

Article

The optimum slash pile size for grinding operations: Grapple excavator and horizontal grinder operations model based on a Sierra Nevada, California survey

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Abstract: The processing of woody biomass waste piles for use as fuel instead of burning them was investigated. At each landing slash pile location, a 132 kW grapple excavator was used to transfer the waste piles into a 522 kW horizontal grinder. Economies of scale could be expected when grinding a larger pile, although the efficiency of the loading operation might be diminished. Here, three piles were ground and the operations were time-studied: Small (20 m long × 15 m wide × 4 m high), Medium (30 × 24 × 4 m), and Large (35 × 30 × 4 m) piles. Grinding the Medium pile was found to be the most productive at 30.65 bone dry tons per productive machine hour without delay (BDT/PMH₀), thereby suggesting that there might be an optimum size of slash pile for a grinding operation. We also examined modeling of the excavator and grinder operations, and we observed that the constructed simulation model well-replicated the actual operations. Based on the modeling, we estimated that the productivity of grinding at a landing area of 710 m² of slash pile location was 31.24 BDT/PMH₀, which was the most productive rate.

Keywords: fuel reduction; slash pile; grinding operation; grapple excavator; horizontal grinder; simulation; Sierra Nevada; California; wildfire

1. Introduction

Increasingly fierce wildfires are currently one of the most severe problems in the western United States. California is also experiencing one of the state's worst droughts of the past century. Under natural fire conditions, a proper amount of thinning occurs and the remaining trees are thereby given a better chance to mature. In contrast, after a century of fire suppression, California's forests are denser and have fewer large trees. For example, from the 1930s to the 2000s, the number of large trees in the Sierra Nevada mountain range in California decreased by half while the density of small trees doubled. Severe fires are increasing in frequency and size throughout the Sierra Nevada, and regeneration is not a given for severely burned forests where seed trees have been killed across large areas [1]. Fuel reduction operations (e.g., prescribed fire, mechanical treatment, mechanical treatment + prescribed fire) are effective to reduce the risk of high-intensity wildfires and return forests to a more fire-resilient landscape [2].

Current 'business as usual' activities for biomass disposal in much of the Sierra Nevada include pile and burn, mastication, and drop/scatter techniques. Notably, the utilization of biomass material for energy production is an appealing option for biomass disposal that can contribute to density management, forest health, and fire hazard reduction. In a previous study, the Placer County Air Pollution Control District (PCAPCD) and the Sierra Nevada Conservancy demonstrated a significant reduction in air emissions through the diversion of forest biomass that had been scheduled for open pile burning [3]. In the project entitled 'Forest Biomass Diversion in the Sierra Nevada' as a next step, the PCAPCD sponsored research that tracked the economic costs and air

emissions generated from the collection, processing, and transport of forest harvest residuals generated at the Blodgett Forest Research Station, the Center for Forestry, the University of California, Berkley in 2012, with the objective of quantifying the emissions reductions gained from using the biomass for energy production compared to open pile burning (Fig. 1).

The market value of forest biomass was not sufficient to cover 100% of the forecasted costs to collect, process, and transport material to the Buena Vista Biomass Power (BVBP) facility, which is the nearest biomass power generation facility located near Ione, California. The PCAPCD therefore offset the cost differential between the forest biomass market value and the actual costs of collection, processing, and transport. A forest biomass processing contractor, Brushbusters Inc., was retained to process and transport six woody biomass waste piles for use as fuel in the BVBP facility. In order to monitor the equipment operating costs and efficiencies as well as the equipment air emissions, we investigated processing the woody biomass waste piles. At each landing slash pile location, a grapple excavator was used to transfer the piles into a horizontal grinder (Fig. 2).



Figure 1. Open pile burning



Figure 2. Grinding operation

In contrast, in Japan, following the 'Feed-in Tariff Scheme for Renewable Energy (FIT)' that was put into practice in 2012, the building of power-generation plants that accept unused forest biomass (such as thinnings and logging residues) and the initiation of the plants' operation are progressing, since the purchase price of unused forest biomass has been set higher than that of other wood-based materials, e.g., mill residues and imported woods. Thus, 1.17 million bone dry tons (BDT) of wood chips derived from thinnings and logging residues were used as energy in Japan in 2015 [4]. With respect to the FIT approval of power generation fueled by unused forest biomass, 38 plants (297 MW of total power output) were already in operation and 89 projects (436 MW) were approved as of February 2017 [5]. Because thinnings and logging residues must be comminuted before energy conversion at a power-generation plant or biomass-fired boiler, increasing numbers of the following operations are expected in Japan: the creation of large slash piles by collecting thinnings and logging residues at landings alongside forest roads or at the stockyards of power-generation plants, and the subsequent processing of the piles by chippers or grinders.

In general terms, economies of scale can be expected when grinding a larger slash pile, although the efficiency of a loading operation may be diminished. With respect to the impact of the slash pile size, Seymour and Teclé [6,7] studied the impact of burning on soil physical properties and chemical characteristics, and the impact of burning on biomass moisture change has also been tested; e.g., [8,9]. The relationship between the slash pile size and the productivity of a grinder has not been established. In the present study, three slash piles (small, medium, and large) were ground, and we time-studied the operations by using a protocol that is similar to a protocol we used previously [10–13]. Based on the results of the time study, we constructed a simulation model of a grapple excavator's loading of logging residues from the varying slash piles and its unloading to the conveyor of a horizontal grinder. We discuss the optimum size of slash piles that would maximize the productivity of the grinder based on our replication of the excavator and grinder operations.

Concerning previous studies related to the modeling of forest operations, Iwaoka et al. [14] calculated the cycle time and productivity of harvesters, and Sakurai et al. [15] calculated those of tower-yarders, processors, and forwarders by determining theoretical formulae of element operations and aggregating them on the basis of a transition probability matrix of element operations. Other research groups predicted the productivity of total logging systems by determining theoretical formulae of the cycle times of forestry machines and by using the system dynamics method [16–18]. In the present study we followed the approach used by Iwaoka et al. and Sakurai et al. in order to construct a simulation model of a grapple excavator operation by analyzing the data of element operations.

2. Materials and Methods

The Blodgett Forest Research Station (BFRS) is 1,198 ha of Sierra Nevada forest land located east of Georgetown, California (approx. 640 km northeast of Sacramento). The woody biomass waste piles at the BFRS include tree tops, limbs, and small trees. The piles were generated from thinning treatments in mixed conifer plantations during the summer of 2012. The treatment objectives were to reduce the fire hazard, increase the average tree vigor, and increase the species diversity. Operations were typical of those in the Sierra Nevada, where young and dense forests have developed following wildfires or even-aged harvests. Plantations were thinned to an average of 272 trees per ha from pre-treatment stocking levels of 549 trees per ha. Four plantations were thinned, covering a total of approx. 32 ha. Because smaller trees were preferred for removal, the average stem diameter (for residual trees) at breast height (DBH) increased from 30.2 to 33.3 cm. Sawlogs with >15.2-cm dia. on the small end and ≥ 3.05 m long were transported to a sawmill for processing into lumber products. Unmerchantable trees (too small to process into sawlogs) plus the tops and limbs of merchantable trees were piled at landings adjacent to the roadside for disposal by open burning; the processing residues had been piled with the intention of burning rather than grinding them, and thus no attention was paid to orienting the tops so that they could be readily fed into the grinder. The overall sizes of the piles generated were typical of thinning operations in young and mature forests, with the bulk volume averaging 1,784 m³ per pile.

At each BFRS slash pile, a grapple excavator was used to transfer the waste material into a horizontal grinder. Wood chips from the grinder were conveyed directly into chip vans operated by Brushbusters, Inc. and transported to the Buena Vista Biomass Power (BVBP) facility, typically a 105-km one-way trip. The equipment and engines used for the loading and grinding operations (Table 1) were sized for the scale of operations that a medium or large landowner might consider. Landing piles for the project contained ≥ 100 green tons (GT) of biomass waste (the equivalent of four chip vans each holding 25 GT). All of the biomass received at the BVBP facility had been chipped prior to transport since the BVBP facility does not have fuel-processing equipment on site. Brushbusters' operations of grinder, excavator, and chip vans were carefully observed and tracked, including the determination of the total operating hours, productive operating hours, diesel fuel use, biomass production, and miles traveled. The data of the amount and moisture content of the transported chips were derived by interviewing the BVBP staff on the day after the transport day.

For our analysis of the relationship between the slash pile size and the productivity of the grinder, we selected the following three piles from the total of six piles and studied their processing, grinding, and transport operations: Small (20 m long \times 15 m wide \times 4 m high; 51.41 BDT), Medium (30 \times 24 \times 4 m; 122.66 BDT), and Large (35 \times 30 \times 4 m; 173.78 BDT) piles. The following element operations of the excavator were monitored: loading (grabbing and pivoting); unloading (releasing and pivoting); shaking waste material off; waiting for the grinder's swallowing of the material; pushing the material into the grinder; reorienting or repositioning material from the pile; loading with moving; unloading with moving. Provided that the shape of each landing slash pile location was rectangular, the amounts of logging residues per m² were calculated as 0.171, 0.170, and 0.166 BDT/m² for the Small, Medium, and Large piles, respectively, and we thus concluded that there was no significant deviation of the amount of residues among the three piles.

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Table 1. Equipment and engines for biomass processing.

Equipment	Grapple excavator	Horizontal grinder
Vendor, model	Link-Belt, 290 LX	Bandit, Beast 3680
Engine, horsepower	Isuzu CC-6BG1TC, 132 kW	Caterpillar C18 Tier III, 522 kW
Length	10410 mm	11890 mm
Width	3400 mm	2845 mm
Height	3270 mm	4115 mm
Weight	29211.4 kg	28122 kg
Maximum reach	10540 mm	-
Capacity	-	890 mm
Infeed conveyor	-	6110 mm × 1520 mm

136 **3. Results**

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During the period of August 20, 2013 through September 4, 2013 on eight separate work days, 601 BDT (928 GT) of forest slash from the BFRS were collected, processed, and transported by Brushbusters for energy use to the BVBP facility. This comprised a total of 37 separate chip van loads, with each delivery averaging 16.3 BDT (25.1 GT).

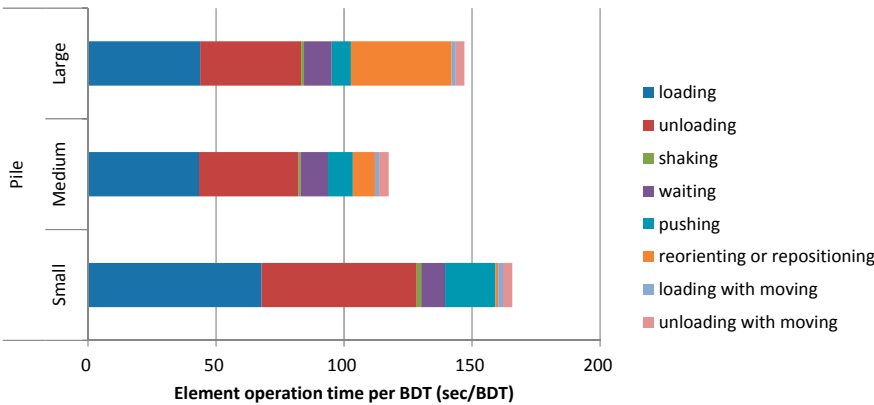
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The results of our time study are shown in Table 2. The times of loading and shaking would be shortened by improving the piling method, such as by orienting the tree tops and limbs so that they can most readily be fed into the grinder. Modifying the infeed conveyor of the grinder, e.g., by extending its length, would improve the times needed for waiting and pushing. With respect to the impact of the slash pile size, the average times of all element operations except for reorienting or repositioning were not influenced by the pile size. The reorienting/repositioning frequency was increased and its average time was lengthened as the size of the pile bulked up. The percentage of the time of reorienting/repositioning to the total observed time was also proportional to the pile size.

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The results of the time study per BDT (Fig. 3) show that grinding the Medium pile was the most productive, at 30.65 BDT/PMH₀ (= 122.66 BDT / 14,408 sec × 3,600 sec/hr). The productivity for the Small pile was 21.73 BDT/PMH₀ (= 51.41 BDT / 8,519 sec × 3,600 sec/hr), and that for the Large pile was 24.49 BDT/PMH₀ (= 173.78 BDT / 25,545 sec × 3,600 sec/hr), thereby suggesting that there might be an optimum size of slash pile for a grinding operation. The Nordic guidelines state that the preferable size for a slash pile is 20–30 m long and a max. of 4 m high [19]; this guideline supports our finding about the Medium pile, of which width was 24 m.

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Figure 3. Element operation time per BDT.

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Table 2. Results of the time study.

Element operation		Pile		
		Small	Medium	Large
Loading	Time (sec)	3484	5312	7614
	Frequency	359	550	802
	Avg. (sec)	9.70	9.66	9.49
	Std. Dev. (sec)	5.55	4.29	4.56
Unloading	Time (sec)	3114	4776	6848
	Frequency	383	594	863
	Avg. (sec)	8.13	8.04	7.94
	Std. Dev. (sec)	3.09	3.00	2.73
Shaking	Time (sec)	92	95	201
	Frequency	14	15	29
	Avg. (sec)	6.57	6.33	6.93
	Std. Dev. (sec)	3.08	2.50	2.84
Waiting	Time (sec)	479	1314	1875
	Frequency	29	71	88
	Avg. (sec)	16.52	18.51	21.31
	Std. Dev. (sec)	18.06	19.95	19.32
Pushing	Time (sec)	1013	1190	1316
	Frequency	132	168	180
	Avg. (sec)	7.67	7.08	7.31
	Std. Dev. (sec)	5.02	4.83	7.06
Reorienting or repositioning	Time (sec)	52	1056	6826
	Frequency	3	11	21
	Avg. (sec)	17.33	96.00	325.05
	Std. Dev. (sec)	2.31	126.17	732.85
Loading with moving	Time (sec)	100	201	284
	Frequency	13	29	33
	Avg. (sec)	7.69	6.93	8.61
	Std. Dev. (sec)	3.82	2.25	3.19
Unloading with moving	Time (sec)	185	464	581
	Frequency	18	47	56
	Avg. (sec)	10.28	9.87	10.38
	Std. Dev. (sec)	6.95	5.44	9.28
Total		8519	14408	25545

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The element operation times of reorienting/repositioning per BDT were 1.01, 8.61, and 39.3 sec/BDT for the Small, Medium, and Large piles, respectively, thus lengthening as the size of the pile bulked up. The calculated weights of slashes per loading were 0.138 BDT/time (= 51.41 BDT / 359 + 13 times), 0.212 BDT/time (= 122.66 BDT / 550 + 29 times), and 0.208 BDT/time (= 173.78 BDT / 802 + 33 times) for the grinding of the Small, Medium, and Large piles, respectively, which suggests that reorienting or repositioning material from the pile could make the amount of slashes per loading

increase and the productivity of the grinder rise. However, reorienting or repositioning from too large a pile may take too much time, resulting in a decline of the overall operational efficiency.

4. Discussion

4.1. Modeling a grapple excavator operation

We aggregated the element operations of a grapple excavator's operation. A theoretical formula of each element operation was determined from the distribution of the monitored element operation time, and each operation time was estimated by substituting random sampling numbers for the theoretical formula. The theoretical formula was expected to follow a lognormal distribution according to the study by Sakurai et al. [15]. The monitored grapple excavator operation was complicated because there are so many branches in the workflow of element operations. We thus constructed a transition probability matrix based on the connectivity of element operations. In the simulation model, the next element's operation was determined by the matrix.

The average times of all of the element operations other than reorienting/repositioning were not influenced by the pile size, as mentioned above. Therefore, concerning these seven element operations, i.e., (1) loading, (2) unloading, (3) shaking, (4) waiting, (5) pushing, (6) loading with moving, and (7) unloading with moving, we put the element operation times monitored at the three piles together and calculate the transition probabilities that would indicate the probability that the next element operation would occur (Fig. 4). The time distribution of each element operation was fit to a lognormal distribution, and a chi-square test of goodness of fit was conducted. The goodness of fit in none of the element operations was rejected at the significance level of 5%, and we were thus able to determine the theoretical formulae of these element operations (Table 3).

		Subsequent element operation						
		loading	unloading	shaking	waiting	pushing	loading with moving	unloading with moving
Present element operation	loading	0.002	0.714	0.033	0.039	0.163	0.037	0.012
	unloading	0.816	0.004	0.001	0.052	0.077	0.003	0.048
	shaking	0.931	0.034	0	0	0.017	0.017	0
	waiting	0.167	0.602	0	0	0.210	0	0.022
	pushing	0.004	0.923	0	0.038	0.019	0.002	0.015
	loading with moving	0.427	0.373	0	0.093	0.093	0	0.013
	unloading with moving	0.719	0.223	0	0.008	0.017	0.033	0

Figure 4. Transition probability matrix of element operations of the grapple excavator.

On the other hand, the frequency of reorienting/repositioning in the time study was low and a distinct relationship with precedent and subsequent element operations was not observed. However, reorienting/repositioning was an element operation that was definitely carried out within the workflow of the grapple excavator operation, and thus the total operation time was estimated based on a theoretical formula. From the results described in the text section above, the relationship between the area of the landing slash pile location, x (m^2), and the time of reorienting or repositioning per BDT, y (sec/BDT), was approximated as follows:

$$y = 0.2397\exp(0.00489x) \quad (r^2 = 0.9992) \quad (1)$$

and then the total time could be calculated by multiplying y by the amount of logging residues at the landing.

Table 3. Theoretical formulae of element operation time.

Element operation	Theoretical formula ¹
Loading	$e^{N(2.140, 0.485)}$
Unloading	$e^{N(2.023, 0.370)}$
Shaking	$e^{N(1.825, 0.383)}$
Waiting	$e^{N(2.625, 0.800)}$
Pushing	$e^{N(1.819, 0.539)}$
Loading with moving	$e^{N(1.987, 0.363)}$
Unloading with moving	$e^{N(2.153, 0.530)}$

¹ $N(m, \sigma)$ is an operator that generates random normal numbers of which average and standard deviation are m and σ , respectively.

In the constructed model, the mass of the landing pile is first set up, and the simulation is started at the element operation of loading. A grapple excavator grabs logging residues out of a slash pile when loading and loading with moving. If the mass of the pile falls below zero after the excavator grabs the residues, the element operation of unloading comes next; then the excavator operation is finally finished. Thus, the total time of the excavator operation is composed of the time calculated by the simulation model and the estimated element operation time of reorienting/repositioning. Incidentally, the amount of residue per grab, z (BDT/time), was approximated as a function of the area of the landing slash pile location, x , from the results described in the last section as follows:

$$z = -2.489 \times 10^{-7} x^2 + 4.292 \times 10^{-4} x + 3.184 \times 10^{-2} \quad (r^2 = 1.000) \tag{2}$$

4.2. Verification of the replicability of the model and an optimum slash pile size

We verified the replicability of the constructed model by comparing the monitored productivities with the values calculated by the simulation. The calculation was repeated 1,000 times for the respective Small, Medium, and Large piles (Table 4). The maximum difference between the monitored value and the average calculated value was 1.7% for the Medium pile, and the highest ratio of the standard deviation to the average calculated productivity was only 3.2% ($= 0.70 / 21.78 \times 100$) for the Small pile; we thus concluded that the constructed simulation model well-replicated the actual operations.

Table 4. Comparison between the monitored and estimated productivities.

Pile	Monitored			Estimated		
	Area of landing (m ²)	Amount of slashes (BDT)	Productivity (BDT/PMH ₀)	Calculation frequency	Avg. \pm Std. Dev. (BDT/PMH ₀)	Rate of Avg. value to monitored (%)
Small	300	51.41	21.73	1000	21.78 \pm 0.70	100.2
Medium	720	122.66	30.65	1000	31.17 \pm 0.75	101.7
Large	1050	173.78	24.49	1000	24.27 \pm 0.38	99.10

For our discussion of an optimum slash pile size that maximizes the productivity of a grinder, we focus next on the area of the landing slash pile location. A simulation was carried out for a landing area between 300 m² (for the Small pile; 20 m long \times 15 m wide) and 1,050 m² (for the Large pile; 35 m long \times 30 m wide) at 10-m² intervals. In the simulation of the respective landing areas, the calculation was repeated 1,000 times. The productivity for each landing was determined based on the averaged total operation time. Since we observed no significant deviation of the amount of

residues among the three piles in the time study, we calculated the mass of the slash pile in an initial state of simulation by multiplying 0.168 BDT/m² (which was the weighted average value of the monitored three piles) by the area of the landing.

Figure 5 shows the results of the simulation. The productivity of grinding at the landing area of 710 m² of slash pile location is 31.24 BDT/PMH₀, which is the highest productivity value obtained. However, the difference in the estimated productivities is small between the areas 690 m² (31.21 BDT/PMH₀) and 730 m² (31.20 BDT/PMH₀), and there is a range in the calculation result for each landing. It should be noted therefore that Figure 5 simply compares the average values of the 1,000-times repeated calculation.

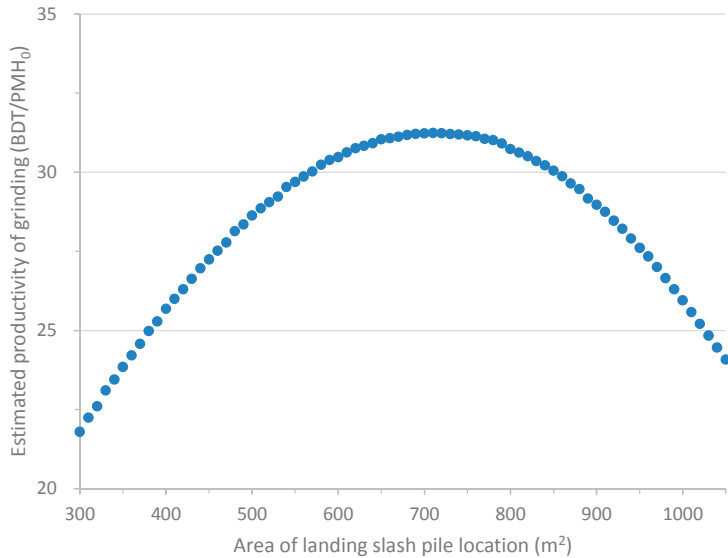


Figure 5. Relationship between the area of landing slash pile location and the estimated productivity of grinding.

5. Conclusions

We constructed a simulation model that can replicate the operations of a grapple excavator and a horizontal grinder based on a Sierra Nevada, California survey, and our study determined the optimum size of a slash pile for a grinding operation, which is expressed in the area of the landing slash pile location. Concerning the versatility of the constructed model, however, the following points should be discussed further so that the accuracy of the model can be improved:

- The shape of each landing, i.e., the ratio of its length to its width, was not considered in the simulation model;
- The theoretical formulae of (1) and (2) were both approximated from only three samples;
- The optimum size of the slash pile for a grinding operation will also depend in part on aspects of the machines used, e.g., their size, engine output, and grinding capacity.

With respect to other results derived from the Blodgett Project, it was demonstrated that utilization of biomass from these large debris piles can result in energy and air quality benefits [20], as follows:

- The energy (diesel fuel) expended for processing and transport was 2.5% of the biomass fuel (energy equivalent);
- Based on measurements from a large pile burn, air emission reductions of 98%–99% for PM_{2.5}, CO, NMOC, CH₄, and BC, and 20% for NO_x and CO₂-equivalent greenhouse gases were observed;
- The delivered cost of \$70/BDT exceeds the biomass plant gate price of \$45/BDT. Under typical conditions, the break-even haul distance would be approx. 48 km.

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