COSTS AND PRODUCTIVITY OF WOODY BIOMASS HARVESTING IN INTEGRATED STAND CONVERSION AND RESIDUE RECOVERY OPERATIONS

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ABSTRACT

COSTS AND PRODUCTIVITY OF WOODY BIOMASS HARVESTING IN INTEGRATED STAND CONVERSION AND RESIDUE RECOVERY OPERATIONS

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Three separate forest biomass harvesting systems, were selected to study the operational performance and costs of systems designed to recover sawlog harvesting residues and silviculturally restore forests through stand conversion operations. These systems include the use of hook-lift trucks to access remote forest residues, energy wood harvesters to collect and improve density of residues through bundling, and integrated operations for the production of both sawlogs and energy wood chips. The overall system productivities were significantly affected by adverse road hauling distances, slash pile material size and arrangement, diesel fuel prices, and appropriate pairings of machinery. Slash pile arrangement and material size were found to have a significant effect on productivity of loading loose slash into trucks and in the bundling of slash. Forest biomass that was not accessible using traditional highway chip vans was successfully removed from previously harvested timber sites with hook-lift trucks. Energy wood harvesters were effective in collecting and compressing slash into bundles, and can be successfully incorporated into centralized grinding operations. Integrated harvesting of both sawlogs and biomas was a good method for silviculturally restoring stands and to produce both high value sawlogs and energy wood chips. Total system costs ranged from $32.98/bone dry ton (BDT) for residue recovery operations including a hook-lift truck to

$46.50/BDT for bundling operations. All operations studied accomplished removal of forest residues for renewable energy production without the practice of open field burning.

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF TABLES

Table Page

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

Chapter 1. Introduction

Recent trends in the United States show increasing interest in replacing fossil fuels with clean and renewable alternatives. Passage of national and state renewable energy portfolio standards, have been effective policies that have instigated research, development, and production of renewable energy, nation-wide (Nicholls et al. 2008). Renewable energy consumption grew by 7 percent between 2007 and 2008, despite a 2 percent decline in total U.S. energy consumption (Beckert and Jakle 2008). Currently the largest source of renewable energy consumption in the U.S. is biomass, representing 53% of total consumption. Biomass is a fuel source derived from recent biological origin, most commonly plants and plant fibers like agricultural crops and forestry residues (i.e. woody biomass).

Woody biomass has one of the highest energy contents of all biomass sources, with over 25 million British Thermal Units (Btu's) per ton (Beckert and Jakle 2008). There are extensive woody biomass resources available, Perlack et al. (2005) found that there were 368 million dry tons available on an annual basis from United States forests. Conventional harvesting and forest fire fuel reduction treatments alone could provide one third of the 368 million dry tons. More recently studies have evaluated all treatable timber land in the Western United States, and found that 97 million acres of forestland are available and estimates of available biomass were reported as high as 617 million dry tons (Nicholls et al. 2008). Unfortunately many constraints prevent the United States utilization from reaching its potential, subsequently only 20% of all biomass power produced comes from the forestry sector, while demand continues to rise.

Despite potential estimated availability of forest biomass, economic barriers are largely responsible for the under-utilization of residues (Han et al. 2004). Forest operations typically focus their efforts on extraction of their primary product usually round-wood or saw-logs with high value. Harvesting, collecting, and transportation of these materials often exceeds their disposal costs, because secondary products (i.e. residues) have such low associated value ($25/green ton in northern California). Woody biomass or residues from conventional timber harvests are most commonly disposed of through piling and a burning. Burning the material at a biomass power plant is favorable compared to open field burning due to technological improvements in reduction of green house gasses being released into the air (99.1%, 98.4%, and 97.1%) for non-methane organic hydrocarbons, carbon monoxide, and particulate matter < 10 microns respectively (U.S. EPA, 1992).

The appropriate harvesting system to be employed is determined by the conditions under which the product is harvested and by the scale of operations. For woody biomass, the nature of the forest site, forestry traditions, infrastructure and the desired level of integration into conventional logging systems all influence choice of technology and methods. Due to variability in terrain, tree crops, infrastructure, transport, and regulations between and within various counties and states, each situation needs to be assessed individually and requires a system designed to suit specific conditions.

The overall objective of this project was to analyze three different systems for harvesting woody biomass either integrated with conventional logging systems or as recovery operations after completion of conventional saw-log operations. Each system was evaluated in terms of production and costs of collection, grinding/chipping, and transportation. Special effort was made to identify critical conditions or variables that affect cost and productivities of these systems, so that one could identify when it would be appropriate to apply these systems to utilize woody biomass (i.e. logging slash and non-sawlog producing whole trees), preventing disposal through burning.

The three systems studied vary in design and focus on new and innovative ways to harvest residues. The three main areas of focus in these operations were: (1) improved access to biomass at harvest sites through innovative and alternative primary transportation methods, (2) densification of residuals using new equipment for improved efficiency in transportation and subsequent stages of operation, and (3) integration of processes into conventional operations to improve collection and reduce costs.

For the first objective, three completed conventional saw-log harvesting sites were selected in Northern California. Sites were clearcut using ground-based shovel logging systems, consisting mainly of second growth redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*). Harvesting sites were located in areas that traditional chip vans could not access due to adverse road conditions such as small turn radius, poor surfacing, steep grades, and inadequate road width. An alternative method of utilizing hook-lift trucks for collection and primary transportation of logging slash was used to improve access to biomass. Residues were packed into dumpster-like containers adapted from the garbage industry. These 40 cubic yard containers were loaded at harvest units by an excavator. A short truck, less than half the size of tradition chip vans, called a hook-lift truck which could access these harvest sites unloaded empty bins and retrieved full bins with its hydraulic hook-lift arm, and delivered them to a grinding site within the forest road network. Chapter 2 evaluates the productivities and costs associated with this method of primary transportation, and defines the critical variables that affected these costs and productivities.

In the second objective, the same three harvesting sites were utilized, but the operation setup was slightly different. During this study residues were harvested with a John Deere 1490D energy wood harvester (i.e. slash bundler), a machine that is used widely in Scandinavia but is relatively new in application to the United States. This machine is essentially a forwarder with a specialized bundling unit mounted in place of the traditional log bunk. The machine operates similar to a hay bailer in that it condenses residues, wraps them with twine, and cuts them into bundles shaped similarly to logs. The result is a dense and easy to handle unit of residues that facilitates improved transportation and long-term storage. Chapter 3 evaluates efficiency and cost when the system from Chapter 2 adds the bundling machine as its first process. Improvements in loading and transportation costs and productivity as well as the significant variables that affect bundling are all addressed in Chapter 3. Extra effort was made during the studies in

Chapters 2 and 3 to address pile type in terms of material size and arrangement and how different combinations of these variables affect loading or bundling productivities.

Chapter 4 covers the final objective of this study, which was the associated production and costs of integrating biomass harvesting operations into traditional saw-log operations. In Northern California many timberland managers are practicing rehabilitation silviculture through stand conversion processes. These stand conversion operations occur in areas that were poorly regenerated after the harvest of virgin timber. These traditionally conifer stocked stands are now dominated by tanoak *(Lithocarpus densiflorus)* which outcompeted conifer seedlings due to its' ability to sprout from stump. Tanoak which is now the main component of stand volume is not commercially valuable, making harvesting of these stands not economically viable in many cases. However, harvesting a second product (i.e. biomass), can provide additional revenue streams while ensuring these stands conversion to more historical high valued conifer stands. A special method called "*input apportioned allocation,"* was used to determine the true productivities and costs associated with producing both saw-log and biomass products. Additionally variables that significantly affected productivities and costs associated with the operation were identified.

Overall conclusions are summarized in Chapter 5. In reporting data, English units were used and can be compared across different system data. Additionally, Chapter 5 outlines future research needs in the field of forest biomass harvesting operations.

CHAPTER 2. Application of hook-lift trucks in centralized slash grinding operations

ABSTRACT

Chip vans are large trucks commonly used for transporting comminuted woody biomass from forests, provided the roads are suitable for the truck. Smaller trucks can effectively negotiate adverse road conditions such as sharp curves and steep grades, and improve access to forest residues (i.e. logging slash). This study evaluated the operational performance and costs of a forest biomass harvesting system, utilizing a hook-lift truck in centralized grinding operations in northern California. A centralized grinding operation utilizing a hook-lift truck was cost effective in collecting previously inaccessible forest residues for energy production. The total system production cost (woods landing-to-chip van) was estimated at $32.98/ bone dry ton (BDT) with an hourly production of 10 to 37 BDT, and a total production of 267.5 BDT.

INTRODUCTION

Rising energy costs, concerns about emissions from fossil fuels, and the threat of wildfires have sparked interest in recovery and removal of woody biomass for multiple benefits (Evans 2008). Woody biomass, including un-merchantable trees, small diameter trees, tops, limbs, and logging slash, produced from mechanical thinning and conventional saw-timber harvesting creates an opportunity for generating power (Han et al. 2004).

The demand for bioenergy and the feedstock used in the process is growing. In recent years more than 20 states across the U.S. have adopted renewable energy portfolios or standards (Nicholls et al. 2008). These standards typically include goals of up to 30% increase in renewable energy production within a 10-15 year time period. Twenty percent of all biomass used for bioenergy comes from the forestry sector, but improvements in supply of feedstock is necessary to meet the demands of today’s renewable energy development and to better utilize biomass that is currently being wasted.

There are many opportunities to harvest woody biomass from forested land across the United States. Fire hazard reduction has become increasingly important due to the potential risk of catastrophic forest fires in the western United States, where 397 million acres are in need of fuels reduction (USDA Forest Service 2000). Un-merchantable materials produced from fuel reductions could be comminuted (i.e. crushed, ground, or pulverized) for energy production. Logging slash accumulated after traditional sawlog harvesting operations are often piled and burned. Approximately 41 million dry tons per year of forest residue produced by traditional logging and land clearing operations goes uncollected in the U.S. (Perlack et al. 2005). These forest residues have long been underutilized due to limited access and high costs associated with collection and transportation (Evans 2008; Han et al. 2004).

There are many methods used to achieve residue recovery on forestland. Bundling forest residues has become increasingly popular in recent years. Specially designed energy wood harvesters collect and compress slash into cylindrical “composite residue logs” (CRL’s). The densification achieved through bundling greatly improves handling, loading, and transportation, since bundles are easily handled compared to loose-slash and have a greater bulk density. Despite these advantages previous studies in the United States have found bundling to be expensive (~$16/BDT), representing nearly half of the total cost of a residue recovery operation for previously thinned stands (Rummer et al. 2004). These high costs were likely a result of low productivity (~8 BDT/PMH) resulting from poor material arrangement and density, and the high capital investment for the energy wood harvester ($450,000). Another common method of residue recovery is in-woods grinding. In this process a grinder operates at a harvest site moving from pile to pile and grinds slash directly into a chip van. However, this method of residue recovery can be limited in application because chip vans hauling ground residues need to be able to access the harvest site.

Chip vans are considered the most cost-efficient mode of transporting woody biomass, provided roads are suitable for these large trucks with long wheel base and turning radius (Rawlings 2004). However, large amounts of woody biomass cannot be collected even when it is located in close proximity to the market because of adverse road conditions (Tiangco et al. 2005). Smaller more maneuverable trucks such as hook-lift trucks (Fig. 1) overcome adverse road conditions to reach sites inaccessible to chip vans (Han 2008).

Previous research in forest biomass harvesting utilizing roll-off container trucks to recover hand piled slash found costs (stump-to-central grinding site) as high as \$22.95/green tons (GT) (Han 2008). These high costs were believed to be a result of poor road conditions which caused low traveling speeds (< 10 mph). Actual chipping utilization rates were averaged to 73.8% in 63 biomass harvesting operations (Spinelli and Visser 2009). In the paper, delays contributing to reduced chipping utilization rates were found to be most common when there was poor coordination between the chipper and the receiving chip trucks which prohibited grinding until their arrival at the harvest site. Since utilization rates are correlated with production rates, these low utilization rates contributed to a low daily production rate. When operating costs are fixed, lower production equates to higher unit production costs (\$/ton). These previous studies have indicated a potential for cost savings with application of smaller trucks and centralized grinding sites where materials can be ground at a later time, decoupling the grinding process.

Figure 1. Hook-lift truck with 40 cubic yard bin used to transport forest residues to centralized grinding site.

The overall objective of this project was to determine the operational cost and performance of a logging residue recovery system. In this study, emphasis was on integration of a hook-lift truck which was used for primary transportation of slash over short forest road distances (< 3 miles) to a centralized grinding operation. Important variables, such as hauling distance and moisture content, were itemized to understand their effects on productivity of collection and transportation. In particular, logging slash piles were characterized to evaluate the effect of slash type on productivity, based on arrangement and size of slash materials.

METHODS

Study Sites

A two week trial was conducted starting in mid-July of 2008 to collect and process woody residues after completion of clearcut timber harvesting operations. Three clearcut harvest sites were located on private forestland in northern California, to study productivities and costs of removing logging slash to produce hog fuel for energy production. These sites were part of one timber harvest plan and ranged from 7 to 32 acres in size. The vegetation at each site varied but was generally dominated by second growth Douglas-fir (*Pseudotsuga menziesii)* and redwood (*Sequoia sempervirens),* with an average stand age of 60 years. The sites were previously harvested using a mechanized ground-based shovel logging system. Log loaders were used to swing (i.e. shovel) whole trees to the roadside for processing. The gross volume per acre of sawlogs removed from the harvest sites ranged from 32 to 47 thousand board feet (MBF). After harvest of sawlogs was complete, slash was either left in "wind-rowed" piles accumulated from sawlog processing or raked into heaping piles by loaders. A forester working for the private landowner suggested these sites were expected to yield 50-75 tons/ac of logging slash left over from clearcut operations (personal communication, M.W. Alcorn 2008. Green Diamond Resource Company, 900 Riverside Rd, Korbel, CA 95550). Data were collected across a wide variety of slope conditions (0-30%) to determine the effects of slope on productivity of collecting and loading slash.

There were many slash pile types in terms of material size and arrangement present across the harvest sites. Slash pile conditions are believed to have an effect on collection and loading of slash. Piles were assessed by two characteristics; the material size (small, mixed, and large) and material arrangement (processor piled, loader piled, side-cast, and side-cast piled). The different combinations of these characteristics formed individual Pile Classes (Fig. 2). Forest roads vary in curvature, surfacing, grade, and width, causing major impacts on accessibility and hauling speed. Forest roads were classified into four types, to determine the effects of various road types on productivity of hauling logging slash from harvesting units to a central grinding site using a hook-lift truck (Table 1). The one-way trip distance from each harvesting site to the centralized grinding site ranged between 0.45 to 2.61 miles, and contained a variety of different road conditions (Fig. 3).

The study was designed so that material from several harvest sites could be pooled at one centralized grinding location nearby (< 3 miles one-way distance; Fig. 3). The system pre-piled logging residues at landings and along roadsides with an excavator (PC 220LC) and loaded slash within reach into 40 cubic yard bins along the roadside. An excavator was chosen for collecting and loading slash because the bucket with thumb attachment was ideal for grappling of loose logging residues. A Hook-lift truck was able to effectively access the harvesting sites and transport the residues to a centralized grinding location using two bins. The truck delivered and unloaded empty 40 cubic yard bins near the excavator. While the excavator loaded empty bins the hook-lift truck

Pile Class 1 = Mixed size material (70% < 5 inches diameter), loader piled

Pile Class 2 = Large size material (70% > 5 inches diameter), processor piled

Pile Class 3 = Mixed size material (70% < 5 inches diameter), side-cast piled

Pile Class 4 = Mixed size material (70% < 5 inches diameter), processor piled

Pile Class 5 = Small size material (70% ≤ 1-3 inches diameter), loader piled

Figure 2. Slash pile classification by material arrangement and size classification.

Table 1. Road type, one-way distance, and average travel speed for transporting slash with a hook-lift truck from harvest sites to a central grinding location in northern California.

Harvest site	Spur road [a]	Dirt road [b]	1 Gravel road [c]	2 Gravel road [d]	Total one-way distance
	--------------------------------(miles)-------------------------------				
Unit A	0.53	0.29	0.68	1.64	2.61
Unit B	0.25	0.92	0.00	1.58	2.50
Unit C	0.25	0.04	0.00	0.41	0.45
Avg. Speed (miles/hr) [e]	5.99	8.06	19.09	29.32	

[a] Spur road = unimproved temporary dirt spur within harvest unit

[b] Dirt road = single lane seasonal dirt road constructed with native soils

[c] 1 Gravel road = one lane gravel road

[d] 2 Gravel road = two lane gravel road

[e] Average speed = distance/observed time traveled

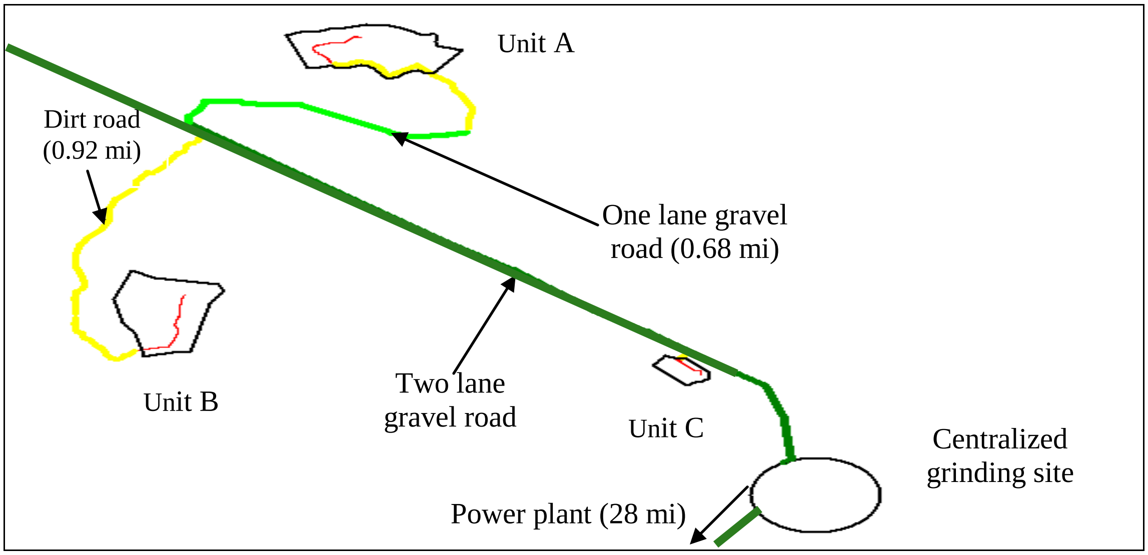

Figure 3. Operation layout map with corresponding road segments, which the hook-lift truck traveled along between harvesting sites and the central grinding location.

delivered full bins to a central grinding location, where the slash was unloaded by tilting the bin backward much like a dump truck. When collection and transportation of materials was complete a grinder (Peterson Pacific 7400) was set up at a centralized grinding site accessible to chip vans. The grinder ground all the slash into hog fuel. Hog fuel was then belt fed into 120 cubic yard chip vans and transported to a local power plant 28 miles from the centralized grinding site.

Data Collection and Analysis

Hourly machine costs measured in dollars per scheduled machine hour (SMH) were calculated using standard machine rate calculation method (Miyata 1980). For each machine in the system purchase price, insurance and tax rates, repair costs, fuel consumption, and labor costs were all obtained from the consulting contractor. Diesel fuel price receipts were averaged throughout length of the operation ($4.60/gallon) and applied to machinery. All machinery was assumed to work 1800 scheduled machine hours annually and have an economic life of ten years except for the grinder which was assumed to have a 5-year economic life (Table 2).

Standard time study techniques were used to characterize each element in a machine operation cycle using a stop watch (Olsen et al. 1998). A hook-lift trucking cycle included traveling empty to the harvest unit, dropping an empty bin at the roadside, positioning the truck, loading a bin filled with slash onto the truck, traveling loaded to the centralized grinding site, and unloading/dumping the slash. An excavator’s loading cycle started from traveling to a slash pile followed by swinging empty to the slash pile,

Table 2. Machine specifications including: purchase price, assumed utilization rate, and fuel consumption provided by the contractor which were used to calculate hourly cost ($/SMH).

Machine	Initial Price	Utilization Rate	Fuel Consumption	Total hourly cost
	($)	(%)	(gal/hr)	($/SMH)
Peterson Pacific 7400 grinder	650,000	85	30	305.41
Komatsu PC-220LC excavator	350,000	90	6	113.94
Komatsu 400 front-end loader	375,000	90	7	107.88
Kenworth T800 hook-lift truck	150,000	90	7	93.45

SMH = Scheduled machine hour

grappling the slash, swinging loaded back to the bin, and compacting slash into the bin. There were no discrete cycle elements in the grinding process, and the time required to fill up the chip vans was measured with no definite cycle elements. Three types of delay time, including operational delays, mechanical delays and personal delays, were recorded when they occurred. This delay information was recorded separately so that it could be excluded to obtain a delay-free working cycle in productive machine hours (PMH) for each process.

Regression models for delay-free cycle time were developed using the pre-identified independent variables associated with each cycle. The collected time study data were screened for normality and outliers using histograms and residual plots, and were used to develop predictive equations by multiple regression with ordinary least squares estimators. The analysis was performed in R 2.4.1 statistical software program. The final predictive models developed in the study include only variables that were found to be statistically significant ($\alpha = 0.05$). Dummy variables were used to examine the effect of slash pile types on delay-free cycle times.

Biomass weight for each cycle was measured using a portable scale (Intercom PT300) located at the centralized grinding site. The truck was tare-weighed before and weighed again after it was loaded. The difference was equal to the weight of slash hauled. Weight measurements were recorded along each axle and the sum of axle weights gave the total weight hauled in tons. Moisture data were collected from all sizes of material (0 to >13 inches) based on diameter size classes (2 inch diameter intervals) of slash as well as from ground material. Wood residues were randomly sampled to estimate moisture content with a Delmhorst BD-2100 hand-held moisture meter on site. A single measurement was used for the small diameter class samples (< 3 in). For the larger size classes the material was cross sectioned and three measurements were taken and averaged to better account for variations in moisture content. Slash moisture content samples (n=375) were randomly collected from logging residue piles to estimate the moisture content for loading and hauling stages of the operation. Moisture content was then sampled again during the grinding stage of the operation to provide an accurate estimate of the grinding cost which occurred after loading and hauling was completed. Moisture content of hog fuel was estimated by change in weight before and after oven drying of samples (n=28) collected from loaded trucks. Moisture content of the slash during loading and hauling was 27.20% and then increased to 36.23% during grinding due to the two days of rain that occurred during grinding activities. These two moisture content values were used to more accurately estimate the cost of separate stages of operation in dollars per bone dry ton ($/BDT). Delivered hog fuel prices in the region during the time of study were surveyed at $50 a bone dry ton (BDT).

The hourly production of each machine was determined by dividing the average weight of bins (tons) by the predicted cycle time (minutes/PMH). Cost per ton of material ($/BDT) was calculated by dividing the machine hourly cost dollars per productive machine hour ($/PMH) by the production rate (BDT/PMH).

Finally, sensitivity analysis was performed to examine the change in system costs with changes in diesel fuel prices and forest road travel distances and conditions. Taking a closer look at these variables would aid in the understanding of how to execute these types of operations while minimizing costs.

RESULTS AND DISCUSSION

Average delay-free cycle time for the excavator to arrange, pick up material, and place it in a bin was estimated from 600 observed cycles and averaged 40 seconds. It took an average of 21 cycles or 14 minutes to fill an entire bin with slash which had an average weight of 4.7 BDT or 6.5 GT. The compacting element of a loading cycle was the most time consuming part of the loading process because the operator took extra effort to maximize the weight of each bin (Table 3). Traveling took the least amount of time (0.01 min) on average because the operator rarely moved the excavator, placing the machine between the pile of slash and the bin within reach of the machines' boom.

The delay-free round trip trucking cycle from the centralized grinding location to the harvest unit was estimated from 58 observed cycles and took on average 28 minutes. The hauling time for the hook-lift truck was relatively long due to adverse road conditions which resulted in traveling speeds of less than 10 mph (Table 1). The long associated round trip and low volume of slash hauled contributed to a low production level which created a system bottleneck. Travel empty and travel loaded consumed the largest amount of a delay-free cycle (8-9 minutes per trip). Empty and loaded travel times were similar because the same routes were used on the way to and from harvest sites. Unloading and loading bins also had similar times (Table 4). Loading the bin was faster on average than unloading the bin because an entire bin was picked up onto the truck. The unloading of a bin required the driver to exit the truck, open the back doors of the

Table 3. Summary statistics for each observed component of a delay-free swing cycle and associated independent variables, for loading 40 cubic yard bins with an excavator (n = 600).

Loading Cycle Element	Variable	Mean	Range	Standard Deviation	Centi-minutes [a]	Proportion of cycle time
Travel	Distance (ft)	1.07	0-40	5.03	1.0	1.7%
Empty Swing	Degrees rotated (90o increments)	139.95	0-270	2.22	7.0	9.6%
Grappling	number of grapples	2.01	1-11	25.74	27.0	34.8%
Loaded Swing	Degrees rotated (90 increments)	145.95	0-270	3.84	9.0	12.3%
Compacting	number of compactions	3.19	1-16	30.34	32.0	41.7%

Note: Centiminutes = minutes/100

[a] Observed averaged time spent for corresponding element of total cycle.

Table 4. Summary of observed trucking cycle time (centi-minutes) and components for a delay-free round trip cycle from grinding site to harvesting site, using a hook-lift truck (n=58).

	Cycle Elements	Distance (ft)	Centi-minutes	Time (%)	
Travel empty	Central grinding site	311	81.0	2.84	
	Two lane Gravel	7,183	336.0	11.83	
	One lane Gravel	1,483	93.0	3.27	
	Dirt	2,340	280.0	9.87	
	Spur	431	78.0	2.74	30.6
Loading	Position	185	282.0	9.95	
	Drop	N/A	94.0	3.32	
	Travel to bin	97	8.0	0.29	
	Load	N/A	91.0	3.21	16.8
Travel loaded	Central grinding site	457	134.0	4.73	
	Two lane gravel	7,183	308.0	10.84	
	One lane gravel	1,483	88.0	3.09	
	Dirt	2,332	303.0	10.67	
	Spur	523	105.0	3.69	33.0
Unloading	Position	88	39.0	1.38	
	Unload	N/A	519.0	18.27	19.6
	Total	24,096	2838.0	100	

Note: 0.90 to 5.22 miles round trip

Centi-minutes = minutes/100

bin, tilt the bin back, and then pull forward to empty the contents much like a dump truck. Positioning was perhaps one of the most overlooked components of a hook-lift truck's cycle time and was highly variable depending on harvest unit accessed. Positioning time represents approximately 11% of total cycle time and 31% of all cycle time relating to non-travel components. Observations indicated that positioning times were minimized when there were abundant road-side turn outs in close proximity to where bins needed to be unloaded or loaded by the hook-lift truck.

An interaction in the multiple least squares regression suggested that the predicted time for an excavator to load a bin with slash was affected by pile class (Table 5). Dummy variables were used to examine the effect of material type and slash pile classification on cycle time as well as their interaction with continuous variables by ANCOVA tests performed within the general linear model. The model for the excavator had high R-square values and low p-values (<0.05), which indicate the equation might be effective in estimating productivity for loading (Table 5).

When evaluating the effect of pile classification on estimated cycle time for loading, Pile Class 4 (typical size material, processor piled) was the only pile class found to have a significant effect on loading (p-value <0.05, $\alpha = 0.05$; Table 6). Using the predicted model for the excavator and holding all other variables constant Pile Class 4 had the longest predicted cycle time of 42 seconds per swing cycle. Pile Class 2 (large size material, processor piled) had the smallest predicted cycle time of 36 seconds per swing cycle, corresponding to a loading time of 12.60 min/bin. This difference in

Table 5. Delay-free average cycle time equation for loading activities.

Machine	Average cycle time estimator (centi-minutes)	r^2	Standard error	P-value	Standard error [a]	F-stat	n
Excavator	= 3.70	0.80			0.24		600
	+ 0.49 (number of compactions)		0.02	< 0.0001		805.90	
	+ 0.04 (travel distance in feet)		0.00	< 0.0001		108.78	
	+ 0.39 (number of grapples)		0.02	< 0.0001		417.78	
	+ 0.21 (loaded swing degrees)		0.027	< 0.0001		60.38	
	+ a (pile classification)			0.002		4.17	
	+ b (material type)			< 0.0001		24.05	
	+ c (material type * number of grapples)			< 0.0001		11.70	
	+ d (material type * number of compactions)			0.024		2.82	

Note: centi-minutes = minutes/100

a-d = Coefficients for pile classification, material type, and interactions, see Table 6.

e.g. if a predicted cycle included pile class 1 use -0.00447 (Table 6) for the "a" coefficient value.

[a] = standard error of the regression equation

Table 6: Loading factor level coefficients and coefficients of interactions used to estimate the productivity of loading slash into bins.

Machine	Average cycle time estimator (centi-minutes)	Standard error	P-value
Excavator	- 0.00447 (pile class 1)	0.03	0.889
	+ 0.00634 (pile class 2)	0.03	0.838
	+ 0.04147 (pile class 3)	0.04	0.269
	+ 0.08724 (pile class 4)	0.03	0.002
	- 0.13058 (pile class 5)	N/A [a]	N/A [a]
	+ 0.05644 (limbs)	0.02	0.015
	+ 0.05731 (tops)	0.03	0.075
	- 0.23894 (logs)	0.03	0.000
	+ 0.12519 (mixed materials)	N/A [a]	N/A [a]
	- 0.13288 (number of grapples * limbs)	0.03	0.000
	+ 0.05822 (number of grapples * tops)	0.03	0.066
	+ 0.15788 (number of grapples * logs)	0.03	0.000
	- 0.08322 (number of grapples * mixed materials)	N/A [a]	N/A [a]
	- 0.02991 (number of compactions * pile class 1)	0.03	0.279
	- 0.06178 (number of compactions * pile class 2)	0.03	0.033
	- 0.04048 (number of compactions * pile class 3)	0.04	0.334
	+ 0.01598 (number of compactions * pile class 4)	0.02	0.519
	+ 0.11619 (number of compactions * pile class 5)	N/A [a]	N/A [a]

Note: centi-minutes = minutes/100
pile class 1 = typical size material, loader piled
pile class 2 = large size material, processor piled
pile class 3 = typical size material, side-cast piled
pile class 4 = typical size material, processor piled
pile class 5 = small size material, loader piled

[a] standard error and P-values not avilable from R statistical program output.

predicted cycle time was linked with compacting, which consumes the largest portion of a total loading cycle and had a significant interaction with pile classes. Processor piled materials (Pile Class 2 and 4) are generally aligned parallel which is preferable for loading into bins because of the reduced need for compacting, especially when materials are of large size. When loaders pile material they tend to rake the slash into piles with lots of air space. The poor arrangement coupled with smaller size material amounts to a greater number of compactions, and a longer loading cycle.

Grinding productivity was calculated by averaging the 19 observed times for loading chip vans since the nature of grinding activities did not provide sufficient variables for developing a grinding regression equation. The observed utilization rate for grinding was 49% due to mechanical problems with the electrical circuit of the grinder. However, when the grinder was functioning properly production was maximized by feeding the grinder with a swing loader and front-end loader, to reduce machine idling. The average observed time for the grinder to belt feed a chip van was 21 minutes. Each chip van carried on average 14.1 BDT/truck. Grinding activities produced a total of 267.5 BDT over a total of 7 hours, which were delivered to the local energy plant.

I was informed by the contractor that the entire residue recovery operation was profitable. Production costs (woods landing-to-chip van) were $32.98 per dry ton for the entire system (Table 7). This total system cost does not include: the cost of moving equipment to work sites, supporting equipment costs, transportation of hog fuel to markets, or profit allowance for contractors conducting operations. With the surveyed

Table 7. Estimated system production and cost for biomass harvesting with centralized grinding and hook-lift truck.

	Loading	Hauling	Grinding	Total [a]
Hourly Cost ($/PMH) [b]	$126.60	$103.84	$595.71	$826.15
Hourly Production (BDT/PMH)	20.10	9.93	36.73	
Cost ($/GT) [c]	$4.59	$7.61	$10.34	$22.54
Cost ($/BDT) [d]	$6.30	$10.46	$16.22	$32.98

Moisture content during loading and hauling stages of operation was 27.20%, and 36.23% during grinding.

[a] Total system cost (woods landing-to-chip van) does not include move in costs, supporting equipment costs, transportation to market, or profit allowance.

[b] PMH: productive machine hour

[c] GT: green ton

[d] BDT: bone dry ton

regional market price of $50/ton (delivered), this operation could be described as relatively expensive but cost effective over short hauling distances in accessing and producing hog fuel for electrical energy production. This suggests that uncounted costs were less than $17.02/BDT.

The cost of grinding $16.22/BDT was the most costly component of the system representing one third of the total production cost. The high cost of grinding stresses the importance of maximizing the grinder's productivity by supplying enough material to the centralized grinding site, and maintaining a constant flow of residues. One would have to increase the number of machines in the loading and hauling stage to supply more than 37 BDT/PMH to the grinder or, in the case of this study wait to grind until all collection and transportation of slash was completed.

Using a hook-lift truck to access harvesting sites was effective, as these trucks have little trouble navigating sharp curves, adverse grades, and poor road surfaces. The detachable bins were well suited for the operation, allowing loading of logging slash into bins to be independent from the hook-lift truck delivering full bins to the centralized grinding site. Hauling costs represented approximately one quarter of the total production cost, but proved to be highly variable depending on road conditions and positioning time. Sensitivity analysis indicated that it was best to minimize road types such as dirt and spur roads. These had traveling speeds of less than 10 mph. Larger roads greatly improved trucking productivity and reduced production costs. Using the predictive equation for cycle time (Table 8) and holding all other variables of system cost constant, every mile

Table 8. Delay-free predictive equation for a hook-lift truck's round trip cycle time (centi-minutes) between the centralized grinding site and a harvest unit.

Round trip delay-free cycle time equation
= 1429 [a]
+ (one gravel road round trip miles)/(one lane gravel road mph)[b] * 6000 centiminutes/hr[c]
+ (two lane gravel road round trip miles)/(two lane gravel road mph)[b] * 6000 centiminutes/hr[c]
+ (dirt road round trip miles)/(dirt road mph)[b] * 6000 centiminutes/hr[c]
+ (spur road round trip miles)/(spur road mph)[b] * 6000 centiminutes/hr[c]

Note: centi-minutes = minutes/100

[a] This constant value represents the average operating time including all cycle time components excluding traveling times on one and two lane gravel roads, dirt roads, and spur roads.

[b] Average travel speed (miles per hour) observed during the study.

[c] Factor converting hours to centi-minutes.

increase of dirt road and double lane gravel road hauling distance equates to a $2.74/BDT and $0.75/BDT increase in the total system cost, respectively. Due to the sensitivity of costs associated with hauling on forest roads, results suggested that total system cost (stump-to-chip van) became high (> $34/BDT) when collection sites were more than 2.5 miles (1.5 miles of dirt road and 1 mile of double lane gravel road) away from the centralized grinding site. Any cost increase due to increased hauling cost would make the operation financially unfeasible considering the current market value of delivered materials (~$50/BDT) in northern California.

One interesting factor that had an impact on the overall system cost was diesel fuel prices which were at a national peak during the study in the summer of 2008. Diesel fuel price assumed for the operation was $4.60/gal. Six months after commencement of operations fuel prices in the region dropped to $2.50/gal. Holding all other variables of system cost constant, every dollar reduction of fuel price represents a $2.56/BDT reduction in overall system cost (Fig. 4).

Biomass removal in this study had a relatively high total system cost of $32.98/BDT when compared to the surveyed regional market value of $50/BDT for delivered fuel, yet removal of forest biomass in this study had many positive and often overlooked benefits. The removal of logging slash piles avoided site preparation requirements, which translated to a cost savings of $100/acre for the land manager (personal communication, M.W. Alcorn 2008. Green Diamond Resource Company, 900 Riverside Rd, Korbel, CA 95550). In addition, removal of these piles replaced the

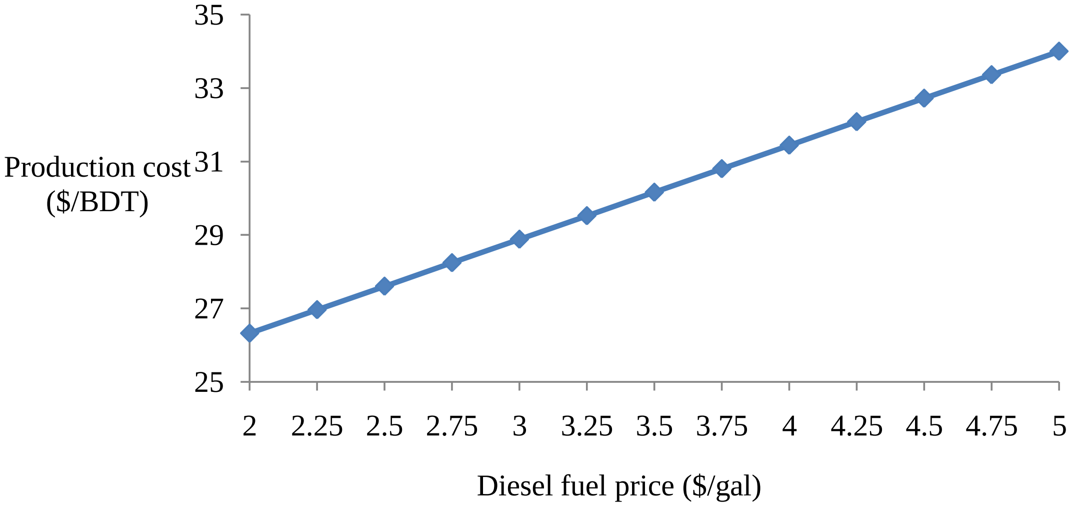

Figure 4. Sensitivity analysis on system production cost with various fuel market prices.

conventional method of logging residue disposal (pile burning), which would have impacted air quality by emission of carbon and other greenhouse gasses into the atmosphere. Finally, the operation was effective in utilizing waste, and providing renewable energy production for the region.

CONCLUSION

This study evaluated harvesting productivity and cost of a wood residue recovery system collecting logging slash for electrical energy production. Productivity for different machines varied from 10 to 37 BDT/PMH, with a total production of 267.5 BDT over 70 hours. Production cost ranged from $6.30 to $16.22/BDT, with a total system production cost (stump-to-chip van including grinding) of $32.98/BDT at a range of 27.20 to 36.23% moisture content.

Loading slash into bins had a low cost of $6.30/BDT. Loading costs could increase if the material was not located within one swing of the road edge because additional travel time per cycle would be required to pick up the slash. The hook-lift truck effectively negotiated adverse forest roads and allowed the removal of slash from traditionally difficult-to-access sites with a cost of $10.46/BDT. Grinding slash was the most expensive part of the operation ($16.22/BDT) due to the high operating cost of the grinder and the loaders needed to feed materials.

Slash pile arrangement and material size were found to have a significant effect on productivity of loading. Typical size material arranged or piled by processors (Pile Class 2) were the most effective pile type yielding the smallest predicted cycle time (36 seconds) for loading. The large size material and parallel arrangement of residues associated with Pile Class 2 were preferable since they required less handling and compacting during loading.

System cost can drastically change with increased hauling mileage on dirt roads due to low travel speeds (<10 mph). Harvest sites should be located within close proximity to a centralized grinding site (< 3 miles). For example, the total system cost increased \$2.74/BDT for every one mile increase in dirt road hauling distance. The cost of the fuel price among other variables was found to have a significant effect on total system cost, resulting in a \$2.56/BDT increase for every \$1/gallon increase in fuel cost.

To keep the total harvesting cost below the market value (\$50/BDT), forest residue recovery operations must be carefully planned to keep the system efficient at the highest level. Centralized grinding sites should be located to minimize travel distance while facilitating a good access to a large amount of logging slash. Harvest sites should provide adequate road-side turnouts in order to minimize the amount of positioning necessary for a hook-lift truck to load and unload bins. Appropriate pairings of machines would substantially improve total system productivity by reducing system bottlenecks. This operation could have performed better if one more hook-lift truck was utilized on longer haul routes in order to better match the production of the prior stage of operation (loading), eliminating the bottleneck in hauling.

Chapter 3. Combining slash bundling with in-woods grinding operations

ABSTRACT

Although extensive woody biomass resources are physically present, forest residues (i.e. logging slash) are under-utilized because collection and transportation costs are often greater than the market value of the materials and limited access to the site. This study was to quantify the operational cost and performance of a biomass harvesting system utilizing a John Deere 1490D energy wood harvester, combined with in-woods grinding operations. The experiment took place at four recently harvested sites in northern California where logging slash was piled or scattered along roadsides or across clearcut units in various amounts and arrangements. Bundles produced at each site were transported to a centralized grinding location where they were ground into hog fuel and delivered to a local energy plant. Productivity for each phase of the operation ranged from 8 to 42 bone dry ton (BDT)/productive machine hour (PMH), with a total production of 280.7 BDT over 70.2 hours. The total system production cost was \$46.50/BDT at 28.95% moisture content. Regression analysis indicated that Pile Classification in terms of material size and arrangement had a significant impact on productivity of bundling ($p<0.0001$). Pile Class 3 (mixed size materials piled and side-casted) yielded the shortest predicted delay-free cycle time of 1.60 minutes/bundle. Single lane dirt roads were found to have the greatest effect on increasing total

production costs by $3.07/BDT per mile. Every $/gal increase in diesel fuel price reflects a $3.52/BDT increase in total production cost for the system.

INTRODUCTION

Bioenergy is the second largest source of renewable energy in the United States, with over 11 gigawatts of installed capacity (Beckert and Jackle2008). Woody biomass, including sub-merchantable trees, small diameter trees, tops, limbs, and logging slash, produced from mechanical thinning and conventional saw-timber harvesting creates an opportunity for generating power (Han et al. 2004). Forest operations have the potential to supply 368 million dry tons of woody biomass annually (Perlack et al. 2005). The annual available biomass in California was estimated at 26.8 million dry tons (Tiangco et al. 2005). Prescribed burning has long been the preferred method of disposing of forest biomass, but mechanical removal of biomass is becoming more popular due to increased restrictions on open field burning, or in areas like the wildland urban interface where burning is not an option.

Forest residues are often not utilized because collection and transportation costs are greater than the market value of the materials (Withycombe 1982). Lack of research in this field makes harvesting and transportation costs notoriously difficult to estimate because there are critical gaps in the data and methods for predicting costs (Rummer 2008).

New, more efficient harvesting equipment like energy wood harvesters with their increased productivity, could reduce the associated costs of handling. These machines compact and bundle woody biomass into log-shaped bundles, and could produce up to 40 or more half ton bundles per hour with a production cost of $16 per dry ton (Rummer et al. 2004). Quantifying costs and productivities of new and innovative systems used to harvest woody biomass from northern California will aid land managers in planning and executing cost effective biomass for bioenergy operations.

The overall objective of this project was to determine operational cost and performance of a biomass collection and densification system, called slash bundler, in combination with a centralized grinding operation. Important variables, such as hauling distance and moisture contents, were itemized to understand their effects on productivity of collection and transportation. In particular, slash piles were characterized to evaluate the effect of slash type on productivity, based on arrangement and size of slash materials.

METHODS

Study Site

The study was conducted in three clearcut harvesting sites which used a ground based shovel logging system in northern California, ranging from 17 to 32 acres in size. Vegetation at each site varied but was generally dominated by second growth redwood (*Sequoia sempervirens)* and Douglas-fir (*Pseudotsuga menziesii)* with an average tree age of 60 years. The three sites had an average tree diameter at breast height (DBH) ranged from 20-22 inches, and ground slopes ranged from 0 to 30 percent. There were many slash pile types in terms of size and arrangement present across these sites (Fig. 5). A forester working for the land owner suggested these sites were expected to yield anywhere from 50-75 tons/ac of slash from clearcut operations (personal communication, M.W. Alcorn 2008. Green Diamond Resource Company, 900 Riverside Rd, Korbel, CA 95550).

A two week trial was conducted to collect and process woody residues after commercial timber harvesting operations. The system collected material pre-piled at landings and along roadsides with a slash bundler (John Deere 1490D, Fig. 6). The bundler compacted and wrapped slash into 10ft long bundles with an average diameter of 27 inches. Bundles were then loaded into 40 cubic yard containers along the roadside with a loader (Hitachi EX 200-3). Bundles were delivered to a central grinding location by hook-lift trucks (Figure 6). The study was designed so that several harvest sites could

Pile Class 1 = Mixed size material, loader piled

Pile Class 2 = Large size material, processor piled

Pile Class 3 = Mixed size material, side-cast piled

Pile Class 4 = Mixed size material, processor piled

Pile Class 5 = Small size material, loader piled

Pile Class 6 = Mixed size material, side-cast

Figure 5. Slash pile classification by arrangement and material size.

Figure 6. John Deere 1490D energy wood harvester which produces the bundles, and hook-lift truck used to haul bundles.

pool material to a centralized grinding location nearby (< 3 miles; Fig. 7). A grinder (Peterson Pacific 7400) was set up at the centralized grinding site and ground all the bundles into hog fuel. Hog fuel was then belt fed into 120 cubic yard chip vans and transported to a local power plant.

Data Collection and Analysis

Hourly machine costs (Table 9) measured in dollars per scheduled machine hour (SMH) were calculated using standard machine rate calculation method (Miyata 1980). For each machine in the system purchase price, insurance and tax rates, repair costs, fuel consumption, and labor costs were all obtained from the contractor, diesel fuel price receipts were averaged throughout length of the operation ($4.60/gal). All machinery was assumed to work 1800 SMH annually and have an economic life of ten years except for the grinder which had a 5 year economic life due to associated wear, and the bundler which was assumed to work 2100 SMH as suggested by John Deere Company.

Time study data was collected to calculate hourly production (bone dry ton (BDT)/productive machine hour (PMH)) using standard time study techniques for each element in a machines operation cycle by stop watch (Olsen et al. 1998). A bundling cycle began when the machine traveled to the slash pile, then grappled and swung slash to the in-feed table, and ended when the bundle produced was cut free from the machine. A loading cycle started when the machine traveled to a bundle, then swung empty to the bundle, grappled the bundle, swung loaded back to the container, and ended when the bundle was compacted into the container. A hook-lift trucking cycle began when the

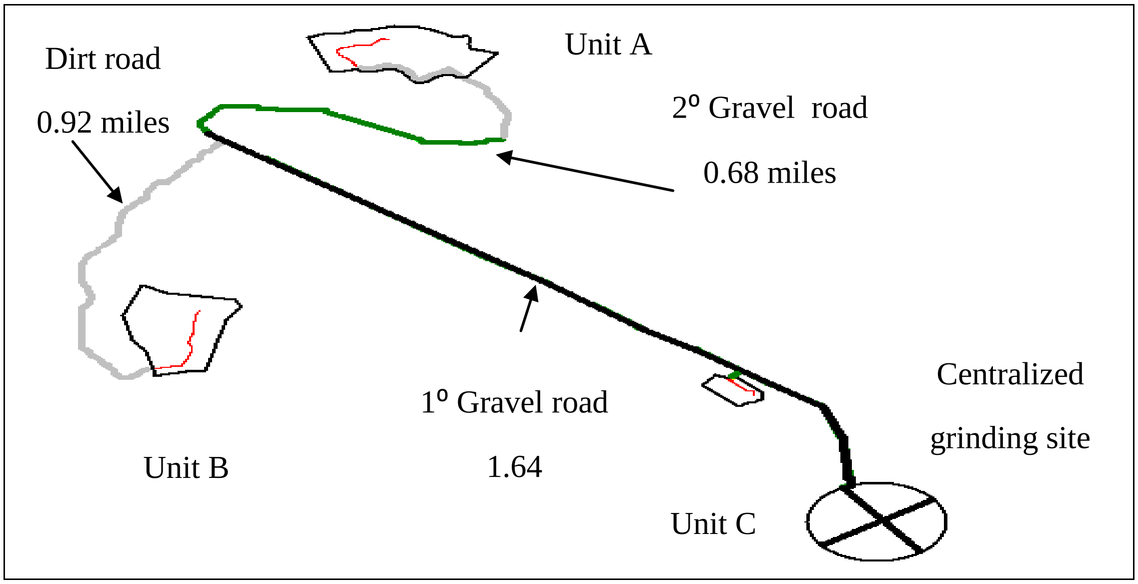

Figure 7: Operation layout map with corresponding road segments.

Table: 9. Assumptions and hourly machine cost ($/SMH) used in the study.

Machine	Initial Price	Utilization Rate	Fuel Consumption	Total houly cost
	($)	(%)	(gal/hr)	($/SMH)
Peterson Pacific 7400 grinder	650,000	85	30	305.41
John Deere 1490D energy wood harvester	500,000	90	3	119.87
Hitachi EX 200-3 loader	350,000	90	6	113.94
Komatsu 400 front-end loader	375,000	90	7	107.88
Kenworth T800 hook-lift truck	150,000	90	7	93.45
Kenworth 600A service truck	120,000	90	7	83.12
Kenworth 900A fuel truck	80,000	90	6	79.23
Kenworth 900A water truck	80,000	90	5	73.74

SMH = Scheduled machine hour

tuck traveled empty to the harvest unit, then positioned for loading, loaded a container filled with bundles, traveled loaded back to the centralized grinding site, and ended when the bundles were unloaded/dumped. Three types of delay times, including operational delays, mechanical delays and personal delays, were recorded.

Regression models for delay-free cycle time were developed using the pre-identified independent variables associated with each cycle. The collected time study data were screened for normality and outliers using histograms and residual plots. The screened data was used to develop predictive equations by running multiple regressions using ordinary least squares estimators, performed in R 2.4.1 statistical software program (R 2006). Final predictive models developed in the study include only variables that were found to be statistically significant (p-value <0.05; $\alpha = 0.05$). Dummy variables were used to examine the effect of slash Pile Classification on delay-free cycle times.

Biomass weight for each cycle was measured using a portable scale (Intercom PT300). The hook-lift trucks were tare-weighed before and after they were loaded to measure the weight of the bundles hauled. The total bundle weight was divided by the number of bundles to determine the average weight/bundle in tons.

Wood residues were randomly sampled to estimate variation and mean in moisture content with a Delmhorst BD-2100 hand held moisture meter. Data was collected from all sizes of material based on diameter size classes of slash as well as from ground material. Slash moisture content samples were randomly collected from bundles. A single measurement was used for the small diameter class samples (< 3 in). For the larger size classes the material was cross sectioned and three measurements were taken and averaged, in order to account for the moisture variability (Han 2008). Moisture content of hog fuel was measured by oven drying samples collected from loaded trucks. Wet-based moisture content averaged 22.55, 24.27, and 28.95 percent for bundling, loading and hauling, and grinding stages of operation respectively. Delivered hog fuel prices in the region during the time of study was surveyed at $50 a bone dry ton (BDT).

RESULTS AND DISCUSSION

Cycle Time Regression Equations

Regression equations developed from the time study data and the variables that significantly affected them ($p < 0.05$, $\alpha = 0.05$) are summarized in Table 10. Both models for the bundler and the hook-lift truck had high r-squared values, indicating that they might be effective in estimating the productivity for loading and hauling.

Bundling cycle time was affected mainly by different handling and arranging activities such as the number of grapples to pick up slash or the number of in-feeds to place the slash on the in-feed table for bundling. The grappling element consumed the greatest amount of time during an average bundling cycle (0.85 minutes, 44.5%), while the traveling element was responsible for the smallest portion of cycle time (0.09 minutes, 4.8%; Figure 8). This was most likely due to the fact that the machine could remain stationary because of the amount of slash available within reach, and spent the greatest amount of time grappling in order to properly align slash for efficient in-feeding. The regression equation also indicated that the number of swing cycles for which the bundler picked up slash and placed it on the in-feed table had a significant effect on cycle time. When considering the effect of pile classification on estimated cycle time for bundling, Pile Class 1, Pile Class 2, and Pile Class 6 were the only pile classes found to be statistically significant (p-value <0.05; $\alpha = 0.05$).

Table 10. Delay-free average cycle time equations for bundling, loading, and hauling activities.

Machine	Average cycle time estimator (centiminutes)	Variable range	Mean	R^2	n	P-value	F-stat	Standard error
Bundler	= 3.87			0.81	300			0.17
	+ 0.03 (travel distance in feet)	0-280	5.56			< 0.0001	72.27	
	+ 0.54 (number of grapples)	1-22	7.61			< 0.0001	303.35	
	+ 0.41 (number of infeeds)	1-11	4.40			< 0.0001	111.45	
	- 0.20 (number of swing cycles)	1-8	4.52			< 0.0001	14.82	
	- 0.08 (pile class 1)					0.002		
	+ 0.13 (pile class 2)					< 0.0001		
	- 0.11 (pile class 3)					0.092		
	- 0.03 (pile class 4)					0.305		
	- 0.03 (pile class 5)					0.210		
	+ 0.13 (pile class 6)					0.038		
Loader	= 3.88			0.54	465			0.20
	+ 0.45 (number of compactions)	1-5	1.23			< 0.0001	216.42	
	+ 0.06 (travel distance in feet)	0-220	1.51			< 0.0001	164.41	
	+ 0.42 (number of grapples)	1-3	1.08			< 0.0001	66.76	
	+ 0.22 (loaded swing degrees)	90-270	126.81			< 0.0001	72.08	
	+ 0.09 (% slope)	5-10	6.58			0.003	8.99	
Hook-lift truck	= 987.40			0.84	30			344.97
	+ 0.22 (loaded primary gravel road distance in feet)	2189-8635	7436.27			< 0.0001	30.16	
	+ 0.22 (loaded dirt road distance in feet)	200-4846	2423.97			< 0.0001	38.56	
	+ 1.44 (position for loading distance in feet)	10-600	261.33			0.011	7.47	

pile class 1 = mixed size material, loader piled
pile class 2 = large size material, processor piled
pile class 3 = mixed size material, side-cast piled
pile class 4 = mixed size material, processor piled
pile class 5 = small size material, loader piled
pile class 6 = mixed size material, side-cast
N/A*= values not avilable from R statistical program output.

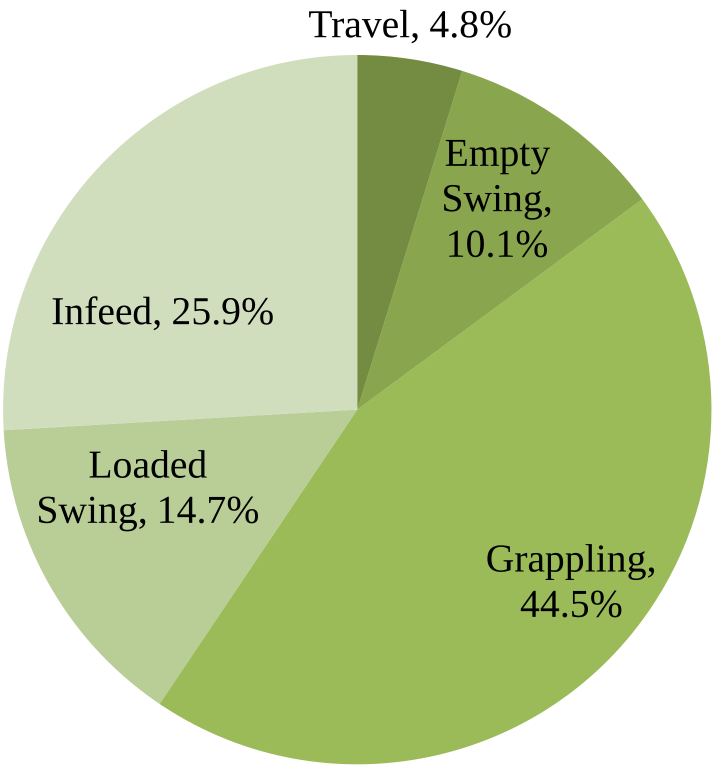

Figure 8. Observed components of a typical bundling cycle, and their percentage of total cycle time.

Grappling to pick up the bundles and compacting them into the bin significantly affected loading cycle time. Loaded swing degrees in which the machine had to rotate to place a bundle in the bin also significantly affected loading cycle time, along with the travel distance necessary to reach a bundle. Regression analysis suggests that decreasing the travel distance and minimizing swing degrees would greatly reduce the predicted cycle time.

The transportation distance along various road types positively affected hauling cycle time. Only loaded hauling distances were used to develop the trucking regression equation because the same routes were used to and from harvest units. The positioning distance for a hook-lift truck to position itself to be loaded was also found to have a significant effect on cycle time because this was done while driving in reverse, and had to be done carefully to properly align the bin for loading by the Hitachi loader.

Production Rates

The hourly production of each machine was determined by dividing the average weight of bundles or bins (tons) by the predicted cycle time (minutes/PMH). Average predicted delay-free cycle time for the bundler to make one ten foot long bundle was 1.74 minutes, meaning the machine produced about 34 bundles per productive machine hour. With the bundles having an average moisture content of 22.55%, and an average length and diameter of 10.1ft and 27.6 inches respectively, the bundler productivity was determined at 8.03 BDT/PMH (Table 11).

Table 11. Predicted delay-free average cycle time and production rate.

	Bundler		Loader		Hook-lift truck	
	Cycle time	Prod. Rate	Cycle time	Prod. Rate	Cycle time	Prod. Rate
	(min)	(BDT [a]/PMH [b])	(min)	(BDT/PMH)	(min)	(BDT/PMH)
Unit A	1.72	8.41	0.46	41.22	34.28	11.49
Unit B	1.93	7.47	0.44	42.77	42.83	9.20
Unit C	1.61	8.97	0.43	43.33	22.37	17.61
Overall	1.76	8.22	0.44	42.32	35.43	11.12

[a] BDT: bone dry ton

[b] PMH: productive machine hour

Using the predicted model for the bundler and holding all other variables constant Pile Class 2 and Pile Class 6 resulted in the longest predicted cycle time of 2.04 minutes (Tables 11, Table 12). Pile Class 3 yielded the smallest predicted cycle time of 1.60 minutes. The difference in predicted cycle time between piles is linked with grappling, which consumes the largest portion of a total bundling cycle. Processor piled materials are generally aligned parallel which is preferable for bundling because of the reduced need for grappling, but larger size materials are harder to grapple and do not bundle as well resulting in poor bundle integrity. When loaders pile material they tend to rake the slash into heaping piles with lots of air space and poor material alignment, which is negligible considering the machine’s compacting force, especially when smaller size materials are bundled.

Average predicted delay-free cycle time for the loader to pick up a bundle, and place it in a bin was 0.44 minutes or 26 seconds (Table 11). It took an average of 21 cycles or 9 minutes to fill an entire bin with bundles which had an average weight of 6.6 BDT, meaning the loader could produce an astounding 42.32 BDT/PMH. The compacting element in a loading cycle was the most time consuming part of the loading process because the operator took extra effort to carefully stack as many bundles as possible inside the bin. Traveling took the least amount of time (0.01 minutes, 3.1%) because bundles were decked along the road-edge minimizing operator’s need travel.

The delay-free trucking cycle took on average 35 minutes, with a production rate of 11.1 BDT/PMH (Table 11). Loading the bin consumed the greatest percentage of the

Table 12. Bundling productivity predicted using regression equations based on slash Pile Classifications.

Pile Class	# Bundles produced	Avg. time (min/bundle)	BDT/PMH	# Bundles/PMH
1	70	1.66	8.7	36
2	31	2.04	7.1	29
3	5	1.60	9.0	37
4	148	1.75	8.2	34
5	40	1.73	8.4	35
6	6	2.04	7.1	29

cycle time (37.2%, 11 minutes) and was longer on average than unloading the bin because a truck had to wait to be loaded at the harvest site by the Hitachi loader. Whereas unloading of a bin took less time (2 minutes), the driver would tilt the bin back and then pull forward to empty the contents like a dump truck. If possible bins should be pre loaded on site and then picked up by the hook-lift truck. Pre loading of bins could reduce total cycle time by up to 8 minutes, increasing the hauling production to nearly 14 BDT/PMH.

The average observed time for the grinder to belt feed a chip van was 21 minutes, which carried on average 20.8 BDT/load. Grinding activities produced a total of 280.7 BDT over a total of 8 hours or 33.14 BDT/PMH.

Production Costs

The production costs ($/ton) including bundling, loading, hauling, and grinding was $34.65/GT or $46.50/BDT (Table 13). Wet-based moisture content of the slash during bundling was 22.55% which increased to 24.27% during loading and hauling stages, and finally increased to 28.95% during grinding. The increase in percentage moisture content was most likely a result of heavy fog, and the two days of rain that occurred during grinding activities.

The average cost of grinding $17.97/BDT was the most costly process of the system, representing nearly one third of the total production cost. The high cost of grinding ($595.71/PMH) reflects the cost of running the grinder, front-end loader, and

Table 13. Estimated system production and cost.

	Bundling	Loading	Hauling	Grinding	Total [a]
Hourly Cost ($/PMH) [b]	$ 133.19	$126.60	$103.84	$595.71	$959.34
Hourly Production (GT/PMH)	$ 10.62	55.88	14.68	46.65	
Cost ($/GT) [c]	$ 12.55	$2.27	$7.07	$12.77	$34.65
Cost ($/BDT) [d]	$ 16.20	$2.99	$9.34	$17.97	$46.50

Moisture content for bundling was 22.55%, 24.27% in loading and hauling, and 28.95% during grinding.

[a] Total system cost does not include move in costs, transportation to market, or profit allowance.

[b] PMH: productive machine hour

[c] GT: green ton

[d] BDT: bone dry ton

Hitachi loader simultaneously, which is necessary in order to achieve the high level of production (33.14 BDT/PMH).

Bundling production costs was the second highest component of system cost at 16.20/BDT. High costs were a function of the high hourly cost $133/PMH and the low production rate of 8.04BDT/PMH. Loading bundles into bins proved to be the most cost effective stage of the harvesting system with a production cost of $2.99/BDT, primarily due to the machine's high rate of production (42.32 BDT/PMH). The densification of slash into bundles made the material easier to handle, and increased the average weight per cycle, thus improving productivity of loading and hauling stages while reducing their production costs.

However, the bottleneck in this system appears to be the bundling stage, with a low production rate compared to the next stage of loading. Decoupling the bundling stage may reduce the potential system bottleneck by creating a buffer of bundles to be loaded and hauled, thus maximizing a loaders utilization rate.

Hauling the bundles to the centralized grinding site cost $9.34/BDT the second lowest component of system cost. Hauling costs represented approximately 15% of the total production cost, but proved to be highly variable depending on road conditions. Sensitivity analysis indicated minimizing road types such as single lane dirt roads which have traveling speeds of less than 10 mph (Table 14) greatly improved trucking productivity and reduced production costs (Fig. 9). Holding all other variables of system cost constant, every mile increase of dirt road hauling distance will cause a $3.07/BDT

Table 14. Road type, one-way distance, and average travel speed.

Harvest site	Spur road [a]	Dirt road [b]	2 Gravel road [c]	1 Gravel road [d]	Total
	--------------------------------(miles)-------------------------------				
Unit A	0.53	0.29	0.68	1.64	2.61
Unit B	0.25	0.92	0	1.58	2.50
Unit C	0.25	0.04	0	0.41	0.45
Avg. Speed (miles/hr) [e]	5.33	8.00	18.00	22.67	

[a] Spur road = unimproved temporary dirt spur within harvest unit

[b] Dirt road = single lane seasonal dirt road constructed with native soils

[c] 2 Gravel road = single lane rocked road

[d] 1 Gravel road = double lane rocked road

[e] Average speed = distance/observed time traveled

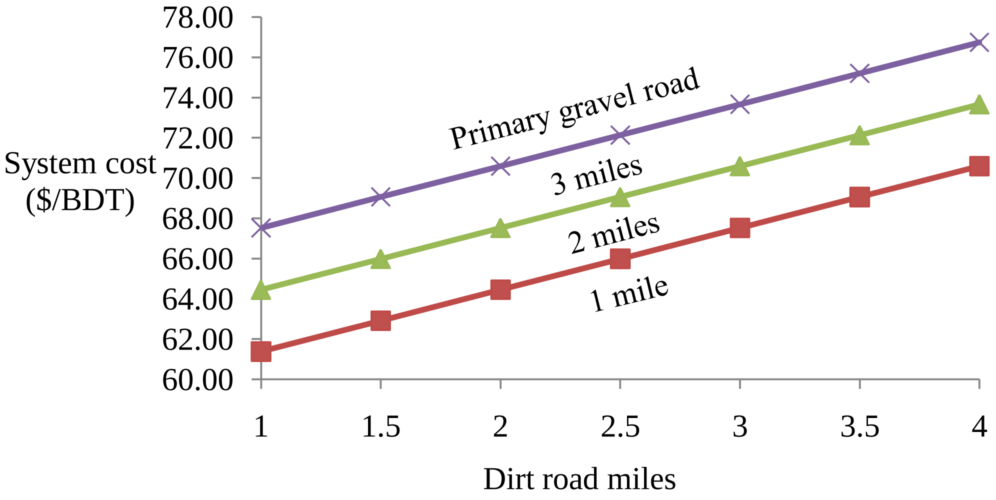

Figure 9. Sensitivity analysis of system production cost on various transportation distances.

increase in total system cost. Due to variability in transportation costs and the high costs associated with hauling on forest roads, it is suggested that a harvest site should be located no more than 5 miles away from the centralized grinding site.

One factor that had an effect on the overall system cost was diesel fuel prices which were at a national peak during the study in the summer of 2008. The cost of diesel fuel during the operation was $4.60/gal. Six months after commencement of operations fuel prices in the region dropped to $2.50/gal. Holding all other variables of system cost constant, every dollar reduction of fuel price represents around a $3.52/BDT reduction in overall system cost (Fig. 10).

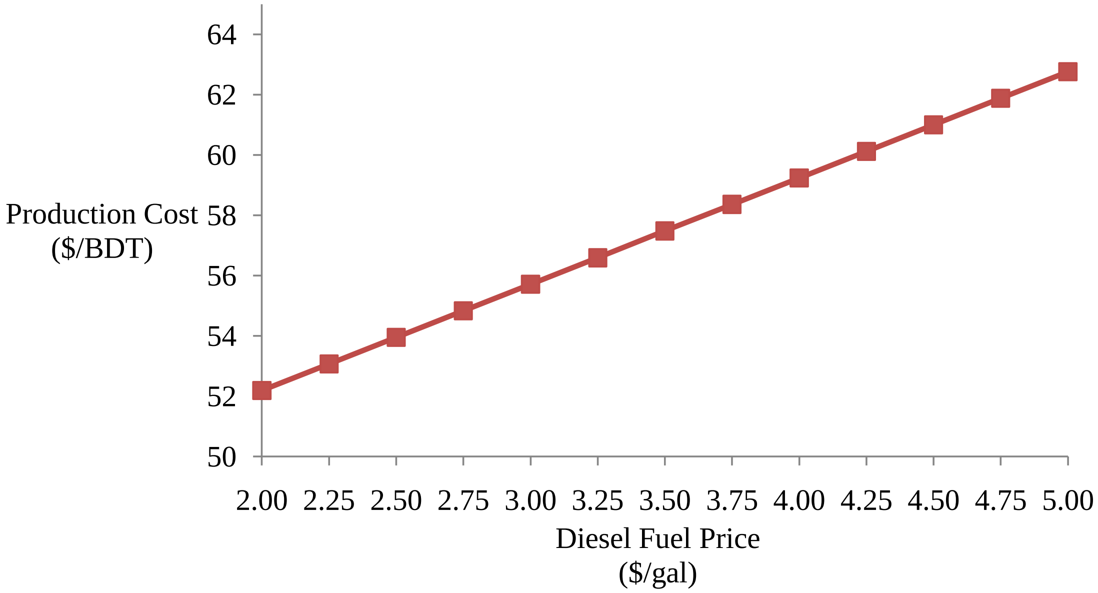

Figure 10. Sensitivity analysis on system production cost with various fuel market prices.

CONCLUSION

This study evaluated harvesting productivity and cost of a wood residue recovery system collecting forest biomass for electrical energy production with the use of a slash bundler. Productivity for different machines varied from 8 to 42 BDT/PMH, with a total production of 280.7 BDT over 70.2 hours. Production cost ranged from $2.99 to $17.97/BDT, with a total system production cost of $46.50/BDT at 28.95% moisture content.

The bundler tested on ground based clearcut sites performed well producing 29-37 10ft bundles per productive machine hour. Slash pile arrangement and material size were found to have a significant effect on productivity of bundling. Pile Class 3 (typical size material, side-cast piled) was found to be the most effective pile type when considering bundling productivity, yielding the smallest predicted cycle time (1.60 minutes).

Loading slash into bins was efficient and had a low cost of $2.99/BDT. Loading costs could be inflated if bundles were not located within one swing of the road edge, because of increased travel per cycle. The hook-lift truck effectively negotiated adverse forest roads and allowed removal of slash from traditionally difficult- to-access sites, without burning slash. Harvest sites ideally should be located within close proximity to a centralized grinding site (< 5 miles).

Due to the complexity of variables and their effects on overall system cost and productivity, it is apparent that operations like the one observed in this study take careful planning and strategic logistical arrangements. System cost can drastically change with increased hauling mileage on single lane dirt roads, due to slow traveling speeds (8 mph). The total system cost will increase $3.07/BDT for every one mile increase in dirt road hauling distance. The cost of the Fuel price was found to have a tremendous effect on total system cost, resulting in a $3.52/BDT for every $1/gal increase in fuel.

Forest biomass was removed successfully from previously harvested timber sites with poor access issues, but the overall system production cost was still not profitable. Appropriate pairings of machines may further reduce system bottlenecks and greatly improve total system productivity.

Chapter 4. Integrated biomass harvesting in stand conversion operations in northern California

ABSTRACT

Integration of biomass harvesting into an active stand conversion operation could reduce the cost of producing energy from wood chips by maximizing the utilization of the equipment on site for multiple products and minimizing tree handling. This study evaluated operational performance and cost of a whole-tree biomass harvesting operation, which was integrated with a sawlog harvest. Three study sites were located in northern California, where the stands consisted of tanoak (*Lithocarpus densiflorus*) mixed with Douglas-fir (*Pseudotsuga menziesii*). Douglas-fir trees were processed into sawlogs while whole trees of tanoak and sub-merchantable materials (small-diameter trees, tops and limbs) were fed directly into a chipper to produce wood chips. Standard time study methods were used to determine harvesting productivity and costs and evaluate interactions between machines (i.e. harvesting activities). Over 26 working days the integrated system produced and delivered to markets 387.11 thousand board feet (MBF) and 5,970 bone dry tons (BDT). Using the apportioned inputs allocation costing method, the total unit production costs from the integrated system were, $34.80/BDT for biomass, and $257.96/MBF for sawlogs. Chipping utilization through activity sampling was found to be 41%, raising the utilization rate by 10% increases production by 5.12 BDT / productive machine hour (PMH). Single lane dirt spur roads were found to be the most costly road type to transport whole trees, representing a $0.08/BDT increase in

transportation cost for every 100 ft increase in traveling distance. Diesel fuel price could raise total system cost by $13.67/MBF or $2.35/BDT for each $1/gallon increase.

INTRODUCTION

In the north coast of California many once commercially productive conifer stands are now over-run by tanoak (*Lithocarpus densiflorus*) which sprouts from stumps outcompeting merchantable conifer species. The transformation in species dominance from conifer to hardwood was the result of poor stocking success following earlier harvests. More than 40,000 acres on private industrial forest land along the north coast of California are now classified silvilculturally as, rehabilitation stands due to under-stocking (<50 ft^2 of basal area per acre; Fig. 11) of conifers (personal communication, M.W. Alcorn 2008. Green Diamond Resource Company, 900 Riverside Rd, Korbel, CA 95550). Converting stand composition through clearcut practices, referred to as rehabilitation harvest have been taking place in northern California, but are expensive due to the large volume of non-merchantable biomass which needs to be removed. If local bioenergy markets are available, non-merchantable biomass could be communited into an energy wood product such as chips or hog fuel (i.e. ground woody biomass). However, forest biomass is often under-utilized because collection and transportation costs are often greater than the market value of the materials (Withycombe 1982).

Bioenergy is the largest source of renewable energy in the United States, with over 11 gigawatts of installed capacity (Beckert and Jakle 2008). Twenty percent of all biomass used for bioenergy is a byproduct of the forest industry however, improvements in the supply of feedstock are necessary to meet the demands of today's renewable energy development. Woody biomass available to use in the woods is not fully utilized because of high costs associated with harvesting and transportation of biomass. Improved

Figure 11. Tanoak dominated stand that was once a productive conifer stand now managed through rehabilitation silviculture.

knowledge on new and innovative systems used to harvest woody biomass from this region would aid land managers in the planning and execution of cost effectively supplying biomass for bioenergy.

Integrated harvesting is defined as a single pass harvesting operation, such that an combustible energy product is produced in conjunction with conventional sawlogs (Hudson et al. 1990). Mitchell et al, 1990 showed that integrated harvesting systems can be effectively used to harvest and supply woody biomass for energy from conventional forestry plantations. Integration of biomass harvesting into an active logging operation could also reduce the cost of producing hog fuel by utilizing the equipment on site for multiple products and minimizing tree handling (Rawlings et al, 2004). Integrated harvesting systems have been applied to fuel reduction thinning treatments to reduce the threat of forest fires. To reduce fuel loads in high density stands, whole trees are felled and removed to landings or roadsides where they are processed into sawlogs and biomass. This approach facilitates slash disposal without open field burning and utilization of biomass for energy production. Largo and Han 2006 showed costs of integrated fuel reduction thinning operations were economically feasible at $116.81/MBF for sawlogs and $38.51/BDT for hog fuel.

There are a variety of work conditions which are favor integrated biomass harvesting operations. First, sites to be harvested need to be readily accessible. Poor road surfacing, tight turns, and adverse grades should be improved prior to operations or limited, since these contribute to longer round trip transportation times and higher transportation costs. Second landing size at centralized processing sites should be maximized or adequate for the flow of incoming material. If more than one harvest unit is pooling material to a processing site several acres may be required to store both products as well as accommodate multiple machines working on site safely. Addressing all of these conditions will aid in maximixing the production of biomass for bioenergy cost effectively.

Delays are recognized as one of the major factors that limit chipping productivity in an integrated system and are an essential part of most time studies. Chipping utilization has been reported in other studies relating to biomass harvesting operations at 73.8% (Spinelli and Visser 2009). Since utilization rates are directly correlated with production rates, lower utilization means lower daily production and higher unit production costs ($/ton). Ideally one would aim to minimize delays hence maximizing productivity when planning an integrated harvesting operation, and take into consideration other operational conditions to best implement an integrated harvesting system.

This study evaluated the operational performance and cost of an integrated biomass harvesting system that harvest sawlogs and combustible wood chips for energy, at the same time in stand conversion clearcut operations. Specific study objectives for this operation were to determine:

1. What is the hourly productivity for each stage of operation and the operation as a whole for both sawlogs and biomass?
2. What is the unit production cost for each stage of operation and the operation as a whole for both products ($/MBF or $/BDT)?
3. What are the major factors that affect the overall cost and productivity of an integrated biomass harvesting system?

METHODS

Study Site

Three clearcut study units (1, 2, and 3) were located on private industrial forestlands in northern California. The stands' compositions ranged from 45 to 82% tanoak (*Lithocarpus densiflorus*), 0 to 7% madrone (*Arbutus menziesii*), and 18 to 48% young growth Douglas-fir (*Pseudotsuga menziesii*). Slopes at these sites ranged from 0 to 45% (Table 15). The three units ranged from 15 to 23 acres in size and, were all classified as under-stocked (< 50 ft^2 basal area of conifer stocking per acre) conifer stands, except Unit 2. Harvest areas were cruised prior to operations with a systematic sampling (31.7 % of the total area) grid of 1/20th acre plots, with a minimum of one plot per acre. Trees larger than 5 inches in diameter at breast height (DBH) were recorded at each plot and used to estimate the pre-harvest stand volumes and average tree size.

Operations Description

All three units were clearcut with a mechanized ground-based shovel logging system. The integrated system utilized one Timbco T445D felller-buncher to cut and bunch whole trees on the ground. Two Komatsu PC300 log loaders were used to swing (i.e. shovel) bunches of whole trees to the roadside. Both loaders took turns loading roadside bunches of logs, whole trees, and tops onto two log trucks for transportation to a centralized processing site (Fig. 12). Whole trees delivered at the centralized processing

Table 15. Pre-harvest stand descriptions for three stand-conversion clearcut units.

	tanoak				Douglas-fir				Pacific madrone				Total		
	Density		DBH		Density		DBH		Density		DBH		Density	DBH	
Harvest site	Mean	% Species	Mean	S.D.[a]	Mean	% Species	Mean	S.D.[a]	Mean	% Species	Mean	S.D.[a]	Mean	Mean	S.D.[a]
	(stems/acre)		(inches)		(stems/acre)		(inches)		(stem/acre)		(inches)		(stems/acre	(inches)	
Unit 1	209.57	82	10.11	4.32	46.09	18	11.78	4.38	0.87	0	6	0	256.52	10.04	4.37
Unit 2	126.21	45	11.21	6.5	133.79	48	10.84	5.3	18.62	7	12.19	9.07	278.62	11.09	6.05
Unit 3	338.33	74	9.38	2.8	120.56	26	13.01	5.26	0.56	0	31	0	459.44	10.67	3.99
												Average	331.53	10.6	4.8

[a] S.D.: Standard deviation

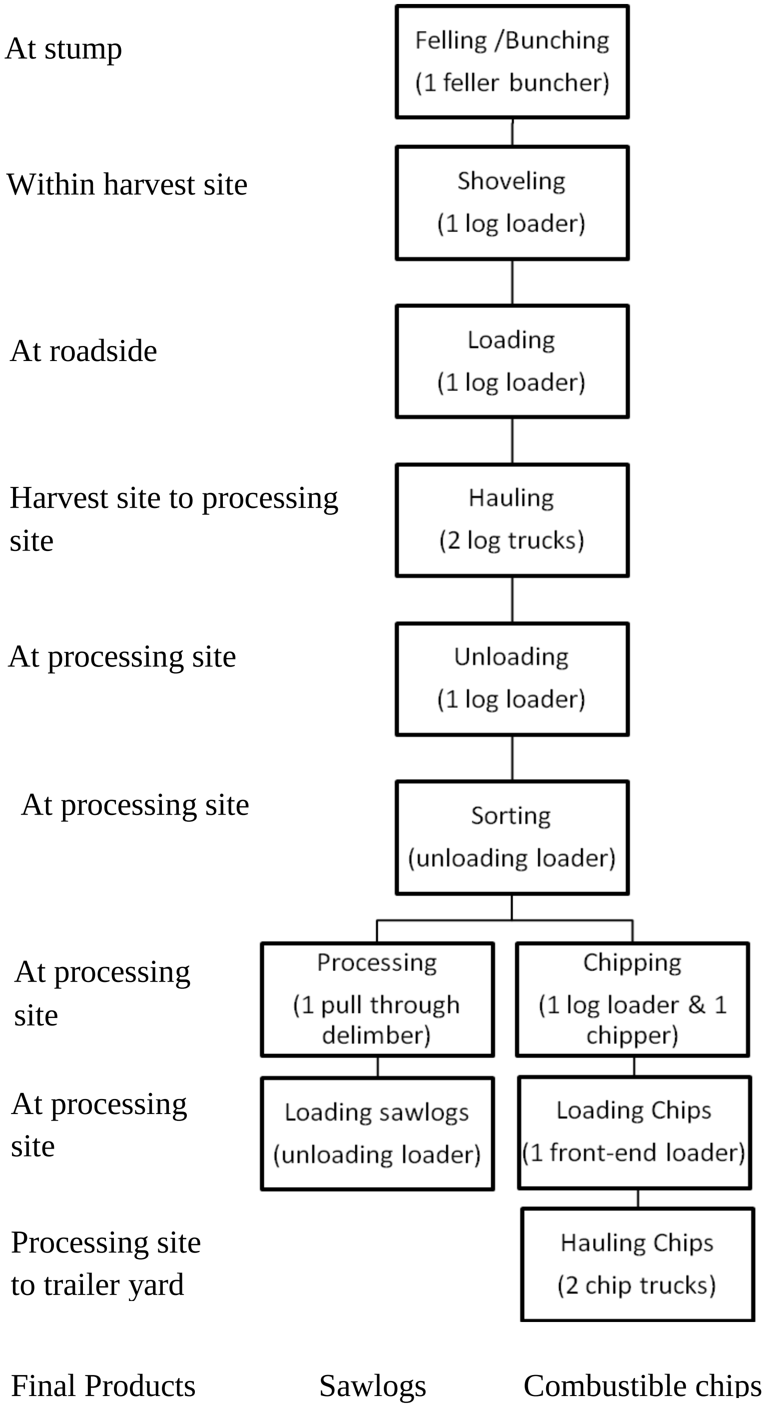

Figure 12: Integrated harvesting system flow chart.

site were immediately unloaded by another Komatsu log loader which worked with a remotely controlled pull through delimber that was equipped with a grapple saw. The Komatsu log loader was also used to process sawlogs and sort non-sawlog (i.e. biomass) trees and residues for chipping.

All materials to be chipped were grappled by an adjacent Linkbelt 3400 swing loader and fed into a Morbark disk chipper. Chips were blown into a large pile on the ground, and then loaded by a Cat 962 G front-end loader with a bucket attached into 45-foot long chip trailers. The trailers were transported by two wood chip trucks, and staged at a trailer yard nearby the highway where many trailers were stored for further transportation to a local energy plant (Fig. 13). Loaded trailers were traded at the yard for empty trailers and returned to the processing site immediately in order to keep the chipper busy. A trucking company was hired to deliver the trailers from the trailer yard to the power plant which took nearly 2 hours for a round trip at 56 miles. Sawlogs that were sorted and processed by the loader were decked at the centralized processing site, which later were loaded onto log trucks and delivered directly to the saw mill from the centralized processing site.

Data Collection and Analysis

Hourly machine costs in dollars per scheduled machine hour ($/SMH) or productive machine hour (PMH) were calculated using standard machine rate calculation methods (Miyata 1980). Delays were defined as all activities that did not directly contribute to the production of the operation. Purchase prices, salvage values, and all

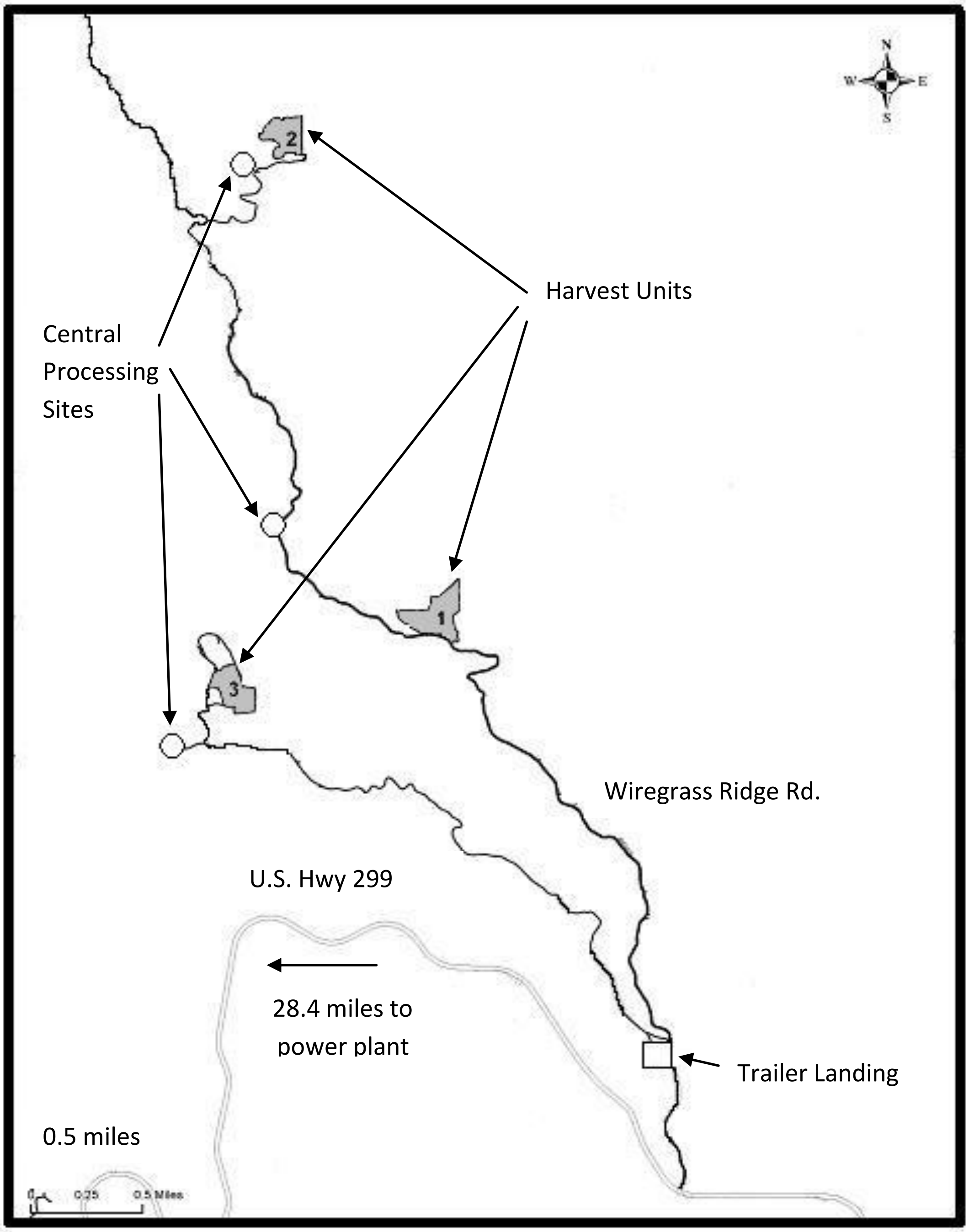

Figure 13. Operation layout map showing three harvest units with corresponding central processing sites. Whole trees and logs were hauled to the central processing sites to process and sort them into biomass and sawlogs.

other necessary information for the standard machine rate calculation were obtained from contractors who owned the equipment. Diesel fuel prices were determined from local market prices effective during the study period. All machinery was assumed to have a 10-year economic life and work 1800 SMH/year, except for the chipper which had a 5-year economic life due to its extensive use.processing sites.

Costs of each stage of operation and the operation as a whole were determined using the apportioned inputs allocation method (Hudson et al. 1990). The method was used to calculate the true costs of a multi-product integrated harvesting system. All operations that produce both biomass and sawlogs allocate their costs equally to both products. Costs associated with stages of operation that produce a single product in their final form, or that only handle one product type are charged solely to that product (e.g. chipping, loading sawlogs).

Activity sampling at the central processing site was recorded over four days of operation by periodically sampling at fixed intervals of time (i.e. every 15 seconds for one hour, three times a day), to determine whether machines were working or not. Through activity sampling one could gain a better understanding of appropriate system balance by calculating individual machine utilization rates which is a ratio of PMH to SMH.

Elemental time-motion data were recorded by stop watch for each machines cycle used in the harvesting system (Olsen et al. 1998). Regression equations were developed using Minitab 15 Statistical Software (Minitab 2006), through ordinary least squares estimators. To predict a machine's delay-free cycle time, average observed values for independent variables in the time study were entered into the developed regression equations. The following describes cycle elements for each phase of harvesting activities:

A felling and bunching cycle started when the machine rotated or traveled empty to a tree. The tree was then cut and the machine rotated loaded and placed the tree in an existing pile or bunch ending the cycle. A shoveling cycle started when the machine rotated or traveled empty to a pile/bunch of trees, grappled the trees, swung loaded to a new pile/bunch or road side, and ended when the machine dropped the trees or compacted them into another pile/bunch. A loading cycle started when the machine rotated or traveled empty to a pile/bunch of trees, grappled the trees, rotated loaded to the log truck, and ended when the trees were compacted onto the log bunks of the truck. A round trip cycle for the log trucks began when the trucks traveled loaded along various roads to the central processing location, where the trees were unloaded, then traveled unloaded back to the harvest unit, and ended when the truck was finished being loaded with trees. An unloading cycle started when the loader swung empty to the log truck, grappled the trees, rotated loaded to a pile/bunch of trees, and ended when the machine dropped the trees in the pile/bunch of trees. A typical sorting cycle started when the machine swung empty toward the pile/bunch of trees, grappled a tree, followed by the tree being delimbed or bucked (sawlogs only), swung loaded to a deck of trees/logs, and ended when the tree/logs are placed on the deck. A chipping cycle started when the trees/tops were placed on the chipper's in-feed table and, ended when the last chips dropped from the chipper’s out-feed shoot. A chip trailer loading cycle began when the front-end loader traveled empty to the pile of chips, then scooped the chips into the loader’s bucket, then traveled loaded to the chip trailer, and ended when the last chips fell into the trailer from the loader’s bucket. A saw log loading cycle started when the loader rotated empty to the deck of logs, grappled the logs, swung back to the truck loaded, and ended when the loader placed the logs onto the truck’s log bunks. A chip trailer hauling cycle began when the truck traveled loaded along various forest road types to the trailer yard adjacent the highway, unloaded the trailer, picked up an empty trailer, traveled back unloaded to the central processing site, and ended when the new trailer was filled with chips.

Average piece size for whole trees was calculated from pre-harvest stand cruise data. Tree diameter information for each species at each harvest unit was used to calculate average tree weight through species specific tables (Snell and Little 1983). The weight of trees was calculated in green tons using a weighted average of individual species weights by harvest unit. These weights were later converted to dry tons using collected moisture content data, and used to predict the productivity for each process of operation that handled whole trees. The average volume and weight per tree removal was 0.12 thousand board feet (MBF) or 0.40 bone dry ton (BDT). Biomass weight for chipping and hauling was tracked by scaling ticket books from the local energy plant. Samples of chipped material were collected in the morning, afternoon, and evening over four days of operation and dried in a laboratory oven to determine their moisture content, which was used to convert green tons to bone dry tons. Log truck volume was tracked by ticket books obtained from the saw mill and averaged throughout the study.

Production rates (i.e. MBF/PMH for sawlogs and BDT/PMH for biomass) for each process were calculated using the delay-free cycle times, for each process. Average delay-free cycle times were calculated using average values for each independent variable associated with a given cycle element (Table 16).

Table 16. Machine regression equations and predicted delay-free cycle times for an integrated harvesting system.

						Average delay-free cycle time[1]
Process	Regression model for delay-free cycle time	Mean	Range	R^2	N	(minutes)
Felling/	= 4.16			0.66	766	0.52/tree(s)
Bunching	+ 0.09 (# trees)	1.10	1-3			
	+ 0.01 (DBH)	10.61	6-26			
	+ 0.22 (loaded swing degrees)	117	0-270			
	+ 0.04 (# grapples)	0.30	0-10			
	+ 0.05 (travel distance in feet)	5.05	0-85			
Shoveling	= 3.81			0.69	363	0.62/tree(s)
	+ 0.18 (% slope)	20.29	5-50.			
	+ 0.37 (# grapples)	1.90	1-10			
	+ 0.28 (loaded swing degrees)	126.99	0-360			
	+ 0.11 (# trees)	2.93	1-10			

Table 16. Machine regression equations and predicted delay-free cycle times for an integrated harvesting system (Continued).

	+ 0.04 (# compactions)	0.55	0-11			
	+ 0.05 (travel distance in feet)	7.46	0-170			
Loading	= 4.60			0.63	440	8.08/truck
	- 0.13 (%slope)	10.19	5-35			
	+ 0.41 (# grapples)	1.90	1-11			
	+ 0.32 (loaded swing degrees)	101.04	0-270			
	+ 0.05 (# compactions)	0.98	0-7			
	+ 0.04 (travel dist in feet)	0.33	0-32			
Hauling	= 2592.8			0.18	70	32.50/trip
	+ 0.40 (loaded spur distance in feet)	1,603.99	89-3,223			
	- 0.01 (loaded single land dirt road distance in feet)	44	0-385			
Unloading	= 4.00			0.65	258	3.46/truck
	+ 0.48 (# grapples)	1.29	1-5			

Table 16. Machine regression equations and predicted delay-free cycle times for an integrated harvesting system (Continued).

	+ 0.28 (loaded swing degrees)	125.93	90-180			
	+ 0.10 (# pieces)	3.42	1-12			
	+ 0.04 (# compactions)	0.15	0-3			
	+ 0.04 (travel distance in feet)	0.45	0-50			
Sorting/ Processing	= 4.02			0.65	311	0.66/tree(s)
	+ 0.53 (# grapples)	2.10	1-10			
	+ 0.20 (loaded swing degrees)	125.45	90-360			
	+ 0.14 (# pieces)	2.26	1-15			
	+ 0.02 (# compactions)	0.39	0-5			
	+ 0.04 (travel distance in feet)	1.79	0-50			
Chipping	= 2.32			0.22	117	0.44/tree(s)
	- 0.42 (# trees)	1.79	1-6			
	+ 0.72 (DBH)	11.09	6-30			
Loading	= 1.83			0.47	375	5.84/truck

Table 16. Machine regression equations and predicted delay-free cycle times for an integrated harvesting system (Continued).

(Biomass)	+ 0.04 (# scoops)	0.99	0-3			
	+ 0.65 (travel loaded distance in feet)	76.27	0-265			
Loading	= 3.82			0.49	107	9.22/truck
(Sawlogs)	- 1.06 (loaded swing degrees)	108.50	90-180			
	+ 1.12 (empty swing degrees)	110.19	90-180			
	+ 0.28 (# grapples)	1.64	1-5			
	+ 0.03 (#compactions)	0.76	0-6			
Hauling biomass	= 615.35			0.79	46	43.87/trip
	+ 0.17 (loaded primary dirt road distance in feet)	17,258.87	0-22,334			
	+ 0.21 (loaded secondary dirt road distance in feet)	3,705.65	0-16,638			

[a] Delay-free cycle times were calculated using average values for each independent variable associated with each element of a given process.

RESULTS AND DISCUSSION

Productivity of Individual Processes in an Integrated Harvesting System

The hauling of whole trees and logs from harvest units to central processing sites yielded the lowest production of all stages of operations. A hauling cycle took 32.5 minutes per round trip (Table 16). Round trip times were highly influenced by traveling speeds associated with different road types. The distance in meters of single lane dirt roads and spur roads within the harvest unit, were the variables that had the greatest effect on cycle time. The productivity of hauling whole trees 33.68 BDT/PMH (combustible chips) or 2.43 MBF/PMH (sawlogs) from the harvest areas to the centralized chipping location was the lowest of all phases of operation. Low production rates for hauling was most likely due to the low availability of sawlogs (20% of the total harvested weight), and the long round trip distance of 1.74 miles.

The highest rates of production were achieved through the unloading of whole trees at the centralized processing sites. An average unloading cycle took only 3.46 minutes per truck. Average production rates for unloading trees at the centralized processing site were 11.40MBF/PMH (sawlogs) or 158.06 BDT/PMH (combustible chips). The unloading of trees was most influenced by the number of grapples to lift the materials off the truck and the swing degrees from the truck to the log deck. These rates were significantly improved from the loading of trees (4.88 MBF/PMH for sawlogs and

67.73 BDT/PMH for combustible chips) because it took less handling to remove a tree from the trucks than to carefully arrange them on the truck.

System Productivity of Harvesting Sawlogs and Biomass

The integrated system was monitored 260 SMH over 26 working days during the summer of 2008. Throughout the study period the system delivered 387.11 MBF of Douglas-fir sawlogs and 5,970.90 BDT of wood chips which had an average moisture content of 43.2%. The total system production rate was (2.43 MBF/PMH for sawlogs or 33.68 BDT/PMH for combustible chips), based on the system productivity that was determined by the lowest stage of production (hauling whole trees).

Activity sampling results indicated that operational efficiency could have been improved by balancing productivity between components in the entire harvesting system. The chipper had an average utilization rate of 41% with a range of 0% to 100%. This also translated to a low utilization rate of 49% for the loader (Linkbelt) which fed the chipper and 43% for the front-end loader which loaded the chips into trailers. This was because all of these machines were dependent upon one another. The Komatsu loader had the greatest utilization rate (74%) at the processing site, because the machine had three tasks of unloading, sorting/processing, and loading sawlogs. Log trucks hauling whole trees were utilized to nearly their full potential (96%) which indicated the need for an additional log truck to keep the processing site busy. However, introducing another log truck into the system would require additional feller-bunchers and loaders at the harvest unit to keep up with trucking over the short round trip hauling distance of 1.74 miles.

Hauling of biomass chips had a relatively low utilization rate (69%) which was primarily a result of low productivity (BDT/PMH) of chipping. If chipping production were to increase, additional trucks would needed for the long round trip cycle (43.87 minutes) from the processing site to the trailer yard adjacent the highway.

Costs for Harvesting Both Sawlogs and Energy Wood Chips

Machine rates, production rates, and production costs for each stage of operation and the operation as a whole are summarized in Table 17. The total hourly system cost of running all the machines used in the integrated harvesting system was $1,936.76/PMH, including ownership, operating, and labor costs. When applying production rates for each harvesting process, we found that the most expensive system process was chipping ($10.77/BDT). This was due to low utilization rates (41%) and the high machine rate for two machines: the chipper and the loader that feeds it. Using the apportioned inputs allocation method the total unit production costs from the integrated system were, $34.80/BDT for combustible chips, and $257.96/MBF for sawlogs. These total system costs do not include the costs associated with supporting machinery, profit margin, move-in, or transportation of products in their final form to markets.

Sensitivity Analysis on Harvesting Production and Cost

Machines used throughout system processes were all assumed to have a utilization rate of 85%. However due to the low observed utilization rate for chipping (41%) as indicated through activity sampling, there could be reduced production and higher costs than what was calculated in Table 17 if all the machines were operating at

Table 17. Harvesting system productivity and costs in an integrated harvesting system.

	Production Rates			Production Costs	
	Sawlogs	Chips	Machine Rates	Sawlogs	Chips
Process	MBF/PMH[a]	BDT/PMH[a]	\$/PMH[a]	\$/MBF[b]	\$/BDT[c]
Felling/Bunching	2.97	41.23	188.24	63.31	4.57
Shoveling	6.59	91.44	176.47	26.76	1.93
Loading	4.88	67.73	176.47	36.13	2.61
Hauling	2.43	33.68	211.76	87.19	6.29
Unloading	11.40	158.06	130.62	11.46	0.83
Sorting/Processing	4.74	65.76	138.36	29.18	1.99
Chipping	0.00	43.52	468.78	0.00	10.77
Loading (Biomass)	0.00	145.82	121.48	0.00	0.83
Loading (Saw-logs)	33.12	0.00	130.62	3.94	0.00
Hauling biomass	0.00	38.84	193.96	0.00	4.99
		Total	1936.76	257.96	34.80

[a] PMH: Productive machine hours.

[b] MBF: Thousand board feet.

[c] BDT: Bone dry ton.

N/A: Not applicable.

utilization rates of less than 85%. Figure 14 shows the possible production rates and costs of chipping with changes in utilization rate. There is a linear relationship between production and utilization rate. Increasing the utilization rate by only 10% can raise chipping production by 5.12 BDT/SMH. The relationship between cost and utilization rate on the other hand is quite different, chipping costs were as low as $10.77/BDT when utilization was 85% and as high as $21.19/BDT when utilization rate fell to 41%. In this sensitivity analysis one could save more than $1/BDT for every 5% increase in chipping utilization rate until they reached 70%, thereafter their savings would be less than $1/BDT. Having a high utilization rate is important since chipping is one of the most expensive stages of operation and because production in following stages of operation are often influenced by chipping. Having a high utilization rate will also increase productivity and reduce costs, saving money for other stages of operation like collection and transportation. It is ideal to maximize utilization rates of all machines and processes involved in integrated systems, potential savings could be as high as $37.34/BDT for biomass alone, if all machines in the system operated at a balanced utilization rate of 85% compared to 41% (Fig. 15).

Transportation of whole trees on log trucks did yield the lowest productivity of all stages of operation 2.43 MBF/PMH (sawlogs) 33.68 BDT/PMH (combustible chips), and was the most expensive stage of operation for the production of sawlogs $87.19/MBF. This was due to low traveling speeds on forest roads (< 7 mi/hr) caused by poor road conditions. These included rough road surface with no gravels, single lane road width,

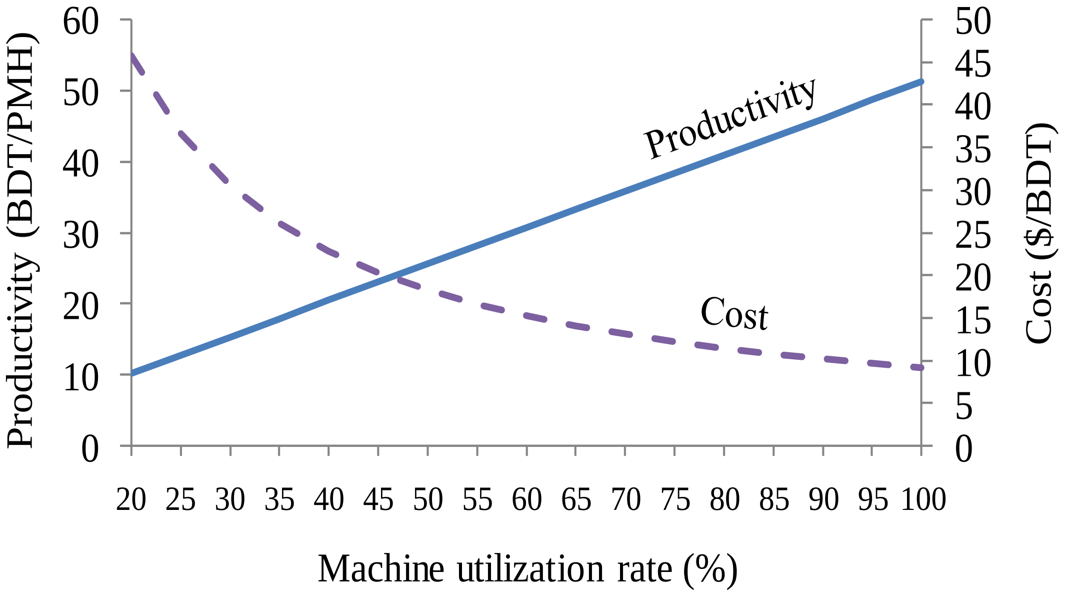

Figure 14. Cost and productivity of whole tree chipping with various utilization rates for associated machine utilization rates. Note: BDT: Bone dry tons, PMH: Productive machine hour, SMH: Scheduled machine hour, Utilization = (PMH/SMH)*100.

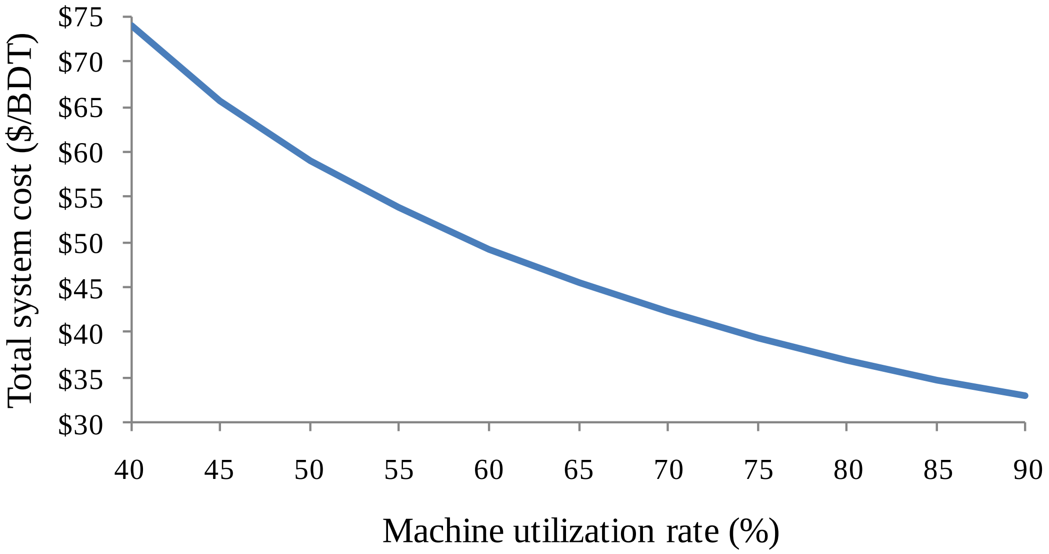

Figure 15. Total system cost for producing biomass in an integrated harvesting system based on varying machine utilization rates.

steep road grades, and sharp curves. In this study the average round trip distance was only 1.74 miles but took 32.5 minutes without delays. There was a noticeable relationship between whole tree hauling costs and whole tree one way hauling distances with relation to road type. Every 100 foot increase of spur road is proportional to a $0.08/BDT increase in the cost of hauling. It should be noted how the increase of mainline or 1 and a half lane width improved dirt road distance, reduces total hauling costs. This relationship between reduction of cost with increased mainline road distance was due to the higher traveling speeds (>16 mi/hr) observed along higher quality road types.

Diesel fuel prices reached a peak at $4.60/gallon in the region during the course of operations in the summer of 2008, and then steadily declined to $2.50/gallon six months after commencement of operations. Fuel costs had a greater influence on cost per unit of product in an integrated harvesting operation. Many machines consumed high rates of fuel per hour. The integrated harvesting operation in this study consisted of 11 machines, including the chipper which had the greatest fuel consumption rate of 30 gallons per hour. Holding all other variables constant, every $1/gallon increase in fuel price is equivalent to an increase of $13.67/MBF or $2.35/BDT in total system production cost (Fig. 16).

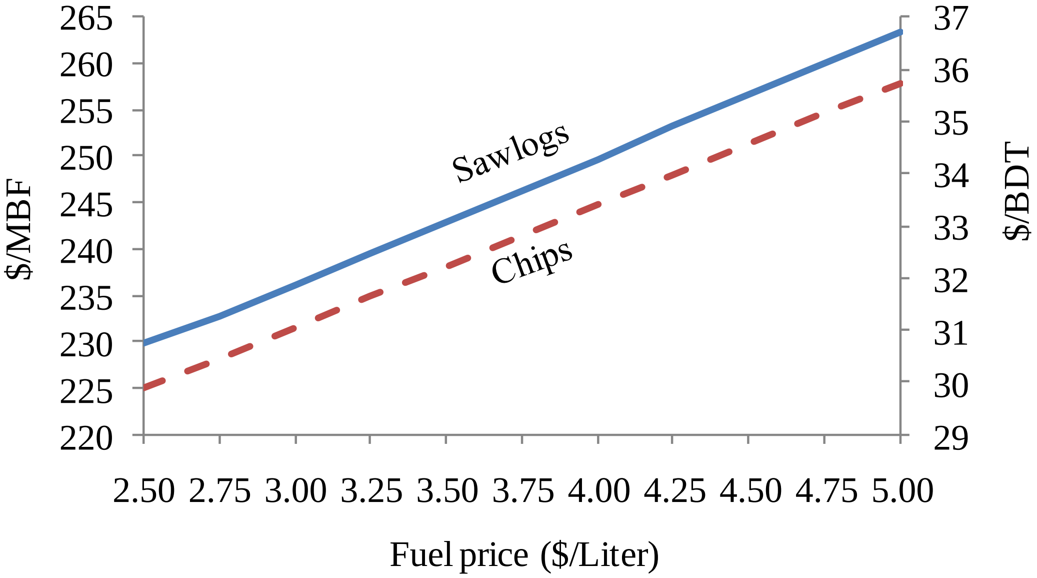

Figure 16. System production cost associated with various diesel fuel prices.

CONCLUSION

During 26 days of operations, the integrated harvesting system produced and delivered 387.11 MBF of sawlogs and 5,970 BDT of chips with an average wet-based moisture content of 43.2%. The total cost for the integrated system was $1,936.76/PMH. It produced Douglas-fir sawlogs at a cost of $257.96/MBF while chipping non-merchantable size material and species into combustible energy wood chips at a cost of $34.80/BDT. Felling and bunching trees was the least productive stage of the entire operation 2.97 MBF/PMH for conifer and 41.23 BDT/PMH for hardwoods. Highest rates of production were achieved by the unloading whole trees at the centralized processing sites (11.40 MBF/hr or 158.06 BDT/PMH). Round trip transportation distances averaged 1.74 miles for hauling whole trees from harvest units to the centralized processing sites, and 8.08 miles for hauling combustible chips from the centralized processing sites to the highway adjacent trailer yard. Loaded trailers were exchanged for empty trailers at the trailer yard. Loaded trailers were then transported to a local energy plant approximately 28 miles away by a contracted trucking service.

The results of activity sampling indicated some room for improvement in balancing productivity between components in the integrated harvesting system. There were four machines working in the processing sites at the same time, but not all machines were working at the same production rate. The most expensive process of chipping ($468.78/PMH) had a utilization rate of only 41%. Ideally machines should be paired to maximize their individual utilization rates, which increases potential production and decrease production costs.

I used sensitivity analysis to evaluate how machine utilization rates, road hauling distances, and diesel fuel costs could affect system costs. Raising the utilization rate of the chipper by only 10% is equivalent to a 5.12 BDT/PMH increase in production, and for every 5% increase in utilization is responsible for a cost savings of $1/BDT until 70% utilization where it decreases thereafter. Transportation costs were found to be the most expensive stage of operation, are correlated with hauling distance and road quality. Ideally single lane dirt spur roads should be minimized due to their slow associated travelling speeds since every 100 ft costs an additional $0.08/BDT in hauling costs. Diesel fuel prices are often overlooked in harvesting operations but can have a substantial affect on total system production cost. This is especially true when using a chipper which consumes 30 gallons/hr, and 10 other pieces of machinery in the system. Each dollar increase in diesel fuel price represents a $13.67/MBF or $2.35/BDT increase in total system production cost.

Careful planning of integrated harvesting systems such as this one, should take into account special relationships between harvest units and processing sites, and appropriate pairings and number of machines, in order to maximize production. System balance is essential in order to match production levels of different system processes, minimizing congestion and improving efficiency. If these concerns are successfully accounted for, an integrated harvesting system could reach its full potential to produce sawlogs and energy wood chips at a high rate with a low cost.

The integrated biomass harvesting of tanoak in a centralized whole tree chipping operation was effective. Previously under-stocked conifer stands with large non-merchantable hardwood components were converted back to productive conifer stands. Forest residues were successfully removed without open field burning. Additionally costs associated with the biomass harvesting operation were minimized by best utilizing machinery on site to produce both biomass and sawlog products.

Chapter 5. Conclusions

Forest biomass harvesting operations are becoming ever more popular as non-renewable energy prices inflate, and managers seek to silviculturally restore stands to more desirable conditions. Additionally legislation like California's AB 32, and federal efforts to reduce green house gas emissions will further stimulate interest in woody biomass energy resources. This study was designed to provide operations information on the performance and financial feasibility of several forest biomass harvesting systems in Northern California. I addressed common challenges faced in operations by forest managers. These include access to residues at harvesting sites, densification of biomass, and successful integration of processes into stand conversion operations. The general conclusions for each topic are summarized:

Application of Hook-Lift Trucks for Improved Access

The hook-lift truck study was conducted on private industrial forest land in Northern California. Stands were clearcut with a ground-based shovel yarding system, harvesting residues were loaded into hook-lift trucks at roadsides and small landings. Residues were delivered by hook-lift trucks to a centralized grinding location where residues from several harvest sites were accumulated. Finally chip vans which could access the centralized grinding site transported the ground hog fuel to a nearby power plant.

Productivity for different machines varied from 10-37 BDT/PMH, with a total production of 267.5 BDT over 70 hours. Production costs ranged from $6.30-$16.22/BDT, with a total system cost of $32.98/BDT at 36% wet-based moisture content. Loading slash into bins had the lowest cost of $6.30/BDT, and was most productive when piles consisted of typical sized material arranged by processors. The hook-lift trucks worked well in accessing residues at harvest sites due their short length, improved ground clearance, and traction control, compared to chip vans. However due to low associated traveling speeds on single lane dirt roads (< 10 mph), and the low average weight per bin (4.7 BDT), harvest sites should ideally be located close to grinding sites (< 5 miles).

Many improvements could be made to this system such as the appropriate pairings of machinery to meet associated production levels in order to minimize system bottlenecks. Ideally, one would want to collect and transport residues from several harvest sites to the centralized grinding site at the same time, compared to one at a time as observed during this small scale experimental study. In longer hauls more than one hook-lift truck should be used in order to keep up with the excavator loading bins. Decoupling collection and transportation phases with grinding is ideal due to the grinder’s high rate of production. This decoupling process can create an effective buffer of residues for grinding and maximize grinding utilization rates which incur the highest production costs of all stages of operation.

Combining the Bundling Process for Densification of Residues

The bundling study took place at the same three harvest sites as the hook-lift study, only this time bundling slash was the first system process. Again residues were loaded into the same hook-lift trucks and transported to the same centralized grinding site. Where materials were ground into hog fuel and transported by chip vans to a local power plant.

Productivity for different machines varied from 8 to 42 BDT/PMH, with total production of 280.7 BDT over 70.2 hours of operation. Production costs ranged from $2.99 to $17.97/BDT, with a total system cost of $46.50/BDT at 28.95% wet based moisture content, excluding support costs. The bundler produced 29 to 37 10ft bundles/PMH, and was most effective in bundling slash that was of typical size and side-cast piled, resulting in an average time of 1.60 delay-free minutes per bundle.

The densification of slash through bundling increased average bin weights to 6.45 BDT, which increased production and reduced costs of loading and hauling residues. Loading bundles into bins had a low cost of $2.99/BDT, and hauling of bundles also had a low cost of $9.34/BDT. However, bundling itself was the system bottleneck with the lowest level of production around 8 BDT/PMH. Bundling incurred one of the highest costs of over $16.00/BDT.

Clearly there is much room for improvement in this system. Decoupling bundling or bundling on site in advance would help improve system production by preventing a bottle neck in bundling. Bundler operators suggested that piling of slash was good but was not ideal for bundling (parallel arrangement, windrowed, consistent size). Again the same transportation challenges are faced in this operation. Even though bin weights were improved by more than one ton, this improvement is negligible over short hauling distances. Harvest sites should still ideally be located within 5 miles of grinding sites. Grinding should also be conducted similarly by a decoupling process, which becomes ever more important in grinding of bundles, which in this study had a lower production than loose slash due to density.

Integrated Biomass Harvesting for Stand Conversion Operations

The integrated harvesting study took place on private industrial forest land in Northern California where several harvest sites were selected for silvicultural rehabilitation through stand conversion. These stands consisted of mostly tanoak that has no commercial saw-log value. The residual Douglas-fir component of the stand would perhaps marginally cover the costs of the harvest. Trees were harvested using a ground based shovel logging system and were yarded to roadsides. Whole trees were loaded on logging trucks and delivered to a centralized processing site where they were sorted by product. Merchantable size Douglas-fir was delimbed and bucked into log lengths and delivered to saw mills. All other materials and whole trees where chipped into hog-fuel and delivered by chip vans to a local power plant.

During the 26 days of operation studied, the system produced and delivered 387.11 MBF of sawlogs and 5,970 BDT of chips, with an average wet-based moisture content of 43.2%. The total cost of the system was $1,936.76/PMH. The system produced

Douglas-fir sawlogs at a cost of $257.96/MBF and chips at a cost of $34.80/BDT. Hauling of whole trees to the centralized processing site had the lowest associated production of 2.43 MBF/PMH for conifer or 33.68 BDT/PMH for hardwoods. Highest rates of production came from the unloading of trees at centralized processing sites (11.40 MBF/PMH or 158.06 BDT/PMH).

Integrated harvesting operations similar to those in my study, often use many machines to facilitate various processes involved with producing two products. Challenges are faced in system balance, where it is ideal to pair the appropriate number of machines in order to meet the production level of the prior processes. In this study much effort was given to the analysis of grinding utilization, which was low (41%). With expensive processes like grinding it is crucial to identify system bottle necks in previous stages of operation to maximize grinding utilization. Decoupling the processes related to harvesting and grinding could provide improvements, but limited landing space often prevents large buffers of residues from grinding, due to safety concerns.

Future Research Needs

Woody biomass is the most ancient widely used source of energy in human history. Forest biomass harvesting operations are not a new concept, they have occurred throughout several decades, fading in and out of popularity, receiving most recognition when market prices peak. Currently, woody biomass for many reasons is not always financially feasible to harvest and transport to market. The success of these operations is dependent upon strategic implementation and reaction to favorable market trends. If forest managers are to accomplish this they will need more research and information relating to these harvests:

One major factor influencing biomass harvesting is the available tons of biomass present at a given harvest site. Currently estimates of slash loading per acre are hard to obtain, because the only accurate method of assessing slash loading is to remove the residues and weigh them. Predicting slash volume before harvest is equally hard and often relies on stand cruising information. Sophisticated technologies like LIDAR have recently improved these stand cruising values, but are expensive and not all land managers can afford them. There is definite need to establish a quick cruising method that can accurately assess slash loading, in tons per acre. Unfortunately, little work has been done in this area, Hardy (1996) developed methods for estimating piled slash volume and smoke production, but these methods only work for piled slash not broadcast slash. Regardless, methods developed by Hardy are not entirely accurate in their conversion from volume to mass due to inabilities to measure air space and density of piles.

Many acres that are in need of either forest restoration or residue recovery occur on steep ground. Most research in forest biomass harvesting systems has evaluated ground based systems that are usually limited to slopes of 50% or less. Perhaps the reason for limited research on steep ground is the higher associated costs with increases in slope in conventional harvesting. Still, if forest biomass harvesting is to reach its full potential, especially in the Western United States, strategies for steep ground operation will have to be implemented. Many suggest that the only way steep ground biomass harvesting will be feasible is to integrate the process into conventional timber harvesting practices.

Despite the interest in integration of biomass harvesting into conventional harvesting practices, few forest managers are willing to try this approach. Due to the recent economic downturn in housing markets, sawn lumber prices have crashed. Managers often fear that including a marginally feasible operation like biomass harvesting into their current harvesting operations will reduce production and inflate costs of harvesting their primary product (saw-logs). With today's poor market conditions for lumber and high fuel prices, most land managers are not willing to take these operational risks through integration. These fears are not necessarily true if one is to consider the greater economic picture; cost savings in site preparation work, benefits of future stand productivity, reduced risk of fire, reduction of green house gas emissions, and creation of new jobs in the forestry sector.

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