m in diameter were created around the patches by removing all other species.

In areas with high-quality white pine overstory trees (first 5 m log straight, no knots over 1.2 cm and at least 40 cm in diameter at the small end), a shelterwood establishment cut was made and the overstory BA was reduced to 18 m^2 ha^{-1}. The highest priority was to remove mid-story balsam fir, red maple, and hemlock stems, along with overstory intolerant hardwoods (Kanoti, 2018).

2.4 Harvesting operation

Cut-to-length harvesting method (using harvester and forwarder) was employed to carry out the partial harvest in both lowland cedar and non-cedar stands. The operation was conducted during winter and extended for 18 days. The machines and the operators were the same for both treatments. The experience of the harvester and the forwarder operator was 8 and 6 years, respectively.

2.4.1 Felling and Processing

A Ponsse Scorpion King (2018) harvester performed felling, delimbing, and bucking within the harvest unit. DFC time was recorded in seconds using a stopwatch. The DFC time for the harvester started when the machine traveled empty to a tree (travel empty), grappled and felled a tree (cutting), moved the felled tree to a nearby deck (decking), and delimbed and bucked felled trees to logs of market-desired length (processing). Independent variables such as distance traveled between the trees (m), number of cuts per cycle, number of logs per cycle, and butt-end diameter (cm) of the felled trees were visually estimated (Table 1). The total number and dimensions of logs processed were also downloaded from the harvester's computing system for each stand.

2.4.2 Extraction

The processed timber was extracted to the landing using a Ponsse Buffalo forwarder (2016). The forwarding trails were tracked using a GPS unit mounted on the forwarder. Traveling empty from the landing to the unit initiated the DFC of the forwarder (travel empty). Travel empty ended as the forwarder stopped for picking up the first logs. Following this, the loading time initiated as the forwarder filled the bunk. While filling the bunk the machine swung empty to reach the logs (swing empty) then grappled logs (grappling or re-grappling), then the boom swung loaded (swing loaded), after which the machine sorted the logs to accommodate maximum payload. Once the bunk was filled the machine traveled back to the landing (travel loaded) and unloaded the timber at the landing. While unloading, the machine followed the reverse of loading. Travel distance (m), number of pieces, log diameter, and species constituted the independent variables recorded (Table 1).

The cedar stand had longer extraction distance to the landing compared to the non-cedar stand. To estimate the actual cost of extraction irrespective of extraction distance, a hypothetical landing was established just outside the stand (at the stand boundary). Time taken by the forwarder to cross the hypothetical landing and the distance to the actual landing was recorded. By deducting the time taken to travel from the hypothetical landing to the actual landing, cost of extraction due to the treatments were evaluated.

2.4.3 Loading

Self-loading trucks manufactured by Peterbilt and Sterling were utilized for loading and hauling the wood to the conversion facilities. The DFC components for loading were swinging empty to grapple the logs (swing empty), grappling the logs, swinging loaded, and sorting the logs. The independent variables included the number of logs, species, and length and diameter of the logs (Table 1).

Table 1. Cycle elements and predictor variables recorded for each operational phase in cut-to-length harvesting operation

Operational phases	Cycle elements	Recorded predictor variable(s)
Felling and processing (Harvester)	Travel to trees Cutting Processing Decking	Number of cuts per cycle Number of logs per cycle Butt-end diameters (cm) Distance between trees (m) Decking distance (m) Species
Extraction (Forwarder)	Travel empty Travel loaded Swing empty Grappling Swing loaded Sorting	Empty travel distance (m) Loaded distance (m) Number of pieces Diameter of log (cm) Species
Loading (Self-loading truck)	Swing empty Grappling Swing loaded Sorting	Number of pieces Diameter of log (cm) Length of log (m) Species

2.5 Operating cost calculations

Machine rates were calculated using the method developed by Miyata et al. (1980). The purchase price, salvage value of machines, economic life, and utilization rates were obtained from the forest management company which owned and operated the logging equipment (Table 2). Hourly machine costs (USD PMH^{-1}, productive machine hour) were calculated using standard machine rate calculation methods. Average DFC time, i.e. cycle time excluding operational, mechanical, and personal delays, was calculated for every operational phase separately for each treatment (Kizha and Han, 2015). The average volume of the log was estimated from the harvester-generated report, scale ticket, and log scaling. Log scaling was performed by measuring the large end diameter, small end diameter, and log length. Average volume for each piece was calculated using Huber's formula (Avery and Burkhart, 1983). By assimilating machine rate, average DFC time, and timber volume, the operating cost was calculated (Soman et al., 2019a; Sahoo et al., 2018).

Table 2. Machine rate and cost of the equipment used in the harvesting. All the information was provided by the forest management company which owned and operated the equipment

Factors	Harvester	Forwarder
Make and Model	Ponsse Scorpion King 2018	Ponsse Buffalo 2016
Purchase price (USD[a])	650,000	400,000
Salvage Value (USD)	200,000	75,000
Variable and operating cost (USD PMH^{-1}[b])	72.93	37.89
Economic life (yrs.)	6	8
Labor cost (USD PMH^{-1})	42.86	40.00
Fuel consumption (L PMH^{-1}[c])	20.57	14.96
Scheduled machine hours (SMH)	12	15
Utilization (%)	70	75
Machine rate (USD PMH^{-1})	219.28	125.77

[a] All prices are expressed in US Dollars;
[b] PMH = Productive Machine Hour;
[c] L PMH^{-1} = Liter per Productive Machine Hour

2.6 Cost allocation

There were different assortments of products from the operations. The assortments were made for different products i.e., cedar, hardwood, and softwood. To understand the cost of felling and processing different assortments, all the DFC from the entire operation were segregated and the cost and productivity were calculated for each assortment separately.

2.7 Sensitivity analysis

Sensitivity analysis helps to understand the impact of a range of independent variables on the dependent variable of interest under a set of conditions (Jovanovic, 2018). Sensitivity analysis was performed with the help of R code developed by Jovanovic (2018), to determine how predictor variables influenced DFC time for the harvester and forwarder. All predictor variables collected for each operational phase were selected (Table 1) and converted to ratios using log-log analysis before sensitivity analysis. For sensitivity analysis, input values for the predictor variables were changed by 20% and 40% in both negative and positive directions to understand the change.

2.8 Statistical analysis

Statistical analysis was performed using R software (version 3.6.0). Initially, datasets were screened for outliers with a 95% confidence interval and checked for normality. Then linear regression models were developed with DFC time as the dependent variable and predictors as independent variables (Table 1). Dummy variables were used to represent species. Backward/forward model selection with lower AIC values was used for model selection and validation using the MASS package (Venables et al., 2002). A standardized variable comparison was performed to establish the variation in cost and productivity of the treatment regardless of the stand condition (Kizha and Han, 2016). A two-sample *z*-test was performed to compare the DBH and DFC time between the lowland cedar and non-cedar stands.

3. Results and Discussion

3.1 Stand inventory analysis

In the cedar stand, a total of 1010 trees with DBH above 15.2 cm were measured from 9 plots as part of the pre-harvest inventory. The stand was dominated by cedar (81%) with a maximum observed DBH of 41 cm, followed by hardwoods (10%), larch (7%), spruce (<1%), white pine (>1%) and balsam fir (>1%) (Table 3). From the stand, 20 m^2 ha^{-1} basal area was removed which resulted in a residual of 30 m^2 ha^{-1} (Kenefic, 2018).

Inventory data for 208 trees from the 24 sample plots in the non-cedar stand revealed the stand was dominated by hemlock (42%) followed by white pine (31%), cedar (10%), red maple (8%), ash (3%), birch (2%), aspen (2%), spruce (1%), balsam fir (>1%) and basswood (>1%). The two-sample *z*-test showed there was a significant difference (*p*-value <0.05) in DBH between the lowland cedar (21 cm) and non-cedar stand (35 cm). This may be associated with the significant difference in DFC time between the stands for different operational phases (Kluender et al., 1997).

Scale tickets showed that a total of 1431 m^3 wood was extracted from both stands (Table 3). From the lowland cedar stand, 72% of logs extracted were cedar followed by hardwood (13%), larch (10%), spruce (2%), fir (<1%), white pine (<1%) and aspen (>1%). In the non-cedar stand, hardwoods (40%) contributed the maximum, trailed by hemlock (26%), cedar (14%), aspen (8%), pine (6%), fir (4%) and spruce (2%).

Table 3. Stand inventory summarized for all standing trees of DBH above 15.2 cm for cedar and non-cedar stand

Stand Attributes	Cedar	Non-cedar stand
Area (ha)	4.4	12.5
Basal Area (m^2 ha^{-1})	50	40
Trees per ha	1196	734
QMD[a] (cm)	21.6	26.4
Species	cedar, spruce, larch, balsam fir, white pine	hemlock, red maple, white pine, spruce, aspen, paper birch, balsam fir, cedar
Total wood harvested (m^3)	419	1012

[a] QMD- Quadratic Mean Diameter

3.2 Harvesting operation

The cost of harvesting the cedar stand (USD 30.45 m^{-3}) was found to be higher than the non-cedar stand (USD 22.79 m^{-3}) (Table 6). The difference in cost of operation does not appear to be directly related to the soil condition. However, additional predictor variables like slope, forwarding trail pattern, species composition, stand density, the silvicultural prescription might have an influence on the cost of operation but were not explicitly considered in the present study (Nakagawa et al., 2007; Soman et al., 2019a). The diameter of the logs handled, and the number of logs handled per cycle were the factors that determined the cost and productivity of each operational phase. Machine productivity and fuel consumption are unlikely to explain the difference in the operation costs, as the harvesting equipment and operators employed in both stands were the same throughout the operation.

Delay-free cycle times were predicted using standardized regression models (Kizha and Han, 2016). The adjusted R^2 values ranged from 0.17 to 0.67, with operational phases for the non-cedar stands having the higher R^2 values (Table 4). The adjusted R^2 values for the regression models developed were found to be in line with other studies in the region (Hiesl and Benjamin, 2015; Soman et al., 2019a; Soman et al., 2019b). There was a little variation in adjusted R^2 values of different operational phases and stands, except for loading. Decking distance was found to have no significant effect on DFC time of the harvester in both stands. For the forwarder in the cedar stand, number of logs, species, and diameter did not contribute significantly to DFC time. In the case of loading, diameter of the log, length of log and species did not have a significant effect on DFC time. The DFC time of the harvester (felling and processing) averaged 0.53 and 0.66 minutes for cedar and non-cedar stands, respectively. For the extraction of logs from the harvest site to the landing, the DFC time was 74.27 minutes for the cedar stand and 54.00 minutes for the non-cedar stand and was directly proportional to the forwarding distance (Table 5).

Table 4. Regression models developed for predicting the delay-free cycle (DFC) time at $\alpha = 0.05$

Machine	Site	Adjusted R^2	Standardized models predicting DFC time
Harvester	Cedar	0.58	DFC = -12.69* + 1.01 (butt-end diameter) * + 6.00 (distance between trees) * + 9.13 (number of cuts per cycle) * – 4.17 (number of logs per cycle) * + 32.24 (hardwood) * + 9.30 (softwood)
	Non-cedar	0.66	DFC = -36.20 * + 1.89 (butt-end diameter) * + 1.32 (distance between trees) * + 4.34 (number of cuts per cycle) * + 7.02 (number of logs per cycle) *
Forwarder	Cedar	0.57	DFC = -53.51* + 3.33 (distance traveled) *
	Non-cedar	0.67	DFC = 21.92 * + 0.30 (butt end diameter) * + 1.07 (distance traveled) * – 2.68 (hardwood)
Loading		0.17	DFC = 20.216 + 2.79 (number of logs per cycle) *

* *p*-value <0.01

Table 5. Stand and operational factors that contributed to the total cost of operation

	Harvester		**Forwarder**	
	Cedar	Non-cedar	Cedar	Non-cedar
Average DFC[a] time (min)	0.53	0.66	74.27	54.00
Volume per log (m^3)	0.13	0.18	0.13	0.18
Average extraction distance (m)			1207	1078
Average extraction distance to hypothetical landing (m)			296	241

[a] DFC-Delay free cycle

3.2.1 Felling and processing

A total of 496 observations were collected from the two stands, 170 and 326 from the non-cedar and cedar stands respectively. For the cedar stand the average DFC time was 31.7 sec. The processing time had the largest contribution (48%) to the DFC time, followed by travel time between trees, decking time, and felling time respectively. The machine was able to produce an average of 1.88 logs per cycle, while the number of cuts per cycle averaged 2.14. The machine traveled an average distance of 1.42 m between successive felling and 0.87 m to a nearby deck. The cost of the operational phase was calculated to USD 9.98 m^{-3} (Table 6).

Similar to the cedar stand, the non-cedar stands also had processing time as the highest contributor (24.0 sec; 61%) to the DFC time and followed similar trends. The machine produced an average of 2.26 logs with an average of 2.56 cuts per cycle. The distance traveled between successive cuts was 2.68 m and to the nearest deck was 0.76 m. The cost of felling and processing was USD 8.03 m^{-3} (Table 6). The *z*-test that compared the average DFC time for cedar and non-cedar stands revealed a significant difference between the stands (*p*-value <0.05).

The cost of felling and processing trees from the lowland cedar stand was higher when compared to the non-cedar stand and is likely due in part to the significant difference in DBH between the stands. Similar observations were made by Kellogg et al., 1992; Puttock et al., 2005; LeDoux and Huyler, 2001. Also, the DFC time of the harvester was significantly different between stands. The higher productive machine hour facilitated by larger-sized trees and a greater number of logs per cycle reduced the cost of felling and processing in the non-cedar stand. These arguments can be substantiated by the regression models developed, where butt-end diameter and number of logs per cycle have a significant effect on DFC time. There was no clear evidence to show that the increased cost of felling in the lowland cedar stand was due to the fragile forest floor because the floor was frozen. But an interesting observation can be made in the travel between trees. Even though the distance between the trees was less, the travel time between the trees was higher in the cedar stand. This might be due to the roughness of the ground or the lack of solidity of the forest floor. But the presence of understory vegetation or the difference in silvicultural prescription can also be a source for more travel time between the trees. Further investigation is needed to determine the reason for this finding.

Another reason for the higher cost in the cedar stand might be due to a greater number of cuts per cycle. The relative number of cuts per cycle was observed to be higher for the lowland cedar stand, further apportioning revealed that a greater number of cuts per cycle was for the cedar trees. Due to the incidence of heart rot disease, which is common in this species (Kenefic et al., 2019), the operator was forced to make a greater number of cuts to get rid of the decayed part from the log. Sensitivity analysis showed a strong relationship between the DFC time and number of cuts per cycle.

3.2.2 Extraction

Extraction contributed about 65% to the cost of the operation (stump to landing). As the average distance of forwarding for the cedar stand was almost 130 m greater compared to non-cedar stands, it led to a 20-minute rise in the DFC time of the former (Table 5). In-woods forwarding contributed the most (48%) to the DFC time followed by travel loaded (23%), unloading (16%), and travel empty. The machine was able to extract 9.7 m^3 of logs per DFC. With a productivity of 5.89 m^3 PMH^{-1}, the cost incurred for the operational phase was USD 20.47 m^{-3} (Table 6).

The average forwarding distance was 1078 m in the non-cedar stand and the DFC time was estimated around 54 minutes (Table 5). The forwarding cycle followed similar trends to that of the cedar stand and the machine extracted 10.0 m^{-3} of logs per non-cedar DFC. The cost of extraction was decreased by 34–41% when the logs were extracted to the landing (hypothetical) just outside the stand (Table 6).

Table 6. Cost and productivity of different operational phases in cedar and non-cedar stands. Values in the parentheses show the cost and productivity to extract wood to the hypothetical landing (excluding the distance to actual landing)

Operational phase	Cost (USD m^{-3})		Productivity (m^3 PMH^{-1a})	
	Cedar	**Non-cedar**	**Cedar**	**Non-cedar**
Felling and Processing	9.98	8.03	20.64	25.60
Extraction	20.47 (13.58)	14.76 (8.75)	5.89 (8.88)	8.16 (13.78)
Loading[b]	1.48		61.21	
Total	**30.45**	**22.79**		

[a] PMH- productive machine hour

[b] Products from both treatments were combined at the landing.

In the present study, the forwarding distance was more than one kilometer (1207 and 1078 m), which can be considered to be the limit for operational-scale logging. The higher forwarding distance costs the operational phase USD 20.47 m^{-3} (lowland cedar) and USD 14.76 m^{-3} (non-cedar). The forwarding cost was dropped to USD 13.58 and 8.75 m^{-3} for lowland cedar and non-cedar stands respectively when the logs were forwarded to a hypothetical landing just outside the stand or at the stand boundary. Having the hypothetical landing helped to understand the change in cost of extraction as the forwarding distance varies and for a meaningful comparison of the cost of extraction between the lowland cedar and non-cedar stands.

At the landing, it took more time to unload logs from the cedar stand due to a larger percentage of small-diameter trees compared to that of the non-cedar stand. During the in-woods movement, loading logs from the lowland cedar (2140 sec) stand took more time than non-cedar (1153 sec). The difference can be attributed to the greater number of logs per handle, distance between the decks and time for segregating different products. This argument is substantiated by the regression models and sensitivity analysis, which showed that when the diameter of log handled increases the number of logs per cycle will decrease and thereby the DFC time will also decrease.

Even though the distance to travel from one stop to another for loading logs in the cedar stand was lesser, the travel time was higher when compared to the non-cedar stand. This change might be due to the difference in forest soil and forest floor conditions.

3.3.3 Loading

A total of 153 loading cycles were observed. On average, it took 49 minutes to load a truck. The average DFC time was calculated as 32 sec which includes 12 sec (37.2%) sorting time. With an average productivity of 61.21 m^3 PMH^{-1}, the loader had the highest productivity for all the operational phases (Table 6 and 7). However, the regression model for the loader had the lowest R^2 values (Table 4) and showed that predictor variables such as length of log, diameter of log and species could only explain part of the variability in the DFC time. The varying operators and the difference in products might be the reason for a lower R^2 value.

Table 7. Cost and productivity of loading operation for different assortments from the harvest

Product	DFC[a] (sec)	Cost (USD m^{-3})	Productivity (m^3 PMH^{-1b})
Cedar pulp	25.88	1.93	44.96
Hardwood pulp	44.83	1.39	62.40
Pine saw log	28.88	1.13	76.28

[a] DFC- Delay free cycle time
[b] PMH- Productive machine hour

The DFC and loading times varied for different products. For loading hardwood pulpwood, it took 46 minutes to load a truck; the average DFC time was 45 sec where the sorting time contributing 59% (27 sec). It took 68 minutes to load a truck with cedar pulpwood. The average DFC time was 26 sec; where sorting time was 8 sec (32%). For loading pine sawlogs, it took 32 minutes, with an average DFC time of 29 sec where the sorting time was 7 sec (24%) (Table 7).

Even after a higher DFC time for loading hardwood pulp, the cost of loading cedar pulpwood (USD 1.93 m^{-3}) was found to be slightly higher than hardwood pulp (USD 1.39 m^{-3}). It took an extra 16.4 minutes to load a sawlog truck of equal payload with cedar pulpwood. The extra time requirement was directly related to the sawmill requirement regarding the orientation of the logs. For cedar logs, the sawmills need the butt-ends to be aligned to a single direction. Other studies have also observed similar trends (Kizha and Han, 2016). Additionally, for cedar pulpwood, the operator loaded a fewer number of pieces each cycle, as he had to orient the logs.

3.4 Sensitivity analysis

3.4.1 Harvester

The sensitivity analysis showed that butt-end diameter has a greater influence on DFC time when compared to other predictor variables. A 20% increase in the butt-end diameter may increase the DFC time from 39.4 sec to nearly 50 sec (7.8%). Similarly, a change in number of cuts per cycle was found to slightly increase the DFC time. The change in the predictor variables like distance between the trees and distance to the deck did not have much effect on DFC time. A 40% increase in the distance between the trees could increase the DFC time to 42 sec (1%) (Fig 2a).

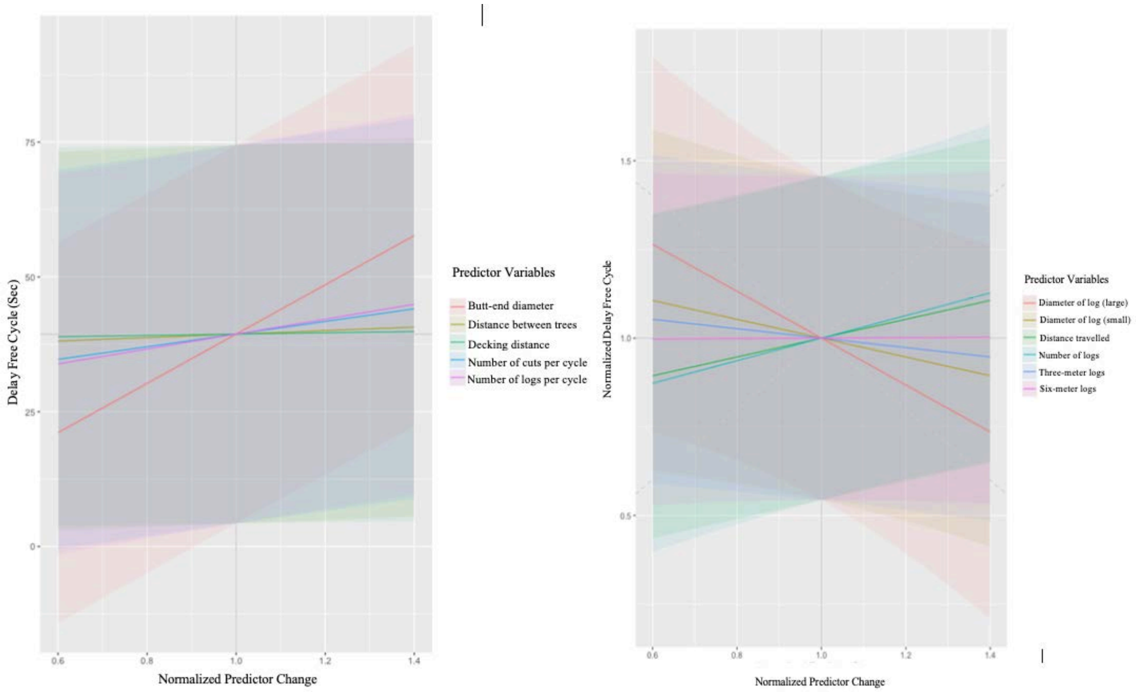

Fig 2a. DFC of harvester **Fig 2b. Normalized DFC of forwarder**

Figure 2. Sensitivity analysis on DFC time of harvesting (cedar stand) equipment at a normalized predictor variable change of 20% and 40%

3.4.2 Forwarder

The change in predictor variables like distance and number of pieces increased the DFC time, thereby reducing the productivity of the operational phase. A 40% increase in diameter of the handled log and number of 3-m length logs could decrease the DFC time by 25 and 10% respectively. Increase in the number of 6-m length logs did not seem to have much change in the DFC time. For the predictor variables, forwarding distance and number of pieces forwarded, a 40% change could increase the DFC time by approximately 12% (Fig 2b).

3.5 Cost allocation based on DFC

While considering the DFC time for producing different assortments, the cost of felling cedar (USD 6.35 m^{-3}) was found to be higher than hardwood (USD 6.09 m^{-3}) and softwood (USD 5.66 m^{-3}), even though it had the lowest DFC time among the three (Table 8). This difference can be connected to the smaller diameter of the cedar trees from the selected stands when compared to hardwoods and softwoods harvested. Smaller diameter leads to lower machine productivity and thereby higher harvesting cost. The smaller diameter of the lowland cedar may be attributed to the muck soil found in the lowland cedar stand, which cannot support larger trees.

Table 8. Cost of felling and processing different assortments available in the harvesting operation

Assortments	DFC[a] (sec)	Cost (USD m^{-3})	Productivity (m^3 PMH^{-1}[b])
Cedar	27.23	6.35	32.45
Hardwood	56.35	6.09	33.83
Softwood	40.06	5.66	36.40

[a] DFC- Delay free cycle time

[b] PMH- Productive machine hour

3.6 Managerial considerations while winter harvesting

Although winter harvesting can be the most ideal for environmental and cost considerations (Berry, 2019), there may be difficulties. Once the snow gets too deep, it is difficult to maneuver machinery. Also, fewer daylight hours during winter will pose challenges to the operators in terms of selecting the trees to be felled and maneuvering across the site (West Fraser, nd). This can additionally create a safety hazard. There is also the need for tire chains to enhance traction of the machines while moving across the frozen ground.

As the logging operation was carried out in the winter season, it was essential to plow the road and landing for providing access for the equipment to the harvesting sites and the smooth functioning of the operation. Therefore, it is necessary to add the cost of snow plowing to the final harvesting cost. In the logging contract, the responsibility for snow plowing was with the landowner. The distance from the primary road to the landing was about 2.7 km with a width of 8 m. The cost for snow plowing the road for a single time was USD 675 (USD 225 hr^{-1}) using a 3.7-m blade. The total cost of snow plowing the road during the operation period was USD 2025. The landing had an area of 2709 m^2. It was plowed three times during the period of operation, and it took a total of five hours using a 2.5-m blade. With the labor cost for snow plowing at USD 70 hr^{-1}, the cost of plowing the landing was USD 350. All together snow plowing incurred an additional expense of USD 2375. The snow plowing has added an extra USD 1.66, 2.35 and 5.67 to every cubic meter of wood harvested from the entire harvesting operation, non-cedar stand and cedar stand respectively.

4. Conclusion

Lowland cedar is an important tree species with great economic implications. Due to the risk in accessibility and forest floor condition, it is challenging to harvest the cedar. Being a fragile ecosystem, harvests should be planned such that there is a minimal detrimental impact on the stand and soil, and also considering the safety of the logging crew. A cut-to-length harvesting method during winter with frozen ground is the most appropriate logging strategy. This study analyzed the economic feasibility of this type of timber harvesting operation in a lowland cedar stand and compared it to a non-cedar stand on sturdy grounds. The cost of harvesting was higher for the lowland cedar stand. There was little evidence of a direct effect of soils on operational costs, likely because the harvest occurred on frozen ground. Nevertheless, soils had an indirect effect on costs due to the role they play in determining tree species composition; cost of harvesting cedar was higher than hardwoods and softwoods. Overall, cost of extraction constituted 65% of the total cost of operation. It was decreased by 34–41% when the landing (hypothetical) was assigned just outside the stands. Sensitivity analysis revealed the change in DFC time with changes in the predictor variables. Quantitative understanding on the effect of predictor variables can help in efficient planning of harvest operations considering the uncertainties.

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