INTERNATIONAL JOURNAL OF FOREST ENGINEERING
2019, VOL. 30, NO. 2, 163–172
https://doi.org/10.1080/14942119.2018.1563851

Harvesting forest biomass in the US southern Rocky Mountains: cost and production rates of five ground-based forest operations

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ABSTRACT

The forests of the southern Rocky Mountains of North America have experienced substantial change since European colonization. High-grade logging, forest grazing practices, and fire suppression have altered once park-like ponderosa pine-dominated ecosystems into dense forests in need of restoration treatments, but such treatments are challenged by the low-value wood products removed during treatment. This study aims to understand and evaluate restoration harvest practices in the southern Rocky Mountains in terms of equipment used, production rates, and costs under both observed and modeled site and stand conditions across the region. During the summer of 2017 we observed five ground-based harvest operations of varying size and capacity across the region and analyzed their characteristics using detailed time study data. Observed stump-to-truck harvest rates ranged from \$19.11 to \$43.25 United States Dollars per tonne with an average of \$29.70 per tonne, and modeled costs based on standardized variables from \$19.95 to \$33.39 per tonne with an average of \$26.19 per tonne. Observed average productivity rates for felling, skidding, processing, loading, and biomass grinding were respectively 22.9, 16.0, 20.7, 27.8 and 49.8 tonnes per scheduled machine hour (SMH). Under modeled conditions for the same functions except grinding, productivity averaged 25.4, 18.6, 23.1, and 28.2 tonnes per SMH. Results from this study will be used as a benchmark for efficiency and costs and to model region-wide biomass production.

ARTICLE HISTORY
Received 15 August 2018
Accepted 22 December 2018

KEYWORDS
Forest operations; restoration; biomass; cost; productivity; Ponderosa pine

Introduction

Ponderosa pine forests of the southern Rocky Mountains evolved under a low-severity frequent fire regime which routinely consumed fuels and maintained low regeneration densities. Most forests were open, dominated by large trees with a grass understory (Covington and Moore 1994; Reynolds et al. 2013). With the arrival of European settlers, the process of fire was excluded from the landscape resulting in higher stem densities and increased risk of stand replacing, high-severity wildfire. Over the past century, environmentally harmful practices such as high-grade logging and grazing cattle in forested areas have amplified the negative effects of fire exclusion (Allen et al. 2002). In recent times, land managers have been working to restore historic forest conditions and the role of fire in the southern Rocky Mountains. Because of this change in stand structure, mechanical treatments are often necessary before reintroduction of frequent low-severity fire (Hampton et al. 2008). These restoration treatments differ from conventional timber harvests in that their primary goal is to improve ecological function through recreation of historic stand structures, therefore the largest and most economically valuable trees are often retained while subdominant, smaller, and less economically valuable trees are removed. In response to forest change and increased risk of severe wildfire, public land managers have created landscape-scale projects like the Four Forests Restoration Initiative (4FRI) in the state of Arizona to both restore historic forest conditions and stimulate local and regional forest product economies (Lucas et al. 2017). The large volume of small diameter, low-grade, and low value wood from restoration treatments has challenged existing regional markets, and the industry is struggling to adapt. One way the industry has adapted is by investing in various forms of biomass energy such as whole-tree chips for thermoelectric power, pellets for wood stoves, and traditional fuelwood for heating (Sorenson et al. 2016). Biomass energy and other markets such as animal bedding and erosion control products now account for the highest sales by value in the region, deviating from historic products of lumber, timbers, and other sawn wood (Sorenson et al. 2016). While information is available regarding the wood products industry in the southern Rocky Mountains, little information is available to land managers, logging contractors, and researchers about logging systems and their associated costs and production rates when used on restoration treatments that include biomass harvest. In other regions, such as the northern Rocky Mountains, biomass harvesting costs have been calculated and the challenges with low-value wood have been explored (Anderson et al. 2012; Bell et al. 2017; Kim et al. 2017). Furthermore, other regions outside of the US Rocky Mountains which utilize biomass have been studied and their operations quantified (Han et al. 2004; Vitorelo et al. 2011; Hanzelka et al. 2016; Di Fulvio et al. 2017; Belbo and Vivestad 2018; Santiago et al. 2018).

The objective of this study is to understand the current state of forest operations in the southern Rocky Mountains in terms of equipment used, structure of harvest systems, stump-to-truck

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logging costs, and production rates, with the goal of improving future operations and expanding biomass utilization in the region. This study is part of a broader project aimed at also understanding: the effects of biomass harvest on forest ecosystems; ways to improve the environmental performance of logging practices; and the public health impacts of woody biomass energy compared to fossil fuels.

Materials and methods

Contractor and site selection

Contractors were selected in January of 2017 based on their willingness to participate in the study, use of operations and equipment characteristic of the region, and a steady workflow of forest restoration-focused contracts. Two of the selected contractors were based in central-eastern Arizona, two in northwestern New Mexico, and one in south-central Colorado. Our goal was to observe 10 consecutive operational days for each operation and use the results to develop recommendations for each operation to improve efficiencies and decrease costs.

Forest restoration-focused contracts already held by the participating contractors were selected as field study sites. Four of the five contractors were operating on United States (US) Forest Service projects, with the fifth operating on a restoration-focused project on a state wildlife management area (Figure 1). Pre-treatment site information was collected for all sites using fixed-radius 0.04 ha plots (0.1 acre) for mature trees (diameter at breast height, DBH ≥ 13 cm), with data collected for tree diameter, species, and height. For saplings (DBH < 13 cm, height > 1.4 m), a 0.004 ha (0.01 acre) fixed radius plot using the same plot center was used to collect the same information as for mature trees. To collect seedling information, three 0.001 ha (0.003 acre) plots were used to sample species composition and average height. The density of small trees was highly variable by site with varying levels of treatment required. On all sites ponderosa pine (*Pinus ponderosa*) was the dominant species, with Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), Gambel oak (*Quercus gambelii*), and quaking aspen (*Populus tremuloides*) as secondary cohabitants (Table 1).

Field data collection

Detailed time study methods (Olsen and Kellogg 1983) were used to evaluate all harvesting functions within each operation (Table 2). Because hot saws operated too quickly for accurate data collection by activity, activity sampling was used periodically, approximately every 45 minutes, to describe the proportion of time spent on individual activities within a cycle. All tree and log diameters were ocular estimates, while distance was estimated with the aid of a laser-rangefinder. Delays were recorded but were not used to develop utilization rates because

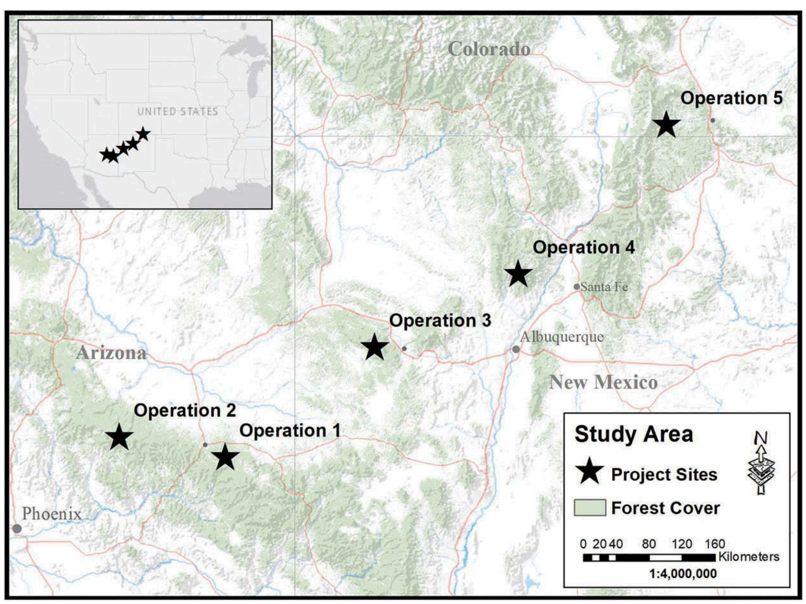

Figure 1. Map of study site locations.

Table 1. Pre-treatment stand conditions.

Operation	Slope (%)	TPH < 10 cm	TPH > 10 cm	BA > 10 cm (m^2/ha)	QMD> 10 cm	Avg Ht (m) > 10 cm	Species composition (% by basal area) PIPO	PSME	ABCO	QUGA	POTR
1	8	638	715	29.4	22.9	12.1	92.5	0	0	7.5	0
2	7	618	404	29.9	30.7	14.3	97.3	0.2	0.1	2.4	0
3	7	41	315	19.0	27.7	12.4	100	0	0	0	0
4	15	2801	694	30.0	23.5	15.3	96.5	1.4	2.1	0	0
5	9	21	299	19.6	28.9	12.8	79.6	17	3	0	0.4

Species key: PIPO, *Pinus ponderosa*; PSME, *Pseudotsuga menziesii*; ABCO, *Abies concolor*; QUGA, *Quercus gambelii*; POTR, *Populus tremuloides*.

Table 2. Cycle descriptions for each function and machine type.

Function and machine type	Timed cycle elements	Independent variables
Felling		
Wheeled hot saw	Total time to build and lay down one bunch	Tally of trees cut per 10 cm size class
Tracked hot saw	Total time to build and lay down one bunch	Tally of trees cut per 10 cm size class, distance traveled (feet)
Harvester	Travel to tree, cut, process	Distance traveled (feet), large-end diameter to 5 cm size class, number of stems cut at once, total number of logs produced
Hand-felling	Travel to tree, pre-limbing, face cut, back cut, delimbing	Distance traveled to tree, tree species, large-end diameter
Skidding		
Rubber-tired grapple skidder	Travel empty, assemble turn, travel loaded, decking/piling	Distance traveled empty (feet), distance traveling between each bunch (feet), tally of bunches assembled, distance traveling loaded (feet)
Processing		
Dangle-head processor	Limb and buck, slash management	Large-end diameter to 5 cm size class, tally of logs produced by sort
Pull-through delimber	Positioning tree in delimber, delimbing, topping, decking	Large-end diameter to 5 cm size class
Loading		
Log loader/Dangle-head processor	Time per swing of logs loaded onto truck	Number of logs in each swing
Biomass grinding		
Horizontal grinder	Time per swing of biomass material into grinder	Categorization of material in each swing (slash, logs, mix, or fines)

the recording of "long delays," defined as delays longer than 30 minutes, were not consistently targeted and recorded.

Logging system descriptions

All operations utilized ground-based harvesting systems, four of which were fully mechanized (Appendix Table A1). Operations 1 and 2 used rubber-tired feller-bunchers followed by rubber-tired grapple skidders and roadside processing with dangle-head processors. Both of these operations had hog fuel markets available to them. After slash piles air dried, horizontal grinders were used to comminute slash directly into chip vans. Operation 3 was a hybrid cut-to-length system using a harvester to fell and process stems in the woods, which provided an even distribution of fuel for a later broadcast burn, followed by a grapple skidder bringing processed logs to the landing. Log trucks were loaded using a dangle-head processor. Operation 4 used a tracked, leveling feller-buncher due to steep slopes, a rubber-tired grapple skidder, and roadside processing with a dangle-head processor. All feller-bunchers used hot saws (also known as rotary disk saws). Operation 5 was a semi-conventional system with hand-felling, tree-length skidding using a rubber-tired grapple skidder, and roadside processing using a trailer-mounted pull-through delimber.

Products produced

Operations 1 and 2 produced the same two sawlog sorts: "large" logs which were 40 cm (16 in) or greater large-end diameter, and "small" logs less than 40 cm (16 in) large end diameter to a 11 cm (4.5 in) top. Preferred sawlog lengths were 4.9 m (16 ft), with 0.61-meter (2-foot) multiples accepted. Operation 1 also produced a chip log with a small end diameter of 5 cm (2.5 in) for a pellet mill producing bagged pellets for home heating. Both Operations 1 and 2 produced hog fuel from whole trees and slash for commercial electricity production. Operation 3 produced one sort of logs with a small-end diameter down to 11 cm (4.5 in) and lengths of 0.6-meter (2-foot) multiples starting at a minimum of 2.4 m (8 ft). Operation 4 had one sort of logs with diameter 6 cm (2.5 in) and greater starting at 2.4 m (8 ft), but preferred lengths of 7.6, 8.2, and 8.8 m (25, 27, 29 ft). These logs were primarily hauled to two integrated mills that produced multiple products such as pellets, dimensional lumber, rough-hewn timbers (vigas), firewood, posts, and rails. Logs were also hauled to other sawmills producing green dimensional lumber for export. Operation 5 produced one sort of tree length logs down to a 10 cm (4-inch) top, which were hauled to a lumber mill with post and pole and pellet facilities.

Cost and productivity analysis

This study examined productivity and cost in two different scenarios: one is based on the observed stand and site conditions for each operation; the other is based on modeled productivity and costs assuming a standard set of stand and site conditions, such as skidding distance and stem diameter. The modeled analysis was used to directly compare operations without site-specific variables influencing productivity and costs.

To estimate machine productivity from cycle time data, ordinary least squares linear regression models were constructed to predict delay-free cycle time based on variables that are easily observed and measured in the field. Models were refined using backwards stepwise selection. For specific operational functions where regression models could not be constructed, summary statistics were used to describe the range of possible values for cycle time. Any model developed that represented multiple operations used randomly selected balanced samples so that each operation was equally represented in the model. Each model, cost, and productivity estimate is given on a per machine basis rather than in aggregate, as some operations had multiple machines performing the same function.

Both observed and modeled costs and productivity estimates were calculated assuming a standard 23.6 tonne (US 26 ton) payload per log truck. Based on this payload and piece counts per load, we estimated a weight per piece for each sort. Allometric equations were used to estimate weights for trees with large end diameters less than 10 cm (4 in) (Jenkins et al. 2003). Machine rates were calculated using purchase prices for new machines in each class of equipment ([USFS Machine rate calculator.] USFS Southern Research Station. 2018) and

Table 3. Assumed purchase prices, utilization rates, and machine rates used for evaluation.

Machine	Horsepower	Purchase Price (USD)	Utilization rate (%)	Cost USD/ SMH[a]
Felling				
Wheeled hot saws	270–285	287,000	60[d]	$133
Tracked hot saw	300	525,000	60[e]	$187
Harvester	177	540,000	70[b]	$183
Hand-felling	5.5	900	50[f]	$71
Skidding				
Rubber-tired grapple	115	300,000	65[e]	$125
skidder	203–263	330,000	65[e]	$143
	300	370,000	65[e]	$156
Processing				
Dangle-head processor	139–166	475,000	75[c]	$164
	190–194	540,000	75[c]	$183
Pull-through delimber	150	65,000	65[d]	$57
Loading				
Trailer-mounted loader	150	175,000	65[e]	$86
Truck-mounted loader	145	250,000	65[e]	$105
Knuckle-boom loader	164–188	277,000	65[e]	$113
Biomass grinding				
Horizontal grinder	765	800,000	85[c]	$421
(including loader)	1050	900,000	85[c]	$473

[a]The following assumptions were held constant: 1500 hours worked per year; 5-year machine life; salvage value 20%; interest rate 6.5%, insurance rate 1.3%; taxes 2%; fuel use 13.35 L/kW-hr (2.63 gal/hp-hr); repair and maintenance at 100% of depreciation; operator wage of $20 per hour; benefits 50% of wage; hand-felling wage $35 per hour; hand-felling benefits 100% of wage; rubber tire replacement 1500 machine hours at $20,000 per set.
Utilization rates were assumed to be different for each function and were sourced from the literature ([b]Adebayo et al. 2007; [c]Anderson et al. 2012; [d]Brinker et al. 2002; [e]Dodson et al. 2015; [f]Miyata 1980).
SMH, scheduled machine hour.

standard costing assumptions (Table 3). Any cost data compared from earlier studies was adjusted for inflation (BLS 2018).

Modeling assumptions

A diameter of 21 cm (8.2 in) was assumed for all modeled felling and processing estimates. Hot saw cycles assumed 2.5 trees at 21 cm in diameter, plus 2.5 trees with diameters less than 10 cm (4 in) per bunch. An average travel distance of 4.3 m per cycle was used to model tracked hot saw cycle time. The harvester model assumed 1.1 stems per cycle with 1.3 logs produced per tree, and a travel distance of 2.4 m (8 ft) per cycle. An average skid distance of 300 m (985 ft) with two bunches assembled containing 10.3 trees per bunch was assumed. Loading was modeled assuming an average of 38 grapple swings required to fully load a truck using the "large" sort of logs.

Results

Productivity models by function

Felling

Hot saw cycle times and bunch compositions varied between operations. Despite major differences between stem sizes in bunch compositions among operations (Figure 2), average cycles were close to one minute and typically resulted in approximately five stems cut per cycle (Table 4). Bunch compositions averaged 2.5 stems per cycle with diameters less than 10 cm (4 in), plus 2.5 stems per cycle with diameters greater than 10 cm (4 in). Wheeled hot saws spent similar time in each activity of the cycle, while the tracked hot saw spent less time moving between trees and a

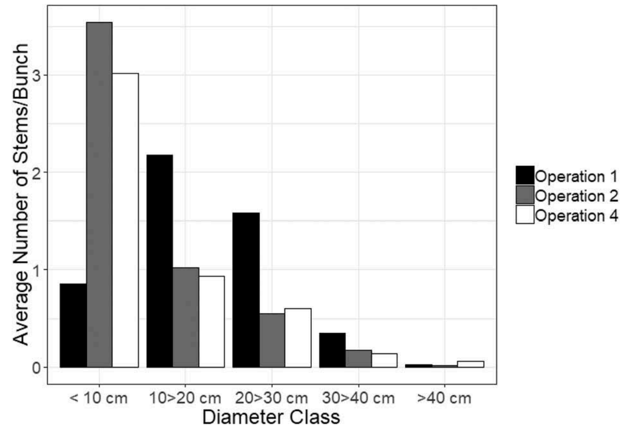

Figure 2. Average number of stems per hot saw bunch by diameter class by operation.

Table 4. Felling summary statistics with observed and modeled productivity.

Factor	Units	Mean values, by operation 1	2	3	4	5
Observed delay-free cycle time	Minutes	0.98	1.14	0.55	0.78	1.84
Diameter	Centimeters	18	10	18	11	22
Distance	Meters	NA	NA	2.4	4.3	6.4
≤10 cm	Stems/bunch	0.86	3.54	NA	3.02	NA
>10 cm	Stems/bunch	4.12	1.76	NA	1.73	NA
Observed delay	Minutes	0.16	0.2	0.23	0.14	0.78
Total stems	Stems/cycle	4.98	5.3	1.1	4.75	1
Productivity observed	Tonnes/SMH	29.3	17.2	13.9	49.8	4.4
Productivity modeled	Tonnes/SMH	30.7	29.3	23.6	38.7	4.6

SMH, scheduled machine hour.

greater proportion of time cutting and bunching (Figure 3). On average, the tracked hot saw cut stems at an observed rate 36% faster than the wheeled hot saws. Observed productivity for all hot saws averaged 32.1 tonnes per SMH, varying from 91% to 155% of the mean (Table 4). Total delay-free cycle time for wheeled hot saws could be modeled based on the total number of stems cut, regardless of stem diameter (Figure 4). Predicting delay-free cycle time for the tracked hot saw was also dependent on the total number of stems cut in addition to the total distance traveled per cycle (Table 5; Figure 5). When modeled, hot saw productivity averaged 32.9 tonnes per SMH, varying from 89% to 118% of the mean.

On Operation 3, where felling and processing were completed with a harvester, the average cut tree diameter was small and included the treatment of regeneration. On average only 0.7 logs per tree were produced. Thirty-two percent of our observations were on trees less than 15 cm at the large-end diameter. Because of the small diameter trees, the harvester produced an average of 13.9 tonnes per SMH. Delay-free cycle time was best correlated with the distance traveled, cut stem diameter, the number of stems cut and processed, and the number of logs produced (Table 5). Modeling harvester productivity based on the larger standardized diameter resulted in a productivity rate of 23.6 tonnes per SMH (Table 4).

Hand-felling resulted in the lowest productivity rate of all felling methods, producing 4.4 tonnes per SMH under observed conditions (Table 4). Hand-felling was best modeled by the diameter of the stem being cut (Table 5). When using

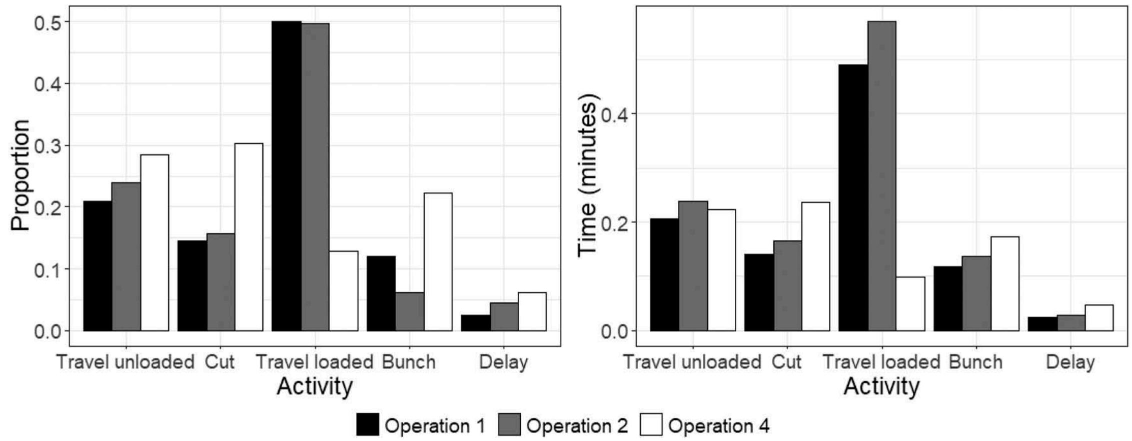

Figure 3. The proportion of time devoted to each potential cycle activity (left) and average time per hot saw cycle in minutes (right) by operation. Operations 1 and 2 are wheeled felling operations, whereas Operation 4 is tracked.

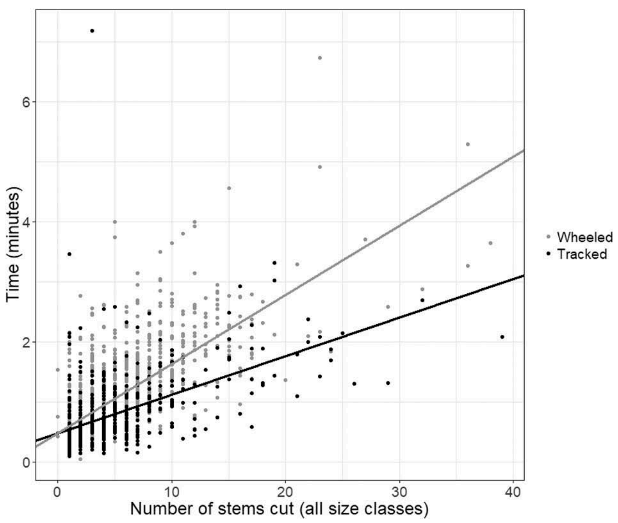

Figure 4. Modeled total cycle time by number of stems cut for hot saws with observed data points. Time for the tracked hot saw is estimated using an average of 4.3 meters traveled.

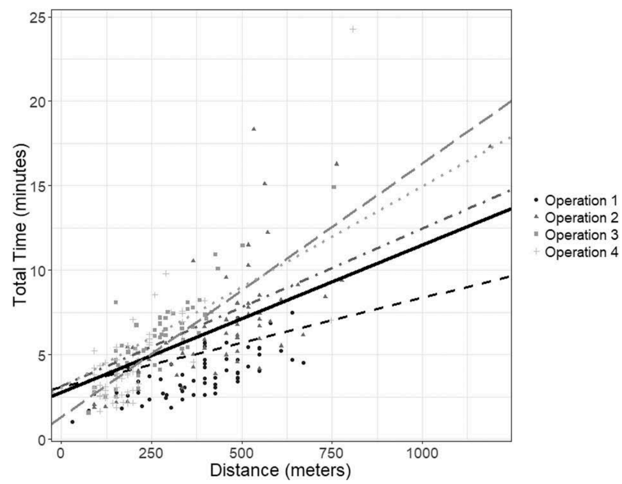

Figure 5. Modeled total cycle time by distance assuming 2 bunches were assembled for operations 1–4 with observed data points, with the thick black line representing the combined skidding model.

Table 5. Prediction models for delay-free cycle time for all felling.

Operation	Intercept	β_1 Number of stems cut	β2 Distance (meters)	β3 Diameter (cm)	β4 Number of logs	R^2
1	0.2709	0.1415	NA	NA	NA	0.52
2	0.5170	0.1079	NA	NA	NA	0.51
Combined wheeled	0.4415	0.1204	NA	NA	NA	0.51
3	−0.2274	0.1442	0.0347	0.0228	0.1883	0.48
4	0.3864	0.0644	0.2060	NA	NA	0.54
5	−2.2070	NA	NA	0.1822	NA	0.50

the standardized diameter of 21 cm, productivity was estimated to 4.6 tonnes per SMH (Table 4).

Skidding

Although skidder size and capacity varied among operations, all machines served the same function and therefore are directly comparable. Operations differed in the average number of bunches assembled, the number of pieces per bunch, and round trip distance (Table 6). Under observed conditions, skidding averaged 16 tonnes per SMH, and varied by operation from 56% to 192% of the mean (Table 6). Operation 4 occasionally processed trees at in-woods landings for slash dispersal purposes, requiring logs to be re-skid to a roadside landing after processing. Although this practice was thought to make slash dispersal more efficient, cycle times that involved re-skidding of slash from a roadside landing were not significantly different than cycles that did not involve return skidding of slash ($p = 0.78$). Skidding that followed hand-felling was significantly slower over the same distances as compared to other operations ($p = 0.02$), therefore it was left out of the combined model. For all operations, delay-free cycle time was estimated based on the total distance traveled and the number of bunches or pieces (in the case of unbunched stems) assembled (Table 7). When modeled, average skidding production was 16.1 tonnes per SMH, and varied from 67% to 132% of the mean.

Processing

Dangle-head processors were the most common processing equipment and had a mean observed productivity rate of 22.9 tonnes per SMH and varied from 92% to 110% of the mean (Table 8). Delay-free processing time with dangle-head

Table 6. Summary statistics and production rates for skidders.

Factor	Units	Mean values, by operation				
		1	2	3	4	5
Observed delay-free cycle time	Minutes	4.50	7.60	6.63	6.08	6.80
Number of bunches		1.3	1.7	3.0	1.4	2.5
Number of pieces		12.7	17.1	8.7	5.5	8.0
Total distance	Meters	384	455	257	206	202
Observed delay	Minutes/cycle	1.34	0.55	0.89	1.16	0.23
Productivity observed	Tonnes/SMH	17.6	9.0	12.6	30.8	10.0
Productivity modeled	Tonnes/SMH	21.3	16.6	16.8	14.9	10.7

SMH, scheduled machine hour.

Table 7. Skidding models to predict delay-free cycle times.

Operation	Intercept	β_1 Distance (100's of meters)	β_2 Number of bunches	R^2
1	0.2202	0.5264	1.4310	0.63
2	−0.2528	0.9310	1.7108	0.61
3	0.1099	1.5003	0.6030	0.85
4	0.3626	1.1940	1.3302	0.79
5	−1.1524	2.8313	0.9026	0.65
Combined model[a]	0.1761	0.8924	1.2311	0.65

[a]Combined model represents Operations 1–4.

processors was based on the large end diameter of the tree, number and sort of logs produced (Table 9). Because processing time depended on log sorts produced and sorts were not consistent between operations, a combined processing model could not be developed. With diameter standardized, an average of 23.5 tonnes per SMH was modeled. Modeled productivity rates ranged from 93% to 107% of this mean. The pull-through delimber had a broken topping saw, so topping was completed by breaking the stem. This resulted in an observed productivity of 7.2 tonnes per hour, 32% of the productivity of a dangle-head processor (Table 8). Meaningful predictive models could not be developed with the data collected.

Loading

Between operations there were large differences in loading cycle times and productivity rates. Observed conditions resulted in an average productivity rate of 27.8 tonnes per SMH and varied from 63% to 160% of the mean, with the lower bound attributed to loading with a dangle-head processor (Table 10). For Operations 1, 2, and 3 predictive models were based on the number of grapple swings to load the truck and log sort (Table 11). Operations 1 through 3 were standardized by using a modeled time given 38 swings assuming the large log sort for all operations. Because statistically-significant models could not be generated for Operations 4 and 5, averages were used. The modeled productivity average for all loading machines was 27.7 tonnes per SMH and varied from 81% to 125% of the mean.

Grinding

Biomass grinding only occurred on Operations 1 and 2. For both operations, grinding was separated in time from other harvesting activities in order to allow slash to air dry, which improves its energy content per unit value. Operation 2 owned two grinders, one of which worked independently on the same site as Operation 1 (labeled in the table as "Operation 2 (Site 1)"). Although two different grinder sizes and makes were used, they had similar delay-free cycle times and productivity. The average productivity from all grinders was 49.8 tonnes per SMH (Table 12). Averages were used to estimate productivity and costs in both the observed and modeled analyses.

Stump to truck costs

The most efficient felling was completed by hot saws in both observed and modeled conditions. Under observed conditions, hot saws cost an average of $5.35 per tonne and under modeled conditions $5.23 per tonne. While the machine rate was more expensive for the tracked hot saw than the wheeled hot saw, the tracked hot saw had the lowest cost per tonne under observed conditions. After standardization, the wheeled hot saw on Operation 1 was the most cost-efficient machine (Table 13). The least efficient felling method was hand-felling, resulting in an observed cost 300% of the mean hot saw felling cost. Under modeled costs the result was

Table 8. Processing summary statistics for all processing. The harvester in Operation 3 is included, but cycle time also includes felling.

Factor	Units	Mean values, by operation				
		1	2	3	4	5
Observed delay-free cycle time	Minutes	0.41	0.58	0.55	1.08	1.46
Large-end diameter	Centimeters	22	22	18	21	22
Large logs produced	Logs/cycle	1.17	0.18	0.77	0.94	1
Small logs produced	Logs/cycle	0.74	2.21	NA	0.52	NA
Delay	Minutes/cycle	0.11	0.15	0.23	0.50	0.40
Productivity observed	Tonnes/SMH	21.0	22.5	13.9	25.3	7.2
Productivity modeled	Tonnes/SMH	21.8	23.4	23.6	25.2	NA

SMH, scheduled machine hour.

Table 9. Processing models to predict delay-free cycle times for dangle-head processors.

Operation	Intercept	β_1 Diameter (cm)	β_2 (Number of large sawlogs)	β_2 (Number of small sawlogs)	R^2
1	0.0466	0.0093	0.1140	0.0383	0.64
2	0.0401	0.0185	0.3812	0.0361	0.47
4	−0.2703	0.0403	0.4331	0.2196	0.47

Table 10. Loading summary statistics.

Factor	Units	Mean values, by operation				
		1	2	3	4	5
Observed delay-free cycle time	Minutes	31.39	20.70	52.64	40.75	36.58
Number of grapple swings		41	25	51	35	36.7
Total pieces		223	144	96	56	87.3
Delay	Minutes	4.66	4.10	10.54	2.96	16.08
Productivity observed	Tonnes/SMH	29.3	44.4	17.5	22.6	25.1
Productivity standardized	Tonnes/SMH	33.6	34.6	22.5	N/A	N/A

SMH, scheduled machine hour.

Table 11. Loading models to predict delay-free cycle times for each operation. The combined model represents operations 1 through 3. β_2 (short log sort) is an indicator variable (1 = short log sort, 0 = long log sort).

Operation	Intercept	β_1 Number of swings	β_2 Short log sort	R^2
1	9.7446	0.4639	7.8852	0.59
2	9.6940	0.3680	2.2493	0.59
3	5.7078	0.9258	N/A	0.46
Combined model	−2.6417	0.9730	N/A	0.72

Table 12. Grinding summary statistics and productivity rates.

Factor	Units	Mean values, by operation 1	2 (Site 1)	2 (Site 2)
Observed delay-free cycle time	Minutes/truck	23.37	20.21	22.44
Total grapple	Swings/truck	73	53.8	36.8
Delay/truck	Minutes	4.44	4.94	8.11
Productivity observed	Tonnes/SMH	46.7	48.6	54.0

similar, with hand-felling 298% of the mean hot saw cost per tonne (Table 13).

Skidding costs were highly variable with an average cost of $10.79 per tonne with costs ranging from 43% to 160% of the mean cost. The high observed skidding cost for Operation 2 was because bunches of small material less than 10 cm in diameter were skid separately from the larger merchantable logs and accounted for a large proportion of bunches skid. The mean modeled skidding cost was $9.17 per tonne. Costs ranged from 73% to 127% of the mean modeled skidding cost. Operation 2 under modeled conditions cost 102% of the mean, indicating near average skidding costs when biomass material was not skid separately from whole trees.

Processing costs were less variable than both felling and skidding costs. The observed average processing cost for dangle-head processors was $7.02 per tonne. Operations varied from 84% to 111% of the mean (Table 13). Processing costs were generally dependent on processing intensity. Tree length processing and the handling of longer logs were more efficient from a processing perspective. Once diameter was standardized in processing models, the mean average cost per tonne was $7.28. Average costs per tonne varied from 89% to 108% of the mean under modeled conditions. Under modeled conditions, the pull-though delimber on Operation 5 cost 111% of the mean cost per tonne when compared to dangle-head processors (Table 13).

Loading was the least expensive function in operations when a loader was used. For knuckle-boom loaders the average observed loading cost was $3.62 per tonne. Operations ranged from 70% to 129% of this observed average cost per tonne (Table 13). Operation 3 which used a processor to load, cost 259% of the observed average cost per tonne for knuckle-boom loaders. Under modeled conditions, the average loading cost for knuckle-boom loaders was $3.68 per tonne. Operations ranged from 89% to 127% of the modeled average cost per tonne (Table 13). The processor loading on operation 3 maintained a high relative cost to knuckle-boom loaders, costing 198% of the average modeled cost per tonne.

Table 13. Observed and modeled total stump-to-truck costs per tonne by operation in USD. Values may not perfectly sum because of rounding.

Function	Operation 1	2	3	4	5
Observed costs ($ per tonne)					
Felling	$4.54	$7.74	$13.17	$3.76	$16.06
Skidding	$8.13	$17.31	$11.37	$4.65	$12.47
Processing	$7.80	$7.38	NA	$5.89	$7.87
Loading	$3.86	$2.54	$9.38	$4.65	$3.42
Grinding	$9.02	$9.24	N/A	N/A	N/A
Round wood cost	$24.34	$34.97	$33.93	$18.94	$39.83
Round wood with biomass cost	$33.36	$44.21	N/A	N/A	N/A
Modeled costs ($ per tonne)					
Felling	$4.33	$4.54	$7.74	$4.84	$15.58
Skidding	$6.72	$9.38	$8.50	$9.59	$11.68
Processing	$7.51	$7.83	NA	$6.51	$7.87
Loading	$3.36	$3.27	$7.29	$4.65	$3.42
Grinding	$9.02	$9.24	N/A	N/A	N/A
Round wood cost	$21.92	$25.02	$23.53	$25.58	$38.55
Round wood with biomass cost	$30.94	$34.26	N/A	N/A	N/A

Grinding costs were similar despite the range in size of grinders, averaging $9.17 per tonne. Grinding costs only varied around this mean from 96% to 106% of the average cost (Table 13). Both grinding operations worked to directly fill 40-foot long trucks and did not grind into piles for later loading.

Total round wood harvesting costs exhibited a wide range in both observed and modeled conditions. The observed average round wood harvest cost was $30.40 per tonne. Costs varied from 62% to 131% of this average under observed conditions (Table 13). Under modeled conditions, the average round wood cost was $26.92 per tonne. Costs varied from 81% to 143% of the average modeled cost (Table 13). The high-end outlier in the range of costs was Operation 5. This is attributed to the high cost of hand-felling, which was not used in other operations. Biomass grinding for Operations 1 and 2 added 32% to round wood production costs under observed conditions, and 39% more under modeled conditions. While grinding biomass increased operational costs, it provided a source of revenue as well.

Discussion

Best practices

The most efficient felling practices were those that considered the skidding operations that followed. Typically, these operators had previous experience operating a skidder and were able to create optimal bunch sizes so that a skidder could achieve a full payload with a single bunch, and seldom needed to assemble a second bunch, or break apart a bunch that was too large for a single cycle. Good felling practices were most evident on Operation 1, where on average the skidder operator had to assemble a second bunch only once every four cycles (Table 6).

The harvester and skidder combination working closely together on Operation 3 made for inefficient skidding but could be preferable for operations that are required to distribute slash throughout the unit for later prescribed burning or for nutrient cycling. Though forwarders are often used in this situation, they are not common in the study area and there is no reference in this region as to what it would cost to use forwarders in restoration treatments. However, we do speculate it would significantly increase production efficiency if one were used in this situation (Becker et al. 2006). Alternatively, a whole-tree system with return skidding of slash could be used to accomplish this same task, although the distribution of slash between the two methods may not be the same (Han et al. 2009). While there were a limited number of observed cycles (n = 9), our results indicate that there was no statistical difference between skidding cycles with an empty back haul and those returning slash to the unit on the back haul. Skidder cycles devoted specifically to dispersing slash without moving any merchantable product would increase costs but may be necessary in some cases.

Hand-felling that did not consistently use directional felling techniques resulted in inefficient skidding (Table 13). The skidder operator was required to assemble multiple stems to create a single turn (Table 6). This resulted in slower cycle times, lower productivity levels, and more costly skidding.

Experienced skidder operators (Operation 1) alternated short and long distance cycles when working directly with the processor to maintain balance and minimize operational delays. This is in contrast to operations that started assembling the bunches nearest to the landing and worked outward, resulting in frequent operational delays in skidding for short skids, and processor delays with longer skids.

Dangle-head processors exhibited the most efficient processing. For tree length processing though, the cost of a pull-through delimber was high but comparable to dangle-head processors (Table 13). If the topping saw on the pull-through delimber had not broken, it may have been more productive and therefore more cost-efficient. While the cost per tonne to operate a pull-through delimber was similar to dangle-head processors, it was significantly less productive and may not be appropriate for higher productivity operations.

The most efficient loading practices used a knuckle-boom log loader and worked from decks that were well-sorted. The least efficient loading was completed by a dangle-head processor which experienced frequent delays from sorting and was limited to fewer logs per swing, thus requiring more swings per load on a more expensive machine (Table 8, Table 13). This is widely understood by most contractors, but the practice is sometimes resorted to when a dedicated loader is not available.

Grinding results indicate that the delay-free cycle time to fill a 12.2-meter (40-foot) chip van was not statistically different between a 765 horsepower and 1050 horsepower grinder, resulting in similar levels of productivity. The primary difference in observed total load time was the average delay per truck. Operators that kept grinders fed with a constant stream of biomass made up of smaller, more frequent grapple swings resulted in shorter, less frequent delays than operators who relied on fewer grapple loads with more material. Not only was this trend exhibited between different machines, it was also observed between different operators on the same machine (Table 12). At face value this result implies that contractors could achieve the same level of grinding productivity with a smaller, potentially less costly machine but because this study did not collect data on long-term repair and maintenance costs it cannot make a fair comparison regarding long-term costs.

Comparison and limitations

Operation 3 was a modified cut-to-length operation. Compared to other studies, the southern Rocky Mountains share similarities with the northern Rocky Mountains regarding the use of a harvester. When operating under conditions with trees greater than 21 cm in diameter that do not involve the treatment of regeneration or small diameter stems, cut-to-length systems can be equally cost-efficient as the whole-tree operations observed in this study. Other studies have also shown that cut-to-length systems and whole-tree systems have similar costs when stand conditions are standardized (Adebayo et al. 2007). Some prescriptions may limit the amount of slash that can be left on the unit, and therefore require pile burning or biomass utilization, making cut-to-length a difficult and expensive system to use.

The cost data in this study indicate that hand-felling is not an efficient felling method and should be replaced by mechanized felling in cases where site conditions are appropriate (Table 13). For individual operators, hand-felling may be used because it represents very low capital investment, but it is also less productive, and in this case is more costly on a per unit basis.

In fuel treatments in other parts of the western US, biomass harvest of small diameter stems is frequently paired with sawlog removal and results in more costly harvesting as almost the same work is needed to cut trees regardless of their size and value (Han et al. 2004; Vitorelo et al. 2011). Biomass opportunities may exist in forest restoration operations, but the operational costs tend to outweigh the associated market value of the biomass, especially when they are not a byproduct of sawlog production. However, wildfires that occur in fuel treatments tend to be smaller and offer potential savings up to 17% in fire suppression costs compared to if the same stand burned without treatment (Thompson et al. 2013, 2017), though this relationship is complex (Thompson and Anderson 2015). In other regions, such as the southeastern US where forest biomass is a marketable product associated with commercial timber harvest, cutting small diameter stems in thinning operations or coppice plantations for biomass energy may be profitable depending on market conditions (Stanturf et al. 2017; Santiago et al. 2018).

In-woods biomass grinding observed in this study is comparable to chipping operations in northern Europe (Belbo and Vivestad 2018). Chipping or grinding of biomass represent significant costs in both cases and needs to be as efficient as possible for biomass to be considered an economically efficient energy source. In this study, improper use of equipment was a significant source of mechanical delays.

A study in the southeastern US that involved cutting small diameter pine trees exclusively for biomass energy found that the cost of harvesting biomass was 52% lower in the southeast than was modeled on the most efficient operation (Operation 1) in the southern Rocky Mountains (Hanzelka et al. 2016). These treatments were clearcutting prescriptions, which are simpler and more efficient to carry out than restoration treatments. The individual felling, skidding, and grinding costs in that study were all less expensive than the average observed and modeled costs in this region. Another study that examined felling costs showed the costs of felling in the southern Rocky Mountain region fit into the range of felling costs experienced in other countries (Di Fulvio et al. 2017).

A limitation of this study is that the costs presented here are only direct stump-to-truck costs and do not include the cost of overhead, administration, transportation to market, or subsequent slash treatment. Some variables not included here, such as trucking costs, play a large role in determining stump-to-gate cost and economic feasiblity (Reddish et al. 2011), often ranging from 33% to 60% of the total stump-to-market expenses (Grebner et al. 2005; Hanzelka et al. 2016).

The lack of markets for small diameter logs from the treatment of stands dominated by small, often non-merchantable trees is a major challenge in the southern Rocky Mountains. Other regions such as the Pacific Northwest US and the southeastern US already have well-developed biomass energy markets because of their short rotation lengths for higher-value forest products and their well-established timber economies that include large-scale co-generation of heat and power at forest industry facilities (Zamora-Cristales et al. 2015; Stanturf et al. 2017). Much of the biomass harvested in this study was used for medium-scale (<30 MW) power production for the electrical grid. Additional facilities of this type and scale could stimulate markets for biomass harvested from restoration treatments. Because the southern Rocky Mountains region does not have a strong timber economy or large-scale biomass facilities, expanding biomass harvest to improve the economic viability of restoration treatments will be challenging.

Conclusion

This study improves land managers' understanding of challenges and costs associated with restoration harvests in the southern Rocky Mountains. Forest contractors now have a reference to compare logging systems they may use in the future and can benchmark their operations using these results.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This project is supported by the Biomass Research and Development Initiative of the U.S. Department of Agriculture, National Institute of Food and Agriculture [2016-10008-25636].

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Appendix

Table A1. Harvesting system descriptions.

Operation	Felling	Skidding	Processing	Loading	Grinding	Trucking
1	Rubber-tired hot saw (Tigercat 726G)	Rubber-tired grapple skidder (CAT 525 B)	Dangle-head processor (CAT 320 D with Waratah 623 C)	Knuckle-boom loader (John Deere 2154 D)	Horizontal grinder, loader (Peterson 4710 B, CAT 320 D)	Log trucks with fixed-length trailers, Chip vans for biomass
2	Rubber-tired hot saws (John Deere 843 L (2) and CAT 573 C)	Rubber-tired grapple skidders (John Deere 948 L (2), John Deere 648 H (2), CAT 555D)	Dangle-head processors (John Deere 2454 D with Waratah 623 C, CAT 324 D with Waratah 623 C)	Knuckle-boom loader (John Deere 2156 G)	Horizontal grinder, loader (Terex-Ecotec 680 (2), CAT 250 D)	Log trucks with fixed-length trailers, 12.2-meter (40-foot) Chip vans for biomass
3	Harvester (John Deere 240D with Logmax 7000 XT)	Rubber-tired grapple skidder (John Deere 748 H)	N/A	Dangle-head processor (John Deere 2054 with Waratah HTH 628)	N/A	Stinger-steered and flatbed log trucks
4	Tracked Hot saw (TimberPro TL735 B)	Rubber-tired grapple skidder (Tigercat 610)	Dangle-head processor (Doosan DX225LL with Waratah 622 B)	Truck-mounted loader (Prentice 280)	N/A	Stinger-steered and self-loading log trucks
5	Chainsaw (Husqvarna 372 XP)	Rubber-tired grapple skidder (John Deere 548 E)	Pull-through delimber (CTR 450)	Trailer-mounted loader attached to delimber (Prentice 310)	N/A	Log truck with fixed-length trailer