Productivity and Cost of Integrated Harvesting for Fuel Reduction Thinning in Mixed-Conifer Forest

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Abstract

Removing submerchantable size trees and forest residues as well as sawlogs is preferred in fuel reduction thinning because it improves treatment effectiveness and avoids slash burning. Fuel reduction thinning was investigated to describe integrated harvesting machine processes and productivity and to characterize stump-to-truck costs for sawlogs and biomass for energy production. This system was studied in mixed-conifer forest on land owned by the US Forest Service in northern California and southern Oregon. Detailed time-study methods were paired with standard machine rate calculation methods to evaluate productivity and costs for the system. Sensitivity analysis and a standardized comparison were performed to evaluate costs and productivity under varying operation parameters. Treatment costs (stump-to-truck; without mobilization, overhead, or profit) were US\$0.42/ft^3 for sawlogs and US\$52.41 per bone dry ton (BDT) for biomass. Standardized unit production costs for sawlog skidding varied little, but the smaller skidder was clearly preferable for biomass tree skidding when external skidding distances exceeded 200 feet. The grinder had the highest hourly cost of any machine in the system and its unit production cost (US\$/BDT) was sensitive to changes in utilization rate. Evaluations on system balance showed that improved utilization of the grinder could be accomplished as the grinder and loader often waited for a chip van. Integrated harvesting was a cost-effective way of implementing fuel reduction thinning method because of the potential for sawlog revenues to offset some of the biomass extraction cost.

Effective fire suppression and high grading are among factors that have led to dense, overstocked stands with an increased chance of canopy fire (Agee and Skinner 2005, Metlen and Fiedler 2006). Abundant small trees and shrubs function as ladder fuels, providing vertical continuity of fuels and allowing surface fires to climb into the canopy as they consume the smaller trees (Van Wagner 1977). Seasonally dry forests such as those in northern California and southern Oregon have more small trees and fewer large trees as well as more fuels than before European settlement (Parsons and DeBenedetti 1979, Bonnicksen and Stone 1982, Parker 1984, Chang 1996, Stephens and Ruth 2005). Resulting catastrophic canopy fires cause great economic damage and ecological disruption. Design and implementation of appropriate silvicultural and harvesting methods can be effectively used to reduce wildland fire hazard in these fire-prone ecosystems (Keyes and O'Hara 2002).

Timber harvesting systems have traditionally been developed to produce wood crops but are now used as a tool to accomplish varied stand management objectives. In addition to wood production, these systems can be used to prevent high-intensity fires, restore late-seral characteristics, and enhance wildlife habitat (Keyes and O'Hara 2002, Agee and Skinner 2005, Adebayo et al. 2007). Harvesting systems can be used as a tool to manage forest fuels because we have limited control over other influences on fire behavior, such as topography and weather (Rothermel 1972).

Conventional sawlog harvesting methods are relatively costly when used in fuel reduction thinning. Forest products produced in fuel reduction operations are primarily from the utilization of smaller trees (<9 in.), and much of this wood is not used to produce dimensional lumber. Lower production with small-wood handling increases the costs

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of fire hazard reduction operations (Han et al. 2004). Additional costs may occur when residues left from sawlog processing and whole trees not producing sawlogs (typically <9 in. diameter at breast height [dbh] in northern California) need to be removed with no burning option. Products such as chips or hog fuel (ground submerchantable trees and logging slash; hereafter ''biomass'') have relatively low value, volatile markets, and a limited number of markets (Hartsough et al. 2008).

When biomass has to be removed mechanically from the site, the overall economics of fuel reduction thinning becomes negative because of the low market value of biomass and increased handling costs. Harvesting system selection and methods, biomass moisture content, and truck travel time substantially affect the cost of small-wood harvesting, particularly when biomass is the primary forest product (Gingras and Favreau 1996; Han et al. 2004, 2010). The biomass harvesting cost is also sensitive to the utilization rates of the machines, especially the grinder's cost and utilization rate, both of which are often heavily influenced by availability of chip vans (Gingras and Favreau 1996, Spinelli and Visser 2008).

Integrated harvesting is a harvesting operation in which a combustible energy product (biomass) is produced in conjunction with sawlogs (Hudson et al. 1990). Integrated harvesting systems are often used in fuel reduction thinning treatments to utilize both sawlog-sized trees and submerchantable trees, removing them from the stand and reducing fire hazard. Integrated harvesting can be a more cost-effective way of treating hazardous fuel conditions than conventional sawlog harvesting because it eliminates the cost of pile-burning slash and risk of fire escape (Pan et al. 2008). Integrated harvesting costs are allocated to either sawlog or biomass functions depending on the machine's activities handling one or both of these products. Machines that handle both sawlogs and biomass have their costs apportioned based on the production amount of each of the products, referred to as the joint product cost estimation approach (Puttock 1995). The cost of machines that handle only one product are charged solely to the production of that product. Stump-to-truck costs for integrated harvesting operations have been reported to range from US$0.59 to US$0.82 per ft^3 for sawlogs and US$30.00 to US$38.51 per bone dry ton (BDT) for biomass (Hartsough et al. 1997, Han et al. 2004, Largo and Han 2004, Harrill and Han 2010). These costs are higher than those found in sawlog-only harvests due to high costs associated with biomass handling activities (Stuart et al. 1981, Adebayo et al. 2007).

Integrated harvesting is an effective way to supply biomass for energy production and leaves stands clear of residues and submerchantable trees. The application of an integrated harvesting approach in fuel reduction thinning treatment effectively reduces the fuel in the stand and eliminates smoke production and the risk of fire escape associated with prescribed burning (Hakkila 1989, Hudson et al. 1990, Nelson and Dutch 1991, Hudson 1995, Han et al. 2004). Drawbacks to integrated harvesting mainly involve increases in overall treatment costs compared with removal of sawlogs only (Hudson et al. 1990, Nicholls et al. 2008). There is limited information on removing biomass and sawlogs with one entry, especially in mixed-conifer stands, which are present throughout the US West.

The aim of this study was to develop an understanding of factors affecting the function of each individual component of an integrated harvesting system and evaluate how the components work together, leading to appropriate machine selection and aiding future cost estimation. The specific objectives of this study were to (1) describe the process and productivity of machines used in an integrated fuel reduction thinning and (2) characterize stump-to-truck costs for integrated harvesting. These results may be used by researchers and land managers to estimate the cost of reducing hazardous fuel conditions given consistency of parameters such as mixed-conifer forest type, similar silvicultural prescription, and similar integrated harvesting system machines.

Methods

Study site and harvesting system

This study took place on the Klamath National Forest as a part of the Mt. Ashland Stewardship Contract (T41S, R1W, Sec. 12, Willamette Meridian). The focus of this vegetation management contract was to restore and create stand structure characteristic of late successional stands, reduce fire hazard, and improve wildlife habitat. Much of the Mt. Ashland area is currently composed of mixed-conifer forests including white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), incense-cedar (*Calocedrus decurrens*), and sugar pine (*Pinus lambertiana*). The harvest unit represented differing amounts of heterogeneity as the majority of the area (>45 ac) was residual white fir, Douglas-fir, and sugar pine displaying late-seral characteristics. Another small (<10-ac) area was plantation ponderosa pine that had been planted in 1963. Variable density thinning was implemented to restore late-successional stand structure as well as create defensible fuel profile zones by thinning.

The study of this ground-based, whole-tree, mechanized harvesting system was conducted on a large (55-ac) thinning unit with gentle slopes (0% to 32%). The initial thinning operation involved several machines working in a decoupled fashion to complete the work over 10 12-hour working days. The feller-bunchers operated a few days ahead of the extraction machines in order to maintain a buffered wood supply between harvesting functions to maximize productivity as well as address skidder operator safety concerns. The stages of this operation collectively constituted an integrated harvesting system for fuel reduction thinning because of the extraction of both large trees (≥9 in. dbh) containing sawlogs and small-diameter (3- to 9-in.-dbh) trees for production of combustible wood products (biomass).

The first machines to enter the stand were three zero tail-swing tracked, ''hot saw'' feller-bunchers (Timbco/Valmet 445EXL). The feller-bunchers began the thinning process by cutting the marked (>9-in.-dbh) trees and unmarked biomass-sized (3- to 9-in.-dbh) trees and laying them in bunches (either sawlog or biomass) along the predesignated skid trails. All trees less than 3 inches dbh were left uncut according to the silvicultural prescription. The skid trails were located by the contractor and approved by the Forest Service timber sale administrator, with a preference for using existing skid trails when available if their slopes were less than 35 percent. The feller-bunchers started cutting at the landing and followed the skid trails as they radiated out toward the unit boundaries. Upon reaching a boundary they turned around and began cutting a large swath of trees on either side of the skid trail and worked their way along the skid trails back to the landing. This process was repeated on all skid trails until the silvicultural prescription was accomplished.

Upon completion of the timber-falling, a Cat 527 hightrack swingboom grapple skidder, along with John Deere 648E and 748GIII rubber-tired dual-stage grapple skidders, were used to complete the task of skidding larger trees, which would become sawlogs, to the landing. Three skidders were used for sawlog extraction to supply the processor with sufficient wood for minimal idle time. Skidders utilized the predesignated main skid trails for the majority of the turns and used random skids to collect wood to build turns. Skidding distances ranged between 30 and 850 feet and averaged 374 feet. The tracked skidder was used more often than the wheeled skidders on the steeper slopes (between 25% and 35%) due to its superior traction and stability.

Machines on the central landing worked in concert with skidders to make room for the subsequent turns of sawlogs. Logs were manufactured using a Waratah dangle-head processor attached to a John Deere 2554 log loader base machine. The limbs and tops were processed into a slash pile, but the roundwood of the tops were kept separate and decked in a large pile for subsequent utilization as biomass or firewood. Production of commercial firewood was proposed but was not realized in the thinning study unit during the period of allowable operations.

The deck of processed sawlogs was then separated into seven different sorts by a John Deere 2054 log loader. Logs were sorted by species and by lengths to facilitate rapid loading of log trucks. Logs from this thinning unit were taken to their respective markets based on species and were hauled either to a sawmill in White City, Oregon (51.5 mi one-way distance) or a sawmill in Yreka, California (48.6 mi one-way distance).

The subsequent biomass operation began after sawlog extraction had been completed. Two rubber-tired skidders (John Deere 648E and 848H) were used to extract biomass tree bunches left along skid trails by the felling operation. There was an average of 13.9 trees per bunch as they were small (3- to 9-in.-dbh) trees. The skidders often built turns that averaged 1.9 bunches (averaged 26.4 trees per turn). The observed skidding distances ranged from 50 to 650 feet and were limited to slopes less than 35 percent. These skidders used the existing skid trail pattern to bring the biomass to the landing where a John Deere 2054 log loader was feeding the grinder (Morbark 4600 XL tracked, 1,050 horse power grinder).

The grinding of biomass was maximized by using both ''hot loading'' directly into chip vans as well as creation of a large pile of ground material at the landing. When chip vans were present, the grinder loaded the comminuted material into the van directly via a conveyor belt to minimize material handling cost. If the landing was large enough, and in the absence of chip vans, the ground material would be deposited into a large pile until there was no room left on the landing.

Data collection and analysis

Stand inventory was conducted prior to and immediately following thinning to quantify stand conditions and evaluate differences in volume (cubic feet per acre), basal area (square feet per acre), density (trees per acre) and species composition. The inventory included all trees down to 3-inch dbh since any trees below this size were retained as advanced regeneration and for wildlife value as cover for terrestrial fauna. A systematic sampling design made up of 0.10-acre fixed-area circular plots ($n = 12$) was established with spacing between plots being 330 by 330 feet. Plot centers were flagged to locate the plots after the thinning had been completed.

Pre- and postharvest stand volumes were estimated to evaluate the impact of the fuel hazard reduction thinning treatment. Multiple-entry form factor equations developed by MacLean and Berger (1976) were used to determine tree volumes in cubic feet (to a 4-in. top). Equations were listed by MacLean and Berger (1976) for all of the species present in the treatment unit (ponderosa pine, Douglas-fir, incense-cedar, white fir, and sugar pine). Form factors were calculated for each individual tree in the cruise data set as a function of tree total height and diameter at breast height. These were limited for certain species to ensure reasonable extrapolation beyond the limits of the data used to develop the equations.

Time and motion study methods using a stopwatch (Olsen and Kellogg 1983) were conducted on each of the machines in the harvesting operation. The resulting data allowed characterization and understanding of the relative frequencies of machine activities (i.e., cycle components) for each phase of the thinning operation as well as recording delays. Additionally, delays were captured and delay-free machine cycle times were calculated along with stand and operations variables. Operational delays were defined as any time a machine was detracting from its own productivity but not detracting from the productivity of the system (e.g., waiting for skid trail to clear or waiting for wood to process). Mechanical delays included fueling, maintenance, cooling down, and repairing machines. Personal delay included lunch time, personal time, and breaks.

Predictive equations were developed for machine cycle times to understand machine production rates (cubic feet per productive machine hour [PMH]) as well as understand what factors affected machine operation. The feller-buncher cycle began as the machine traveled away from the bunch and toward the standing tree, cut the trees, and then ended with traveling back to the bunch and laying the trees down in the bunch. The skidder cycle began as the skidder left the decking area of the landing, traveled to the next turn, built the turn, grappled the turn, and then returned to the landing. The processor cycle began when the processor grappled a tree, processed the tree into logs, piled the tops, and then returned for another tree. Log loader cycle began with swinging empty grapples to the deck, grappling, swinging logs toward the truck, log branding, and bunking the logs. Independent variables, such as skidding distance and the number of trees per turn that affected machine productivity were recorded and related to each machine activity.

Predictive models were developed using analyses of covariance (ANCOVA) using ordinary least squares with Minitab 16 statistical analysis software (Minitab Inc. 2010). ANCOVA predictive models were trained using 70 percent of the data; 30 percent were randomly selected to be set aside for model validation (Adebayo et al. 2007). Equation coefficients were then calculated using the entire data set in the validated model. Data were transformed and standardized residual plots were reviewed using visual inspection of residuals to minimize heteroscedasticity (Ramsey and

Schafer 2002). In order to evaluate and reduce multicollinearity of the covariates, matrix plots, variance inflation factors, and Pearson correlation values were generated. Moderate correlation values among covariates led to the use of stepwise regression methods to minimize Mallows' Cp values, thus maximizing adjusted r^2 values. Mallows' Cp value is a criterion that focuses on the trade-off between bias due to excluding explanatory variables and extra variance caused by multicollinearity (Mallows 1973).

Once the best model was identified by stepwise regression, ANCOVA analyses were run by including both the categorical variable as well as the best model of the covariates. Categorical variable coefficients were given with exception of the final factor in each category which were aliased (omitted because it can be calculated from the coefficients of the other factors in the category; Minitab Inc. 2010). The final predictive equations developed were then validated by generating predicted delay-free cycle times for the machines using predictor variable values. These were then tested against the observed delay-free cycle times using a paired *t* test ($\alpha = 0.05$; Adebayo et al. 2007, Spinelli and Visser 2008).

Hourly cost figures (US dollars per scheduled machine hour (SMH) and per PMH) were calculated using standard machine rate methods (Miyata 1980, Brinker et al. 2002). Initial purchase price information and interest rates were obtained from local equipment dealers and lenders, respectively, to reflect general machine process for broader application of the results. Salvage values, utilization rates, tax information, lubrication costs, repair and maintenance costs, and economic lives were obtained from Brinker et al. (2002). Fuel consumption rates (gallons per hour) were calculated as a function of machine horsepower and transmission type and were checked for accuracy with contractor estimates (Brinker et al. 2002). Overhead, mobilization, support vehicles, and profit allowance were not included in hourly machine cost estimates.

Production rates for sawlog and biomass operations were derived by using field data collected from this study combined with biomass (weight of trees) prediction equations (Jenkins et al. 2003). Production rates for the sawlog operation were calculated using log scaling data derived from log deck sampling at the end of each day. Log sampling was stratified by species and then again by log length. Volume per log (cubic feet) was calculated using Smalian's cubic volume formula (Dilworth 1954). The number of trees or number of logs per cycle were recorded and used to determine volume per cycle for each machine. A combination of observed cycle time, utilization, and volume per cycle data resulted in machine production estimates, expressed as cubic feet per PMH.

Biomass production rates were obtained different ways based on the machine in question. Using species-specific tree mass equations (Jenkins et al. 2003), moisture content, and inventory data for trees thinned from the stand, we estimated the dry weight for each small (3- to 9-in.-dbh) tree removed. Feller-buncher productivity was calculated using the average dry weight per tree and the number of trees cut per cycle. The average dry weight per tree, the number of trees per bundle, and the number of bundles per turn were used to calculate skidder productivity. An average of the chip van weights was used for calculation of the productivity for the other machines used for biomass production. The chip van weights were obtained from the scaling information catalogued by the Klamath National Forest.

Operator skill influences the cost and productivity of forest operations and should be considered when estimating treatment costs. An experienced crew can have a direct effect on planning and layout time and cost as well as lowering unit production cost by increasing the level of productivity (Murphy et al. 2003). Bolding (2002) determined that operator skill was most important in loading and unloading as well as machine maneuverability in the study of a forest fuel reduction resulting in energy wood production. The work experience of the operator for each machine in this study is presented in Table 1.

Moisture content measurements of the ground material were used to convert the cost of the operation from green tons to BDT and were obtained by sampling. Six samples were taken during the grinding operation by placing hog fuel into sealed plastic bags to prevent evaporative loss of moisture. Sampling times were stratified throughout the day (morning, midday, and afternoon) to ensure accurate representation of the entire operation. Dry weights were obtained by oven drying samples at 60°C and weighing periodically until no additional mass was lost.

Standardized skidding comparison evaluated each of the skidders using the productivity equations developed for the three sawlog and two biomass skidders with standardized predictor variables for each of the machines. Values of the variables used for the standardized comparison for sawlog skidding were 61.67 percent utilization rate, 5.5 trees per cycle, and external skidding distance ranging from 100 to 600 feet; the variables for biomass skidder comparison were 60 percent utilization rate and the skidding distances previously mentioned.

Results and Discussion

Integrated harvesting operations in mechanical fuel reduction thinning

Stand conditions and thinning operations.—The initial stand condition showed both horizontally and vertically continuous fuels, with abundant ladder fuels as illustrated by the numerous small-diameter trees shown in the reverse-J diameter distribution (Fig. 1). The silvicultural prescription truncated the distribution, raising the canopy base height and lowering the canopy bulk density by introducing large

Table 1.—Experience for each of the operators on their machine types.[a]

Machine type	Make/model	Operator experience
Feller-buncher	Timbco/Valmet 445EXL 1	5 y
Feller-buncher	Timbco/Valmet 445EXL 2	15 y
Feller-buncher	Timbco/Valmet 445EXL 3	13 y
Small-wheeled skidder	John Deere 648E 1	6 mo
Small-wheeled skidder	John Deere 648E 2	2 y
Large-wheeled skidder	John Deere 748H	3 y
Large-wheeled skidder	John Deere 848H	1 y
Tracked skidder	Cat 527	20 y
Processor	John Deere 2554	1 y
Loader	John Deere 2054	2 y
Grinder	Morbark 4600XL	12 y

[a] Several operators had operated other machine types prior to their current assignments.

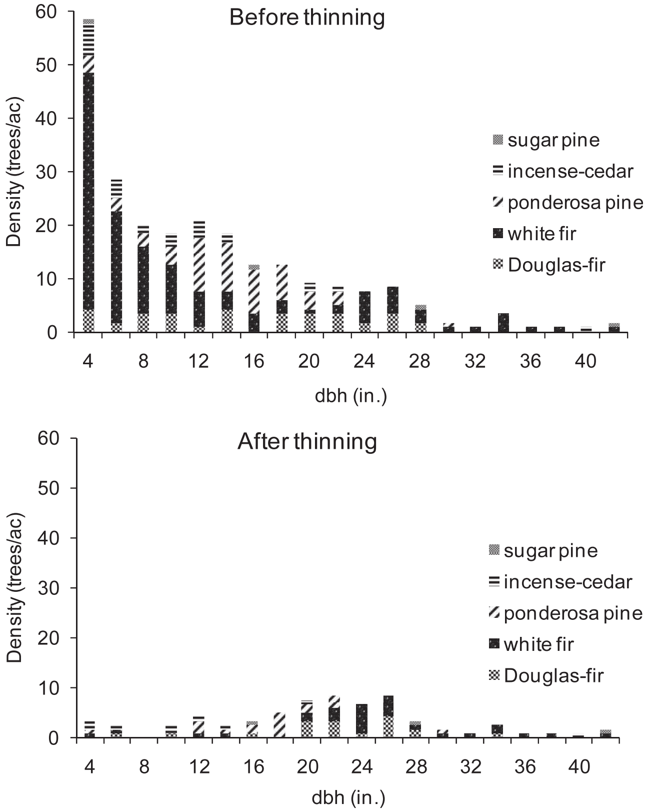

Figure 1.—Diameter distributions before and after restoration and fuel reduction thinning in late-successional reserve mixed-conifer stand in northern California.

Table 2.—Stand canopy fuel estimates as modeled by Fuels Management Analyst Plus version 3 (Carlton 2005).

	Canopy bulk density (lb/ft^3)	Canopy base height (ft)
Prethinning	0.0055	19
Postthinning	0.0036	45

gaps, resulting in an aggregated or patchy stand structure (Table 2). The thinning resulted in a 33.3 percent basal area reduction from 272.0 to 181.4 ft^2/ac, after removal of 2,442.0 ft^3/ac of stemwood volume (Table 3).

The sawlog extraction phase operated in a decoupled fashion with the feller-bunchers ahead of sawlog extraction machines by 3 days. This decoupling ensured a sufficient supply of wood to allow skidding to proceed at maximum productivity. The felling of trees is also dangerous when many pieces of equipment are present, and this decoupling served also to enhance skidder operator safety. Processing of trees into logs and loading of logs onto trucks was simultaneous with skidding. The biomass extraction phase was also decoupled in that it began after the sawlog extraction machines had left the unit. The biomass extraction machines were not decoupled from one another; they worked together to skid, process, and load biomass. Comparisons of machine operation activities were not included because they would not be valid comparisons; operations such as this have not been captured in previous studies.

Felling.—The three feller-bunchers concurrently performed the felling and handling of sawlogs and biomass trees so that only a single machine pass was necessary in any given area. The sawlog-sized trees and biomass-sized trees were cut in alternating cycles and laid in separate bunches. Bunches were placed at a 45° angle to the skid trail to facilitate the skidding of bunches while keeping them out of the road. The amount of time spent performing each of the several activities shows relatively little time spent handling sawlogs as compared with biomass (Fig. 2). The average delay-free cycle times for sawlog and biomass cutting cycles were 0.51 and 0.82 minutes, respectively.

Within the categories of sawlog and biomass handling, felling activity was further divided into the components of the harvesting process. The machine processes for sawlog and biomass handling were similar except for the difference in cutting time (Fig. 3). Much more time was spent cutting biomass material because more stems were cut during a biomass machine cycle. The average number ($\pm$standard deviation) of stems cut per cycle for the sawlog cycle was 1.2 $\pm$ 0.09 stems and for the biomass cycle was 4.6 $\pm$ 0.20 stems.

Skidding.—Skidding for sawlog production was done in concert with the processor and loader to extract large trees (>9 in. dbh). Three skidders were used by the contractor in an effort to balance the production of the different harvesting functions because too few skidders would leave the processor waiting for wood and underutilized. The machine-specific activity allocations reveal that traveling loaded and operational delays were common activities for skidders (Table 4). Skidder delays were primarily a result of waiting on the processor to clear the landing area, waiting for another skidder to clear the trail, or handling slash (64.21%, 3.32%, and 19.42%, respectively; percentage of total delay time). In consideration of the subsequent biomass

Table 3.—Stand characteristics and scope of mechanical fuel reduction thinning treatment.[a]

	Pretreatment, mean (SE)		Posttreatment, mean (SE)		Removed, estimate (%)[b]	
	Sawlog-sized trees	Biomass-sized trees	Sawlog-sized trees	Biomass-sized trees	Sawlog-sized trees	Biomass-sized trees
Basal area (ft^2/ac)	257.3 (15.1)	14.7 (3.5)	180.7 (14.8)	0.7 (0.4)	76.6 (29.8)	14.0 (95.2)
Density (trees/ac)	130.8 (6.1)	106.7 (18.8)	60.8 (4.0)	5.8 (2.6)	70.0 (53.5)	100.9 (94.6)
Volume (ft^3/ac)[c]	8,724.0 (713.1)	207.6 (53.4)	6,480.2 (659.4)	9.4 (5.3)	2,243.8 (25.7)	198.2 (95.5)
Mean dbh (in.)	17.6 (0.6)	4.7 (0.2)	22.2 (0.9)	4.7 (0.5)		
Composition (%, vol)	97.7	2.3	99.9	0.1		

[a] Sawlog-sized trees are trees $\geq$9 inches diameter at breast height (dbh) producing sawlogs (roundwood product intended for sawing), utilized down to a small-end diameter of 6 inches. Biomass-sized trees are trees between 3 and 9 inches dbh producing biomass, a combustible energy product composed of ground wood.

[b] Percent calculated as [(Pretreatment – Posttreatment)/Pretreatment].

[c] Volume calculated using multiple-entry form factor equations given in MacLean and Berger (1976).

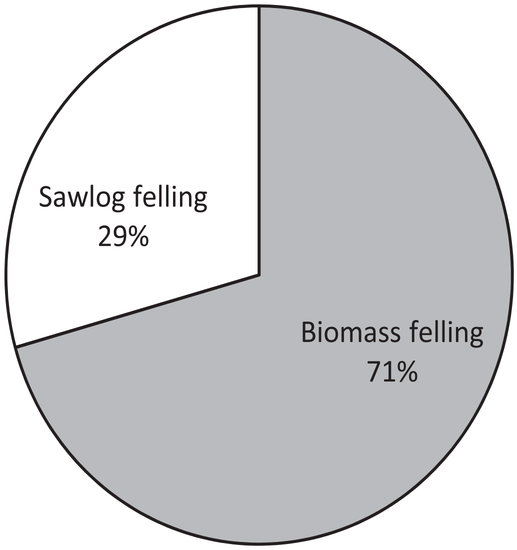

Figure 2.—Time spent for the three "hot saw" feller-bunchers during 3 hours of observation of an integrated harvesting operation in a whole-tree fuel reduction thinning (n = 276).

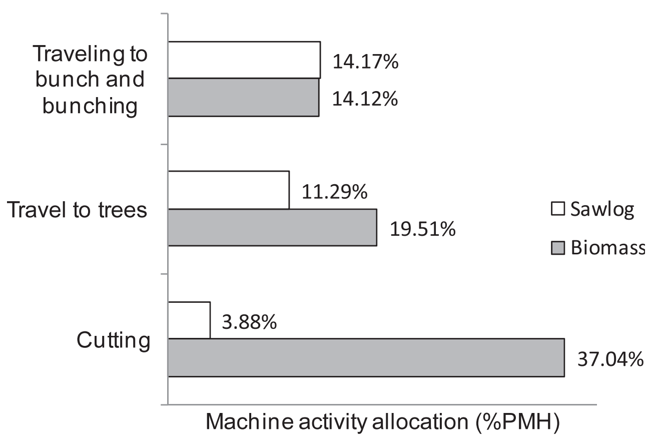

Figure 3.—Comparison of time spent cutting either sawlogs or biomass for specific felling activities (n = 276). Average delay-free times for sawlog and biomass cutting cycles were 0.51 and 0.82 minutes, respectively.

Table 4.—Average time spent per cycle for skidding activities during the sawlog harvesting phase (n = 77).[a]

	Large-wheeled John Deere 748GII I	Small-wheeled John Deere 648E	Tracked Cat 527
Travel empty	1.02 (20.29)	1.44 (14.29)	2.02 (14.28)
Positioning	0.11 (2.21)	0.00 (0.00)	0.32 (2.25)
Turn building	1.00 (19.92)	1.07 (10.58)	1.26 (8.93)
Pre-bunch biomass	0.00 (0.00)	0.13 (1.29)	1.36 (9.63)
Grappling	0.51 (10.20)	0.55 (5.45)	0.42 (2.95)
Travel loaded	1.17 (23.14)	2.45 (24.33)	4.17 (29.42)
Decking	0.40 (7.99)	0.54 (5.35)	0.71 (4.98)
Delay (operational)	0.82 (16.25)	3.91 (38.71)	3.90 (27.57)
Avg. cycle time	5.04 (100.00)	10.09 (100.00)	14.16 (100.00)

[a] Values are in minutes with the percentages of average cycle times for each machine in parentheses.

operation, skidders handled slash by piling with their grapples instead of pushing slash with their blades to minimize incorporation of soil and thus maximize biomass feedstock quality.

Extraction of the biomass-sized tree bunches (3 to 9 in. dbh) from the thinning was concurrent with production of woody biomass for energy production. The two skidders used for primary transport (stump to landing) of the biomass differed substantially in size, yet their machine-specific activity allocations showed strong similarities (Fig. 4). Average skidding turn times for large and small skidders were 5.75 and 5.35 minutes, respectively. This similarity in skidding times was likely due to highly comparable turn volumes. Because of the low density of the biomass bundles, the smaller skidder was not limited by turn weight and forced to skid less volume than the large skidder (turn weights for large and small skidders were, respectively, 1.41 and 1.37 BDT).

Processing.—The processor manufactured logs of different lengths (35, 26, and 17 ft) down to a small-end diameter of 6 inches outside bark. The logs were then decked between the processor and loader for the loader to sort and load. The processor was supplied with whole trees continuously by the skidders with few instances (7.9% of total time observed) of the processor having to wait for trees. The processor spent additional time piling biomass, primarily tops, to streamline subsequent utilization (Fig. 5).

The processing of residual biomass (i.e., slash) from sawlog manufacturing and smaller trees (3 to 9 in. dbh) into a marketable forest product was accomplished using a grinder. A Morbark 4600XL hammer grinder (1,050 hp) produced woody biomass for energy production. Quality control of biomass feedstock size was accomplished using a screen in which two-thirds was perforated with 4-inch apertures and one-third had 6-inch apertures.

Screen size affected production rate because larger screen sizes allowed passage of larger particles, thus increasing production. The grinder took, on average, 24.35 minutes to hot load 23.1 green tons or 16.0 BDT (30.8% moisture content conversion factor used) into chip vans. Harrill and Han (2010) found similar chip van loading times for a comparable grinder in a forest residue recovery operation. They reported 21 minutes for the grinder to load 14.1 BDT into a chip van. Pan et al. (2008) provided a predictive

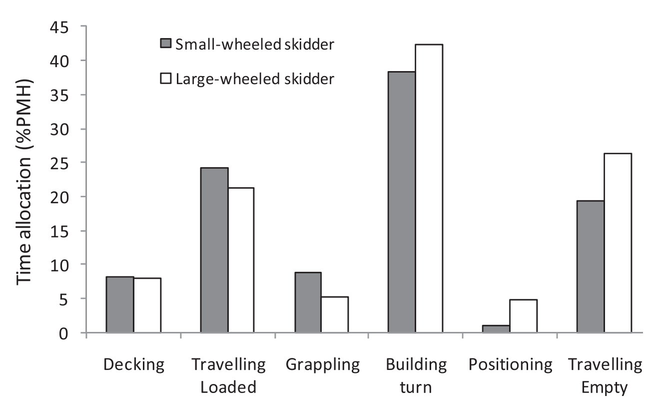

Figure 4.—Time spent for specific cycle components for biomass skidders. Average turn size was 26.41 trees, and 1.9 bunches were collected to build a turn at 13.9 trees per bunch (n = 51).

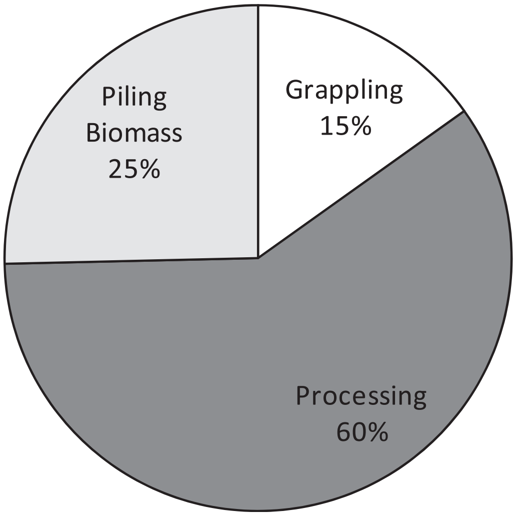

Figure 5.—Delay-free time spent for the dangle-head processor manufacturing sawlogs and piling biomass. Average delay-free cycle time observed was 0.64 minute per tree (n = 166).

equation where the green weight (pounds) of hog fuel was a significant ($P < 0.05$) predictor of the time the grinder required to load a chip van. The van weights in this study were within the range of the model training data Pan et al. (2008) used to develop this equation, but we found no significant relationship between chip van weight and loading time ($n = 7$).

The operator's strategic utilization of the landing area aided in increasing the grinder's production rate. Hot loading of chip vans was preferred because it required less material handling, but in the absence of chip vans the biomass was blown into a large pile to avoid idle time for the grinder. This pile began at the corner of the landing farthest away from the skidders' decking area and progressed toward the skidders, filling the landing, with the exception of a lane just wide enough for chip van access. Having a grinder that was self-mobile (on tracks) was important in grinder positioning for efficient use of the landing area.

To comminute the roundwood of the tops of sawlog trees and whole biomass trees, a chipper might have been more favorable; however, a chipper would have been less effective at converting slash into a biomass. Hammer grinders often have higher energy requirements than chippers but have greater flexibility in the material they can accept and have lower maintenance due to rugged design (Pottie and Guimier 1985).

Loading.—Sawlogs were loaded onto stinger-steered double-bunk log trucks and occasional short-log trucks. The loading process was slowed by the need to brand logs (8.53% of the loader's time was spent branding), which was required for the timber sale in the National Forest. Log trucks were loaded until the onboard scales read a load weight of approximately 25 tons (or 35 tons if the truck was specially equipped and traveled to the Oregon sawmill).

The machine activities captured for the loader during the biomass operation were during hot loading of chip vans. Interestingly, swinging the empty grapples toward the wood took more time than swinging the loaded grapples (10.95% as opposed to 7.97%, respectively) toward the infeed table of the grinder. This phenomenon was due to the operator swinging the empty loader slowly to evaluate which pieces would maximize the grinder's productivity without overloading the grinder and slowing it down.

Predictive equations for harvesting productivity.—Predictive models for the machines estimate delay-free cycle time for a machine, using the corresponding independent variables for each cycle element (Table 5). Assumptions used for the data analysis were met because data were independent, heteroscedasticity was minimal, and models' multicollinearity was mild or moderate. These models were all validated using a paired t test ($\alpha = 0.05$) comparing observed with predicted delay-free cycle time for the reserved data (30% of observed data). Following validation, equation coefficients and P values were calculated using the entire data set in the validated models (Table 5).

Production costs for sawlogs and biomass

Sawlogs.—The overall unit production cost for sawlog production was US\$0.42/ft^3 (Table 6). Skidding had the highest harvesting function cost at US\$0.17/ft^3. This represents 40 percent of the total sawlog system production cost. Production rates for all of the machines in the sawlog harvesting operation ranged from a maximum of 1,456.45 ft^3/SMH to a minimum of 366.20 ft^3/SMH at 60 to 65 percent machine utilization rates.

The sawlog harvesting unit production cost developed here was lower than those found in past studies (Hartsough et al. 1997, Han et al. 2004, Largo and Han 2004). The decoupled nature of this integrated harvesting system that resulted in high production rates lowered the cost observed in this study. As found in other studies (e.g., Han et al. 2004), skidding was more costly than any other sawlog harvesting function such as felling and processing.

The system balance of the sawlog harvesting system was particularly interesting and telling of the efficiency of the system (Table 6). Production rate totals for harvesting system functions (i.e., skidding, felling, etc.) illustrate system balance more clearly than individual machine production rates (i.e., large-wheeled skidder, tracked skidder, small-wheeled skidder, etc.). The total felling production was the highest of all the harvesting functions, but it did not affect productivity of the follow-up harvesting because it was decoupled from the remaining extraction functions. Skidding had the second highest production rate, illustrating a slight system imbalance. Processing had the lowest production rate of all the harvesting functions, indicating the bottleneck (lowest production rate) in the system. Despite the bottleneck, the system seemed relatively well balanced, and the addition of another processor would have resulted in excessive production and led to lower utilization due to idle time waiting for skidders to deliver trees. Additionally, excessive production of two processors would have overwhelmed the log loader because its production capability was lower than the capability of two processors.

Utilization rates used in the cost calculations are standard rates described by Brinker et al. (2002) to represent typical operations. These cost figures should result in greater applicability for future cost estimation. Observed utilization rates were not used in cost calculations to minimize potential bias resulting from a short observation window (10 days) because the delays recorded may not be representative of the operation as a whole (Table 7). Felling

Table 5.—Predictive models estimating delay-free cycle time for several machines in the integrated harvesting system.

Forest product	Machine	Avg. delay-free cycle time (cmin)[a]	SE (coefficient)	Independent variable		P value	r^2 (adj)	n[b]	Validation P value[c]
				Mean	Range				
Sawlog	Feller- buncher	ln(DFCT) = 2.7664	0.2163			<0.001	59.40	111	0.051
		+0.1758 × ln(DTT)	0.0506	10.23	1–76	<0.001			
		+0.3140 × ln(DTB)	0.0419	8.89	1–55	<0.001			
		+0.0941 × (TPC)	0.2026	1.2	1–2	0.090			
	Skidders	ln(DFCT) = 2.8473	0.7711			0.001	57.37	77	0.823
		+ 0.3132 × ln(TED)	0.1533	374.09	50–850	0.047			
		+0.2330 × ln(TLD)	0.1119	378.57	30–850	0.043			
		+0.0637 × (TPC)	0.0332	5.49	2–12	0.061			
		+ Skidder type[d]	NA[e]			NA			
	Processor	DFCT = 22.253	0.0055			<0.001	44.97	166	0.238
		−659.63(1/DBH)	0.0004	12.58	9–20	0.001			
		−141.80(1/CUTS)	0.0027	1.94	1–6	0.009			
		+3003.0[1/(DBH × CUTS)]	0.0002	25.51	8–90	0.081			
		+Species[f]	NA			NA			
	Loader	ln(DFCT) = 3.6021	0.0665			<0.001	42.97	244	0.339
		+0.2280 × (NumLogs)	0.0316	2.01	1–6	<0.001			
		+Log branding[g]	NA			NA			
Biomass	Feller-buncher	ln(DFCT) = 2.8623	0.1205			<0.001	58.93	165	0.554
		+0.3817 × ln(DTT)	0.0457	10.65	1–60	<0.001			
		+0.0960 × ln(DTB)	0.0308	7.96	1–50	0.002			
		+0.3441 × ln(TPC)	0.0471	4.6	1–13	<0.001			
	Skidders	DFCT = 35.28	62.950			0.579	69.66	51	0.265
		+0.9841(TED)	0.2746	292.25	50–650	0.001			
		+0.7559(TLD)	0.2985	275.69	75–600	0.017			
		+Skidder size[h]	NA			NA			

[a] DFCT = delay-free cycle time; DTT = distance to tree; DTB = distance to bunch; TPC = trees per cycle; TED = travel empty distance; TLD = travel loaded distance; DBH = diameter at breast height (in.); CUTS = number of cuts made; NumLogs = number of logs manufactured; distances are measured in feet.
[b] Seventy percent of observed data were used to develop predictive models, 30 percent were reserved for model validation.
[c] P value for paired t test between observed and predicted cycle times.
[d] Categorical adjuster for skidder type. Use 0.0319 for tracked skidder, 0.0174 for small-wheeled skidder, and −0.0493 for large-wheeled skidder.
[e] NA = coefficient P values not available from Minitab 16 statistical program output.
[f] Categorical adjuster for tree species. Use 0.0087 for incense cedar, −0.0052 for Douglas-fir, −0.0014 for ponderosa pine, and −0.0020 for white fir.
[g] Categorical adjuster for log branding. Use 0.2145 if logs were branded or −0.2145 if logs were not branded.
[h] Categorical adjuster for skidder size. Use 22.37 for small-wheeled skidder and −22.37 for large-wheeled skidder.

production used was an average of the production of the rate across the three machines.

Biomass harvesting.—The biomass harvesting cost estimate (US$52.41/BDT stump to truck) in this study was higher than those found in literature (Hartsough et al. 1997, Rummer et al. 2003, Han et al. 2004, Largo and Han 2004, Pan et al. 2008, Harrill and Han 2010). A low utilization rate of the grinder may cause increased unit production cost; Spinelli and Magagnotti's (2010) figure of 75 percent utilization (based on 63 chipping and grinding operations) was used to broaden the applicability of our cost figures for future cost estimation. It is important note that the use of a

Table 6.—Production rates, machine utilization rates, and unit production costs for sawlog operation.[a]

Function	Machine	Production rate with no delays (ft^3/PMH)	Utilization rate (%)[b]	Production rate with delays (ft^3/SMH)	Machine hourly cost (US$/SMH)	Unit production cost (US$/$ft^3$)
Felling	Timbco/Valmet 445EXL[c]	2,361.65	60	1,416.99	129.61	
Total felling production				4,250.96	388.83	0.09
Skidding	John Deere 748 GIII	1,181.19	60	708.72	83.35	
	John Deere 648 E	610.33	60	366.20	77.19	
	Cat 527	862.15	65	560.39	110.36	
Total skidding production				1,635.31	270.90	0.17
Processing	John Deere 2554/Waratah head	1,647.59	65	1,070.93	117.71	0.11
Loading	John Deere 2054	2,240.70	65	1,456.45	78.07	0.05
Total production cost					1,515.27	0.42

[a] PMH = productive machine hour; SMH = scheduled machine hour.
[b] Utilization rates listed were obtained from Brinker et al. (2002) to make cost figures representative of a typical operation and more broadly applicable for future cost estimation.
[c] Three feller-bunchers of the same model were used, and three times of an hourly cost was added to the total machine hourly cost. The production rate presented was an average of those three machines' hourly productivity.

Table 7.—Summary of observed delays by machine over 5 days of operation.

Machine/function	Make/model	Delay type (%)[a]			Total
		Operational[b]	Mechanical[c]	Personal[d]	
Feller-buncher (sawlog and biomass)	Timbco/Valmet 445 EXL 1	8.1	24.8	0.0	32.9
	Timbco/Valmet 445 EXL 2	23.4	7.5	0.0	30.9
	Timbco/Valmet 445 EXL 3	19.0	5.5	0.0	24.5
Skidder (sawlog)	John Deere 748GIII	16.3	0.0	0.0	16.3
	Cat 527	27.6	0.0	0.0	27.6
	John Deere 648E	38.7	0.0	0.0	38.7
Processor (sawlog)	John Deere 2554	13.3	2.1	0.0	15.4
Loader (sawlog)	John Deere 2054	23.7	0.0	0.0	23.7
Skidder (biomass)	John Deere 848H	2.7	0.0	0.0	2.7
	John Deere 648E	7.3	0.0	3.0	10.3

[a] Percentage of total observed machine time spent delaying for a specific machine.
[b] Operational delay includes any time a machine is detracting from its own productivity but not detracting from the productivity of the system.
[c] Mechanical delay includes fueling, maintenance, cooling down, and repairing machines.
[d] Personal delay includes lunch time, personal time, and breaks.

team consisting of a grinder and a loader has a direct impact on grinding costs, as illustrated in Figure 6. The delivered softwood biomass/hogfuel prices for the Pacific Northwest ranged from US$34 to US$51 per BDT during the period of operation (Glass 2010), meaning that the revenues from the removal of biomass from the stand would be less than the total cost of biomass harvesting and transportation.

The biomass phase of this integrated harvesting system for fuel hazard reduction had unique attributes to its production analysis. The feller-bunchers, loading, and grinding functions were well matched in terms of bone dry ton per scheduled machine hour, with the skidding being less productive. The skidding appeared to be the bottleneck (lowest productivity) in this system, but it was mainly due to the skidders' lower utilization rate because their production capability was much higher at 27.41 BDT/PMH (Table 8).

Based on field observations, the main system inefficiency was caused by the lack of chip vans available for hot loading (an average of 3.35 h of chip van availability in a 12-h workday). The deficiency of landing area to accommodate biomass piling on the ground in absence of a chip van also contributed to its inefficiency. This unit was one of many in the area. Thus, the grinding phase crew had to travel from landing to landing in search of free space to operate. The average landing size in the area was 0.43 acre and the average distance that the machines (two skidders, loader, and grinder) had to travel between these landings was 0.26 mile. With additional chip vans or larger landings, the unit production cost of the grinder would have been lower, and thus the stump-to-truck cost of the operation would have been lower than US$52.41/BDT (Fig. 6).

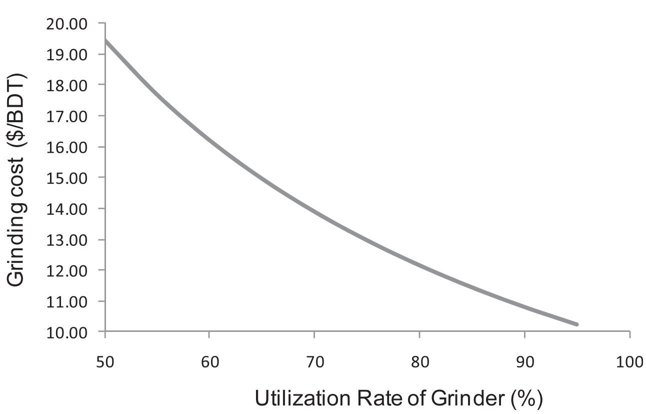

Figure 6.—Effect of machine utilization rate on grinding cost. Machine rate calculation with varying utilization rates were used to develop this sensitivity analysis. With a utilization rate of 75 percent, the cost of the grinder was US$12.97 per bone dry ton.

Standardized comparison for skidding

Standardized sawlog skidding costs were the same or similar to each other for different sizes and types of skidders in this standardized comparison (Table 9). The small-wheeled skidder (John Deere 648E) was consistently slightly more costly than the other two throughout all of the skidding distances. The two larger skidders (John Deere 748GIII and Cat 527) had the same or similar unit production cost throughout all skidding distances. The similarity in unit production costs among these skidders was a function of size (horsepower and physical size/mass). The smaller skidder (648E) had a lower hourly cost (US$77.19/SMH), but it had lower turn volume (147.09 ft^3 per turn) because of horsepower restriction, whereas the 527 had higher hourly cost (US$110.36/SMH) and larger turn volume (161.49 ft^3 per turn). The large-wheeled skidder (748GIII) was more cost effective not because of larger turn volume (hourly cost and turn volumes of US$83.35/SMH and 138.41 ft^3 per turn, respectively), but because it was able to travel faster due to its higher horsepower. Based on these results, any of these machines appeared to be a good choice for this harvesting operation.

Biomass skidding unit production costs revealed an intuitive preference for the smaller skidder. The larger skidder was more costly across all external skidding distances. The difference in turn volumes between large and small skidders was less noticeable than with sawlog skidding because the material was much less dense. Field observation showed that turn volume for the biomass skidders was primarily dictated by grapple size and the grapple sizes of these machines were similar. Based on these results, the smaller skidder (John Deere 648E) is far more economical to use for biomass skidding than the large skidder (John Deere 848H).

Table 8.—Production rates and costs for biomass harvesting in a mechanical fuel reduction thinning operation.[a]

Machine	Make/model	Production rate with no delays (BDT/PMH)	Utilization rate (%)	Production rate with delays (BDT/SMH)	Machine hourly cost (US$/SMH)	Unit production cost (US$/BDT)
Feller-buncher[b]	Timbco/Valmet 445 EXL	10.43	60	6.26	129.61	
Felling totals		31.29		18.77	388.83	20.72
Large skidder	John Deere 848H	13.51	60	5.29	89.56	
Small skidder	John Deere 648E	13.90	60	5.56	77.19	
Skidding totals		27.41		10.85	166.76	15.37
Loader	John Deere 2054	29.54	75	22.16	74.23	3.35
Grinder (tracked)	Morbark 4600XL	29.54	75	22.16	287.31	12.97
Totals					917.13	52.41

[a] BDT = bone dry ton; PMH = productive machine hour; SMH = scheduled machine hour.
[b] Three feller-bunchers of the same model were used, and three times of an hourly cost was added to the total machine hourly cost. The production rate presented was an average of those three machines' hourly productivity.

Table 9.—Standardized skidding unit production costs for an integrated harvesting system in a mechanized fire hazard reduction thinning operation.[a]

Skidding distance (ft)	Sawlog (US$/ft^3)			Biomass (US$/BDT)	
	748GIII	527	648E	848H	648E
100	0.07	0.07	0.08	7.78	6.09
150	0.09	0.09	0.10	9.22	7.22
200	0.10	0.11	0.11	10.93	8.56
250	0.12	0.12	0.13	12.95	10.14
300	0.13	0.13	0.14	15.35	12.02
350	0.14	0.15	0.15	18.19	14.25
400	0.15	0.16	0.16	21.57	16.89
450	0.16	0.17	0.17	25.56	20.02
500	0.17	0.18	0.18	30.30	23.73
550	0.18	0.19	0.19	35.91	28.13
600	0.19	0.19	0.20	42.57	33.34

[a] Standardized comparison utilizing delay-free cycle time equations for each of the machines and standardized variables to evaluate costs. Average number of trees per cycle (5.5) and average utilization rates for sawlog (61.67%) and biomass (60%) skidding were used. BDT = bone dry ton.

Conclusions

The integrated harvesting system accomplished the silvicultural prescription for this stand and the management objectives. This treatment minimized the vertical continuity of fuels by removing the majority of ladder fuels as well as lowering the canopy bulk density by thinning and introducing gaps in the canopy to reduce the horizontal continuity of canopy fuels. The variable density thinning prescription for this stand retained several cohorts of trees while opening gaps for advance regeneration to establish yet another cohort of trees. Additional cohorts enhance the structural heterogeneity and habitat value of the stand. As a result, the mean diameter of the stand increased to function also as restoration to a more fire-resilient stand structure.

The harvesting costs developed here represent a unique pairing of sawlog and biomass product extraction in an integrated harvesting system. The sawlog extraction phase had a stump-to-truck cost of US$0.42/ft^3, which was lower than the unit production costs reported by similar studies. Biomass production costs (stump to truck) were higher than reported in previous studies at US$52.41/BDT. Integrated harvesting operations may become more common as they represent a way to remove small-diameter fuels from the forest without the smoke and risk of fire escape associated with prescribed burning, while having the potential to produce energy from a renewable source.

System balance can affect productivity, a major influence of unit production cost. The sawlog extraction phase of this integrated harvesting operation showed only slight system imbalance where the processor had a slightly lower production rate than the other harvesting functions. The biomass utilization phase had a substantial system imbalance that affected the unit production cost of the whole system. Lack of chip vans and (or) lack of landing space caused a severe bottleneck in the system that led to low observed grinder utilization. Grinding unit production cost was sensitive to machine utilization; given the high hourly cost of this machine it is important to minimize its delay time.

Results of this study will help inform researchers and land managers of the cost of fuel reduction thinning for future treatment cost estimation. With increased accuracy in cost estimation, the funding may be used to treat more of the high-risk areas across the forests of the western United States.

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