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Cost and Productivity of Tethered Cut-to-Length Systems in a Dry-Forest Fuel-Reduction Treatment: A Case Study

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Fuel-reduction treatments on steep slopes across federal forests of the western United States have been limited by the high costs associated with cable logging on steeper slopes combined with poor market prospects for small-diameter material (Bolding 2003, Rummer 2008, Han et al. 2016). The emergence of tethered cut-to-length harvesting systems and small wood markets (e.g., biochar) could decrease costs and increase revenue generated from treatments. Over the course of 3 weeks, we observed both tethered (steeper slopes) and untethered cut-to-length fuel-reduction treatment on the Fremont-Winema National Forest in south-central Oregon and interviewed operators. We used those data to derive and contrast hourly costs and productivity for the harvester and forwarder. This was the first time a tethered harvester and forwarder were used in a fuel-reduction treatment on federal forests in this region. We developed and tested a variety of work time model forms for each machine. The mean utilization rate for the harvester was 64 percent on 17 tethered consolidated corridors but 87 percent on 28 untethered consolidated corridors. Similarly, the forwarder had a mean utilization rate of 76 percent on 30 tethered trips and 89 percent on 114 untethered trips. This reduced utilization rate could be because of the direct effects of tethering, the increased complexities of operations associated with steeper slopes, and the stand characteristics (e.g., lower stand density and tree sweep) associated with steeper slopes. Costs during tethered operations were higher than during nontethered operations, but lower than previous reports using cable logging.

Keywords: steep slope harvesting, forest restoration, cable assist logging

Wildland fire is a subject of continuing concern in western North American forests. Most dry western forests evolved in concert with fire, adapting to it, or even becoming reliant on it to maintain some plant communities and stand structures (Lotan 1976, Ryan et al. 2013). For most of the 20th century, the dominant response to wildland fire was immediate suppression. Combined with grazing and other land-management practices, particularly on federal lands, this eventually led to overstocking of trees, vigor loss, and ultimately increases in fire intensity, severity, and size. Although this change has been developing over the past few decades, there is a growing recognition of the detrimental effects of fire exclusion, opening the way for prescribed fire, wildland fire use, and fuels treatments to attempt to address the problem (Stephens and Ruth 2005). However, in the mountainous west of the United States, many stands are considered unsuitable for fuels treatments because of constraints imposed by steep slopes (North et al. 2015). The dry forests of the Klamath Basin in southern Oregon and northern California provide an example of this situation. Jain et al. (2012) rated 86.4 percent of forest land in the region as being in a "hazardous" state. Jain et al. (2012) also identified 41 percent of the western states dry forest area as being on slopes of greater than 40 percent. In addition, no local small-diameter wood markets exist to absorb the lower-quality material, requiring it to be piled and burned on site and further increasing the cost of treatment. Arriagada et al. (2008) simulated harvesting timber for fuel-reduction purposes on 12,039 Forest Inventory and

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Analysis (FIA) plots from 12 states in the West using six harvesting methods. Ground-based methods, where they could be used on flatter slopes, were about 25–50 percent of the cost of the cable logging methods on the steeper slopes.

Two technologies are being studied to identify possible solutions to these problems: tethered cut-to-length harvest systems and biochar production. Tethered cut-to-length systems may have the potential to bring a lower cost option to steep slopes as compared to cable systems. Stampfer (2016) suggested that for thinning in central Europe, the harvest cost per cubic meter for a harvester and forwarder was one-half the cost of chainsaw felling, cable yarding, and processing at the landing. The use of a tethered harvester and tethered forwarder was more expensive, but was still only two-thirds the cost of the cable yarding option. Interest in harvesting on steep slopes with harvesters and forwarders is widespread (e.g., Bolding and Lanford 2002, Amishev et al. 2009, Ghaffariyan et al. 2012, Flint 2013, Berg et al. 2017, Strandgard et al. 2017, Holzfeind et al. 2018). However, direct comparisons between studies is difficult, as studies are widely spread around the world under a variety of conditions (Lindroos and Cavalli 2016).

Biochar, a relatively new forest product used as a soil amendment in the horticultural and agricultural industries, could provide a market for small-diameter material that is currently nonmerchantable in this region. This study looks to fill in some of the gaps in both technologies, describing the cost, productivity, and behavior of tether-equipped cut-to-length systems on a fuel-reduction treatment on the Fremont-Winema National Forest in south-central Oregon and, by extension, the cost and availability of potential biochar feedstock under those same conditions. One question to be addressed is whether tethering behaves like a fixed or variable cost. Cut-to-length operations using harvesters and forwarders are a small but growing harvest method in Oregon with perhaps 25 pairs of machines currently operating in Oregon. This study documents the first tethered harvester–forwarder operation on the Fremont-Winema National Forest, and this particular timber sale was modified to permit this experiment.

Methods

We gathered data in two ways, direct observation of harvest operations and direct correspondence with both the logging contractor (Miller Timber Services, Philomath, Oregon) and a representative of the equipment manufacturer (Ponsse North America, Coburg, Oregon).

Direct Observation

Field observations were recorded between July 12, 2016 and July 29, 2016 on Pilot Project Unit 10 on the Bly Ranger District, Fremont-Winema National Forest in south-central Oregon. These observations include felling, processing, decking, forwarding, and piling activities on 10.9 hectares (27 acres), approximately 43 percent of the 25.5 hectares (63 acres) that were treated in total. The unit is a dry mixed-conifer stand ranging between 1,800 and 1,900 m in elevation. Slopes ranged from 12 to 70 percent with a mean slope of 38 percent. Soils were primarily loamy-skeletal, derived from a parent material of ash over top of basalt (R. Rone, personal communication, 2017). No precipitation occurred during the period of observation. The pretreatment stand was dominated by white fir (*Abies concolor*) and ponderosa pine (*Pinus ponderosa*) with scattered conifers of other species.

The pretreatment stand averaged 33.3 square metres of basal area per hectare (145 square feet of basal area per acre), with a treatment goal of thinning down to a mean of 11.5 square metres of basal area per hectare (50 square feet per acre) with a "clumpy" distribution of leave trees throughout the landscape (Figure 1). Trees were preferentially chosen for removal by size, species, and vigor. Smaller trees were preferentially removed, to a maximum diameter of 53.3 cm (21 in.). Species removal preferences targeted western juniper (*Juniperus occidentalis*), lodgepole pine (*Pinus contorta*), white fir, incense-cedar (*Calocedrus decurrens*), and ponderosa pine, in that order. Unhealthy trees were also preferentially removed, except for five needle pines (*Pinus lambertiana* and *Pinus monticola*), which were retained regardless of all other considerations.

Cutting and processing were carried out using a Ponsse Bear harvester (Figure 2). The Ponsse Bear weighs approximately 24.5 tonnes with 240 kW of engine power and a boom with a reach of 10 m. Logs were extracted with a Ponsse Elephant King forwarder. The Ponsse Elephant King has 210 kW of engine power with a boom reach of 9.5 m and is rated for a maximum carrying capacity of 20 tonnes. Both machines use an eight-wheeled double-bogey design. Each machine was run by a single, highly experienced operator for the duration of observation. Both machines were tether-equipped; when and where each machine would tether was left to each operator's discretion. A few trees were marked on the first day of operations to aid the harvester operator in identifying which trees to cut and the desired density of tree retention. After the first day, neither corridors nor individual trees were preselected or marked, leaving decisions regarding navigation and tree selection to the harvester operator's discretion. In general, the forwarder would follow in the harvester's path, but only after the harvesting had been completed. All forwarding for the duration of observation was adverse (uphill travel when loaded) or done along roads of low gradient. The majority of logs were taken to one of 10 roadside decks to await truck loading. All log transport was carried out using straight bed trucks with log bunks pulling a short log trailer (maximum log length of roughly 8 m) with a maximum log capacity of approximately 30 tonnes. All loading was carried out by the forwarder.

Operations were recorded using a pair of hat-mounted GoPro Hero Silver 4 cameras, one worn by each operator for the duration of each shift, excluding fire watch (a period of 1–2 h at the end of each shift spent watching for signs of any accidental ignitions that could have occurred during that shift). Each camera

Management and Policy Implications

Fuel-reduction treatments on steep slopes across federal forests of the western United States have been limited by the high costs associated with cable logging on steeper slopes combined with poor market prospects for small-diameter material. A timber sale on the Fremont-Winema National Forest, the first of its type on federal lands in the region, illustrated the potential for tether-assisted harvesters and forwarders to provide fuel-reduction treatments in mountain forests. The need for tethering, although related to slope steepness, was heavily influenced by ground surface conditions. Costs during tethered operations were higher than during nontethered operations, but lower than previous reports using cable logging.

Figure 1. Stand conditions before treatment (above) and after treatment (below) on Pilot Project Unit 10 on the Fremont-Winema National Forest (photo taken by the lead author, Joshua Petitmermet).

used on-board power via a USB cable to avoid the need to change batteries. Recordings were saved in-camera to Samsung Pro Plus 128 GB MicroSDXC memory cards. Memory cards were changed twice per day, once at midday and once at shift's end. Each time memory cards were changed, the video on the card was transferred to one of several external hard drives. The camera for each machine was turned on when that machine was turned on for the day, and turned off when that machine was shut down at the end of each shift. To aid in corridor identification and measurement, the treatment area was flown over via drone on August 8, 2016, and the resulting images were stitched together into a georeferenced photograph (Figure 3).

Correspondence

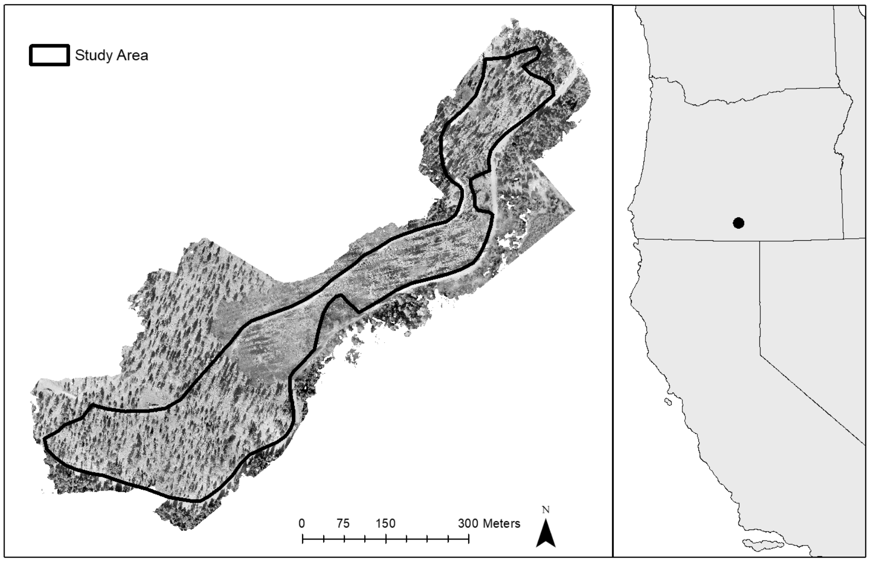
To obtain information on costs, the authors corresponded with both a representative of the manufacturer and a representative of the logging contractor. In general, the manufacturer was asked for specific information pertaining to machine costs, and the contractor was invited to comment on that information. Much of the requested cost data is highly variable and/or considered confidential, so the numbers presented here should be treated as reasonable approximations, not exact values. To describe some of this uncertainty, the information from correspondence was used to generate a "low-cost" machine rate scenario and "high-cost" machine rate scenario using the machine rate format described by Brinker et al. (2002).

Field Data Processing

Recordings were processed manually using Windows Media Player. Each video was partitioned into three components: active time, delay time, and excise time. Active time was defined as all time in which some part of the machine was in motion, including any delays of less than 30 s. Delay time was defined as all time in which the machine was inactive for longer than 30 s, including breaks, lunches, and both administrative and mechanical delays. Excise time was defined as all delays of any length that were incurred as a direct result of this study. In general, excise time consisted of 5–6 min per machine per day, the time required to change memory cards in each camera. Excise time was excluded from analysis.

The time for each video was further partitioned into units of interest. For the harvester, the sole unit of interest was the corridor. For the forwarder, the units of interest were the bunk (while forwarding) and the truck (while loading short log trailers). Forwarder bunks were further identified as being one of three types: productive, deck

Figure 2. Ponsse Elephant King forwarder (above) and Ponsse Bear harvester (below) on tethered thinning operations in the Oregon Coast Range (photo taken by the lead author, Joshua Petitmermet).



State boundary data taken from Unites States Geological Survey
National Boundary Dataset, available online at [viewer.nationalmap.gov]

Figure 3. Study location and area of observed operations, Pilot Project Unit 10, Fremont-Winema National Forest, Oregon.

(pile) consolidation, and carriage. Productive bunks are all those where previously ungathered material is collected and deposited to a deck or roadside. Deck consolidation bunks are all those where the forwarder moves parts of a pre-existing roadside deck to another deck, generally when less than a single truck load remains in the first deck. Carriage bunks are a specific case of deck consolidation bunk created when the forwarder loads several bunks on short, steep corridors without untethering, unloading those bunks temporarily at roadside and then returning to reload and move that material to a deck. Time spent on deck consolidation bunks was prorated to all productive bunks to account for that time in a uniform manner; time spent on carriage bunks was prorated among all productive bunks in the corridor that produced those carriage bunks.

A tally of pieces (logs) loaded and the associated corridor of origin was kept for each bunk and truck. Each piece counted was classified as a saw log, or a "feedstock" log. Saw logs were defined as those of commercial species and grades acceptable to local mills, predominantly white fir and ponderosa pine with minimal defect to a 15.2 cm (6 in.) top. Feedstock logs are all those of species or conditions unacceptable to local mills that could be transported in log form for use as feedstock for processing into biochar. This includes logs of any species to a 10.2 cm (4 in.) top, and saw logs rejected because of sweep, damage, or defect. Because of the lack of an existing pulp or biochar market in the region, feedstock logs were loaded onto trucks for weighing, and then unloaded into piles for burning at a later date.

Only the front bunk of each short log trailer was used for feedstock weighing, and time spent unloading feedstock logs after weighing was treated as excise time for the purposes of analysis. Utilization rates, defined as the active time divided by the total time, were calculated for each corridor and bunk observed. A mean utilization rate for each machine was calculated as the time-weighted mean of those observed utilization rates. Utilization rates were not calculated for truck loading. The majority of observed delay time associated with truck loading was administrative; time used by the operator filling out forms for the mill and landowner. Since all feedstock logs remained on site, those delays only occurred on saw log loads, creating the illusion of a significant gap in utilization rates. To address this, all truck loading rates were calculated in terms of productive hours only.

The piece counts and truck weights were used to calculate a mean piece weight for each material type by pile and for the stand as a whole. The stand mean values were then used to calculate the weight of material removed by the forwarder with each bunk (aka "turn" or "trip") as well as the weight of material produced by the harvester in each corridor. In several cases, corridors had to be consolidated for analysis because of the difficulty in determining the weight associated with that corridor. Corridors were only consolidated if they were adjacent to each other and either all tethered or all untethered. Individual bunk information was also summed for each corridor for the purpose of work time analysis. The bunk may be the most intuitive modeling unit for the forwarder, but multiple bunks in the same corridor violate any assumption of independence among observations. What the forwarder does on one bunk in a corridor inherently determines the distance traveled and the quantity and type of material collected for all subsequent bunks in that same corridor.

All cubic volume estimates were calculated as a function of green weights based on USDA Forest Service FIA protocols for calculating species-specific bark and wood weights from green volumes. All specific gravities and bark volume were taken directly from the values provided in the most recently released FIA dataset for the state of Oregon (United States Department of Agriculture 2017). With an estimated species mix of 70 percent white fir and 30 percent ponderosa pine, we obtained a conversion ratio of 1.5 cubic meters per green tonne (48.9 cubic feet per green US ton). Conversion to dry weights will vary by season, length of time decked, and species. Although our field measurements and base costs were made on green weights, an assumed mean moisture content of 42 percent wet basis (72 percent dry basis) was used for conversion to dry weight cost based on summer data in southern Oregon reported by Kim and Murphy (2013).

All board-foot volume estimates were calculated as a function of cubic volume estimates, using the board feet per cubic foot of bolewood inside bark ratios established by Keegan et al. (2010). Specifically, we used the Westside Scribner ratio for the state of Oregon: 148 board feet per cubic meter (4.2 board feet per cubic foot) for our cost conversions. Applied to the wood-only volume estimates of our 70/30 species mix, this results in 0.20 thousand board feet (MBF) per green tonne (0.18 MBF per green US ton). This may differ from locally scaled volume, as both Eastside and Westside Scribner rules are used in Oregon, with the crest of the Cascade mountain range as the line of demarcation between them (Fonesca 2005). When comparing costs to other harvesting studies that use board-foot scale, addressing log scale in comparable units is important.

The length of each corridor and transit distance for each bunk were measured in ArcMap 10.4 using post-treatment drone photos and, where necessary, natural landmarks identified in the harvester and forwarder videos. The length of a corridor was defined as the total distance traveled between the start of one corridor and the next, with the start of each corridor being defined by the first tree cut or the first harvester tread going off road, whichever occurred first. The transit distance for each bunk was defined as the total pile-to-pile distance, starting from the pile where the last log of the previous bunk was unloaded to the pile where the last log of the current bunk was unloaded.

Model Building

After processing, the information for both machines was imported into RStudio for analysis and model building. These models are intended to find an effective means of estimating the time required to treat a given area and to answer a key question: does tethering behave like a fixed or variable cost? Can it be accurately described solely by the delay time required to tether and untether, or is there an ongoing productivity cost incurred by reduced mobility and/or increased difficulty in material handling while tethered? Machine travel distance-tethered and distance-untethered were introduced as potential explanatory variables to represent the joint effect of slope and soil conditions (power, traction, and disturbance). Strandgard et al. (2017), observing non-tethered forwarders on slopes up to 45 percent, found that slope did not have a significant effect on work time or productivity, but that corridor work time was significantly influenced by extraction distance. Berg et al. (2017), studying untethered forwarders on –50 to +50 percent slope, found that including slope explained little of the variation in individual trip cycle time. However, Bolding (2002) had observed that slope was a significant variable for predicting total productive time for a Ponsse Ergo Harvester on slopes from 0 to 46 percent.

Several methods have been used for model building. Some researchers have created models for discrete elements of the single trip time and summed the elements to explain cycle time (e.g., Dykstra 1976, Nurminen et al. 2006), and others have explained individual trip time directly by a linear combination of factors (e.g.,

Table 1. Machine rate method inputs by machine and machine rate scenario.

Machine	Harvester		Forwarder	
Machine rate scenario	High cost	Low cost	High cost	Low cost
Purchase price ($)	950,000	850,000	750,000	650,000
Machine life (years)	5	5	5	5
Salvage rate (percent)	40	50	40	50
Mean utilization rate (percent)	78	78	86	86
Repair and maintenance (percent)	30	15	30	15
Interest (percentage of mean investment)	10	10	10	10
Insurance/tax (percentage of mean investment)	4	4	4	4
Fuel consumption (liters per hour)	40.54	40.54	27.90	27.90
Fuel cost ($ per liter)	0.64	0.64	0.64	0.64
Lube and oil (percent)	36.7	36.7	36.7	36.7
Wage/benefit ($/hour)	35	35	35	35
Scheduled hours (hours per year)	2,000	2,000	2,000	2,000
Yearly fire watch (percent)	30	30	30	30
Mean shift length (hours)	12	12	12	12
Mean fire watch length (hours)	1.5	1.5	1.5	1.5
Total cost per scheduled hour ($/h)	188	155	160	131
Total cost per productive hour ($/h)	242	199	186	152

Ledoux and Huyler 1992), rather than summing individual trip elements (e.g., travel out, load, forward, unload). We take a third approach. We estimate the total trip time to complete a corridor, rather than the time to complete an individual trip. We believe this has several advantages over the other approaches. What happens in the next work element is often influenced by the last work element, or planning for the subsequent work element, and so they are not independent. Regressing corridor trip time on the independent variables for the harvesting corridor smooths out this interaction and, as we will see, produces a much better fit than is typically observed at the individual trip level. Some interaction still exists: where the operator places one harvesting corridor is dependent on the adjacent corridor. The use of time per corridor has the penalty of requiring observation over a greater period to provide an adequate sample size.

A number of approaches have been used to identify the best-fitting model. Stepwise regression has been perhaps the most common method used following the algorithm proposed by Efroymson (1960). In each step, a variable is considered for addition to or subtraction from the set of explanatory variables based on some prespecified criterion, often a sequence of *F*-tests. The method has been criticized for overfitting, and some have called for its use to be discontinued (e.g., Snyder 1991). Other techniques have been developed that penalize the number of explanatory parameters such as the Akaike information criterion (AIC) (Akaike 1974) and Bayesian information criterion (BIC) (Schwarz 1978). BIC generally penalizes explanatory parameters more heavily than AIC. AIC attempts to find the model that gives the best prediction without assuming any of the models were correct, whereas BIC assumes one of the models is the true model and tries to find the true model (Dziak et al. 2012). The so-called corrected AIC model, or second-order estimate, AIC_c, developed by Hurvich and Tsai (1989), slightly increased the parameter weighting. We chose to use AIC_c to identify the most predictive model. AIC_C predicts the relative likelihood of one model being correct for a given data set when compared to another, and is expressed as both an AIC_C score and an evidence ratio (Motulsky and Christopoulos 2004).

The following model forms were considered for both machines:

$$\mathrm{PMM} = \beta_1 \mathrm{ctot} + \beta_4 \mathrm{cdi}. \tag{1}$$

$$\mathrm{PMM} = \beta_2 \mathrm{utot} + \beta_3 \mathrm{ttot} + \beta_4 \mathrm{cdis}. \tag{2}$$

$$\mathrm{PMM} = \beta_1 \mathrm{ctot} + \beta_5 \mathrm{udis} + \beta_6 \mathrm{tdis}. \tag{3}$$

$$\mathrm{PMM} = \beta_2 \mathrm{utot} + \beta_3 \mathrm{ttot} + \beta_5 \mathrm{udis} + \beta_6 \mathrm{tdis}. \tag{4}$$

$$\mathrm{PMM} = \beta_4 \mathrm{cdis} + \beta_7 \mathrm{csaw} + \beta_{10} \mathrm{cbf}. \tag{5}$$

$$\mathrm{PMM} = \beta_5 \mathrm{udis} + \beta_6 \mathrm{tdis} + \beta_7 \mathrm{csaw} + \beta_{10} \mathrm{cbf}. \tag{6}$$

$$\mathrm{PMM} = \beta_4 \mathrm{cdis} + \beta_8 \mathrm{usaw} + \beta_9 \mathrm{tsaw} + \beta_{11} \mathrm{ubf} + \beta_{12} \mathrm{tbf}. \tag{7}$$

$$\begin{aligned}\mathrm{PMM} = {} & \beta_5 \mathrm{udis} + \beta_6 \mathrm{tdis} + \beta_8 \mathrm{usaw} \\ & + \beta_9 \mathrm{tsaw} + \beta_{11} \mathrm{ubf} + \beta_{12} \mathrm{tbf}.\end{aligned} \tag{8}$$

where: PMM is the time required to complete the corridor, in productive minutes; ctot is the total weight of material produced in the corridor, in green tonnes; cdis is the total distance traversed in the corridor, in meters; utot is the weight of material produced while untethered, in green tonnes; ttot is the weight of material produced while tethered, in green tonnes; udis is the untethered distance traversed in the corridor, in meters; tdis is the tethered distance traversed in the corridor, in meters; csaw is the weight of saw-log material produced in the corridor, in green tonnes; cbf is the weight of biochar feedstock produced in the corridor, in green tonnes; usaw is the weight of saw-log material produced while untethered, in green tonnes; tsaw is the weight of saw-log material produced while tethered, in green tonnes; ubf is the weight of biochar feedstock produced while untethered, in green tonnes; and tbf is the weight of biochar feedstock produced while tethered, in green tonnes.

Models were named H1 through H8 for the harvester and F1 through F8 for the forwarder, corresponding to the equation numbers listed above. Values for the independent variables are listed in Table 3. All model fitting was performed with RStudio's built in lm() function. AIC_C scores were computed using the AIC_C() function from the MuMIn R package v1.15.6. Although stepwise regression is not used in the AICc procedure, all *P*-values reported in relation to individual variables were generated via *t*-test by the lm() function and are equivalent to the *P*-value obtained by an extra sum of squares *F*-test comparing models with and without that variable.

Results and Discussion

Utilization and Productivity

A total of 107 h of video across 45 consolidated corridors (made from 61 individual corridors) was collected and analyzed for harvester operations. The harvester demonstrated a mean utilization rate of 87 percent on the 28 fully untethered consolidated corridors and 64 percent on the 17 fully or partially tethered consolidated corridors, providing an overall mean utilization rate of 78 percent. The tethered utilization may be an underestimation of the true mean because of three long duration delays that occurred during tethered observation: a cable break, a fire weather shut down, and a hose break that required driving to a nearby town for a replacement part. Those three incidents alone accounted for a nearly 4.5 h of delay, more than a quarter of the total delay time observed for the harvester.

For the forwarder, a total of 131 h of video was collected and analyzed, comprising 95 h of forwarding across 144 bunks and 36 h of loading across 49 trucks. Of the 144 bunks, 131 were productive bunks, with eight pile consolidation bunks and five carriage bunks. The forwarder mean utilization rate was 89 percent on the 114 untethered bunks, 76 percent on the 30 tethered bunks, yielding a mean of 86 percent overall. On mean, each bunk carried 11.9 tonnes, with a mean of 11.1 tonnes per bunk while tethered and 12.2 tonnes per bunk while untethered. In nearly all cases, the limiting factor appeared to be bunk volume, rather than load weight, regardless of tether status. Of 49 truck loadings observed, 36 were saw log loads, and 13 were feedstock log loads. According to our per-bunk and per-corridor calculations, the total weight of feedstock logs removed in the area of observation was equal to 27 percent of the total weight for all material. According to the final weight tallies and mill receipts for all 25.5 hectares (63 acres) treated, the total weight of feedstock logs (812 green tonnes) produced during treatment was 25 percent of the total for all material (3,225 green tonnes).

Both the harvester and forwarder demonstrated a notable drop in mean productivity while tethered (Table 2), but it is important to note that this may not be a direct result of tethering itself. The steeper sections of the site often had lower stocking, smaller trees, and intermittent rock outcroppings, each being likely to reduce productivity independently of slope or tether use.

Table 2. Observed rates of machine utilization and production.

		Tethered	Untethered	Mean
Harvester utilization	Percentage active time	64	87	78
Harvester production	Green tonnes per SMH	9.5	16.5	13.6
	m^3 per SMH	14.5	25.2	20.8
	MBF per SMH	1.9	3.3	2.7
Forwarder utilization	Percentage active time	76	89	86
Forwarder production	Green tonnes per SMH	13.5	17.8	16.7
	m^3 per SMH	20.6	27.2	25.5
	MBF per SMH	2.7	3.6	3.3
		Feedstock logs	Saw logs	Mean
Forwarder loading	Green tonnes per PMH	35.3	59.4	48.4
	m^3 per PMH	53.9	90.7	73.9
	MBF per PMH	7.0	11.8	9.7

Lower productivity is also seen when comparing the loading of feedstock and saw logs on to trucks, but the explanation in that case is much clearer. Feedstock logs are considerably smaller and more irregular in size and shape, requiring more time and care in grabbing, moving, and packing. Similarly, feedstock logs are far more likely to be “fumbled” and drop out of the forwarder’s grip while in motion, requiring a second motion for retrieval.

Machine and Logging Cost

Machine costs were calculated using the machine rate methods described by Brinker et al. (2002). Machine cost, machine life, and salvage value were provided by the manufacturer. Fuel consumption was based on mean fuel consumption during the period of data collection. We added an additional estimate of $1.31 per scheduled hour to account for costs associated with fire watch service required under Oregon statute, depending upon fire district and fire level, which can be up to 3 h in length.

The high-cost machine rate scenario generated harvester costs of $188 and $242 per scheduled and productive machine hour respectively and forwarder costs of $160 and $186 per scheduled and productive machine hour respectively. The low-cost machine rate scenario generated harvester costs of $155 and $199 per scheduled machine hour and productive machine hour respectively and forwarder costs of $131 and $152 per scheduled and productive machine hour respectively. These scheduled and productive hour costs do not include contractor profit and risk allowance, supervision, administration, or the fixed cost of equipment mobilization. These costs include our firewatch cost estimate of $1.31 per scheduled hour for both machines ($1.68 and $1.53 per productive machine hour for the harvester and forwarder respectively).

If we assume that both feedstock and saw logs can be sold, the stump-to-truck costs (including loading) are $27.30 and $25.22 per green tonne ($24.77 and $22.88 per green US ton) for feedstock and saw logs respectively under the high-cost machine rate scenario and $23.09 and $21.34 per green tonne ($20.95 and $19.36 per green US ton) for feedstock and saw logs respectively under the low-cost machine rate scenario. On a cubic volume basis, this results in estimated stump-to-truck costs of $17.87 and $16.51 per cubic meter ($0.51 and $0.47 per cubic foot) for feedstock and saw material respectively under the high-cost machine rate scenario, and $15.12 and $13.97 per cubic meter ($0.43 and $0.40 per cubic foot) under the low-cost machine rate scenario. On a board-foot

Table 3. Mean, minimum, and maximum observed values for proposed harvester and forwarder model variables (n = 45).

			Harvester			Forwarder		
Variable	Variable description	Unit	Mean	Minimum	Maximum	Mean	Minimum	Maximum
cdis	Total distance traversed in corridor	m	228.8	20.1	1,410.3	798.8	82.3	5,349.8
udis	Untethered distance traversed in the corridor	m	244.1	0.0	1,410.3	581.4	0.0	2,301.2
tdis	Tethered distance traversed in the corridor	m	203.7	0.0	634.3	217.3	0.0	3,386.3
ctot	Total weight of material produced in corridor	Green tonnes	34.7	0.2	200.0	34.8	1.3	193.1
utot	Weight of material produced while untethered	Green tonnes	37.9	0.0	200.0	27.4	0.0	137.3
ttot	Weight of material produced while tethered	Green tonnes	29.5	0.0	70.1	7.4	0.0	145.1
csaw	Weight of saw-log material produced in corridor	Green tonnes	22.4	0.2	140.6	25.5	1.3	135.7
usaw	Weight of saw-log material produced while untethered	Green tonnes	27.0	0.0	140.6	19.7	0.0	111.3
tsaw	Weight of saw-log material produced while tethered	Green tonnes	22.4	0.0	60.9	5.8	0.0	117.2
cbf	Weight of biochar feedstock produced in corridor	Green tonnes	9.6	0.0	59.5	9.2	0.0	57.4
ubf	Weight of biochar feedstock produced while untethered	Green tonnes	11.1	0.0	59.5	7.6	0.0	35.8
tbf	Weight of biochar feedstock produced while tethered	Green tonnes	7.1	0.0	22.6	1.6	0.0	27.9

volume basis (Westside Scribner), this results in estimated stump-to-truck costs of $137 and $126 per MBF of feedstock and saw logs respectively under the high-cost machine rate scenario and $116 and $107 per MBF of feedstock and saw logs respectively under the low-cost machine rate scenario. We recognize that the use of a mean board-foot scaling conversion underestimates the cost differences between the feedstock and saw logs on a board-foot basis, as the saw log is larger than the feedstock material.

When there is no market for feedstock logs, as at the time of observation, that feedstock material is piled and burned at the roadside, incurring an additional burning cost of approximately $13.34 per hectare (P. Cheng, personal communication, 2017). If we assume that the saw logs must also bear the costs of cutting, gathering, piling, and burning the feedstock material (business as usual), the estimated stump-to-truck cost of saw log material rises to $32.75 per tonne, $21.44 per cubic meter, and $164 per MBF under the high-cost machine rate scenario and $27.74 per tonne, $18.16 per cubic meter, and $139 per MBF under the low-cost machine rate scenario. The estimation of these "business-as-usual" costs was not the original intent of the study, but they are a useful benchmark for comparison. The business-as-usual cost serves as the most accurate estimate of stump-to-truck treatment costs at the time of the study and as a worst-case (highest-cost) scenario for the immediate future, should a market for feedstock material fail to develop.

Model Results and Implications

The strongest corridor time model differed between machines. The harvester model was strongest with the simplest model (Table 4). The use of only total weight of material produced and total distance traveled, Model H1, provided the best fit of the eight model forms tested. When those totals were partitioned by tether status or material type, the coefficients for those subgroups proved nearly identical to the total and each other in all cases. This suggests that the harvester use was largely insensitive to both material size

Table 4. Summary of harvester models.

Model	Adjusted R^2	Variable	Intercept	ctot	utot	ttot	cdis	udis	tdis	csaw	usaw	tsaw	cbf	ubf	tbf
		β	0	1	2	3	4	5	6	7	8	9	10	11	12
		Units	NA	Green tonnes	Green tonnes	Green tonnes	m	m	m	Green tonnes	Green tonnes	Green tonnes	Green tonnes	Green tonnes	Green tonnes
H1	0.9412	Coefficient	8.11	1.38	–	–	0.24	–	–	–	–	–	–	–	–
		P-value	.138	<.001	–	–	<.001	–	–	–	–	–	–	–	–
H2	0.9412	Coefficient	10.03	–	1.41	1.21	0.23	–	–	–	–	–	–	–	–
		P-value	.085	–	<.001	<.001	<.001	–	–	–	–	–	–	–	–
H3	0.9412	Coefficient	9.95	1.33	–	–	–	0.25	0.22	–	–	–	–	–	–
		P-value	.087	<.001	–	–	–	<.001	<.001	–	–	–	–	–	–
H4	0.9399	Coefficient	10.14	–	1.38	1.25	–	0.24	0.23	–	–	–	–	–	–
		P-value	.087	–	<.001	<.001	–	<.001	<.001	–	–	–	–	–	–
H5	0.9398	Coefficient	8.12	–	–	–	0.24	–	–	1.38	–	–	1.34	–	–
		P-value	.143	–	–	–	<.001	–	–	<.001	–	–	.02	–	–
H6	0.9398	Coefficient	10.02	–	–	–	–	0.25	0.22	1.35	–	–	1.22	–	–
		P-value	.09	–	–	–	–	<.001	<.001	<.001	–	–	.039	–	–
H7	0.9384	Coefficient	10.17	–	–	–	0.24	–	–	–	1.43	1.24	–	1.28	0.97
		P-value	.09	–	–	–	<.001	–	–	–	<.001	<.001	–	.04	.396
H8	0.9368	Coefficient	10.25	–	–	–	–	0.24	0.23	–	1.41	1.26	–	1.23	1.11
		P-value	.09	–	–	–	–	<.001	<.001	–	<.001	.001	–	.064	.414

Table 5. Summary of forwarder models.

Model	Adjusted R^2	Variable	Intercept	ctot	utot	ttot	cdis	udis	tdis	csaw	usaw	tsaw	cbf	ubf	tbf
		β	0	1	2	3	4	5	6	7	8	9	10	11	12
		Units	NA	Green tonnes	Green tonnes	Green tonnes	m	m	m	Green tonnes	Green tonnes	Green tonnes	Green tonnes	Green tonnes	Green tonnes
F1	0.9072	Coefficient	1.72	2.11	--	--	0.05	--	--	--	--	--	--	--	--
		P-value	.775	<.001	--	--	<.001	--	--	--	--	--	--	--	--
F2	0.9128	Coefficient	7.66	--	2.17	2.9	0.03	--	--	--	--	--	--	--	--
		P-value	.241	--	<.001	<.001	.054	--	--	--	--	--	--	--	--
F3	0.9157	Coefficient	6.93	2.34	--	--	--	0.02	0.06	--	--	--	--	--	--
		P-value	.258	<.001	--	--	--	.228	<.001	--	--	--	--	--	--
F4	0.914	Coefficient	6.48	--	2.36	2.2	--	0.02	0.06	--	--	--	--	--	--
		P-value	.322	--	<.001	.003	--	.252	.037	--	--	--	--	--	--
F5	0.9104	Coefficient	1.94	--	--	--	0.04	--	--	1.92	--	--	3.29	--	--
		P-value	.742	--	--	--	.004	--	--	<.001	--	--	<.001	--	--
F6	0.9242	Coefficient	8.62	--	--	--	--	0.001	0.05	2.11	--	--	4.11	--	--
		P-value	.143	--	--	--	--	.95	<.001	<.001	--	--	<.001	--	--
F7	0.921	Coefficient	8	--	--	--	0.02	--	--	--	2.04	2.14	--	3.43	7.52
		P-value	.203	--	--	--	.303	--	--	--	<.001	.001	--	<.001	<.001
F8	0.9233	Coefficient	7.12	--	--	--	--	0.002	0.05	--	2.2	1.5	--	3.98	6
		P-value	.252	--	--	--	--	.919	.067	--	<.001	.047	--	<.001	.012

and tether status, given the conditions on our site. This, in turn, implies that tethering on the harvester may function as a fixed cost, incurring delays because of the physical act of tethering and untethering, but not consistently slowing travel or material processing to a degree we could detect.

The strongest forwarder results required more complex models (Table 5). Partitioning distance traveled into tethered and untethered distance and total material weight into saw log weight and feedstock weight, Model F6 improved model performance as measured by adjusted R^2 and AIC_C score (Table 6). The coefficients for these subgroups proved notably different as well, with tethered travel taking more time than untethered travel, and feedstock logs taking more time than saw logs. Partitioning saw and feedstock collection by tether status also provided notably different coefficients, but resulted in lower adjusted R^2 values and higher AIC_C scores. The relatively large differences in tethered and untethered coefficient values suggest that tethering on the forwarder may function as both a fixed and variable cost, not just incurring the delay required to tether and untether, but also reducing the mean speed of travel and material processing while tethered. The adjusted R^2 values (Table 6) using work time per corridor are considerably higher than others have reported using individual trip time, as the dependent variable since the work time to complete a corridor is the sum of a number of trips, which results in damping the differences between individual trip times.

The differences in AIC_C scores (Δ_i) failed to provide convincing evidence for any model on either machine, suggesting that if several independent data sets were collected, they might have different best models (Burnham and Anderson 2002). Burnham and Anderson (2002) suggested that (a) nested models with $\Delta_I < 2$ have substantial empirical support, (b) it is entirely plausible for a model with an inferior score to be the best model of the group, and (c) nested models with $\Delta_I > 10$ have so little support that they could be omitted from future consideration. All models (H1–H8, F1–F8) had $\Delta_i < 10$, although models H8 ($\Delta_i = 9.8$) and F1 ($\Delta_i = 8.2$) are the weakest by the Burnham and Anderson criteria (Table 6).

The idea that the models are all reasonably effective for the data can be further supported by the similarity of their predictions (Table 7). When supplied with our observed mean distances and tonnage for a single hectare, we find estimated treatment times ranging from 419 to 432 productive minutes for the harvester (with a mean of 425 and standard deviation of 3.9) and 433 to 464 productive minutes for the forwarder (with a mean of 448 and standard deviation of 8.8). The harvester costs range from $1,689 per hectare to $1,739 per hectare (with a mean of $1,713 and standard deviation of $15.5) and the forwarder costs range from $1,313 per hectare to $1,393 per hectare (with a mean of $1,351 and standard deviation of $26.6). We assume that harvester and forwarder balancing at the harvest unit timescale is not an issue because harvesting and forwarding are decoupled. At longer timescales, consideration of equipment balance may be an issue that can be addressed through longer shift hours or additional shift days. Truck delay because of the availability of the forwarder to load the trucks was not measured.

Partitioning Costs between Tethered and Untethered Operations

Combining the production data from Table 2 with the machine rate estimates (Table 1), the stump-to-truck cost of using the tether is about 1.47 times the cost when the tether is not being used (Table 8). This ratio is somewhat higher than that reported by Stampfer (2016), who estimated the cost ratio, in thinnings, of

Table 6. Relative model strength by second order, evidence ratio, and adjusted R^2.

Harvester models					Forwarder models				
Model	Adjusted R^2	AIC_C	Δ_i[a]	Evidence ratio-H1[b]	Model	Adjusted R^2	AIC_C	Δ_i[a]	Evidence ratio-F6[c]
H1	.9412	423.31	--	1	F1	.9072	533.27	8.15	58.85
H2	.9412	424.74	1.43	2.04	F2	.9128	531.29	6.17	21.87
H3	.9412	424.8	1.49	2.11	F3	.9157	529.45	4.33	8.71
H4	.9399	427.36	4.05	7.58	F4	.914	531.94	6.82	30.27
H5	.9398	425.85	2.54	3.56	F5	.9104	532.75	7.63	45.38
H6	.9398	427.43	4.12	7.85	F6	.9242	525.12	--	1
H7	.9384	430.14	6.83	30.42	F7	.921	528.89	3.77	6.59
H8	.9368	433.07	9.79	133.62	F8	.9233	528.97	3.99	7.35

[a] Absolute difference in AIC_C scores between a given model and the best model. AIC_C, Akaike's Information Criterion.
[b] Evidence ratio, how many times more likely it is that H1 is correct for these data when compared to a given model.
[c] Evidence ratio, how many times more likely it is that F6 is correct for these data when compared to a given model.

Table 7. Estimated machine time per model form, machine cost for one hectare treated.

Estimated time (productive machine minutes/ha)				Estimated cost (high machine cost, $/ha)			
Model	Harvester	Model	Forwarder	Model	Harvester	Model	Forwarder
H1	432	F1	462	H1	1,739	F1	1,393
H2	419	F2	435	H2	1,689	F2	1,313
H3	426	F3	441	H3	1,717	F3	1,329
H4	425	F4	439	H4	1,710	F4	1,322
H5	430	F5	455	H5	1,732	F5	1,373
H6	424	F6	454	H6	1,708	F6	1,369
H7	425	F7	445	H7	1,711	F7	1,342
H8	421	F8	453	H8	1,697	F8	1,368
Mean	425	Mean	448	Mean	1,713	Mean	1,351
SD	3.9	SD	8.8	SD	15.5	SD	26.6

Table 8. Mean costs of tethered and untethered operations during study for high and low machine cost estimates.

	Tethered	Untethered	Ratio
High machine cost	$/green tonne	$/green tonne	
Harvester	19.83	11.41	1.74
Forwarder	15.25	12.46	1.22
Stump-to-truck	35.08	23.87	1.47
Low machine cost	$/green tonne	$/green tonne	
Harvester	16.88	9.72	1.74
Forwarder	12.81	10.51	1.22
Stump-to-truck	29.69	20.23	1.47

Note: Forwarder cost includes loading.

using a tethered harvester/forwarder compared to a conventional harvester/forwarder to be 1.34.

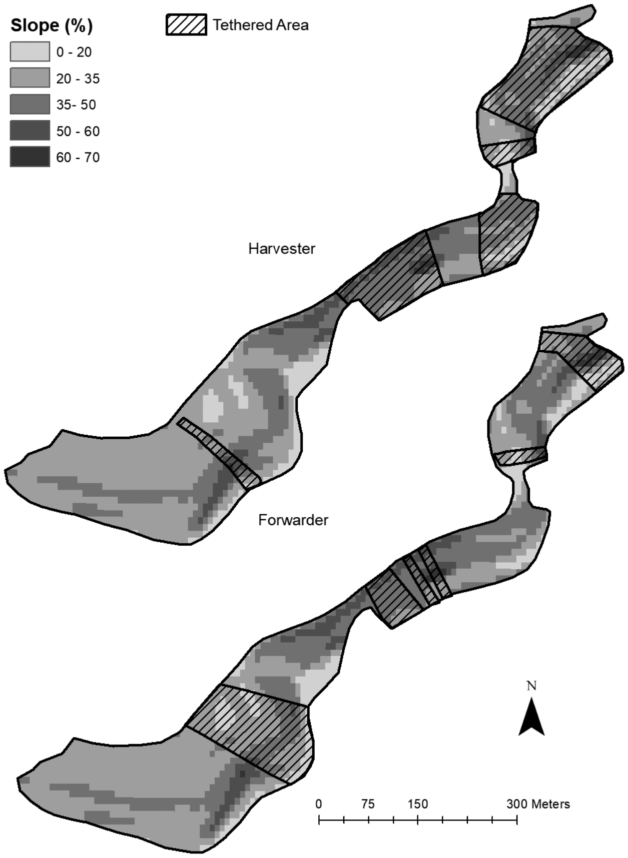
These estimates of the increased costs for tethered operations of both the harvester and forwarder may be inflated because of factors not directly attributable to tethered operations on other sites. The tethered operations had slightly higher delays for weather-related shutdown. Also, the steeper slopes on the site where tethering was used often coincided with decreased levels of stand stocking and increased numbers of rock outcroppings (increasing the difficulty of maneuvering). Neither factor was effectively captured in the data, even though either could have increased the cost difference between tethered and untethered operations to a degree that might not be observed on other stands or landscapes.

We did not have the opportunity to directly compare costs on this study area with other harvesting methods, but the mean harvesting plus forwarding costs in our 2016 study were 15–35 percent higher than those Arriagada et al. (2008) reported for their mean harvester–forwarder operations in their simulations of fuel-reduction treatments throughout the West, unadjusted for inflation. The Consumer Price Ratio for 2016/2008 was 1.11 (BLS 2018). Some of the cost difference is also explained by the additional investment cost of the tether winch. Given that Arriagada et al. reported that the harvester–forwarder mean cost on slopes less than 40 percent was one-third of the mean costs of cable logging per acre on slopes greater than 40 percent, we can infer that there is considerable potential to reduce fuel treatment costs in some mountain forests using tethered harvesters and forwarders.

Model Use

While the models presented here fit the data relatively well, potential users must keep two facts in mind to avoid overstating model effectiveness or returning unreasonable results. First, whereas isolated slopes on the study sites reached up to 70 percent slope, steeper tethered operations have been observed in other regions, and we cannot project that machine behavior will remain consistent on those extreme slopes. There may be a slope threshold beyond which the time required for any given action is significantly increased because of increased difficulty of maneuvering and material handling, or reduced operator confidence. Second, the models in this study use total distance traveled, not mean forwarding distance.

For planning purposes, the distance traveled for the harvester can be estimated as a function of the linear distance required to cover an area, given a mean length of boom extension. For example, if we assume a 10 m maximum reach and a mean boom extension of 80 percent, this would result in a cutting swath 16 m wide, requiring 556 m of linear distance for that swath to cover 1 hectare. As a result of this assumption, the mean in-stand distance traveled by the harvester to treat a single hectare should be between 556 m (on shallow slopes where the harvester can avoid driving back on its own trail) and 1,112 m (on steep slopes where the harvester must go out and back on a single trail with no deviation). It is important to note that this estimate does not include the distance required to move from corridor to corridor, which could significantly underestimate the true distance traveled for stands with short mean forwarding distances. During this study, we observed a mean harvester distance traveled of 943 m per hectare.



Slope raster generated from United States Geological Survey Digital Elevation Products, available online at [viewer.nationalmap.gov]

Figure 4. Areas of tethered and untethered operation by machine type. Note the difference in harvest unit area where each machine was tethered.

Distance traveled for the forwarder can be estimated as a function of mean forwarding distance, material loading, and bunk utilization. The weight of material to be gathered (in tonnes per hectare) can be divided by an assumed mean bunk weight (in tonnes per trip) and rounded to produce a number of trips per hectare. The number of trips per hectare can be multiplied by the mean forwarding distance to produce an estimate of the total forwarder distance traveled per hectare. This should be subject to a minimum distance traveled per hectare, calculated as a function of boom reach (as described above) to avoid underestimating the distance traveled when very small quantities of material are being removed. As with the harvester distance estimate, this does not include the distance required to move from corridor to corridor and may underestimate the true distance traveled when mean forwarding distances are short. During this study, we observed a mean forwarder distance traveled of 3,315 m per hectare with a mean of 12 bunks per hectare.

General Observations and Limits on Inference

The study was designed with the goal of collecting data while interfering in operations as little as possible, and we largely succeeded at that goal. However, it also identified aspects of cut-to-length systems that make them relatively difficult to study, as well as peculiarities of the study area itself that limit the ability to draw broad inference from the results. Unlike cable logging, corridor location with ground-based systems is more flexible. Both machines tended to wander while untethered, a behavior Flint (2013) observed in his flat ground unit. In our study, even while tethered, it was not uncommon for the forwarder to gather or shovel material from one corridor while in another, particularly along the tops of ridges and the bottoms of valleys where corridors often converge, overlap, or terminate in close proximity to each other. This porosity is what necessitated the consolidation of some corridors for this analysis.

In addition, variability in soil conditions prevented this study from being able to make any confident inferences on the general effect of slope on operations. The interaction between soil strength and ground slope on the limits of off-road vehicle performance is well known (e.g., Visser and Stampfer 2015, Sessions et al. 2017). Both operators commented that the weak soils on this site drove the decision to tether at flatter slopes than they were accustomed to in western Oregon. Both operators expressed concerns over getting bogged down and/or causing undue damage to the soil, and made the decision to use the tether to address those concerns (C. Cano and J. Vidrio, personal communication, 2016). Differences in machine weight, machine weight distribution, trail condition at time of use, and subjective operator judgment call on a corridor-by-corridor and bunk-by-bunk basis, which may partially explain the differences in when and where each machine used their tether (Figure 4).

Lastly, whereas our results indicate that tethering on a harvester behaves like a fixed cost, and tethering on a forwarder behaves like a fixed and variable cost, it is possible that this behavior is actually an operator effect and not a machine effect. Operator effects have long been known to have a significant and difficult-to-quantify effect on machine productivity (Gullberg 1995), and our use of a single operator per machine does not allow a means of identifying the difference between a machine effect and an operator effect. However, this case study serves as a starting-point for examining the potential of these tethered cut-to-length systems. The conditions of the site and treatment did not allow us to study the effects of extreme slopes, forwarding distances, haul direction, tree retention density, or operator experience with any level of rigor. A more controlled study, with a wider variance in site conditions could do a great deal to corroborate the results found here.

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