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**Research Article**

# Effects of Pre-Bunching Trees With a Tethered Feller-Buncher on Cable Logging Productivity and Costs: A Case Study in Southern Oregon

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## Abstract

Winch-assist or tethered logging technology is rapidly being adopted by the forest industry across the western United States to replace conventional and dangerous manual tree falling in cable logging areas. Although the safety benefits of the technology are widely acknowledged, the effects of tethered mechanized timber falling and pre-bunching on the subsequent cable yarding operations have not been thoroughly investigated. We conducted a field study in southern Oregon to compare manual versus mechanized timber falling side-by-side for their impacts on the productivity and costs of cable logging operations. Our study shows that the costs of mechanized timber falling were higher than manual falling owing to high costs of tether equipment, but the ability of the felling machine to pre-bunch trees into piles along designated skyline corridors made subsequent cable yarding operations significantly more efficient. The efficiency gained during yarding was sufficient not only to offset cost increase in felling but also to reduce the total production costs of felling and yarding operations by 32% compared with cable yarding after manual timber falling.

**Study Implications:** This study quantifies potential efficiency gains during cable yarding by pre-bunching trees with a tethered felling machine. The results show the efficiency gained during yarding is sufficient enough not only to offset cost increase in felling, but also to reduce the total production costs compared to manual timber falling. This study provides an indication of the potential economic benefits of using mechanized timber falling and pre-bunching on steep slopes, as well as where the potential benefits come from, providing the logging industry with practical insights that can help decision-making and evaluation for the adoption and investment of tether technology.

**Keywords:** winch assist, cable assist, steep slope harvest, mechanized tree falling, logging safety

Recent development and applications of winch-assist or tethered logging technology make mechanized timber harvesting possible in steep terrain (Cavalli and Amishev 2019, Holzfeind et al. 2020). Since it was introduced in the Pacific Northwest of the United States (PNW) during the early 2010s, the technology has been rapidly adopted by the timber industry to improve worker safety (Garland et al. 2019).

Although the safety benefits of tethered harvesting are widely acknowledged, the high capital investment required to purchase the tether equipment is a major barrier for many logging contractors in the PNW region. The current lack of information on productivity and production costs of such equipment makes investing in the technology more difficult due to the uncertainty of its economic benefits.

A few studies have evaluated productivity and costs of tethered harvesting systems; most have focused on ground-based timber falling and extraction equipment such as tethered cut-to-length systems (Holzfeind et al. 2018, Green et al. 2019, Petitmermet et al. 2019). In the PNW region, a tower yarder cable logging system has been the dominant timber extraction method for steep terrain since the early 1960s (Conway 1976). Cable logging practices will likely continue, as the capital investment has already been made, and the industry prefers whole-tree harvesting and long-log processing for both transport and milling. The PNW region timber industry has adopted the tethered logging technology primarily for timber falling and as part of the conventional cable logging systems.

Use of tethered equipment may directly affect productivity and costs of timber falling operations in steep terrain. In addition, the ability of felling machines to move and pre-bunch logs along the skyline corridor can affect productivity during the yarding phase. Effects of pre-bunching of trees on subsequent timber extraction have been extensively studied on relatively gentle slopes where traditional ground-based equipment can operate (LeDoux et al. 1987, McNeel and Dodd 1997, Visser and Stampfer 1998). More recent studies have investigated potential use of ground-based equipment for

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timber falling using the new technology and pre-bunching on steeper slopes to assist grapple-yarding operations (Amishev and Evanson 2010, Acuna et al. 2011). Pre-bunching logs with less expensive equipment increases payload sizes to improve productivity of the more expensive extraction equipment. Economic benefit can result when the additional costs of pre-bunching are offset by the additional efficiency gain during subsequent extraction, e.g., skidding, forwarding or cable yarding operations.

A variety of tethered harvesting systems are already used in Europe and New Zealand at different scales and costs (Cavalli and Amishev 2019, Holzfeind et al. 2020). However, tethered systems currently used in the PNW for timber falling require a large capital investment. To date, economic benefits have been unclear when comparing the practice of traditional methods (e.g., manual timber falling with chainsaw) to pre-bunching with more expensive equipment. To the best of our knowledge, no field study has determined costs and productivity for conventional cable logging operations where manual timber falling is compared to use of tethered with pre-bunching.

The aim of this study was to quantify the effects of tethered timber falling and pre-bunching on productivity and costs of conventional swing-yarder cable logging in the PNW. We applied two timber falling methods side-by-side within a clearcut harvest unit, hand falling and mechanized falling with a tethered feller-buncher. Felled timber was then extracted by the same swing yarder to quantify the effects of pre-bunching logs on yarding operations. We conducted a detailed time study on both timber falling and cable yarding activities to estimate productivity and production cost of falling and yarding operations. The recorded field data were used to develop standardized comparisons between hand and mechanized timber falling.

This article summarizes the study results and presents direct and indirect impacts of mechanized timber falling on productivity and costs of cable logging operations. Our study offers the PNW logging industry and others practical insights for evaluation and decision-making on investment in tether technology.

## Methods

### Harvesting Unit and Equipment

The harvest unit is located near Sutherlin, Oregon (43.30628° W, 123.09587° N) on forestland privately owned by Lone Rock Resources. The unit lies between 380 and 520 m above sea level on silty clay loam soils with the average slope of 45% facing southwest. The area climate includes cool wet winters and warm dry summers, a mean annual precipitation of 880 mm, and mean annual temperature of 11.6°C.

The 17-ha harvest unit was clearcut from mid-March to mid-April 2018. The unit was a 60-year-old Douglas-fir plantation stand with the estimated average net merchantable volume of 475 $m^3$/ha (Table 1). The harvest unit was split into three area sections (Figure 1). The machine-cut area was approximately 10 ha in size, cut using a feller-buncher (Tigercat LS855E[1]) with a directional felling head. The feller-buncher was tethered to an upslope anchor machine (Caterpillar 330D) equipped with a remote-controlled synchronized winch system (Summit Winch Assist). The hand-cut area was approximately 3.6 ha, cut manually with chainsaw. Although a minimum crew of two people is required to work as a team during timber falling for safety (Oregon OSHA 2014), one timber faller performed cutting activity during our field observation because the research crew provided visual, audible, and radio contact with the timber faller.

After timber falling, both machine and hand-cut areas were whole-tree yarded. A Thunderbird TSY255 swing yarder with a motorized slack-pulling carriage (ACME 528) and the same logging crew were used for both areas. The logging crew consisted of a yarder operator, a chaser, a rigging slinger, and two choker-setters. All machine operators, yarding crew, and timber faller were experienced professionals with at least 3 years of industry experience.

The upper unit strip was cut and logged with a shovel logger prior to our study to provide easy access and view for the swing yarder. This gentle-slope area was excluded from our study (Figure 1). Our study objective was to quantify the effects of mechanized timber falling and pre-bunching on yarding efficiency; therefore, we did not observe processing and loading operations beyond the yarding phase of logging. The following operations were observed for collecting time study data samples on the specified dates in 2018.

- Hand cut area: manual timber falling (March 19) and cable yarding (March 26–28)
- Machine cut area: mechanized timber falling and timber swing and bunching (March 29), and cable yarding (April 10–12)

### Detailed Time Study

A detailed time study was conducted separately on timber falling and yarding operations in machine and hand-cut areas. A delay-free cycle time (DFCT) for each operation was defined consisting of multiple time elements (Table 2). Each time element was measured manually by a two-person crew using hand-held stop watches. The time at the beginning of each element was recorded as time of day to the second. Time-stamped video footage was taken during hand and machine falling operations to fill in missing data from manual recording. Any activities that deviated from the predefined time elements were considered as delays, regardless of time duration.

A work cycle for hand timber falling consisted of the times walking to the next tree, felling the tree with a chainsaw, and removing stump edges (Table 2). The third time element was performed when the stump exposed sharp edges, to prevent other trees from falling and breaking

**Table 1.** Description of the harvest unit used in the study.

| Description | Value |
|---|---|
| Total area | 17 ha |
| Average ground slope | 35% |
| Mean dbh | 41 cm |
| Stand volume | 475 $m^3$/ha |
| Stand density | 374 trees/ha |
| Mean tree volume | 1.27 $m^3$/tree |

[1]Mention of trade names in this paper is for informational purposes only and does not constitute an endorsement by any state, federal, or funding agency.

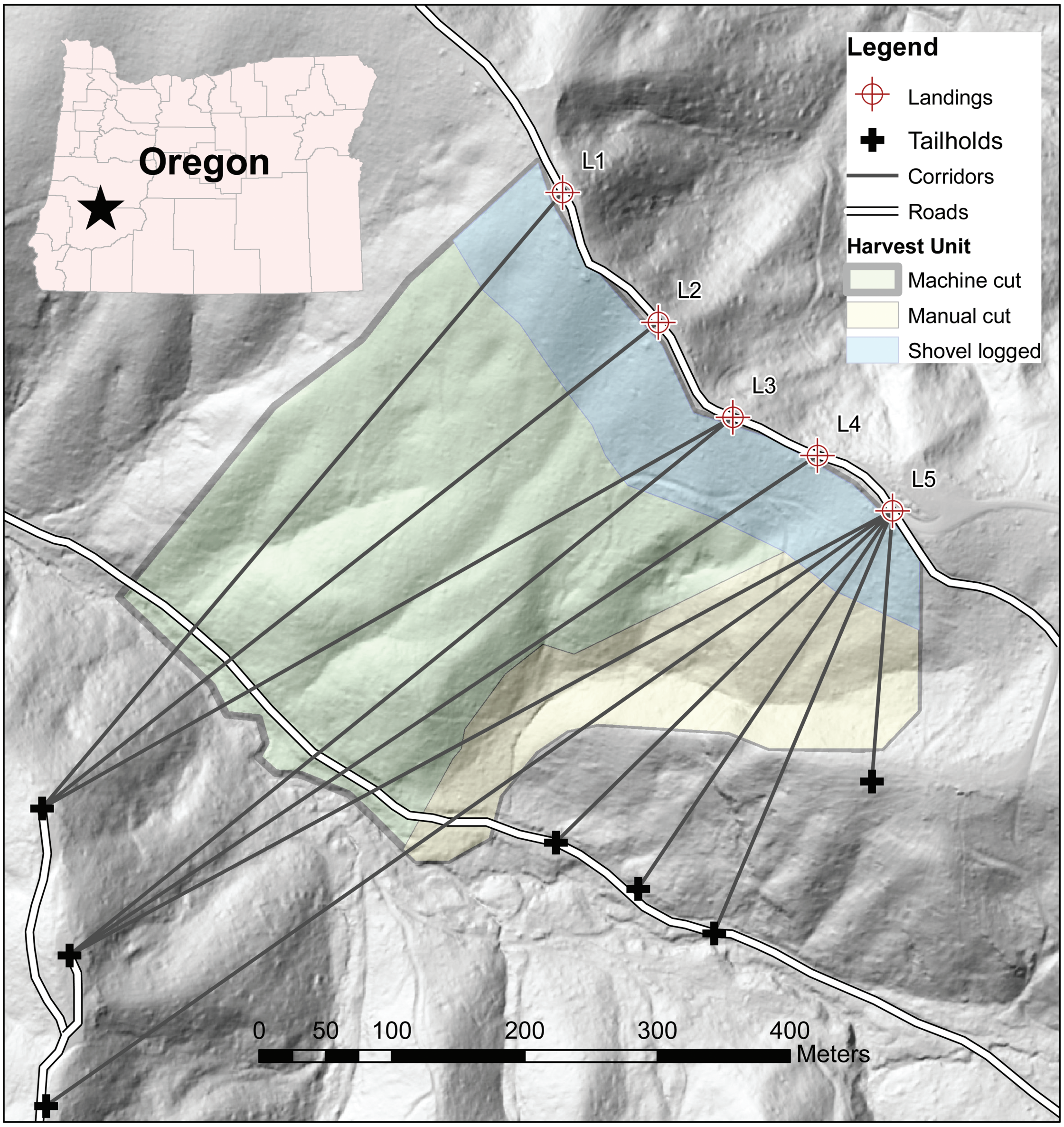


**Figure 1.** The 17-ha study harvest unit located near Sutherlin, Oregon. The harvest unit consists of 10 ha of machine-cut area (green or bottom left), 4 ha of hand-cut area (yellow or bottom right) and 3 ha of the upper strip along the ridge top road (blue). The upper strip was excluded from our study as it was harvested prior to our data collection.



on the stump. No delimbing and topping was performed during timber falling as trees were logged in a whole-tree form. Other variables associated with the work cycle that were collected during hand falling include walk distance to the next tree and tree size class. Walk distance was measured as the number of steps taken by the timber faller multiplied by the average step distance (i.e., 76 cm). The cut-tree diameter at breast height was measured in the designated subsections of the harvest unit, classified by size (<36 cm, 36 – 51 cm, >51 cm) and color-painted according to its size class prior to cutting.

During machine timber falling, the tethered feller-buncher normally felled trees and placed them next to the machine corridor while moving downslope. It then swung felled trees toward the skyline corridor while moving upslope. Timber falling work cycle times were recorded as: move to the next tree; prepare to cut, including brushing and positioning of felling head; fell and locate the tree on the ground. Swing operation times were recorded for moving and for swing and bunch. Additional factors associated with machine falling and swing work cycles were recorded. We measured equipment travel distance between trees or bunches by counting track rotations and multiplying it by the length of machine track (i.e., 4.3 m). Tree size class was observed during machine falling. During machine swing, the feller-buncher often performed multiple swings at one stop and grabbed multiple trees per swing. The number of swings and total number of pieces were recorded per work cycle for swing and bunching.

The time elements recorded for yarding operations include outhaul, hook, inhaul, and unhook. Outhaul distance in each cycle was estimated using carriage location relative to the 9.1 m distance marks preestablished on the ground. Lateral yarding distance was also estimated from the distance marks in the hand-cut area. Lateral yarding distance was not measured

**Table 2.** Delay-free cycle time, time elements and explanatory variables measured during the time and motion study.

| Work cycle | Time element | Explanatory variables |
|---|---|---|
| Hand timber falling | Walk to tree: Begins when timber faller starts walking, and ends when chainsaw touches tree | Travel distance to next tree (T_dist, ft)[a] |
| | Fell: Begins when chainsaw starts undercutting, and ends when tree is completely felled to the ground | Tree size class |
| | Remove stump edges: Begins when tree is felled to the ground and ends when timber faller starts walking to the next tree | • Size1: dbh < 36 cm<br>• Size2: 36 cm ≤ dbh ≤ 51 cm<br>• Size3: dbh > 51 cm |
| Machine timber falling | Move to tree: Begins when the machine starts moving and ends when it stops for cutting | Travel distance (T_dist, ft)[a] |
| | Prepare to cut: Begins when the machine stops traveling and starts getting ready for cutting, including brushing and positioning of felling head, and ends when saw touches tree | Tree size class<br>• Size1: dbh < 36 cm<br>• Size2: 36 cm ≤ dbh ≤ 51 cm |
| | Fell: Begins when cutting starts and ends when tree is released and placed on the ground. | • Size3: dbh > 51 cm |
| Machine timber swing | Move to tree bunch: Begins when the machine start traveling and ends when it stops traveling for swing | Travel distance (T_dist, ft)[a] |
| | Swing and bunch: Begins when boom starts to swing, and ends when trees are released and the machine is ready to travel to the next location | Number of swings (Swing)<br>Number of pieces (Piece) |
| Yarding | Outhaul: Begins when carriage starts moving away from landing and ends when rigging slinger signals stop | Outhaul distance (Out_dist, ft)[a] |
| | Hook: Begins when carriage stops and ends when logs are in skyline corridor and carriage starts moving toward the landing. This time element includes lateral yarding in the hand-cut area. | Lateral distance (Lat_dist, ft)[a] |
| | Inhaul: Begins when carriage starts moving toward the landing and ends when carriage stops | Number of pieces (Piece) |
| | Unhook: Begins when carriage stops at the landing and ends when carriage starts moving away from landing | |

[a]Distance in feet was measured and used for regression analysis in this study.

**Figure 2.** Photo of the study harvest unit showing pre-bunched tree piles along designated skyline corridors in the machine-cut area.

in the machine-cut area because logs were already piled along predetermined skyline corridor and no lateral yarding was necessary (Figure 2). The number of log pieces was counted for each cycle.

## DFCT Regression Models

DFCT regression models were developed for each of the felling and yarding operations through multiple least-squares linear regression analyses on the DFCT data using R 4.0.3 (R Core Team 2020). For the DFCT regressions of both hand and machine timber falling, travel distance and tree size class were used as numerical and categorical explanatory variables, respectively. Machine swing DFCT regression used numerical explanatory variables: machine travel distance, number of swings, and total number of pieces swung in each cycle. Numerical variables for both machine and hand-cut areas include cable yarding cycle time regression, outhaul distance, and the number of pieces. Lateral distance was used as an additional explanatory variable for the hand-cut area only.

The purpose of regression models in this case study was to develop a standardized comparison of system productivity between hand and machine cut methods under similar work conditions, such as yarding distance and tree size, rather than for statistical inference for productivity prediction in other sites. Therefore, we used all the data in model development without cross-validation of the model.

## System Productivity and Production Cost

Productivity of each timber falling and yarding operation was estimated as timber volume per productive machine hour excluding delay times (PMH or $PMH_0$), based on the average turn size and DFCT. We estimated the average turn size using the average number of trees per cycle multiplied by the average tree volume obtained from the stand cruise data (Table 1). We used the average DFCT estimated by the regression models using the observed average values of explanatory variables.

General comparisons between hand- and machine-cut methods were made for felling and yarding productivity in scheduled machine hours (SMH) by applying utilization rates of individual machines. We used the commonly applied machine utilization rates published in Brinker et al. (2002), except for hand falling (Table 3). These generalized utilization rates were used to prevent bias that could be induced from a small data pool. We applied a utilization rate for hand falling derived from the observed data in this study and local work hour practices because there is no published generalized rate available. It is a conventional practice in western Oregon that timber fallers work 6 hours/day at cutting due to the high physical workload (Francisca Belart, personal communication via email, Oregon State University, Aug. 30, 2021). The timber faller's utilization rate and hourly wage were adjusted to reflect this local practice.

Hourly costs of each operation were calculated using the standard machine rate calculation method (Miyata 1980) based on the cost parameters shown in Table 3. Machine rate calculation was categorized by cost factors of owning, operating, and labor costs per scheduled machine hour. Using machine productivity and hourly rates, we calculated the unit production cost ($/m$^3$) as the result of dividing hourly costs ($/SMH) by hourly productivity (m$^3$/SMH) for each operation. Comparisons were then made between hand- and machine-cut methods in terms of unit production costs to determine the effects of mechanized timber falling and pre-bunching on the cost-efficiency of felling and yarding operations.

# Results

## Time Study Data

We observed a total of 27.7 hours of logging operations, including timber falling and yarding in the hand-cut area and 25.3 hours in the machine-cut area (Table 4). Among the observed hours of hand falling, 23% were identified as delays. The delays ranged from 0.3 to 11.2 min., mainly due to refueling and personal breaks. Although we observed 292 trees felled by the feller-buncher for machine timber falling, size class of 72 felled trees was not determined because of either unpainted or unidentifiable colors of faded paint, especially for the larger size classes. We removed the machine falling cycles with no color identification from the dataset, resulting in 220 complete cycles that were used for regression analysis. We observed more trees swung by the feller-buncher than those trees felled during our observation, as previously felled trees in the machine corridor were moved and bunched along with newly felled trees. During machine falling and swing, we observed eleven short delays, mainly caused by personal delays and occasional debris removal from the felling head.

We observed yarding operation delays in the hand-cut area ranging from 18 seconds to 1.4 hours, due mainly to personal breaks and cable road changes. No mechanical yarding delay was observed. In the machine-cut area, yarding operations during the first day of observation occurred at the boundary of the hand and machine-cut areas, resulting in extrac-



**Table 3.** Utilization rates and cost parameters used in hourly machine rate calculation.

| Cost Inputs | Chainsaw | Feller-buncher + anchor machine with winch | Swing yarder (used) |
|---|---|---|---|
| Purchase price (USD) | 1,300 | 1,250,000 | 700,000 |
| Salvage value (%) | 20 | 20 | 20 |
| Economic life (years) | 1 | 5 | 4 |
| SMH yr$^{-1}$[a] | 2000 | 2000 | 2000 |
| Interest, insurance and taxes (%) | 15 | 15 | 15 |
| Fuel consumption (l/PMH)[a] | 0.7 | 58.5 | 41.9 |
| Fuel price ($/l) | $0.79 | $0.79 | $0.79 |
| Lubrication (%)[b] | 37 | 37 | 37 |
| Maintenance and repair (%)[c] | 100 | 100 | 100 |
| Labor wages ($/SMH)[d] | 34 | 28 | 140 |
| Labor fringe benefits (%) | 50 | 50 | 50 |
| Utilization rate (%) | 40 | 65 | 65 |

[a]Scheduled machine hour (SMH) and productive machine hour (PMH).
[b]Lubrication cost is calculated as a percentage of fuel costs.
[c]Maintenance and repair costs are estimated as a percentage of straight-line depreciation.
[d]Labor wages for cable logging include one yarder operator, one rigging slinger, one chaser, and two choker setters at the average rate of $28/SMH.

**Table 4.** Observed work hours, delays and utilization rates.

| Group | Operation | Total trees | Work Hours (SMH) | Delay | | Utilization (%) |
|---|---|---|---|---|---|---|
| | | | | N | Time (SMH) | |
| Hand-cut area | Felling | 123 | 2.6 | 10 | 0.6 | 77 |
| | Yarding | 797 | 25.1 | 19 | 5.1 | 80 |
| Machine-cut area | Felling | 292 | 4.0 | 11 | 0.2 | 95 |
| | Swing | 761 | | | | |
| | Yarding | 1061 | 21.3 | 23 | 4.0 | 81 |

tion of mixed trees from both hand and machine-cut areas. The first day's data, therefore, were excluded from the dataset for regression analysis. Compared with the hand-cut area, the machine-cut area experienced more frequent but shorter delays caused by skyline length adjustments, waiting for the processor equipment, personal delays, and a one-time cable road change.

When compared against the machine-cut area, the hand-cut area appears to have a larger variability in timber falling and yarding cycle times (Figure 3). Several cycles were beyond 1.5 times the interquartile range and may be considered outliers. However, we did not exclude them from our analyses as they were considered normal logging operations.

The average DFCT from the observed 123 cycle times of hand timber falling was approximately 59 seconds with 71% of the average cycle time being spent on felling. Cycle times included 19% on walking and 10% were spent on cutting stump edges (Table 5). Average walking distance between trees to cut was estimated at approximately 5.8 m. In contrast, machine falling took a mere 27 seconds to cut a tree and an average travel distance of 2.7 m. The average travel distance was smaller than hand falling because the machine could cut multiple trees at a single location (i.e., there were cycles without a move). The machine-cut area had a relatively larger proportion of trees in Size Class 1 due to incomplete data from larger tree size classes caused by faded, less visible paint, and variations within the harvest unit.

Although the observed average yarding distance was 83% longer in the machine-cut area than the hand-cut area, the average cycle time was similar between the two areas (i.e., approximately 4 min.). However, we observed a large difference in turn size. The average turn size in the hand-cut area was 2.7 trees as compared to the average turn size of 4.7 trees in the machine-cut area, 74% larger than that of the hand-cut area.

Recorded time elements reflected the differences in working conditions and production rates. Due to shorter yarding distance in the hand-cut area, the average outhaul and inhaul times were smaller than those in the machine-cut area (Table 5). However, hooking time was substantially longer in the hand-cut area despite the smaller number of trees to handle per cycle because lateral yarding was necessary to bring felled trees to the corridor. Lateral yarding was not needed in the machine-cut area because felled trees were already bunched along the skyline corridor by the tethered feller-buncher. A larger unhooking time in the machine-cut area reflects the

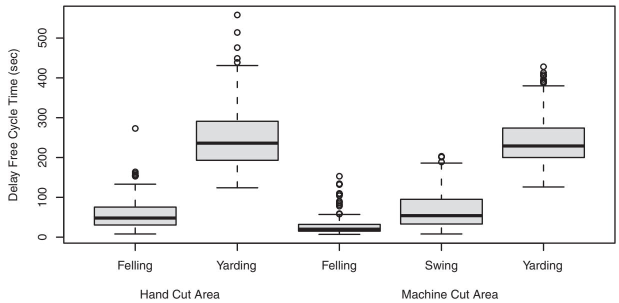


**Figure 3.** Boxplots of observed delay-free cycle times for felling and yarding operations in the hand and machine-cut areas.

**Table 5.** Summary statistics (mean ± standard deviation) for time elements and explanatory variables in each operation collected during detailed time study.

| Group | Operation | Number of cycles (N) | DFCT[a] (sec) | Time element (sec) | | Explanatory variable | |
|---|---|---|---|---|---|---|---|
| | | | | Element | mean ± sd | Variable | mean ± sd |
| Hand cutting | Felling | 123 | 58.7 ± 40.7 | Move | 11.0 ± 10.3 | Travel dist. (ft) | 18.9 ± 11.8 |
| | | | | Fell | 41.8 ± 31.8 | Tree Size Class[b] | Size 1 (45)[c] |
| | | | | Stump cut | 6.0 ± 10.3 | | Size 2 (42) |
| | | | | | | | Size 3 (36) |
| | Yarding | 293 | 245.0 ± 72.7 | Outhaul | 24.6 ± 19.6 | Outhaul dist. (ft) | 399.0 ± 237.4 |
| | | | | Hook | 134.8 ± 55.0 | Lateral dist. (ft) | 37.0 ± 13.7 |
| | | | | Inhaul | 34.1 ± 18.4 | Number of pieces | 2.7 ± 0.8 |
| | | | | Unhook | 52.1 ± 19.9 | | |
| Machine cutting | Felling | 220 | 27.2 ± 21.4 | Move | 6.4 ± 15.5 | Travel dist. (ft) | 8.7 ± 21.9 |
| | | | | Cut prep. | 10.2 ± 11.2 | Tree Size Class[b] | Size 1 (125)[c] |
| | | | | Fell/Bunch | 10.6 ± 6.2 | | Size 2 (66) |
| | | | | | | | Size 3 (29) |
| | Swing | 87 | 68.8 ± 68.8 | Move | 16.6 ± 17.7 | Travel dist. (ft) | 16.7 ± 21.9 |
| | | | | Bunch | 52.1 ± 40.5 | Number of swings | 3.4 ± 2.6 |
| | | | | | | Number of pieces | 8.7 ± 8.4 |
| | Yarding | 195 | 241.8 ± 61.6 | Outhaul | 27.8 ± 14.5 | Outhaul dist. (ft) | 728.7 ± 260.3 |
| | | | | Hook | 103.9 ± 38.3 | Number of pieces | 4.7 ± 1.6 |
| | | | | Inhaul | 49.9 ± 13.6 | | |
| | | | | Unhook | 60.2 ± 23.3 | | |

[a]Delay-free cycle time.
[b]Categorical variables (Size1: dbh < 36 cm; Size2: 36 cm ≤ dbh ≤ 51 cm; Size3: dbh > 51 cm).
[c]Numbers in parentheses are the number of cycle time samples in each tree size class.

larger number of trees to unhook at the landing compared with the hand-cut area.

## DFCT Regression Models

The multivariate linear regression models developed for DFCT estimation in each logging operation resulted in adjusted $R^2$ values ranging from 0.47 to 0.89 (Table 6). All models were statistically significant in explaining the variations in DFCT when an F-test was conducted ($P < 0.001$). The models show that the majority of the explanatory variables were highly significant. There were a few insignificant variables ($P > 0.05\%$) in the full model, including travel distance for hand falling and the number of pieces for machine swing and yarding. Insignificant variables were removed for the final model in Table 6 as they had a very minimal effect on the model fit. Unlike the hand-cut area, the number of pieces was not a significant factor for yarding cycle time in the machine-cut area. Based on our observation, the reason was probably because choker setting time did not widely vary with the number of trees choked in the machine-cut area as they were already piled together as shown in Figure 2. Tree size class was a significant factor for both hand and machine falling, but its influence was much larger in hand falling than machine falling. The models show that estimated cycle time would increase by 21 and 73 seconds in hand falling, respectively, as tree size class changes from 1 to 2 and from 1 to 3. In contrast, the increments decreased to 4 and 12 seconds for machine falling.

## Productivity of Timber Falling and Yarding

For comparison of productivity between hand- and machine-cut methods, the observed average values of explanatory variables were entered into the regression models to estimate the average cycle time for each operation (Table 7). The combined average distance of 162 m (531 ft.) was used for both hand- and machine-yarding regression models for standardized comparison because the average yarding distance was different for hand- and machine-cut areas. For tree size, Size Class 2 was used as the average value.

Results show that it would take 51 seconds on average to fell a tree of Size Class 2 by manual chain saw and 29 seconds for the same size tree using a tethered feller-buncher. Machine falling was 44% more productive than hand falling. However, because of higher hourly costs of tethered equipment, production cost of machine falling was 130% higher than hand falling. The cost of machine falling increases to 190% when a machine swing and pre-bunching operation is added to the felling costs.

Yarding times in the hand-cut area would average 269 seconds per cycle compared to an average of 207 seconds for yarding in the machine-cut area. Yarding after tethered machine falling would have a 23% faster cycle time than yarding after hand falling. In addition, because of the difference in turn size, yarding after machine falling could transport 77% more volume to the landing per cycle than yarding after hand falling. This combination of faster cycle time and larger turn size results in a 125% higher productivity in yarding after machine falling compared with yarding after hand falling.

## Production Costs

The unit production costs ($/m³) per operation were calculated after applying the general machine utilization rates of 65% and machine hourly costs to the hourly productivity estimated from the average cycle time and turn size. Unit costs ranged from $0.9 to $13.9/m³. Tethered machine swing and yarding after hand falling were the least and most expensive operations, respectively (Table 7). Because felling and yarding are usually performed separately with no interference, no bottleneck function was considered in calculating the system-wide productivity. Our results show that for our cost and utilization assumptions, tethered machine falling and pre-bunching can save approximately 32% of the total

**Table 6.** Linear regression models developed to estimate delay-free cycle time of each logging operation.

| Group | Operation | Delay-free cycle time (DFCT) (sec)[a] | Std. Error | *P* value | Adj-$R^2$ | F-statistics (*P*-value) |
|---|---|---|---|---|---|---|
| Hand cutting | Felling | DFCT = 29.84 | 4.030 | < 0.001 | 0.56 | < 0.001 |
| | | + 20.87*Size2 | 5.801 | < 0.001 | | |
| | | + 73.38*Size3 | 6.046 | < 0.001 | | |
| | Yarding | DFCT = 100.41 | 13.88 | < 0.001 | 0.47 | < 0.001 |
| | | + 0.1762*Out_dist | 0.015 | < 0.001 | | |
| | | + 0.863*Lat_dist | 0.258 | < 0.001 | | |
| | | + 15.81*Piece | 3.805 | < 0.001 | | |
| Machine cutting | Felling | DFCT = 17.69 | 1.122 | < 0.001 | 0.67 | < 0.001 |
| | | + 0.750*T_dist | 0.038 | < 0.001 | | |
| | | + 4.42*Size2 | 1.869 | 0.0191 | | |
| | | + 12.18*Size3 | 2.561 | < 0.001 | | |
| | Swing | DFCT = 2.49 | 3.097 | 0.4240 | 0.89 | < 0.001 |
| | | + 0.714*T_dist | 0.068 | < 0.001 | | |
| | | + 14.79*Swing | 0.689 | < 0.001 | | |
| | Yarding | DFCT = 115.36 | 8.971 | < 0.001 | 0.53 | < 0.001 |
| | | + 0.1735*Out_dist | 0.012 | < 0.001 | | |

[a]Explanatory variable names and units of measurement are defined in Table 2.

**Table 7.** Machine productivity and production costs estimated for the hand- and machine-cut methods using the average values of explanatory variables. These cost estimates were developed for comparison purposes only and do not reflect costs associated with logging operations at the landing, equipment mobilization, landing and road construction or any other management and overheads.

| Operation | Input | | Cycle | | Hourly productivity | | Machine rate ($/SMH) | Unit Cost ($/m$^3$) | |
|---|---|---|---|---|---|---|---|---|---|
| | Variable | Value | Time (sec) | Prod. (m$^3$) | m$^3$/PMH | m$^3$/SMH | | Machine | System |
| Hand Falling | Size class[a] | Size 2 | 51 | 1.3 | 90.2 | 36.1 | 52.5 | 1.5 | 15.4 |
| Hand Yarding | Outhaul (ft)[b,c] | 531 | 269 | 3.4 | 46.0 | 29.9 | 416.3 | 13.9 | |
| | Lateral (ft)[c] | 37 | | | | | | | |
| | # of pieces | 2.7 | | | | | | | |
| Machine Falling | Move (ft)[c] | 8.7 | 29 | 1.3 | 159.7 | 103.8 | 347.0 | 3.3 | 10.4 |
| | Size class | Size 2 | | | | | | | |
| Machine Swing | Move (ft)[c] | 16.7 | 65 | 11.0 | 614.8 | 399.6 | 347.0 | 0.9 | |
| | Number of swings | 3.4 | | | | | | | |
| Machine Yarding | Outhaul (ft)[b,c] | 531 | 207 | 6.0 | 103.6 | 67.3 | 416.3 | 6.2 | |

[a]Average tree size of 1.27 m$^3$ was used (Size class 2).
[b]Combined average distance from both hand and machine-cut areas.
[c]Distance in feet was measured and used for regression analysis in this study.

felling and yarding costs compared with the hand falling and yarding method.

## Discussion

The economic benefit of using tethered equipment shown in this study was derived from whole tree pre-bunching that significantly improved cable yarding productivity. This positive impact of pre-bunching on steep-slope cable yarding has also been determined in a few previous studies, although at different amounts of productivity increase. For example, Acuna et al. (2011) reported a 25% increase in grapple yarding productivity as the result of pre-bunching with a self-leveling feller-buncher in Australia. The study reported the average turn size increased by 46% with bunched trees, but cycle time also increased by 17% compared with yarding unbunched trees. Amishev and Evanson (2010) reported a 113% increase in grapple-yarding turn size from a case study in New Zealand where a tethered excavator presented bunched trees to the grapple yarder. Their second case study involved a tethered feller-buncher to fell and pre-bunch trees for grapple yarding. Turn size increased by 67% compared with grapple yarding of individual trees. Production cost savings were estimated at 17.5%. In these two case studies, no difference in grapple yarding cycle time was observed between bunched and unbunched trees.

Each of these studies demonstrated the potential increase in yarding productivity by use of mechanized timber falling and pre-bunching on steep slopes, despite differences between the previous studies and our study (e.g., grapple yarding versus cable yarding with chokers, site conditions). Actual increases in yarding productivity could vary with site-specific maximum payload capacity of the yarding system. Realization of maximum benefit from pre-bunching would require monitoring the payload per yarding cycle and fully using the maximum payload capacity.

More frequent cable road changes occurred in the hand-cut area. Fan-shaped, narrowly spaced skyline corridors were created to reach and yard hand-felled trees while avoiding excessive lateral yarding. In our case study, six skyline corridors were laid out to harvest the 3.6-ha hand-cut area, for a total corridor length of approximately 1.2 km placed within the unit (Figure 1). In contrast, five corridors totaling 1.9 km were laid out for a much larger machine-cut area (10 ha). More frequent cable road changes may increase delays, decreasing the utilization rates of cable yarding. If this difference in delay time during yarding operations was included in the cost estimation, the tethered machine falling case would further surpass hand falling by a productivity increase and production cost reduction.

Use of heavy equipment on steep slopes may have potential impacts on soil disturbance (Cambi et al. 2015). Tethered mechanized timber falling may also affect skyline corridor layout, corridor spacing, and the amount of payload traffic on each skyline corridor. Each of these potential effects could lead to a different area coverage and level of soil impact. For example, we observed a lower density of skyline corridors in the machine-cut area but higher log traffic per corridor. Potential trade-offs may occur between area coverage and intensity of disturbance. Adoption of steep-slope tethered logging requires building a reliable foundation of research, including environmental studies, to ensure the long-term sustainability of soils (Cavalli and Amishev 2019, Holzfeind et al. 2020).

## Conclusion

This study shows that despite higher costs of timber falling by tethered equipment in steep terrain, the ability of the felling machine to pre-bunch trees into piles made the subsequent yarding operation much more efficient than a hand falling operation. The efficiency gained during yarding not only offset the cost increase in felling, it further reduced the combined production costs of felling and yarding operations. Although our results from one case study may not represent other harvest sites or work by other equipment or logging crews, they do identify productivity and cost factors that lead to potential economic benefits of using mechanized timber falling and pre-bunching on steep slopes.

Like any other observational field study of forest operations, our study had several limitations. Lack of repetition limits statistical inferences on the variables influencing machine productivity. Factors that were not considered in this study may influence productivity of other machines or the whole logging system. For example, a large influx of timber to the landing due to increased yarding productivity would require a larger landing space, higher loading capacity, and better coordination of trucking to take full advantage of the improved efficiency in yarding. We focused only on productivity and financial aspects of tethered operations in this study. Adoption of new logging technology should also be examined for its safety and environmental performance. Future research is certainly warranted to better understand the full spectrum of benefits and risks of the new logging technology under various work environments.

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## Conflict of Interest

The authors declare no conflicts of interest.

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