A Productivity and Cost Comparison of Two Systems for Producing Biomass Fuel from Roadside Forest Treatment Residues

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Abstract

Forest operations generate large quantities of forest biomass residues that can be used for production of bioenergy and bioproducts. However, a significant portion of recoverable residues are inaccessible to large chip vans, making use financially infeasible. New production systems must be developed to increase productivity and reduce costs to facilitate use of these materials. We present a comparison of two alternative systems to produce biomass fuel (i.e., ''hog fuel'') from forest residues that are inaccessible to chip vans: (1) forwarding residues in fifth-wheel end-dump trailers to a concentration yard, where they can be stored and then ground directly into chip vans, and (2) grinding residues on the treatment unit and forwarding the hog fuel in high-sided dump trucks to a concentration yard, where it can be stored and then reloaded into chip vans using a front-end loader. To quantify the productivity and costs of these systems, work study data were collected for both systems on the same treatment unit in northern Idaho in July 2009. With standard machine rate calculations, the observed costs from roadside to loaded chip van were \$23.62 per bone dry ton (BDT) for slash forwarding and \$24.52 BDT^{-1} for in-woods grinding. Results indicate that for harvest units with conditions similar to the test area, slash forwarding is most appropriate for sites with dispersed residues and long-distance in-woods grinder mobilization. For sites with densely piled roadside residues, in-wood grinding is likely to be a more productive and less costly option for residue recovery.

Forest operations for timber harvest, precommercial thinning, fuels management, and other vegetation treatments generate large quantities of treatment residues (also called ''slash''), including tops, limbs, cull sections, and unmerchantable roundwood. These by-products are a promising source of biomass for the production of energy, fuels, and products because they are widespread, renewable, and can be used to produce products that offset the use of fossil fuels and reduce greenhouse gas emissions (Jones et al. 2010). Use of forest residues can also improve the financial feasibility of some silvicultural prescriptions by reducing site preparation costs and can improve air quality in areas where open burning is a common method of residue disposal (Gan and Smith 2007, Jones et al. 2010).

The most prevalent use of forest residues is as hog fuel for combustion boilers used in the generation of heat and electricity. In this article, the term ''hog fuel'' denotes woody biomass fuel produced from forest residues, fuelwood, and wood waste by all methods of comminution, including grinding, chipping, and shredding. Combustion of hog fuel and other by-products by the forest industry accounts for more than 50 percent of all biomass energy in the United States (US Department of Energy 2011). In some regions, electric utilities, industrial boilers, and institutions with wood-fired heating systems represent additional hog fuel demand outside the forest sector. To meet this demand,

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grinders and chippers are commonly deployed to manufacturing facilities and log landings to process wood waste and forest residues into hog fuel. Under some conditions, particularly as a component of precommercial and fuel reduction thinnings, mechanized harvesting and processing systems are used to produce hog fuel from whole trees. These systems have been studied under a wide range of conditions (e.g., Han et al. 2004, Bolding and Lanford 2005, Mitchell and Gallagher 2007, Demchik et al. 2009, Pan et al. 2010). Hog fuel can also be made from forest residues that are dispersed or piled on the treatment unit as a result of cut-to-length or roadside processing systems, but these operations tend to be more costly and less productive than processing concentrated wood waste or whole trees. As a result, forest residues that are technically recoverable are often financially unavailable and are frequently left on site to decompose or are burned in place to reduce the risk of fire and to open growing space for regeneration. Although forestland currently supplies 68 million bone dry tons (BDT) of logging residue biomass in the United States, an additional 10 to 43 million BDT may be recoverable from operations that combine residue recovery and forest thinning, depending on delivered price (Smith et al. 2009, US Department of Energy 2011). In order for these residues to be used for production of bioenergy and bioproducts, efficient methods of handling, processing, and transportation must be developed.

Forest residues are costly to process into hog fuel because they tend to be spatially dispersed and heterogeneous in size and form, and as a result they are difficult to handle efficiently (Desrochers et al. 1993). Transportation costs present an additional barrier to use. Because hog fuel is bulky, relatively low in value, and often produced far from end users, maximizing load size by using large chip vans for transportation is the industry standard in most parts of the country. In-woods grinding operations typically grind biomass directly into the trailers of large chip vans, which can have payloads of up to 35 BDT, depending on trailer size, axle configuration, and road restrictions. However, in mountainous regions, treatment units are often inaccessible to these trucks because low standard forest roads are narrow, steep, and winding. In situations where large chip vans cannot access a treatment unit, smaller vans can be used, or residues and hog fuel can be forwarded to a concentration yard that is accessible to large trucks, but these options involve added costs.

Production systems using hook-lift trucks equipped with roll off bins have shown some promise in facilitating the use of forest residues that are inaccessible to large chip vans. Harrill and Han (2010) reported that slash forwarding using hook-lift trucks could be cost-effective in recovering forest residues for \$32.98 BDT^{-1} from woods to chip van (US dollars presented throughout this article), at a rate of 10 to 37 BDT per productive machine hour (PMH). In that study, hook-lift trucks were used to deliver residues from inaccessible treatment units to a centralized grinding operation as a component of a commercial timber harvest. Combining hook-lift trucks and slash bundlers (e.g., John Deere 1490D energy wood harvester) is also an option. That system has been reported to produce 8 to 42 BDT PMH^{-1} at a cost of \$46.50 BDT^{-1} (woods to chip van) on recently harvested sites in northern California (Harrill et al. 2009). Although productivity may be relatively low (e.g., 4 BDT PMH^{-1}), hook-lift systems have been shown to be effective in fuel treatments that included little or no merchantable timber extraction for a cost of \$31.18 BDT^{-1} (woods to concentration yard; Han et al. 2010). Modified high-sided dump trucks and off-highway dump trucks have been used to forward residues and hog fuel to an accessible concentration yard (Rawlings et al. 2004), but to date these systems have not been examined using controlled work study methods. Although not typically used in conventional grinding operations, many of these systems integrate a van-accessible biomass concentration yard into operations to increase transportation efficiency by maximizing payload for delivery to end users. However, this approach has the added costs of double handling material, which must be balanced against gains from using large vans.

Previous forest operations research provides valuable information that can be used to understand, predict, and reduce the costs of biomass use as part of an integrated harvesting operation or as a stand-alone enterprise. However, it is difficult to compare the various systems examined in different studies because of high variability in site conditions, equipment, operators, and other confounding variables. The objective of this study was to evaluate the productivity and costs of two alternative systems on the same treatment unit. The two systems evaluated were (1) forwarding residues to a concentration yard where they were stored and then ground directly into chip vans and (2) grinding residues on the treatment unit and forwarding the hog fuel to a concentration yard where it was stored and then reloaded into chip vans (Fig. 1). We refer to these systems as ''slash forwarding'' and ''in-woods grinding,'' respectively. The rationale for this research is to provide information that will help forest managers and contractors evaluate options for biomass use and configure forest operations to meet both financial and nonmarket objectives (such as reducing smoke from open burning) associated with biomass use where topography and site conditions limit chip van access. In the long run, increasing productivity and reducing costs will improve the viability of bioenergy and biofuels production using forest biomass and will allow forest managers to treat more acres at a lower cost.

Methods

This research used standard work study methods to compare the two systems (Miyata 1980, Olsen et al. 1998, Brinker et al. 2002). Detailed time study data were used to develop multiple least-squares linear regression models of delay-free cycle time that were used to compare the systems and evaluate the effect of a variety of predictor variables on cycle time. Although delays are discussed, we do not use field data to calculate machine utilization rates, which are typically quantified using long-term, shift-level studies. Cycle rates are applied to average cycle weights to estimate machine and system productivities. Estimated productivities are then applied to standard machine rate calculations to calculate system costs for both the observed systems and hypothetical optimized systems.

Study site and forest operations

Beginning in July 2009, slash forwarding and in-woods grinding systems were tested in succession to process a total of 1,300 BDT of forest residues from a clear-cut in northern Idaho. Roundwood harvest was completed on the unit in September 2008, 9 months prior to biomass harvest. The 60-year-old stand was dominated by Douglas-fir (*Pseudotsuga*

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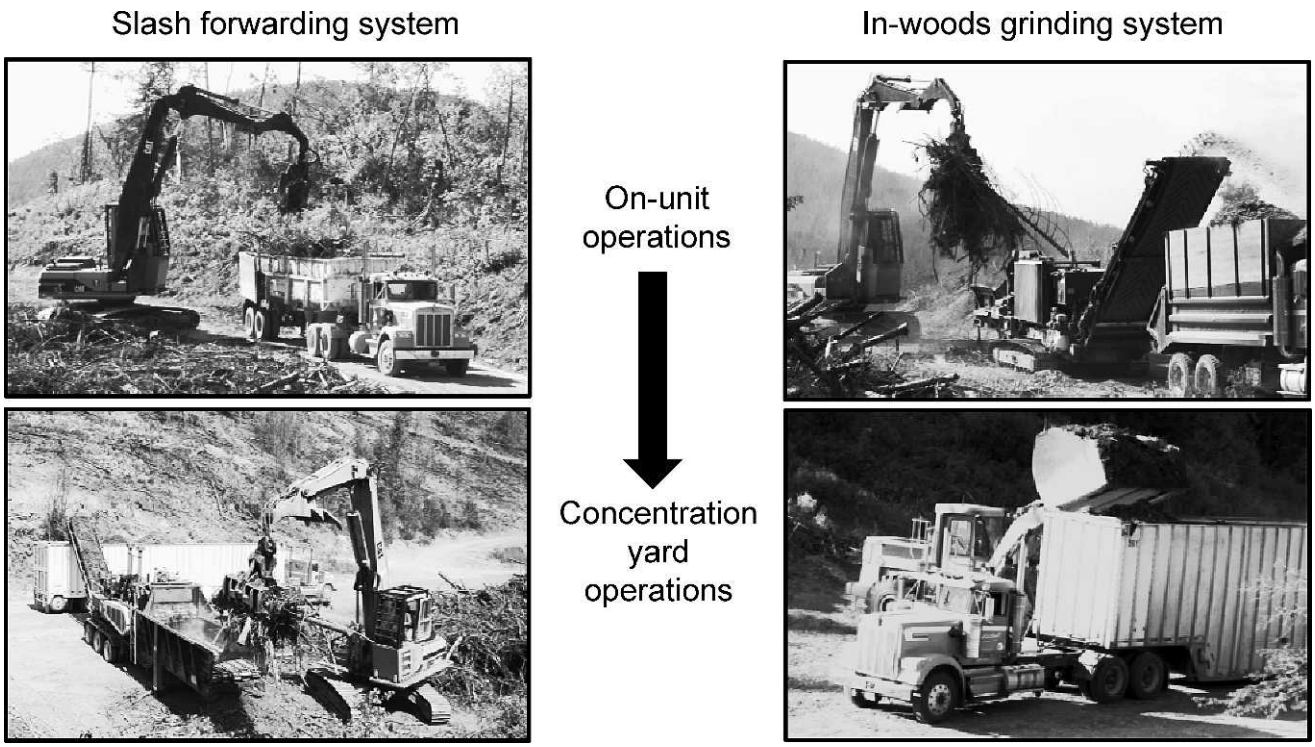

Figure 1.—The slash forwarding system (left) transports forest residues in end-dump trailers to a concentration yard, where they can be stockpiled and ground into large chip vans. The in-woods grinding system (right) processes residues on the treatment unit and transports hog fuel to the concentration yard, where it is stockpiled and loaded into chip vans with a front-end loader.

menziesii, 22% by harvest volume), true firs (*Abies* spp., 45%), and western redcedar (*Thuja plicata*, 30%). Slopes on the unit are dominated by northeast and southwest aspects on opposite sides of a first-order drainage, with an average slope of 25 percent and a maximum slope of approximately 55 percent (Fig. 2). Ground-based, whole-tree harvesting with roadside processing resulted in dense, side-cast residues piled almost continuously along the road that crosses the unit. Residues were a relatively consistent mix of tops and limbs with a smaller proportion of cull sections and unmerchantable logs.

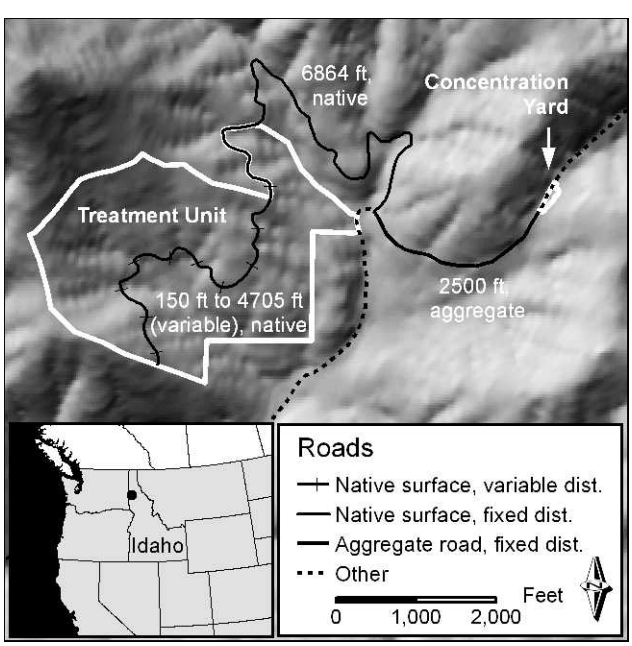

Figure 2.—Site map showing the three road segments traveled by trucks in both systems. Chip van access to the treatment unit is limited by narrow roads and tight curves that follow the contour of the hillside.

From the harvest unit to the concentration yard, trucks traveled between 1.2 and 2.3 miles on a native surface forest road and 0.5 mile on an aggregate-surface road, for a round trip distance of 1.7 to 2.8 miles (Fig. 2). Average grades for the native surface and aggregate road segments are 4.7 and 7.9 percent, respectively. Chip van access to the site is limited primarily by high drainage dips, tight curves that follow the contour of the hillside, few pullouts, and limited sites to turn around. Trucks cannot pass one another on the road and must coordinate travel between pullouts by radio. The location of the 0.8-acre concentration yard was selected because it was close to the harvest site, accessible to chip vans, large enough to accommodate equipment and stockpiled biomass, and in the same ownership as the harvest site. All hog fuel produced in this study was taken to Clearwater Paper in Lewiston, Idaho, which is a 165-mile round trip from the concentration yard. We did not quantify the productivity and costs of transporting hog fuel from the concentration yard to the cogeneration facility, which are assumed to be identical for both systems.

The same contractors were used in both systems, with slash forwarding followed immediately by in-woods grinding. Table 1 lists the equipment used in each system, not including support vehicles such as a water truck for dust control, fuel truck, and personal vehicles. Both systems used similar Kenworth tractors equipped with either an end-dump trailer or a straight frame dump body. In the slash

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Table 1.—Summary of equipment used in the slash forwarding and in-woods grinding systems.[a]

Configuration/machine (make/model)	Purchase price ($)	Fuel use (gal h^{-1})	Base use (%)	Machine rate ($ SMH^{-1})[b]
Slash forwarding				
Grapple loader (Caterpillar 322B LL)	280,000	6.7	90	103.46
End-dump tractor/trailer	100,000	4.5	90	65.08
Grapple loader (Caterpillar 325 LL)	320,000	8.0	90	113.71
Horizontal grinder (Peterson 7400, wheeled)	510,000	35.0	85	255.26
In-woods grinding				
Grapple loader (Caterpillar 322B LL)	280,000	6.7	90	103.46
Horizontal grinder (Peterson 4710B, tracked)	502,000	30.6	85	240.53
Dump truck, modified with high walls	90,000	4.5	90	62.45
Front-end loader (Caterpillar 966D)	180,000	8.6	90	97.70

[a] Machine rate calculations are based on methods in Brinker et al. (2002).
[b] 2009 US dollars per scheduled machine hour (SMH).

forwarding system, a Caterpillar 322B grapple loader was used to load residues into end-dump trailers, which delivered the residues to the concentration yard (Fig. 1). End-dump trailers were used for slash forwarding because they were readily available to the contractors and could withstand in-bed compactions by the loader without damage. They were not used for in-woods grinding because narrow roads required loading from behind and their long bed and low sides are not well suited for loading evenly from behind off the grinder conveyor. At the concentration yard, a Caterpillar 325 grapple loader was used to feed a Peterson 7400 wheeled grinder, which loaded hog fuel directly into chip vans.

In the in-woods grinding system, the Caterpillar 322B grapple loader was used to feed residues into a Peterson 4710B tracked grinder, which conveyed hog fuel into high-sided dump trucks (Fig. 1). From a research standpoint, it would be preferable to use the same grinder in both systems, but as is common in the region, the road conditions made the treatment unit inaccessible to the wheeled grinder, requiring the tracked grinder to be used for in-woods grinding. Straight frame dump trucks were modified with extended bed walls, which facilitate loading from behind and are suitable to contain hog fuel in the bed, but not engineered to withstand loader compactions. These trucks delivered hog fuel to the concentration yard, where it was stored and then loaded into chip vans with a Caterpillar 966D front-end loader.

Data collection and regression analysis

With standard work study techniques (Olsen et al. 1998), continuous time study data were collected and used to calculate delay-free cycle times for each machine in both systems. Times for the elements of each cycle were recorded using a centiminute stop watch and snap-back timing. In addition, predictor variables hypothesized to affect cycle time were recorded for each cycle element (Table 2). For each machine, ordinary least-squares linear regression was used to predict delay-free cycle time based on these variables. Prior to the start of operations, the concentration yard and all road segments were measured, mapped, and marked with labeled flags placed at 100-foot intervals using a measuring wheel. During cycle timing, distances were estimated by eye based on the position of roadside flags by the researcher recording cycle times, who was riding in the truck cab (for truck cycles) or stationed on the ground close to the equipment being observed. The empty travel and loaded travel elements of the trucking cycles include a constant aggregate-surface distance of 2,500 feet between the concentration yard and native surface road, a constant native surface road segment of 6,864 feet to reach the treatment unit, and a variable native surface road segment between 150 and 4,705 feet across the unit.

For the empty and loaded swing elements of grapple loader cycles, swing arc was quantified as the number of 90° arcs traversed in the swing, which was estimated by eye. Three residue characteristics were used as predictor variables in the grapple loader cycle time regression model: type of pile, type of material handled in each grapple cycle, and ground slope under the pile, measured in degrees with a clinometer. An indicator variable was used to identify the type of residue pile being handled: processor piled (0) or loader piled (1). The material handled in each grapple cycle was categorized into one of four classes (branches, tops, mixed branches and tops, or logs), with three binary indicator variables used to represent the four material classes (Harrill et al. 2009). Although trucks in the two systems hauled different materials, the predictor variables recorded for the truck cycles were the same. In our regression analysis we combined the two truck data sets and present a single cycle time regression equation that includes an indicator variable for the truck (0 = end-dump trailer, 1 = dump truck). The coefficient of this variable reflects differences in truck cycle time between the two systems (Olsen et al. 1998). The same approach was used for the grinder regression model, with an indicator variable used for truck type filled by the grinder (0 = chip van, 1 = dump truck). Although total cycle times for grapple loaders feeding grinders were recorded, individual cycle elements were not timed or used to produce cycle time regression equations for these loaders because they are considered to be part of the same production unit as the grinder they are feeding.

All delays were recorded with a stopwatch and classified in one of three categories: personal delay, mechanical delay, and operational delay. Although delays were recorded to facilitate calculation of delay-free cycle time, this study was too short to adequately quantify utilization rates for the machines in these systems (Olsen et al. 1998). As a result, productivity and costs for individual machines were calculated using generalized utilization rates (Brinker et al. 2002). Baseline utilization was set at 90 percent for all

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Table 2.—Cycle elements and associated predictor variables for each machine.

Machine	Cycle elements	Recorded predictor variable(s)
Grapple loader	1. Empty swing	Swing arc (count of 90° arcs)
	2. Handling	No. of handling grapples
	3. Loaded swing	Swing arc (count of 90° arcs)
		Machine slope (°)
		Pile class (0 = processor piled, 1 = loader piled)
		Material class (4 classes, 3 parameters, 0 or 1)
	4. Release	No. of compactions
Trucks	1. Empty travel	Distance (ft, variable forest road segment only)
	2. Positioning for loading	Distance (ft)
	3. Loading	Pile slope (°)
		No. of loader cycles
	4. Loaded travel	Distance (ft, variable forest road segment only)
	5. Positioning for unloading	Distance (ft)
	6. Unloading	None
Grinder	1. Loading	Configuration (0 = chip van, 1 = dump truck)
		No. of grapples
Front-end loader	1. Empty travel	Distance (ft)
	2. Scooping	None
	3. Travel loaded	Distance (ft)
	4. Unloading	None

machines except the grinder, which has a baseline utilization rate of 85 percent (Table 1).

Both systems used three trucks, but the three trucks in each system were not identical; owing to equipment availability, each system used two long-bed trucks and one short-bed truck. The bed dimensions, nominal bed volumes, and cycle weights of the trucks are shown in Table 3. Cycle weights (i.e., payload) for the equipment used in this study are estimated based on a sample of truck weights taken with Intercomp PT300 portable scales and on weights of loaded and unloaded chip vans provided by the weigh station at the cogeneration plant. Because truck weights were measured for a subsample of truck cycles, cycle weight is not used as a predictor variable in the cycle time regression equations. However, for both systems, we believe that cycle weight is reflected effectively by the number of loader cycles used to fill the truck, which is used as a predictor.

In regression analysis, Statistical Analysis System software version 9.2 (SAS Institute Inc. 2004) was used for all calculations and statistical tests. A significance level of $P = 0.10$ was used to assess the significance of tests unless otherwise noted. The Durbin-Watson test was used to test for autocorrelation and lack of randomness in residuals and the Kolmogorov-Smirnov test was used to test for normality. In addition to the full regression models using all predictor variables measured, we present reduced models based on stepwise selection using 0.15 as the significance level for entry and the significance level to stay.

Productivity

All cycle weights were normalized to BDT using average moisture content (percent) calculated from 43 samples collected during field operation and oven dried in the laboratory (Simpson 1999) and from 55 chip van averages reported by the cogeneration facility, which were based on two ovendried samples from each truck. Averages for laboratory analysis and facility reporting are 24.4 ± 2.0 percent and 24.1 ± 1.6 percent (95% confidence interval [CI]), respectively. We used average moisture content of 24.2 percent applied across all cycles rather than a time series in calculating cycle weights because there were no rain events during the study and the relationship between moisture content and ordinal date appears to be nonlinear, with the highest daily average moisture content falling in the middle of operations. This is probably a result of variable drying rates over 9 months due to aspect and slope (Fig. 2), rather than changes in residue moisture content that occurred during the study. Although not used in calculations, we estimated the dry bulk density of hog fuel produced in this study to range from 0.19 to 0.25 ton yard^{-3} based on the net weights and estimated volumes of 55 chip vans. For reference, Briggs (1994) reported the dry bulk

Table 3.—Summary statistics for truck and chip van capacities.

Equipment	Bed dimensions (in.)[a]	Bed volume (yard^3)	Cycle weight (BDT cycle^{-1})[b]		
			n	Mean	SE
End-dump trailer, short	50 × 83 × 318	28.2	32	3.64	0.145
End-dump trailer, long	58 × 86 × 378	40.3	13	4.60	0.432
Dump truck, short bed	89 × 96 × 190	34.6	6	3.96	0.265
Dump truck, long bed	95 × 112 × 240	54.4	14	6.83	0.322
Chip van	Variable	95–115	55	23.40	0.376

[a] Rounded values for bed dimensions may not multiply exactly to measured volumes.
[b] Bone dry tons (BDT) per cycle.

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density of loose and compacted hog fuel with 51 percent bark content to be 0.21 and 0.27 ton yard^{-3}, respectively.

Cycle weights (BDT per cycle) are multiplied by cycle rates to determine machine productivity in BDT per scheduled machine hour (SMH). Cycle rate is the number of cycles per SMH. For both systems, the productivity of operations on the treatment unit is assumed to be independent of the productivity of operations at the concentration yard because both residues and hog fuel can be stockpiled in sufficient quantities to decouple the operations. System productivities are calculated by combining individual machine productivities in each part of the system (on-unit and concentration yard) and accounting for system imbalances (i.e., inferred operational delays) by constraining the productivity of each part of the system to that of the least productive component. Trucking is the least productive on-unit component in both systems.

The trucks used in slash forwarding traveled longer distances because slash forwarding was implemented first and began at the unit boundary most distant from the concentration yard. In order to provide an appropriate comparison of productivities and costs of the two systems, we used cycle time regression equations to normalize the cycle time used for productivity and cost calculations to the average distance traveled by all trucks in the study. The resulting calculations compare the two systems as if the trucks in each system had the same average variable native surface road distance and account for differences in average speed between the two trucks on different road segments.

In addition to the observed productivities and costs of the two systems, we present the productivities and costs of optimized systems for comparison. In the field, both systems were configured to use three trucks to haul either residues or hog fuel from the treatment unit to the concentration yard. Unfortunately, each of these systems included one truck that was smaller than the other two. Calculations for the optimized systems are hypothetical and assume that both systems use three of the larger trucks, accounting for differences in travel speed, cycle time, and cycle weight between the small and large trucks in each configuration. We also perform a sensitivity analysis to show how changes in system productivity affect system costs.

Machine rates and cost calculations

Machine rates (Table 1) were calculated based on methods described by Miyata (1980) and Brinker et al. (2002). Equipment purchase prices were provided by the contractor or determined by regional market prices for similar equipment and assumed to be subject to a 10 percent interest rate on capital. Labor costs are \$35.25 SMH^{-1} and include the average 2009 base wage for forestry equipment operators in Idaho (\$18.69 SMH^{-1}; Bureau of Labor Statistics 2009), plus fringe benefits and taxes paid by the employer. Off-road diesel cost was set at \$2.46 gallon^{-1} (the average price for 2009 in the study region), with fuel consumption calculated as a function of equipment horsepower. In addition to fuel costs, variable equipment costs include lubrication at 40 percent of fuel cost, repair and maintenance cost at 100 percent of depreciation, and the cost of tires, where appropriate. Additional assumptions include an insurance rate of 4 percent of purchase price, use of 2,000 SMH y^{-1}, and a 25 percent salvage value after a useful life of 10 years for trucks, 7 years for loaders, and 4 years for grinders. Machine rates were multiplied by machine productivities to calculate machine costs in 2009 US dollars per BDT.

Results

Machine cycle times and cycle time regression equations

The slash forwarding system uses two grapple loaders—one to load residues into end-dump trailers on the treatment unit and one to feed the grinder at the concentration yard. The in-woods grinding system uses a grapple loader to feed the tracked grinder on the treatment unit and a front-end loader used to fill chip vans. Average cycle times for the three grapple loaders in these two systems are not statistically different ($P = 0.9058$). Cycle times for loaders paired with grinders are 0.46 minute per cycle (min cycle^{-1}) for grinding at the concentration yard and 0.44 min cycle^{-1} for in-woods grinding, compared with 0.45 min cycle^{-1} for the loader filling end-dump trailers on the unit (Table 4).

Each grapple loader cycle includes four elements: empty swing, handling, loaded swing, and release. Cycle time regression equations were not calculated for grapple loaders feeding grinders because they are assumed to be a component of the grinder production unit, rather than an independent production unit. For the grapple loader filling end-dump trailers, the number of motions used to compact residues in the trailer during release and the number of motions used to manipulate residues on the pile during handling are significant predictors of cycle time (Table 5). The ground slope under the machine also affects cycle time, with steeper slopes up to a maximum of 10.5 percent associated with shorter cycle times. The coefficient for swing arc is also significantly different from zero. Material type and pile class are not significant predictors of cycle time in this model, which accounts for about 46 percent of the variation observed in grapple loader cycle time. The reduced model based on stepwise selection methods has four predictors and accounts for 46 percent of the observed variation (Table 6). This model has randomly distributed residuals (Durbin-Watson, $D = 1.712$), though the distribution of residuals is slightly leptokurtic (Kolmogorov-Smirnov, $D = 0.0928$, $P < 0.0100$; kurtosis = 2.196).

For grinders, a cycle consists of filling either a chip van or a dump truck. Average cycle times for the grinders used in these systems were 28.9 minutes to fill a chip van and 11.4 minutes to fill a dump truck (Table 4). In theory, the two grinders have similar production capacity ratings, but

Table 4.—Mean delay-free cycle time by system and machine.

System/machine	Observed machine cycle time (min cycle^{-1})		
	n	Mean	SE
Slash forwarding			
Grapple loader	301	0.45	0.01
End-dump trailer	51	35.43	0.57
Grapple loader	172	0.46	0.01
Grinder	11	28.87	0.93
In-woods grinding			
Grapple loader	265	0.44	0.01
Grinder	41	11.4	0.57
Dump truck	23	38.18	0.63
Front-end loader	66	1.83	0.05

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Table 5.—Cycle time (min) regression models for the grapple loader, grinders, front-end loader, and truck used in the slash forwarding and in-woods grinding systems.

Machine	Parameter	Estimate	SE	Std. est.[a]	t	P	Model F/P	Model adj. R^2
Grapple loader (slash forwarding)	Intercept	0.333	0.027	0	12.22	<0.0001	32.22	0.4568
	No. of compactions	0.097	0.007	0.612	13.94	<0.0001	<0.0001	
	No. of grapples	0.029	0.006	0.235	5.32	<0.0001		
	Slope under machine	−0.016	0.003	−0.236	−4.99	<0.0001		
	Total swing arc	0.019	0.010	0.086	1.95	0.0524		
	Material, tops	0.034	0.030	0.052	1.11	0.2662		
	Material, logs	0.013	0.027	0.022	0.47	0.6395		
	Material, mixed	0.008	0.018	0.025	0.45	0.6524		
	Pile class	−0.004	0.018	−0.011	−0.21	0.8352		
Grinder	Intercept	9.024	2.931	0	3.08	0.0034	231.25	0.9003
	No. of grapples	0.315	0.045	0.646	7.01	<0.0001	<0.0001	
	Truck type	−6.463	1.788	−0.333	−3.61	0.0007		
Front-end loader	Intercept	0.875	0.260	0	3.36	0.0013	7.86	0.1742
	Distance (loaded)	0.005	0.002	0.356	2.48	0.0159	0.0009	
	Distance (empty)	0.002	0.003	0.128	0.89	0.3784		
Truck	Intercept	−37.560	19.749	0	−1.90	0.0617	17.04	0.6126
	No. of loader cycles	0.344	0.073	0.782	4.70	<0.0001	<0.0001	
	Travel distance (ft)[b]	0.010	0.003	5.140	3.16	0.0024		
	Type × travel distance	−0.009	0.003	−3.566	−3.13	0.0027		
	Truck type	61.088	21.191	7.103	2.88	0.0054		
	Unload distance (ft)	0.017	0.007	0.211	2.32	0.0235		
	Load distance (ft)	0.003	0.002	0.129	1.19	0.2374		
	Pile slope (°)	0.037	0.039	0.081	0.94	0.3495		

[a] The standardized regression coefficient, which is the result of a regression analysis on variables standardized to have a mean = 0 and a standard deviation = 1, can be used to compare the relative effects of predictor variables on cycle time.
[b] Distance traveled on variable forest road segment only, not total travel distance.

performance in the field shows significant productivity differences associated with system type. Regression analysis indicates that both the number of grapple cycles during the grinder cycle and the truck type (chip van or dump truck) are significant predictors of grinder cycle time, with the model based on these two variables accounting for about 90 percent of the variation observed for grinder cycle time, with random, normally distributed residuals (Table 5).

In the in-woods grinding system, chips are loaded into chip vans at the concentration yard using a front-end loader, with each cycle consisting of four elements: empty travel, scooping, loaded travel, and unloading. The average cycle time and cycles per load for the front-end loader were 1.83 min cycle^{-1} and 11 cycles per van, filling a chip van in 20.13 minutes, on average (Table 4). Loaded distance traveled is a significant predictor of cycle time for the front-end loader, but the coefficient of determination of the regression model is low, with adjusted $R^2 = 0.1742$ for the full model (Table 5) and adjusted $R^2 = 0.1769$ for the reduced model (Table 6), which both have random, normally distributed residuals.

Average travel speeds for the two types of trucks are similar, and are faster on the aggregate-surface road than on the native surface road (Table 7). However, end-dump

Table 6.—Cycle time (min) regression models for the equipment using stepwise selection methods with 0.15 for the significance level.

Machine	Parameter	Estimate	SE	Std. est.[a]	t	P	Model F/P	Model adj. R^2
Grapple loader (slash forwarding)	Intercept	0.338	0.025	0	13.5	<0.0001	64.70	0.4618
	No. of compactions	0.098	0.007	0.614	14.29	<0.0001	<0.0001	
	No. of grapples	0.029	0.005	0.238	5.59	<0.0001		
	Slope under machine	−0.017	0.003	−0.242	−5.57	<0.0001		
	Total swing arc	0.021	0.010	0.092	2.12	0.0352		
Front-end loader	Intercept	0.999	0.219	0	4.57	<0.0001	14.97	0.1769
	Distance (loaded)	0.007	0.002	0.435	3.87	0.0003	0.0003	
Truck	Intercept	−36.108	19.949	0	−1.81	0.0748	22.36	0.6007
	No. of loader cycles	0.299	0.070	0.680	4.31	<0.0001	<0.0001	
	Travel distance (ft)[b]	0.010	0.003	5.249	3.19	0.0022		
	Type × travel distance	−0.009	0.003	−3.564	−3.08	0.0030		
	Truck type	62.832	21.488	7.306	2.92	0.0047		
	Unload distance (ft)	0.003	0.002	0.176	1.55	0.1256		

[a] The standardized regression coefficient, which is the result of a regression analysis on variables standardized to have a mean = 0 and a standard deviation = 1, can be used to compare the relative effects of predictor variables on cycle time.
[b] Distance traveled on variable forest road segment only, not total travel distance.

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Table 7.—Observed truck speeds.

	Speed (mph)[a]			
	End-dump ($n = 51$)		Dump truck ($n = 23$)	
Road segment	Mean	SE	Mean	SE
Aggregate, empty	18.19	0.34	15.94	0.49
Aggregate, loaded	16.56	0.30	17.77	0.40
Native, empty	11.25	0.18	10.63	0.13
Native, loaded	11.25	0.21	11.59	0.22

[a] mph = miles per hour.

trailers hauling residues have faster average cycle times than dump trucks hauling hog fuel (Table 4). Even though end-dump trailers hauled longer average distances because the slash forwarding system was evaluated first, their average cycle time was 35.4 min cycle^{-1}, compared with 38.2 min cycle^{-1} for dump trucks. Based on standardized cycle times calculated post hoc using the cycle time regression model (Table 5), end-dump trailer cycles were about 7 minutes shorter than dump truck cycles for the average distance traveled by all trucks in all cycles. Faster cycle times for the trucks used in slash forwarding reflect shorter times for the loading element of the cycle related to lower average payloads (Table 3). Average times for the trucks to be loaded were 4.67 minutes for end-dump trailers compared with 11.92 minutes for dump trucks, with means significantly different from one another ($P < 0.0001$).

Among the independent variables used to predict truck cycle time, the number of grapple loader cycles during the loading element of the truck cycle, variable travel distance, and truck type are the strongest predictors of cycle time (Table 5). In addition, interaction between truck type and travel distance is significant and has a relatively large effect on predicted cycle time (Table 5). Positioning distance for unloading is also significant, but the coefficients for positioning distance for loading and pile slope are not significantly different from zero (Table 5). The reduced model includes five predictor variables and accounts for almost as much variation as the full model, with adjusted $R^2 = 0.6007$ and 0.6126, respectively (Tables 5 and 6). Both regression equations have random, normally distributed residuals.

In summary, we observed statistically significant differences in cycle time between the trucking components of the two systems and between the two grinders. Grapple loaders deployed in the three different situations do not appear to have different cycle times. In addition, a number of different variables influence cycle time in a statistically significant way and can be used to predict cycle time and resulting productivity for these systems.

Machine and system productivities

In the slash forwarding system, the grapple loader is capable of loading end-dump trailers at a rate of 45.7 BDT SMH^{-1} (Table 8). However, this grapple loader is subject to significant operational delays associated with trucking capacity. At the baseline utilization rate of 90 percent, end-dump trailers move residues at a rate of 6.78 BDT SMH^{-1}, with three trucks in the system increasing productivity to 20.3 BDT SMH^{-1}. This is 25.4 BDT SMH^{-1} lower than loader productivity at 90 percent utilization. For comparison, the grinder at the concentration yard is not operationally constrained by residue trucking and can operate at a production rate of 41.18 BDT SMH^{-1}, as long as sufficient residues are piled at the concentration yard.

In the in-woods grinding system, hog fuel is delivered to the landing by dump trucks at a rate of 7.71 BDT SMH^{-1} (Table 8). With three trucks in the system, the collective rate is 23.13 BDT SMH^{-1}. This is slightly less than the productivity of the in-woods grinder filling these trucks, which is 26.71 BDT SMH^{-1} at 85 percent utilization. The highest productivity machine is the front-end loader used to fill chip vans with hog fuel piled at the concentration yard, which loads hog fuel at 62 BDT SMH^{-1}. As long as there is enough material piled at the concentration yard and a chip van is ready for loading, the front-end loader is not operationally constrained by the on-unit part of the system and can work at full productivity. Accounting for imbalances in machine productivities that result in operational delays, the in-woods grinding system is more productive in both the on-unit and concentration yard operations than the slash forwarding system (Table 9).

Machine and system costs

Individual machine costs (dollars per BDT; Table 8) are a function of productivity and machine rate. System costs are a function of individual machine costs, accounting for imbalances in machine productivity. Table 9 shows system productivities and resulting costs for both systems. The ''observed'' columns show the productivities and costs for the systems as they were observed in the field, with one small truck and two large trucks in each system. For the treatment unit to concentration yard component of the systems, productivity is lower for slash forwarding (20.33 BDT SMH^{-1}) than for in-woods grinding (23.13 BDT SMH^{-1}), but the hourly cost for slash forwarding (\$298.70 SMH^{-1}) is substantially less than for in-woods grinding (\$531.34 SMH^{-1}). The net result is a significantly lower cost per ton to deliver material from the treatment unit to the concentration yard for slash forwarding (\$14.69 BDT^{-1}) compared with in-woods grinding (\$22.97 BDT^{-1}). For the concentration yard part of the system, the cost per ton is far lower for the in-woods grinding (\$1.55 BDT^{-1}) compared with slash forwarding (\$8.93 BDT^{-1}), which includes a grinder at the concentration yard. The sum of the two parts of the system results in a slightly lower total system cost for slash forwarding (\$23.62 BDT^{-1}) compared with in-woods grinding (\$24.53 BDT^{-1}).

The ''optimized'' columns in Table 9 show productivities and costs calculated from field data for hypothetical systems that use three large capacity trucks. These calculations account for variation in both cycle time and cycle weight associated with truck type. As expected, optimizing truck size improves the productivity and lowers costs for both systems. Replacing the smaller truck in each system with a larger truck provides similar marginal gains in productivity of the treatment unit to concentration yard component for both systems (+2.05 BDT SMH^{-1} for slash forwarding and +2.06 BDT SMH^{-1} for in-woods grinding), but a greater marginal reduction in costs for in-woods grinding (–\$1.88 BDT^{-1} compared with –\$1.35 BDT^{-1} for slash forwarding).

Although total costs are similar for the two systems, the proportions of total costs attributable to trucking, grinding, and loading are different (Fig. 3). The trucking component of the slash forwarding system is responsible for the highest proportion of total costs, accounting for 41 percent of the

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Table 8.—Delay-free cycle times, rates, and capacities for individual machines, with corresponding productivities and costs.

Configuration/machine	Cycle time (min cycle^{-1})	Cycle rate (cycle SMH^{-1})[a]	Cycle weight (BDT cycle^{-1})[b]	Productivity (BDT SMH^{-1})	Cost ($ BDT^{-1})
Slash forwarding					
Grapple loader	0.45	120.00	0.38	45.72	2.26
End-dump trailer	34.1[c]	1.58	4.28[d]	6.78	9.60
Grapple loader	0.46	117.39	0.37	43.43	2.62
Grinder	28.87	1.77	23.40	41.18	6.20
In-woods grinding					
Grapple loader	0.44	122.73	0.22	27.25	3.80
Grinder	11.4	4.47	5.97	26.71	9.01
Dump truck	41.1[c]	1.31	5.87[d]	7.71	8.10
Front-end loader	1.83	29.51	2.13	62.85	1.55

[a] Cycles per scheduled machine hour (SMH).
[b] Bone dry tons (BDT) per cycle.
[c] The truck cycle times used here are different from the averages reported in Table 5 because they are calculated based on the average distance traveled for all trucks across both systems.
[d] Average for the three trucks used in the system.

total cost of $23.62 BDT^{-1}. Loading the trucks with residue accounts for 21 percent of the total cost, and grinding, including the grapple loader used to feed the grinder, is about 38 percent of total cost. In contrast, for the in-woods grinding system, the loader and grinder together account for 61 percent of the total cost of $24.52 BDT^{-1}, followed by trucking at 33 percent, and loading hog fuel into chip vans with the front-end loader, which is 6 percent of total cost.

Several additional costs should be considered to fully understand the total delivered costs of hog fuel produced by these systems. The system costs in Table 9 include loading chip vans, but they do not include transporting hog fuel to the end user. For this study site, additional transportation costs were calculated to be $26.12 BDT^{-1} based on a machine rate of $110 SMH^{-1}, a utilization rate of 90 percent, a cycle weight of 23.4 BDT, and a 5-hour round trip, which includes 4 hours of travel time, a 30-minute unload time, and 30-minute load time. For both systems, transporting machines to and from the site and other move-in/move-out costs are not included. For the in-woods grinding system, the system cost does not include the fixed cost of walking the tracked grinder onto and off of the unit. In this case, an 8-hour (SMH) round trip adds an additional $1,924.24 to the system, which spread over 1,300 BDT of hog fuel, adds an additional $1.48 BDT^{-1} to the cost of in-woods grinding. Furthermore, calculations do not include costs associated with support operations, such as dust control and fuel delivery, which are often overlooked and can add $15 BDT^{-1} or more to the cost of operations (Harrill et al. 2009).

Discussion

At $23.62 and $24.52 BDT^{-1}, these two systems were similar in system costs and within the range of biomass operations previously studied. Although it is difficult to compare operations because of differences in site condi-

Table 9.—Observed and optimized productivities and costs for the on-unit and concentration yard components and for the complete system.[a]

Variable	Component/system			
	Observed		Optimized	
	Slash forwarding	In-woods grinding	Slash forwarding	In-woods grinding
Treatment unit to concentration yard				
Productivity (BDT SMH^{-1})[b]	20.33	23.13	22.38	25.20
Cost per hour ($ SMH^{-1})[c]	298.70	531.34	298.70	531.34
Cost per ton ($ BDT^{-1})	14.69	22.97	13.35	21.08
Concentration yard				
Productivity (BDT SMH^{-1})	41.34	62.85	41.34	62.85
Cost per hour ($ SMH^{-1})[c]	368.97	97.70	368.97	97.70
Cost per ton ($ BDT^{-1})	8.93	1.55	8.93	1.55
System total				
Total cost per hour ($ SMH^{-1})[c]	667.67	629.04	667.67	629.04
Total cost per ton ($ BDT^{-1})	23.62	24.52	22.27	22.64

[a] Optimized costs assume that all trucks in each configuration are the large payload variety and model the new system based on the capacities and cycle times of only the higher payload trucks.
[b] Bone dry tons (BDT) per scheduled machine hour (SMH).
[c] Cost per hour is a sum of individual machine rates in dollars per SMH from Table 1 for all equipment in the component or system and does not account for the variable utilization rates used to calculate system productivities and total cost.

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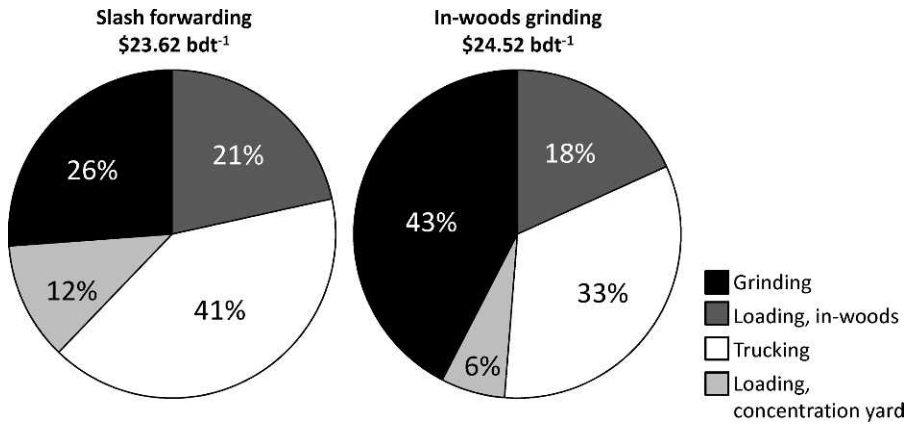

Figure 3.—Proportion of system costs associated with each of the four production units in each system. Each system includes three trucks in the trucking unit.

tions, equipment configurations, and other variables, based on several recent articles these costs are generally less than those reported for hook-lift trucks and slash bundlers (e.g., Harrill et al. 2009, Han et al. 2010, Harrill and Han 2010), similar to or more costly than those reported for integrated operations (e.g., Bolding et al. 2009, Baker et al. 2010), and more costly than those reported for whole-tree chipping operations (e.g., Mitchell and Gallagher 2007).

These results illustrate the importance of understanding how the configuration of machines within a production system can affect costs. The productivity of both of these systems is dependent on being able to stockpile residues or hog fuel at a concentration yard that is appropriately balanced with system productivity. Slash forwarding is more severely affected by running out of stocks at the concentration yard. At the study site, slash forwarding costs would increase from \$23.62 to \$32.84 BDT^{-1} if the concentration yard grinder were forced to wait for end-dumps to deliver residues for processing at a rate of 20.33 BDT SMH^{-1}, rather than grind piled residues at 41.34 BDT SMH^{-1}. In contrast, the cost for in-woods grinding would increase from \$24.52 to \$27.19 BDT^{-1} if the front-end loader were forced to wait for dump trucks to deliver hog fuel to the concentration yard at a rate of 23.13 BDT SMH^{-1}, rather than load chip vans at 62.85 BDT SMH^{-1}. Presumably, both systems would incur similar additional costs if empty chip vans waiting to be loaded experienced longer operational delays as a result of low concentration yard stocks.

A number of other factors can affect the productivity of these systems. For in-woods grinding, the most expensive piece of equipment, the grinder, is operationally constrained by trucking. If trucking is poorly balanced with grinder productivity, system costs rise more quickly than in the slash forwarding system, where a single loader, not the combination of a loader and grinder, is constrained by trucking. However, system balance does not appear to be a problem with the in-woods grinding system in this study. At 23.13 BDT SMH^{-1} for trucking and 26.71 BDT SMH^{-1} for grinding, three dump trucks were relatively well balanced with grinder productivity. This system could not absorb a fourth truck without causing operational delays in trucking. Although not appropriate for calculating utilization rate, operational delays observed in the field for trucks in this system averaged 4.08 $\pm$ 1.60 min cycle^{-1} (95% CI), primarily because of waiting at pullouts and inadequate staggering (i.e., bunching) of truck cycles, which resulted in trucks waiting to be filled. In general, the configuration of residue on the unit is more likely to negatively affect the productivity of this system. Conditions at the research site were well suited to in-woods grinding. With abundant, deeply piled roadside residue, the tracked grinder and its loader could stay in the same position for three or more truck cycles, and then move only a short distance on the road, typically double the loader's reach, to access more residue for grinding. Although this study does not quantify the operational delays associated with moving the grinder between dispersed piles, it is reasonable to assume that the same amount of residue, configured in dispersed piles, would result in lower grinder utilization and higher system costs.

Balance does appear to be a problem for the slash forwarding system, where the productivity of trucking is 20.34 BDT SMH^{-1} and the productivity of loading is 45.72 BDT SMH^{-1}. Hypothetically, three additional end-dump trailers could be added to the system to balance trucking productivity with loading productivity. This change would reduce system costs from \$23.62 to \$16.27 BDT^{-1}. However, road conditions make this option unrealistic for this site. With three trucks in the system, narrow roads with limited pull-outs resulted in operational delays. The observed average operational trucking delay of 2.61 $\pm$ 0.76 min cycle^{-1} (95% CI) in this system was primarily due to waiting at pullouts. Six trucks would be unworkable on 2.3 miles of low standard forest road. If trucks could pass each other more easily on the road, it may be possible to increase overall productivity by adding more trucks, but better roads would also be more likely to allow chip vans to access the unit, making slash forwarding unnecessary.

In both the observed and optimized scenarios, the in-woods grinding system is more productive and has a lower total hourly equipment cost than the slash forwarding system, but it is also more costly on a BDT basis (Table 9). This counterintuitive result is due to the independent nature of operations on the unit and at the concentration yard. Operations at the concentration yard are assumed to be unaffected by operations on the unit because material can be stockpiled. The sensitivity analysis in Figure 4 illustrates the effect that decreasing the productivity of operations has on the costs of both systems. As system productivity declines

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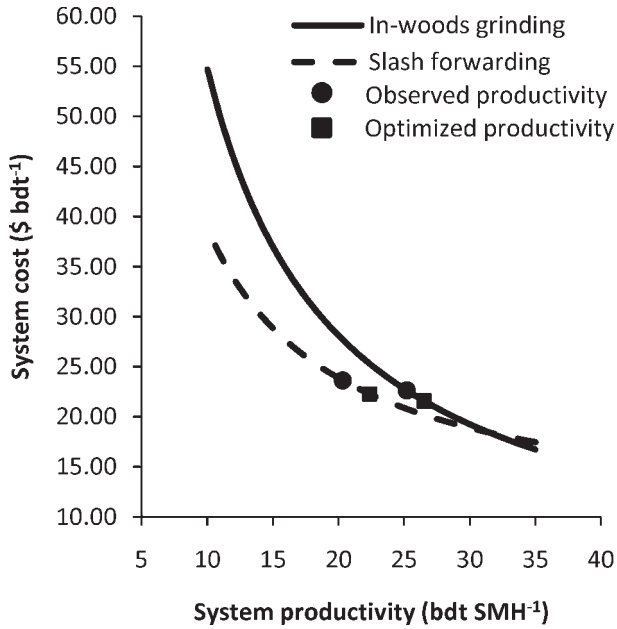

Figure 4.—Sensitivity analysis showing the effect of system productivity in bone dry tons (BDT) per scheduled machine hour (SMH) on system costs. For both systems, operations at the concentration yard are assumed to be independent of in-woods operations.

as a result of factors such as operational delays and longer travel distances, cost per BDT for in-woods grinding increases faster than cost per BDT for slash forwarding. As mentioned previously, this is because the in-woods grinder is subject to lower productivity, whereas in the slash forwarding system only the loader is subject to lower productivity. In the slash forwarding system, the grinder, which has the highest machine rate, is independent of operations on the unit. This effect is especially important to recognize for sites where conditions are less ideal for in-woods grinding, such as units where residues are concentrated in dispersed piles. If piles are dispersed and accessible to trucks, slash forwarding is a good option to consider.

For both systems, residue that is piled but inaccessible to trucks would need to be forwarded to the roadside. Using traditional forest equipment, such as a wheeled forwarder, to bring residue to the road is likely to increase costs significantly, but machines developed to collect and process residue into bundles show some promise for reducing costs associated with collecting and using dispersed residues (Harrill et al. 2009).

Although productivity and costs are important variables in evaluating alternative systems, there may be other operational considerations that make one system preferable over the other. For example, with hog fuel piled at the concentration yard, proficient chip van drivers can load their own trucks using the front-end loader. Self-loading using a front-end loader or an overhead hopper system is an attractive option in situations where delays between chip vans would significantly reduce the productivity of the grinder in the slash forwarding system. Plausibly, this difference would be reflected in system costs, but even if slash forwarding is the less costly option, a manager may choose in-woods grinding to incorporate flexibility in chip van scheduling. Depending on moisture content and combustion risk, it is also possible that dense hog fuel piled at a concentration yard poses less of a fire hazard than residues piled at the same site. On a dry weight basis, concentrating residues also requires a larger concentration yard because of their lower bulk density. Large concentration yards may be difficult to find in areas with steep slopes, which is exactly the type of terrain where chip van access is limited.

Alternatively, slash forwarding may be an attractive option, regardless of short-term costs, if residues can be stockpiled and cured in a location that has year-round road access, and then ground into hog fuel when seasonal road restrictions and limited access result in reduced supply and higher hog fuel prices. Problems associated with long-term storage of high moisture content ground material make this option less feasible for in-woods grinding. Because end-dump trailers hauling residues are generally volume constrained before they are overweight, hauling green residues to a concentration yard may have the added benefit of improving residue handling by the loader, with green limbs and tops easier to compact and less likely to break apart during compaction. Breakage can result in more material falling onto the road during loading and hauling, and smaller grapple cycle weights at the concentration yard, both of which decrease productivity and increase costs. Operational characteristics like these should be considered when choosing between systems.

Conclusions

In this study, slash forwarding and in-woods grinding have very similar productivities and costs. With some caution, these results may be used to estimate the productivities and costs of similar operations with similar site conditions. More broadly, this study helps assess the general conditions under which one system may be less costly than the other. Specifically, in-woods grinding is especially well suited for dense, side-cast residues that minimize delay due to grinder movement between piles. Because its on-unit costs are lower, slash forwarding appears to be most appropriate for situations where operational factors or site conditions would negatively affect in-woods grinder productivity, including dispersed piles and long-distance grinder mobilization. For both systems, accurately predicting productivities and costs is highly dependent on the cost structures and operational constraints of individual firms, especially because they are reflected in the machine rates and utilization rates for different pieces of equipment.

Much of the interest in expanding biomass use is being driven by broad economic considerations and interest in nonmarket benefits, including offsetting the costs of fuel reduction and salvage treatments, reducing greenhouse gas emissions, and providing new sources of revenue for forest-dependent communities. In a market context, capturing these benefits will require efficient bioenergy and bio-products supply chains. The forest industry is the cornerstone of forest biomass use and has the potential to reduce costs and increase biomass supply by improving the efficiency of feedstock logistics, especially the collection, processing, and transportation of treatment residues that are currently being burned on-site. Higher productivity and reduced costs achieved through operations research and through developing new production systems has the potential to allow forest managers to treat more forestland at lower cost. As markets for bioenergy and biobased

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products expand, additional research should work to develop new systems and new equipment to meet increased demand for forest biomass in efficient and sustainable ways.

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