Productivity and cost of whole-tree and tree-length harvesting in fuel reduction thinning treatments using cable yarding systems

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ABSTRACT
Cable yarding systems are often used to reduce hazardous fuels in dense overstocked forest stands on steep terrain (>35%) in the western United States. However, treatment costs tend to be high. The aim of this study was to broaden our knowledge by evaluating two different harvesting methods (whole-tree (WT) and tree-length (TL)) used for fuel reduction thinning treatment on mixed-conifer forest stand. Different harvesting methods greatly affected the productivity and cost of fuel reduction thinning, especially in felling and yarding operations. Total sawlog removal costs (stump-to-truck) were US$26.13/m³ in the WT-harvested unit and US$24.01/m³ in TL harvested unit. TL thinning resulted in higher felling time and lower production rate due to increased amounts of time for processing trees at the stump. In yarding operation, however, TL method had a higher production rate than WT method because TL method had higher number of pieces per yarding cycle. Processing production rates at a landing were relatively similar throughout treatments although trees in a TL thinning unit were already limbed and bucked at the stump. Loading productivity was consistent throughout treatments because loading occurred independently from other activities. For fuel reduction thinning treatments using a cable yarding system, TL thinning was more cost-effective than WT thinning if leaving tree tops and branches on site is acceptable from a fuels management perspective.

Introduction
Dense, overstocked stands have increasingly contributed to the cause of catastrophic wildfires: federal land managers have identified 29.5 million hectares (ha) of National Forest lands in the western U.S. that are characterized as having unnatural or excessive amounts of woody vegetation (USDA Forest Service 2003). These stands generally require a mechanical thinning as a silvicultural method to improve fire-tolerances (Graham et al. 2002) and the implementation of appropriate silvicultural and harvesting methods can effectively reduce wildland fires in these fire-prone ecosystems (Keyes and O’Hara 2002).

Treatments to reduce hazardous fuel accumulations in California’s forests often involve mechanical thinning because it effectively addresses the high levels of fuel connectivity in high-density stands and allows the use of prescribed burning with reduced risk of fire escaping. Fuel reduction thinning generally defines the reduction of surface and ladder fuels with thinning trees, removing underbrush, and limbing trees (Pan et al. 2008). However, the economics of mechanical fuel reduction thinning are often in question to forestland managers because thinning treatment costs are typically costly (Vitorelo et al. 2012). Several studies have examined fuel reduction thinning involving various machines and systems to address questions related to harvesting productivity and costs (Lowell et al. 2008; Pan et al. 2008; Bolding et al. 2009). Stand conditions (e.g. tree size, thinning intensity, and slope) and harvesting system (e.g. ground-based or cable yarding) and methods (e.g. whole-tree or tree-length) were found to be critical factors to consider when evaluating economic feasibility of fuel reduction treatments. The unit cost of removing smaller diameter trees is generally higher than those for larger diameter trees (Lowell et al. 2008). In addition, the unit cost of harvesting low volumes per acre is higher than those for higher volumes per acre. Kellogg et al. (1996) found that total skyline harvesting costs for thinning treatments could range from approximately 7 to 32% more than those for conventional clearcut treatments. Thinning intensity can also influence yarding production and cost. Yarding production increased and costs decreased as thinning intensity increased because of an increase in the average number of logs per turn (Hochrein and Kellogg 1988).

The topography in the western U.S. is often too steep (>35%) for ground-based systems to be effectively harvested. Cable-harvesting systems often are used to
harvest timber in steep terrain, but harvesting with a cable system is typically more expensive than with a ground-based system (Daigle 1992). Harvesting cost in fuel reduction thinning ranges from US$370 (ground-based) to US$1360 (cable yarding) per ha, which is often higher than the potential revenues from selling the products produced from thinning (LeVan-Green and Livingston 2001). Kellogg et al. (1999) found that cable yarding operations often result in narrow profit margins or even a loss because of high-operating cost in thinning operations.

In the western U.S., whole-tree (WT) and tree-length (TL) harvesting methods are commonly used in mechanized fuel reduction thinning operations. In the WT harvesting method, the tree is felled and delivered to landing with limbs and tops attached to the stem. This method is considerably efficient for a significant reduction of fuels in the forest stand because most of the felled biomass is removed from the site (Han et al. 2004). However, fuel reduction thinning with WT harvesting method often triggers concerns related to long-term site productivity and sustainable forest production because nutrients are removed with the plant materials harvested (Elliott and Knoepp 2005). For this reason, managers often consider using cut-to-length (CTL) or TL harvesting for fuel reduction thinning operations. In a typical CTL or TL harvest, trees are felled and processed at the stump and only the bole wood is removed from the site. However, thinning costs with CTL harvesting were found to be 10–20% more expensive than WT harvesting when ground-based systems were used (Adebayo et al. 2007). The higher cost in CTL harvest was associated with more labor inputs on the ground and the difference between WT and CTL harvesting costs increased with decreasing tree size (Han et al. 2004). These findings are helpful when selecting an appropriate harvesting method and system that meets both fuel treatment and cost management objectives. Additional information on nutrient impacts and economic feasibility from different harvesting methods and systems are needed to make better mechanical fuel treatment decisions, especially on steep ground thinning operations.

This field-based study was designed to enhance our knowledge of how to efficiently and economically implement two different harvesting methods (WT vs. TL) in fuel reduction thinning operations using cable yarding system in a mixed conifer stand on steep grounds. The specific objectives of this study were to (1) compare the thinning productivity and stump-to-truck cost for each harvesting method and (2) identify important factors that affect thinning productivity at each phase of the operations for both harvesting methods.

**Materials and methods**

**Study site and harvesting system**

This study took place on the Klamath National Forest as a part of the Mt. Ashland Stewardship Contract in northern California, US. The focus of this vegetation management contract was to restore or create stand structure characteristics of late successional stands, reduce fire hazard, and improve wildlife habitat. Much of the Mt. Ashland area is comprised of mixed conifer forests including white fir (Abies concolor), Douglas-fir (Pseudotsuga menziesii), ponderosa pine (Pinus ponderosa), incense-cedar (Calocedrus decurrens), and sugar pine (Pinus lambertiana). The thinning site was 8.1 ha in size and the ground slope between 37 and 68%. Our experiment site was divided into two units (4.05 ha for each unit). Each unit was randomly assigned with one of the two different harvesting treatments using a cable yarding system: (1) WT and (2) TL harvesting method. The thinning prescription in this study was to reduce wildland fire hazard by promoting forest health and growth. In each unit, the marked (>22.86 cm in diameter at breast height (DBH)) trees and unmarked biomass-sized (2.54–22.86 cm) trees were cut. and all trees less than 2.54 cm in DBH were left uncut according to the silvicultural prescription. The thinning resulted in structural diversity by providing a mosaic of tree densities and heights and creating a variety of habitats for plants and animals.

The WT harvesting method used in this study consisted of chainsaw felling and a cable yarding system to yard trees to the landing with limbs and tops still attached. However, all trees larger than 50.8 cm in DBH were bucked at the stump using a chainsaw and yarded to the landing. A dangle-head processor attached to a CAT322L log loader base machine at the landing processed the whole trees to seven different sawlogs sizes. Higher value sawlogs were produced first. The limbs and tops left from the tree processing were accumulated into a slash pile and the roundwood of the tops were kept separate and decked in a large pile for subsequent utilization as biomass or firewood. The processed sawlog deck was separated into seven different sorts by a CAT322C log loader. Logs were sorted by species and log length to facilitate rapid truck loading. Logs from this thinning were hauled to a sawmill in either White City, Oregon or Yreka, California.

In the TL harvesting method, chainsaws were used to fell and process trees at the stump, followed by bole-wood-only yarding using a cable yarding system. Although logs were already limbed on three sides and bucked at the stump, a processor finished manufactured sawlogs of different lengths (3.1–13.1 m) down to a small-end diameter of 15.2 cm outside bark at the landing. In both units, yarding was done using a Madill 071 yarder (240 HP) with Eagle Eaglet motorized clamping carriage run by five crews: a yarder operator, a hooktender, two choker-setters and a chaser with 7–35 years of experience. Yarding distances ranged from 76 to 290 m.

**Data collection and analysis**

A pre-harvest timber cruise was conducted prior to thinning operation to quantify stand conditions. A
systematic sampling design, made up of 0.04 ha fixed–area circular plots, was established with 100 by 100 m spacing. In each plot, trees down to 2.54 cm DBH were recorded for species, DBH, and height since any trees below this size were retained as advanced regeneration. This data was used to estimate the average DBH, tree height, stand density (trees/ha), volume (m$^3$/ha), and basal area (m$^2$/ha) for each unit. Allometric equations developed by MacLean and Berger (1976) were used to estimate pre-harvest tree volumes in cubic meter (to a 10.2 cm top) for all of the species present in the study units. The experimental design showed similarities in stand and ground condition between WT and TL harvesting units (Table 1). There were no significant differences in mean DBH between WT and TL harvesting units (p > 0.05).

Machine costs (US$/scheduled machine hour (SMH)) and harvesting productivity (m$^3$/productive machine hour (PMH)) for each machine were calculated using standard shift-level and detailed time study methods. Hourly machine costs (US$/SMH) were estimated using standard machine rate calculation methods (Miyata 1980; Brinker et al. 2002; Table 2). Information on machine prices, insurance, taxes, interest, lubrication cost, repair and maintenance cost, and labor cost were obtained from the project contractor. Fuel consumption for each machine was estimated by machine horse power (HP). Diesel prices were determined from local market prices during the study. Estimated economic life for all the machines was set at 5 years with an assumption 1800 SMH/year. Salvage value was estimated at 20% percent of the initial machine price. Overhead and profit allowance were not included in the cost analysis.

Detailed time studies were conducted to calculate thinning productivity (m$^3$/PMH) and evaluate interactions between equipment, personnel, and harvesting attributes on each phase of the thinning treatment: felling, yarding, processing, and loading (Olsen and Kellogg 1983). Production rates for each phase of thinning were compared between WT and TL harvesting systems. Individual cycle components for each turn were timed with a stopwatch, delays were uniquely identified with their causes (mechanical, operational, and personal), and independent variables were recorded.

Regression equations were developed for felling, yarding, processing, and loading delay-free cycle times to determine machine production rates (m$^3$/PMH) and to understand how independent variables might affect harvesting productivity. A felling cycle in WT harvesting unit consisted of traveling to the tree and felling. In TL harvesting unit, a felling cycle included traveling to the tree, felling, limbing, measuring, and bucking. Independent variables collected during felling operations were species, DBH, slope, travel distance, and use of wedge. In both units, a yarding cycle consisted of the following sequence: carriage traveling out from the landing, lateral cable traveling out to felled tree(s) or log(s), hooking the tree(s) or log(s), lateral cable traveling in, carriage traveling to the landing, and unhooking the tree(s) or log(s). The independent variables collected were: yarding distance, lateral distance, and number of pieces per cycle. The processor’s cycle elements included: grappling a tree or log, processing the tree into logs, and piling the tops. Lastly, log-loader cycle consisted of swinging the empty grapple to the deck, grappling, swinging logs toward the logging truck, and bunking the logs.

Stepwise regression analysis of detailed time study data and evaluation of interactions between harvesting attributes were performed using SPSS (SPSS Inc. 1998) to develop prediction models of harvesting productivity. In all of the prediction models, normality tests, residual plots, and the Durbin–Watson test were used to search for a suitable subset of explanatory variables. Furthermore, a forward selection method was used to search for a suitable subset of explanatory variables. The following was used:

\[
\text{Productivity} = \text{Constant} + \text{Species} + \text{DBH} + \text{Slope} + \text{Travel Distance} + \text{Use of Wedge}.
\]

The independent variables collected during felling operations were species, DBH, slope, travel distance, and use of wedge. In both units, a yarding cycle consisted of the following sequence: carriage traveling out from the landing, lateral cable traveling out to felled tree(s) or log(s), hooking the tree(s) or log(s), lateral cable traveling in, carriage traveling to the landing, and unhooking the tree(s) or log(s). The independent variables collected were: yarding distance, lateral distance, and number of pieces per cycle. The processor’s cycle elements included: grappling a tree or log, processing the tree into logs, and piling the tops. Lastly, log-loader cycle consisted of swinging the empty grapple to the deck, grappling, swinging logs toward the logging truck, and bunking the logs.

**Table 1.** Stand characteristics of the whole-tree (WT) and tree-length (TL) harvested units prior to thinning operations.

| Characteristics | WT unit | TL unit |
|-----------------|---------|---------|
| Average DBH* (cm) | 9.9 | 7.6 |
| Average height (m) | 7.0 | 5.2 |
| Average basal area (m$^2$/ha) | 9.6 | 5.1 |
| Stand density (trees/ha) | 957.8 | 794.2 |
| Stand volume (m$^3$/ha) | 34.3 | 16.3 |
| Thinning intensity (%) based on basal area | 94 | 92 |
| Species composition (%) based on basal area | | |
| Douglas-fir | 64 | 62 |
| Ponderosa pine | 23 | 15 |
| Sugar pine | 6 | 1 |
| White fir | 4 | 3 |
| Incense-cedar | 2 | 19 |

*diameter at breast height

**Table 2.** Hourly machine cost (US$/scheduled machine hour (SMH)) used in this study.

| Machine | Initial price (US$) | Total hourly cost (US$/SMH) |
|---------|---------------------|-----------------------------|
| Madill 071 Yarder with eagle eaglet motorized clamping carriage | 250,000 | 239.46 |
| CAT 322L Processor | 450,000 | 134.62 |
| CAT 322C Loader | 300,000 | 139.88 |
variables that were significant \((p < 0.05)\). In order to evaluate and reduce multicollinearity, the matrix plots, Variance Inflation Factors (VIF), Pearson correlation values, and Mallow’s CP values were generated and tested. To validate the developed regression models, 30% of the observed data were randomly selected as reserved data. Then, prediction models developed from 70% of the observed data were used to predict times for the reserved data. A paired \(t\)-test was used to evaluate the differences between observed (30% of the data) and predicted travel times (70% of the data). In our data analysis, both the acceptable error level and significance level were set to 5% \((\alpha = 0.05)\).

**Results and discussion**

**Harvesting productivity and delay-free cycle times**

The average time and relative frequency of hand-felling cycle elements for WT and TL harvesting methods are shown in Figure 1 and Table 3. Hand-felling cycle elements and times varied greatly between WT and TL harvesting methods \((p < 0.05)\). The average felling delay-free cycle times in WT and TL units were 1.11 and 2.20 min, respectively (Table 3). TL harvesting had longer felling delay-free cycle time because of additional time needed to process logs at the stump. In WT harvesting, felling time was the largest component of the total hand-felling delay-free cycle time at 81% and traveling to the selected tree made up 19% of the total delay-free cycle time. In TL harvesting, measuring and limbing (41%) and cutting (30%) activities were the two largest components of total hand-felling delay-free cycle time. Except for processing time at the stump, the biggest time difference between WT and TL harvesting units was found in traveling time (0.21 minutes in WT and 0.5 minutes in TL). This was because a faller in the TL unit often traveled back to the stump after processing down the length of the tree. The production rates for both harvesting methods were determined by combining the average delay-free cycle time with the cycle volume. The production rates for hand-felling were 18.96 m\(^3\)/PMH in the WT unit and 15.80 m\(^3\)/PMH in the TL unit. Even though delay-free cycle times in the WT unit were less than half of those in the TL unit, WT harvesting only had a slightly higher production rate because basal area was larger in the WT unit than the TL unit (Table 1). These results are consistent with observations from other studies that tree size is the most important measurable variable affecting felling productivity (Kellogg et al. 1986, 1999; Hartley and Han 2007).

In the yarding phase, the average total delay-free cycle time and relative frequency of the yarding cycle elements for WT and TL harvesting methods are shown in Figure 2 and Table 3. WT harvesting had shorter yarding delay-free cycle time compared to TL. The average delay-free cycle time for yarding was 2.60 min for the WT unit and 3.59 min for TL unit. This difference might be attributed to lateral yarding operation. The time spent pulling cable laterally was significantly longer in the TL unit than the WT unit although both units had similar lateral yarding distances (10.7 m in the WT unit and 11.6 m in the TL unit). In addition, the ground was steeper in the TL unit compared to the WT unit. The TL unit also had a larger amount of logging slash on the ground from processing trees at the stump. The logging slash interfered with the choker-setter’s movement and produced lot of hang-up problems during lateral yarding.
operation. In both harvesting methods, hooking was the most time-consuming of the yarding cycle elements. The sum of lateral outhaul, hook, and lateral inhaul time in WT and TL units consumed 54 and 55% of the total yarding delay-free cycle time, respectively. The hooking and unhooking time was relatively similar throughout the treatments, but carriage out and in time in the TL unit were significantly higher than those in the WT unit ($p < 0.01$). Carriage travel time was influenced by the external yarding distance of each unit. The average yarding distance for the WT unit was 72.5 m and 118.6 m in the TL unit. The yarding production rates in the WT unit was lower compared to the TL unit, even though the WT unit had shorter average delay-free yarding cycle time (Table 3). This result was attributed from the differences of turn volume between WT and TL units (1.39 m$^3$/cycle in the WT unit and 2.28 m$^3$/cycle in the TL unit). Turn volumes were lower in the WT unit because of the additional weight of green foliage and branches hauled to the landing. For this reason, more volume per turn was observed in the TL unit than the WT unit. Therefore, increasing volume per turn was more important than reducing the delay-free cycle time when trying to increase yarding productivity. In our study, skyline road change times were similar between WT and TL units. The average skyline road change time for the WT unit was 39 min ($n = 3$, SD = 11 min) with an average yarding distance of 207 m. The average skyline road change time for the TL unit was 40 minutes ($n = 4$, SD = 8 min) with an average yarding distance of 232 m. These values were very comparable with past studies (Kellogg et al. 1986, 1999; Hartley and Han 2007).

The processor manufactured different log lengths (3.1–13.1 m) from whole trees and bole-woods at the road-side landing area. In our study, the average processing delay-free cycle time in the TL unit (0.99 min/cycle) was higher than the WT unit (0.82 min/cycle), even though bole-wood in the TL unit were already limbed and bucked at the stump (Figure 3 and Table 3). Processing cycle volumes in WT and TL units were 0.85 and 1.13 m$^3$/cycle, respectively. These results might be due to larger diameter trees in the TL unit. Processing production rates between WT and TL units were relatively similar throughout treatments due to higher cycle volume in the TL unit (Table 3).

Log trucks were loaded from a cold deck by a dedicated loader resulting in a consistent loading delay-free cycle time and production rate between the TL and WT units. Log trucks were loaded until the onboard scales read a loaded weight of ~25 tons. In our study, average loading time per truck was slightly longer in the WT unit compared to the TL unit, but there was no significant difference between two treatment units. Average loading production rates in WT and TL units were 60.5 m$^3$/PMH and 59.4 m$^3$/PMH, respectively.

**Delay-free cycle time regression equations**

Regression equations developed from the detailed time study predict delay-free cycle time for each machine. It evaluates all the associated independent variables for each cycle element to determine which factors influence the models. Equations were developed separately for WT and TL units. All models were validated using a paired t-test ($z = 0.05$). Differences between the observed and predicted delay-free cycle times for all equations in both units were insignificant ($p > 0.05$),
suggesting that the developed regression equations were good predictors (Tables 4 and 5).

In both units, the felling equation indicated that tree size, the use of wedge, and traveling distances between trees positively impacted the felling delay-free cycle time. The distance traveled between trees was directly related to thinning intensity. A stand with a heavier thinning prescription would require shorter traveling distances, resulting in shorter felling delay-free cycle time. In the WT unit, slope at the stump was also indicated as a significant variable affecting felling time (Table 4). The equation suggested an increase delay-free cycle time with an increase in slope. In the TL unit, the number of buck cuts was found to be one of the most significant variables influencing felling delay-free cycle time (Table 5). Similar results were also found in several past studies (Kellogg et al. 1986, 1999; Largo and Han 2004; Hartley and Han 2007). They reported that a large tree size had increased delay-free cycle times because it required increased amounts of time for cutting and bucking.

Yarding delay-free cycle times were positively influenced by lateral yarding and yarding distances, meaning that a decrease in lateral yarding and yarding distance would reduce yarding delay-free cycle time (Tables 4 and 5). However, this result should be carefully applied in conventional cable yarding systems requiring guylines because the use of shorter yarding and lateral distance would cause higher yarding costs due to an increase in skyline road changing time. Research from past studies found that the number of pieces or amount of volume per cycle were indicated as the most significant variable impacting yarding delay-free cycle time (Kellogg et al. 1986, 1999; Largo and Han 2004; Hartley and Han 2007). However, in our study, this variable was insignificant ($p > .05$) in

### Table 4. Delay-free average cycle time equations for whole-tree thinning. All variables included in the equations had significant $p$-value less than 0.05.

| Operations          | Average cycle time estimator (centi-min.) | Mean  | $n$   | $r^2$ | $C_p^a$ | Validation $p$-value$^b$ |
|---------------------|------------------------------------------|-------|-------|-------|---------|---------------------------|
| Chainsaw-felling    | **DFCT**                                   | 208   | 0.77  | 6.15  | 0.72    |                           |
|                     | = 235.497                                 |       |       |       |         |                           |
|                     | + 0.070 (DBH in centimeter)$^2$           | 30.2  |       |       |         |                           |
|                     | + 6.340 (move to tree distance in meter)  | 3.1   |       |       |         |                           |
|                     | − 59.116 lnd (slope in percent)           | 46.5  |       |       |         |                           |
|                     | + 78.082 (wedge)                         | 0.04  |       |       |         |                           |
| Yarding             | **DFCT**                                  | 156   | 0.37  | 4.31  | 0.51    |                           |
|                     | = 177.149                                 |       |       |       |         |                           |
|                     | + 1.941 (lateral distance in meter)       | 9.3   |       |       |         |                           |
|                     | + 0.845 (yarding distance in meter)       | 72.2  |       |       |         |                           |
| Processing          | **In(DFCT)**                              | 65    | 0.26  | 4.12  | 0.39    |                           |
|                     | = 4.128                                   |       |       |       |         |                           |
|                     | + 0.109 (number of logs per piece)        | 2.0   |       |       |         |                           |
| Loading             | **In(DFCT)**                              | 78    | 0.40  | 4.56  | 0.61    |                           |
|                     | = 3.539                                   |       |       |       |         |                           |
|                     | + 0.412 (number of logs)                  | 1.2   |       |       |         |                           |

$^a$Mellows’ $C_p$ statistic.
$^b$p-value provided by a paired $t$-test between predicted and observed cycle times.

### Table 5. Delay-free average cycle time equations for tree-length thinning. All variables included in the equations had significant $p$-value less than 0.05.

| Operations          | Average cycle time estimator (centi-min.) | Mean  | $n$   | $r^2$ | $C_p^a$ | Validation $p$-value$^b$ |
|---------------------|------------------------------------------|-------|-------|-------|---------|---------------------------|
| Chainsaw-felling    | **ln(DFCT)**                             | 188   | 0.82  | 6.25  | 0.76    |                           |
|                     | = 3.010                                   |       |       |       |         |                           |
|                     | + 0.031 (DBH in centimeter)               | 37.6  |       |       |         |                           |
|                     | + 0.243 ln$^2$ (move to tree distance in meter) | 11.4  |       |       |         |                           |
|                     | + 0.545 (number of bucking)              | 0.94  |       |       |         |                           |
|                     | + 0.298 (wedge)                          | 0.10  |       |       |         |                           |
| Yarding             | **DFCT**                                  | 121   | 0.78  | 6.78  | 0.81    |                           |
|                     | = 312.125                                 |       |       |       |         |                           |
|                     | + 3.619 (lateral distance in meter)       | 9.6   |       |       |         |                           |
|                     | + 0.875 (yarding distance in meter)       | 59.5  |       |       |         |                           |
| Processing          | **DFCT**                                  | 52    | 0.52  | 5.29  | 0.69    |                           |
|                     | = −32.280                                 |       |       |       |         |                           |
|                     | + 56.348 (number of cuts per piece)       | 2.4   |       |       |         |                           |
| Loading             | **DFCT**                                  | 76    | 0.38  | 4.06  | 0.29    |                           |
|                     | = 30.482                                  |       |       |       |         |                           |
|                     | + 27.915 (number of logs)                | 1.3   |       |       |         |                           |

$^a$Mellows’ $C_p$ statistic.
$^b$p-value provided by a paired $t$-test between predicted and observed cycle times.

$^c$DFCT: delay-free cycle time.

$^d$ln: natural logarithm.
predicting yarding delay-free cycle time. This difference might be a result of our data collection methods. Most of the yarding cycles had a consistent number of pieces (3 or 4 trees or bole-woods) for over 150 yarding cycles. Predictive equations covering various work conditions could have been generated if the operations were performed under different conditions. In all yarding cycles slope, turn volumes and material were fairly consistent.

The equations developed for processing indicated that the number of logs per piece was the only factor influencing delay-free cycle time for both WT and TL units (Tables 4 and 5). In the WT unit, tree size in DBH was excluded in the equation due to multicollinearity with the number of logs per cycle. For the loading cycle equations, the number of logs was found to be a significant variable to predict loading delay-free cycle time ($p < 0.05$).

**Fuel reduction thinning costs for WT and TL harvesting methods**

The overall stump-to-truck sawlog production costs (US$/m^3$) and percentage of total for WT and TL harvesting units were summarized in Table 6. Total sawlog production costs (stump-to-truck) were US$26.13/m^3 in the WT unit and US$24.01/m^3 in the TL unit. The main reason for this cost difference was due to the high yarding costs in the WT unit. Even though TL unit had longer yarding delay-free cycle time, smaller turn volume in the WT unit resulted in higher yarding costs. Yarding costs in both harvesting systems were the highest cost component (59% of total cost in WT units and 54% in TL units) of the total fuel reduction thinning using cable yarding system. Therefore, small increases in yarding productivity could significantly reduce the overall production costs. Yarding costs ($15.54/m^3$ in WT unit and US$13.07/m^3 in TL unit) in this study were comparable with those (US$13.42–US$16.60/m^3) found in a past study (Kellogg et al. 1999). However, in another skyline thinning study, yarding costs ranged from US$18.01/m^3 to US$22.60/m^3 (Kellogg et al. 1986). Lower yarding costs in our study were mainly caused by the higher turn volume (2.28 m^3/turn), compared to a past study (1.59–2.03 m^3/turn; Kellogg et al. 1986).

In hand-felling operations, the TL unit had higher production cost than the WT unit due to additional limbing and bucking activities to manufacture bole-wood at the stump. Similar results were also reported from Kellogg et al. (1999). They suggested that “limb and measure”, which accounted for the most felling delay-free cycle time, would provide the greatest opportunity to reduce felling costs. In our study, the mechanical delimber used on the landing at WT unit allowed 20% decrease in the felling costs. Felling costs (US$3.53/m^3 in WT units and US$4.24/m^3 in TL unit) in this study were comparable with those (US$3.53–US$3.88/m^3) found in a past study (Kellogg et al. 1986, 1999).

Processing cost in the WT unit was slightly higher than those in the TL unit. Although the TL harvesting method already limbed and bucked trees at the stump during felling operations, higher felling costs did not fully compensate lower processing costs. Loading costs for WT and TL units were same (US$2.83/m^3), because final manufactured log sizes and types between two different treatments were similar and loading occurred independently from other operation activities.

**Conclusion**

This field-based study was conducted to assess the economic feasibility of whole-tree (WT) and tree-length (TL) fuel reduction thinning using cable yarding systems. Total sawlog production costs (stump-to-truck) were US$26.13/m^3 in the WT harvested unit and US$24.01/m^3 in TL harvested unit. The difference in fuel reduction treatment methods greatly affected the cost and production of harvest operations, especially in felling and yarding production. As expected, tree size in both units greatly influenced felling productivity and cost. Limbing and bucking trees at the stump in the TL unit was found to be the major factor increasing delay-free cycle time. In yarning operation, although the WT unit had shorter yarding delay-free cycle time than the TL unit, higher production rate and lower production costs were found in the TL unit. This result was caused by mainly the differences in turn volume of the two units. As the turn volume of the logs increased, yarding productivity also increased significantly without impacting the overall average yarding delay-free cycle time. Processing time and production rates at a landing were relatively similar throughout treatments, although trees in the TL unit were already limbed and bucked at the stump. Lower processing cost in the TL unit was not enough to offset additional costs incurred by manually processing trees at the stump during felling operation. Loading productivities and costs were consistent throughout treatments because loading occurred independently from other activities. Log trucks were loaded from a cold deck by a loader, resulting in a consistent production in loading between two treatments.

Our study indicated that TL harvesting was more cost-effective than WT harvesting. It should be noted that TL operations leave tree tops and branches on site, which may not be acceptable from a fuels management perspective. It should be noted that this case study was developed under specific work and stands conditions. Therefore, these results should be used cautiously and applied to similar stands and machine.

| Table 6. Stump-to-truck sawlog production costs (US$/m^3) and percentage of total for whole-tree and tree-length units. |
|---------------------------------|---------------------------------|
| **Whole-tree (WT)** | **Tree-length (TL)** |
| **Cost (US$/m^3)** | **Percent of total** | **Cost (US$/m^3)** | **Percent of total** |
| Hand-felling | 3.53 | 13 | 4.24 | 18 |
| Yarding | 15.54 | 59 | 13.07 | 54 |
| Processing | 4.24 | 16 | 3.88 | 16 |
| Loading | 2.83 | 11 | 2.83 | 12 |
| Total | 26.13 | 100 | 24.01 | 100 |
configurations because the economic feasibility of different thinning methods using a cable yarding system is often determined by the thinning intensity and biomass utilization. Therefore, further replications of this study would be needed in order to increase confidence in the applicability of its conclusion to other situations.

Disclosure statement
No potential conflict of interest was reported by the authors.

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