PROCESSING AND SORTING FOREST RESIDUES: COST, PRODUCTIVITY AND MANAGERIAL IMPACTS

Waste to Wisdom: Subtask 2.1.2

Feedstock Development

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Processing and sorting forest residues: Cost, productivity and managerial impacts

Anil Raj Kizha and Han-Sup Han

Abstract
Feedstocks generated from processing forest residues have traditionally been considered as a low valued product. The economic potential of these materials can be enhanced by emerging biomass conversion technologies, such as torrefaction, briquetting, and gasification; however, these systems require higher quality feedstock. The objective of this study was to determine the cost of processing and sorting forest residues to produce feedstock, so that the best comminution machines (i.e. chipper vs. grinder) could be used to better control feedstock size distribution. The tree tops left from sawlog processing and small-diameter trees were delimbed and separated from the slash pile. Three harvest units were selected and each unit was divided into three sub-treatment units (no-, moderate, and intensive sorting). Results showed that the cost of operations were higher for the sorted sub-units when compared to the non-sorted. The total cost of operation felling to loading) for sawlogs was lowest at 40.81 $ m-3 in the nosorting treatment unit, followed by moderate (42.25 $ m-3) and intensive treatment unit (44.75 $ m-3). For biomass harvesting, the cost of operation (felling to delimbing and sorting) ranged from 27 -29 $ oven dry metric ton-1. The most expensive operational phase was primary transportation; therefore, cost of treating the forest residues had less impact on the overall cost. The cost increase (1,150 $ ha-1) of sorting forest residues could offset cost savings from avoided site preparation expenses (1,100 $ ha-1), provided that the forest residues were utilized.

1. Introduction

Forest residues generated from timber harvesting operations, in the form of dead trees, branches, tree tops, chunks (offcuts), non-merchantable tree species and small-diameter trees, have traditionally been regarded as economically low value products. These by-products are generally utilized as feedstock for energy production, as they are widespread, renewable, and can be used to offset the use of fossil fuels and reduce greenhouse gas emissions [1].

In regions where there are markets for biomass or pulp, a variety of treatments, including debarking stems, removing foliage, field drying, etc. are carried out to enhance the quality of the feedstock [2]. Such treatments have been found to accelerate drying, reduce contamination, and support comminution through chippers for generating uniform sized materials [3]. The cost associated with these treatments, while documented, often cannot be compared with operations in other regions, because the harvest operations are species, site, and practice specific [4].
In northern California, approximately 157 and 110 oven dry metric tons (ODMT) ha^{-1} of forest residues can be recovered from a typical even-age managed ground-based and cable yarding operations, respectively [5]. However, the markets (primarily restricted to wood based power plants) for these woody biomass are limited by the transportation distance due to the low price [6]. This means, forest residues generated from any timber harvest units out of the power plant procurement regions are piled and burned on-site. Additionally, slash burning can only be carried out during specific burn windows of the year [7]; and these burnings can have a negative impact on air quality and be detrimental to human health [8].

One of the greatest barriers for utilizing traditional feedstock that were produced from grinding logging slash is its inherent low quality in terms of size distribution. As these forest residues are mixed with chunks, branches, and tree-tops, they can only be comminuted using a grinder producing non-homogenous sized feedstock. This plays a major barrier in the economic feasibility of conversion into value added forest products. Emerging biomass conversion technologies (BCT) such as torrefaction, briquette, and gasification can increase the economic potential of these residues. Therefore, advantage of treating feedstock for BCTs are not only restricted to generate higher income compared to traditional feedstock, but also assists in collecting feedstock from previously inaccessible areas, as the extra cost in secondary transportation can now be justified with the increase in value for the harvested products. Further, the utilization of forest residues instead of open burn effectively facilitates re-planting tasks and reduces negative environmental impacts such as fire hazard and pest outbreak (7). However, to meet the feedstock specifications set by BCTs, the forest residues will have to be treated to minimize contamination, facilitate comminution via chipper, reduce moisture content, and improve handling / transportation efficiency [9].

The overall goal of this study was to produce high quality (i.e., less contamination from dirt, and uniform in size) feedstock through sorting and processing (delimbing) tree tops generated from integrated timber harvesting operations, which could be further chipped rather than grinded to produce uniform size feedstock (Fig. 1). The specific objective of this study was to evaluate cost of the sawlog and biomass harvest operation by estimating the hourly production rate and unit production cost for each stage and the operation as a whole. The study also focused on determining the differences in cost associated with varying degrees of processing and sorting forest residues.

2. Methodology
2.1. Definition used in this study

Forest residue: Materials generated from timber harvesting operation other than sawlogs that are typically of lesser or no economic value. These were further classified into non-merchantable trees, small-diameter trees, slash, and tree tops.

- Non-merchantable tree species: Trees species which are currently not in demand in the sawlog market in northern California; for e.g., hardwood species, such as tanoak (*Notholithocarpus densiflorus* (Hook. & Arn.) Manos et al.). They are used as feedstock for energy purpose, or firewood.
- Small-diameter trees: Trees of both non-merchantable and sawlog species having a diameter at breast height (dbh) less than 20 cm and are not generally accepted by sawmills for lumber manufacturing in northern California. The size of the merchantable timber varies from region.
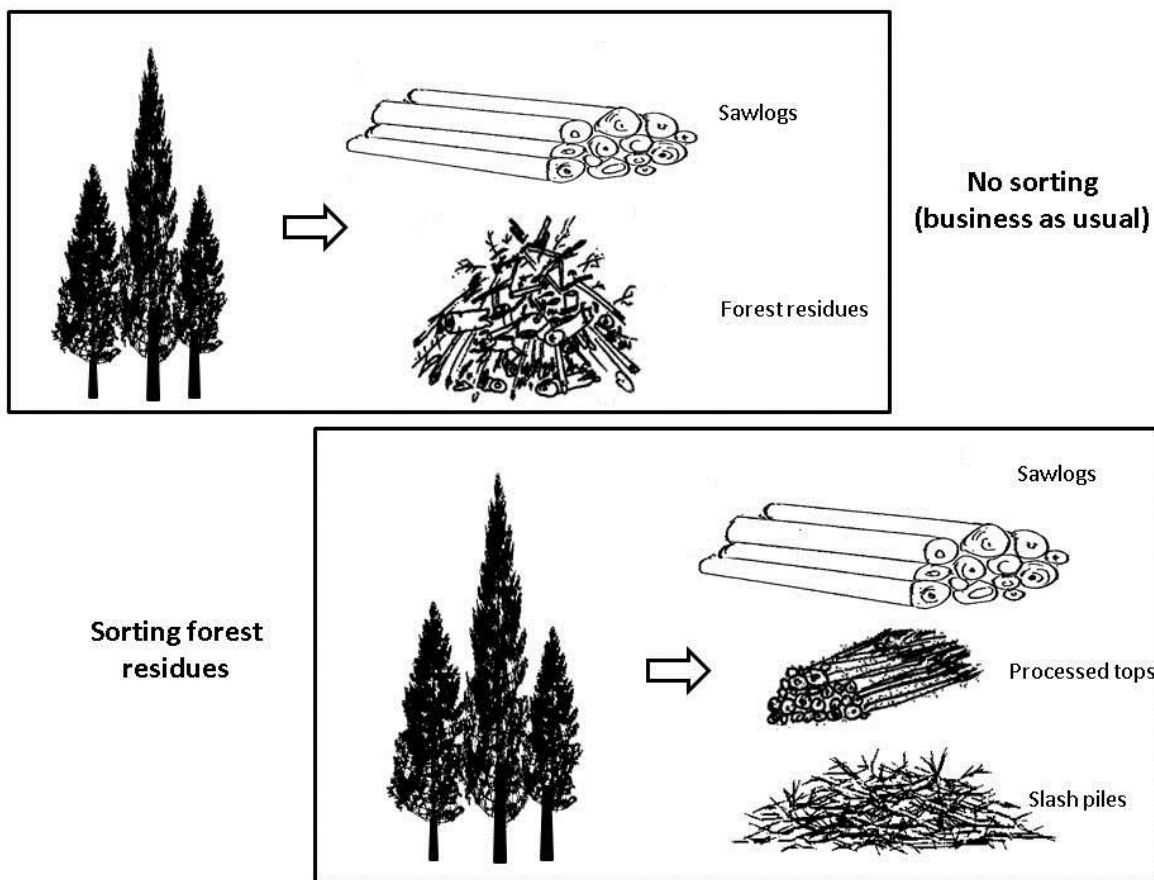
Figure 1. Demonstrating processing and sorting treatment for forest residues from timber harvest units.

- Slash: The component within the forest residues generated from sawlog processing typically consisting of chunks, foliage, branches and other broken material not appropriate to be comminuted by a chipper.
- Tree tops: The wood material within bole (main stem) from 15 cm diameter level onwards to the tip of the crown for both conifer and hardwood trees. During sorting, tree tops were bucked from the sawlog component by the processor and were separated from the slash pile, as they could be fed to a chipper to produce homogenous size particles. Broken logs and small-diameter trees were also piled along with the tops. The tree tops were further divided into two sections:
  - Processed tree tops: Tree tops delimbed (foliage removed along the entire length) to the top 15 cm length.
  - Unprocessed tree tops: The intensive sorting treatment had an unprocessed tree top sort for conifer and hardwood. Here, tree tops were not delimbed and had branches with leaves and needles still attached to them.
- Sawlog component: Merchantable trees with a diameter at breast height (dbh) of 20 cm or greater which will be eventually processed to lumber at a saw mill. In northern California, only softwoods had sawlog markets.

2.2.Stand and site description

The study site comprised of three even-age managed stands on an industrial timberland property in Humboldt County, California (41°02'18" N, 123°55'35" W) (Fig. 2). The sites primarily consisted of even-aged (averaging 60 years) second- and third- growth coast redwood (*Sequoia sempervirens* (D. Don) Endl.), Douglas-fir (*Pseudotsuga menziessii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and tanoak. The sites ranged from 520 to 730 m above mean sea-level with ground slopes up to 111 percent (48°). The climate for the region is characterized by maritime influence from the Pacific Ocean, and receives approximately 119 cm of rain annually, with an average temperature of around 11° C [10].
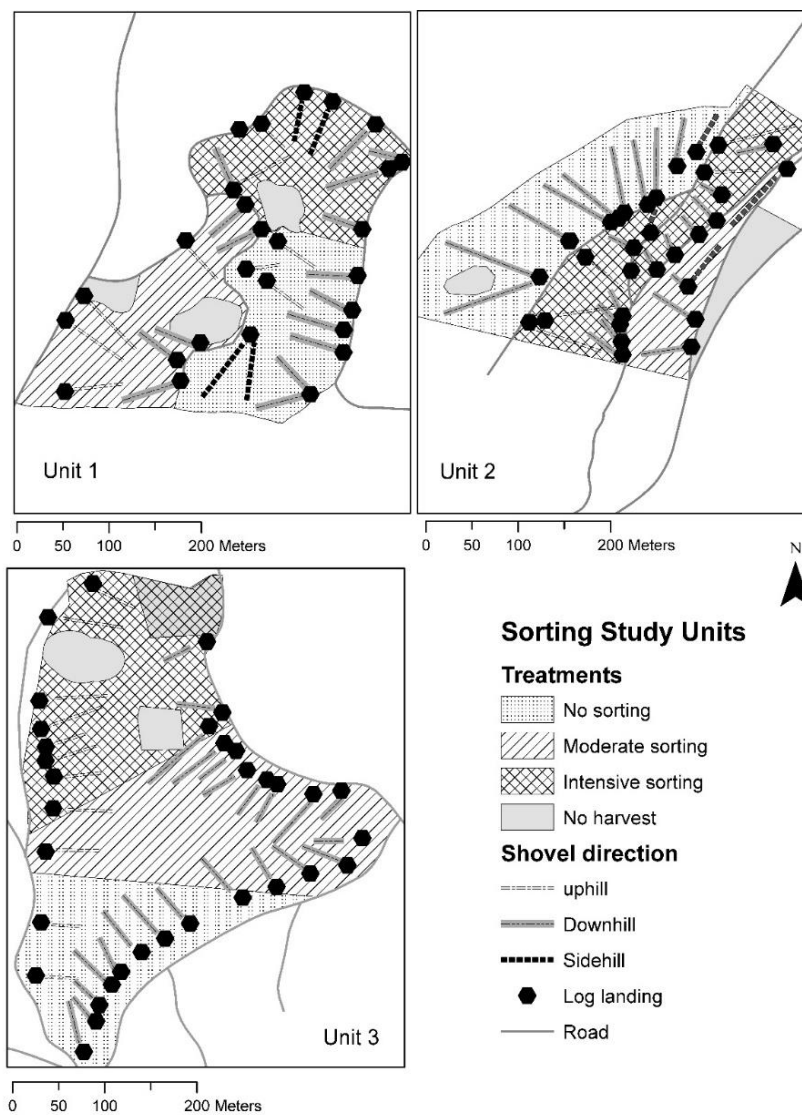

Figure 2. Study units, sub-units, and shoveling direction for forest residues processing and sorting study in Humboldt County, California.

2.3.Experimental designs and treatments

Three field-based treatments were carried out to investigate the effects of sorting and processing the forest residues at varying intensities on the productivity and cost of sawlog and biomass operation. The timber harvest units were located approximately 1.6 km apart from each other. Each unit was subdivided into three equal sub-units, which were assigned one of the following treatments:

1. No sorting: Typical residue management adopted by timber landowners in the region, therefore regarded "business as usual". The focus of the processor in this treatment was on the sawlogs. Forest residues generated from sawlog processing were piled near the log landing area. Piles consisted of tree tops, chunks, branches, broken logs, foliage, and small-diameter trees. However, hardwood trees (non-merchantable) were decked separately.
2. Moderate sorting: The tree tops were processed and sorted into conifer and hardwood piles by the processor. The remaining slash generated during sawlog and forest residues processing consisted of chunks, foliage, and branches were piled separately.
3. Intensive sorting: Forest residues were processed and sorted into five categories:
    Processed conifer tops (PC); Unprocessed conifer tops (UC)
    Processed hardwood tops (PH); Unprocessed hardwood tops (UH); Slash

A stand inventory was done at 10% sampling intensity (0.04 ha fixed-radius circular plots) using a systematic sampling design (Table 1). All three units were clear-cut and both sawlog and biomass components were brought to the landing. The operations were decoupled, with each machine ahead of the consecutive machine by one week: for example, a feller-buncher operated one week before a shovel machine moved into the unit. All three treatments were operated by the same harvesting machines and operators, except for felling. The operation spanned over two months during the summer of 2014.

Table 1. General characteristics of the treatment units for the forest residues sorting and processing study. Stand inventory summarized all standing trees above diameter at breast height (dbh) of 2.5 cm

Unit	Treatments	Area (ha)	Average yarding distance (m)	Basal area (m^2 $ha^{-1)}$)	Average dbh (cm)	% of Hardwood[a]
	No sorting	3	36	46	18	4
1	Moderate sorting	3	45	80	18	8
	Intensive sorting	3	43	56	18	4
	No sorting	3	54	88	18	50
2	Moderate sorting	2	24	103	18	54
	Intensive sorting	3	31	108	18	51
	No sorting	3	36	94	23	38
3	Moderate sorting	3	55	82	18	40
	Intensive sorting	3	49	81	18	44

[a] percentage of total number of hardwood trees compared to the total trees in the unit

3.4. Cycle elements for each harvesting activity phase

To calculate delay-free cycle times, a detailed time study was conducted using standard work study techniques [11]. Elemental time-motion data were recorded by a centi-minute stop watch for each machine. Additionally, predictor variables hypothesized to affect cycle time were recorded for each cycle element (Table 2). Delays were defined as all activities that did not directly contribute to the production of the operation. Delays for every machine in the operation were classified into three categories: personal, mechanical, and operational. Delays were recorded to better understand factors influencing productivity and not to quantify utilization rates for the machines in these systems [11].

Table 2. Cycle elements and associated predictor variables for each machine in the integrated timber harvesting operation focused at sorting forest residues.

Component	Cycle elements	Recorded predictor variable(s)
Felling	travel empty cutting time bunching time	trees cut per cycle tree species butt-end diameters (cm) distance between trees (m) distance to bunch (m)
Shoveling	travel empty swing empty grapple time swing loaded travel loaded	walking distance (m) swinging distance (m) distance loaded (m) trees per cycle butt-end diameters (cm) tree species angle rotation (45°, 90°, and 180°) direction of shovel (uphill vs. downhill)
Processing	swing empty grapple time processing sawlog processing biomass sorting sawlog sorting biomass	tree species butt-end diameters (cm) logs per cycle/ sawlog pieces per tree short length logs medium length logs long length logs number of biomass pieces processed tops unprocessed tops
Loading and sorting (sawlogs)	swing empty grapple time swing loaded	logs per cycle short length logs medium length logs long length logs total board feet

Felling and bunching: Sorting of forest residues began with the feller-buncher. All three units used the same make and model of feller-buncher (John Deer 959K) which separated the biomass from the sawlog trees, as opposed to bunching them together or using the forest residues as "slash mats". There were two operators and machines during the study. Units 1 and 2 were felled by one operator while the third unit was felled using a different operator and machine. The cycle time started when the machine released a tree and traveled empty to the next tree (travel empty) followed by the cutting of the tree (cutting time), the machine then rotated while loaded, and placed the tree in an existing pile or bunch (bunching time), ending the cycle. Distances for various phases of the cycle were visually estimated.

Shovel yarding (primary transportation): The primary transportation (stump to landing) was done using a shovel machine (Caterpillar 568) equipped with a log grapple, which brought all trees to the roadside for processing. At the landing, the trees were separated into conifers (sawlogs), and biomass piles.

The total delay-free cycle for the shovel was calculated in a series of steps. First, the individual swing cycle time for each shovel turn was calculated. The swing cycle time started when the machine traveled empty to a pile/bunch of trees (travel empty), swung empty to a pile (swing empty), grappled the trees (grappling time), rotated loaded to a new pile/bunch and completed the cycle when the machine dropped the trees or compacted them into another pile/bunch (swing loaded). Often the shovel loader travelled with a load to the nearest bunch (travel loaded). On other occasions, the loaded time ended without reaching the full stretch of the 17-m boom (trees were placed in between) in order to adjust the orientation of the trees or re-grapple (to get a better grip) the tree. These cycles were noted during data collection and were regarded as partial cycles, which were later combined to get a whole cycle. The average yarding distance (AYD) was measured for each sub-unit (Fig. 3). The total cycle time was calculated by multiplying the AYD with the swing cycle time and dividing by the average of swing distances (SD) per cycle.
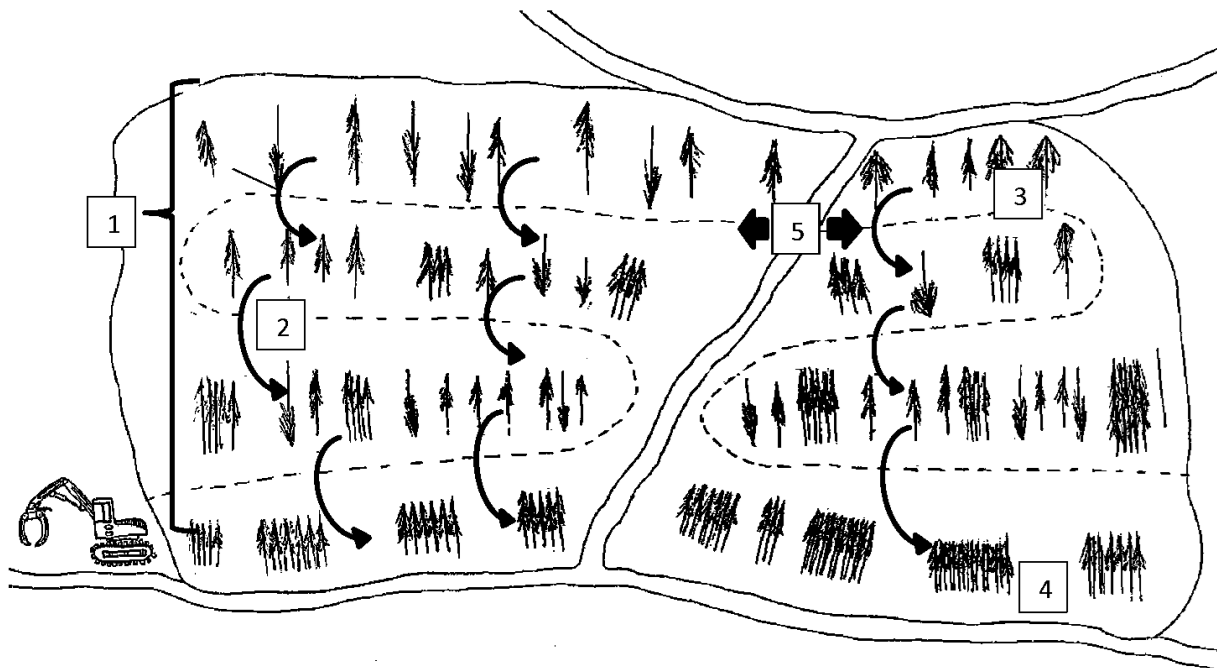
Figure 3. Yarding pattern and direction in shovel logging; where, 1. average yarding (shoveling) distance; 2. swing distance; 3. felled trees; 4. unprocessed log decks; and 5. shovel machine movement beginning from the roadside. The dashed arrow represents the direction of shovel machine movement and the solid arrow shows the movement of wood.

Swing cycle time = travel empty +swing empty +grappling time +swing loaded +travel loaded

$$Total\ cycle\ time\ = \frac{Swing\ cycle\ time\ \times AYD}{SD}$$

For the swing empty and swing loaded, swing arcs were visually estimated in degrees traversed, and was broadly divided into 45, 90, and 180º. The trees handled in each grapple cycle were categorized to biomass or sawlog trees. In addition, the shovel direction (uphill vs. downhill), walking distance (distance travelled by the shovel machine to reach a pile, without load), distance loaded (distance travelled by the shovel machine with load), and swinging distance (distance of the wood getting displaced during each swing movement) were recorded (Table 2).
Processing: A dangle-head processor (John Deere 2454D with Waratah processing head) processed sawlogs and biomass trees at the log landing at varying levels of intensities for the three different treatments (Fig. 4). During sawlog processing, the processor delimbed the tree tops up to the tip of trees for the moderate and intensive sorting treatments. Processed tree tops were separated from the slash and sorted into two piles (based on species) for the moderate sorting treatment and four (PC, UC, PH, UH) for the intensive sorting. Sawlogs were separated based on species into three conifer (Douglas fir, western hemlock and coast redwood) piles.

Figure 4. Dangle-head processor (John Deere 2454D with Waratah processing head) at the log deck processing and sorting for the intensive sorting treatment.

The cycle time for the processor began when the dangle head swung empty to the log deck (swing empty). This was followed by grappling the log (grapple time), swing loaded, processing the log, and ending the cycle when the sawlog was placed in a deck (processing time). Processing and sorting time for the biomass was calculated by the extra time spent on tree tops for processing and sorting it in separate decks. The length of a processed sawlog was divided into three categories: short logs (4 m long and smaller), medium logs (4 to 11 m long), and long logs (11 m and longer). This classification was done to simplify data collection, as it was difficult to visually estimate the log lengths during processing.

Loading and sorting (sawlogs): The loading and sorting was exclusively done for the sawlog component by a John Deere 2954D loader. Both phases had similar cycle time elements, which started when the machine swung empty to deck of sawlog (swing empty). This was followed by grappling the sawlog (grapple time), and ended with swing loaded, when the sawlog were placed on the log truck bunk (loading) or placed in separate log piles (sorting).

3.5. Machine rate calculation

Purchase prices, salvage values, economic life, utilization rate, wages and benefits for crew were obtained from the timberland company which owned and operated the equipment (Table 3). Accordingly, all machinery was assumed to have 10-years of economic life while working 2200 scheduled machine hours (SMH) per year with a machine utilization rate set at 80 percent. Diesel price was set at 1.01 $ liter^{-1}, which reflected average local market prices during the study. Hourly machine costs in dollars per scheduled machine hour ($ SMH^{-1}) were calculated using standard machine rate calculation methods [12].

Table 3. Machine rates and other costs of the equipment used in the treatment, not including support vehicles such as water truck for dust control, fuel truck, and personal vehicles. The fuel and labor cost was estimated at 1.01 $ liter^{-1} and 47.20 $ h^{-1}, respectively. Machine rate per productive machine hours ($ PMH^{-1}) were calculated using the values of 2,200 SMH (schedule machine hours)/year, 59% fringe benefits, 10% interest, 80% utilization and 3% insurance (provided by the timberland company, which operated and owned the machines).

	Felling and bunching	Primary transportation	Processing	Sorting and loading
Make	John Deere	Caterpillar	John Deere	John Deere
Model	959K	568	2454D	2954D
Purchase price	$ 625,000	$ 500,000	$ 610,000	$ 425,000
Operating cost	$ 58	$ 46	$ 56	$ 42
Fuel use (Liter PMH^{-1})	37	30	23	23
Machine rate ($ PMH^{-1})	$ 177	$ 161	$ 165	$ 135

The cost and productivity for harvesting sawlog and biomass components were analyzed separately.
Joint products allocation was used to estimate the cost for the different operational phases [13]. The elemental cycle for biomass trees (non-merchantable species and small-diameter trees) were

recorded separately for each machine, based on the tree species and the butt-end diameter. For primary transportation, as all trees were hauled together, a volumetric ratio of biomass trees to the sawlog trees brought to the landing was first determined from the shoveling dataset and allometric equations. The total cost of the shoveling operation, calculated from machine rates, was then allocated for each component based on this ratio. The tree tops were assumed to have a free ride with the sawlog component until the processing phase (by-product allocation; [13]). The unit cost of sawlog harvesting consisted of felling, shoveling, processing, sorting and loading; whereas biomass trees only included cost associated with felling to processing and sorting of the tree top.

The average sawlog piece size was determined in cubic meter for each sub-unit by randomly scaling 991 sawlogs from different log decks. The average number of sawlog pieces per tree (needed to calculate the productivity of the feller-buncher and shovel machine) was estimated during processing for each species. Localized allometric equations were used to calculate the weight for biomass trees and the volume for the sawlog [14–16]. Density factors were used to convert from volume to weight or vice versa [17].

Regression models were developed using IBM SPSS Statistical Software 21. Ordinary least squares estimators were used to predict delay-free cycle time based on explanatory variables (Table 2). Standardized variable comparison was utilized for each machine to reflect the differences in cost and productivity due to the treatment, irrespective of variation in stand conditions and harvesting operations [18]. Dummy variables were used for representing the unit and species. The datasets were initially screened for outliers, after which scatterplots were developed for each variable to check if the relationships between transformed independent and dependent variables were linear. Several transformation models were developed and compared to verify; the models which met the assumption of normality were selected. Multi-collinearity was tested using a tolerance value greater than 0.1 and variance inflation factor (VIF) less than 10. Analysis of variance (ANOVA) was performed to determine if there was any difference for species and dbh of trees between sub-units within each unit.

4. Results and discussion

4.1. Stand conditions
A total of 1,113, 2,052 and 1,705 trees (both sawlogs and biomass) were measured from the timber cruise plots for Units 1, 2 and 3, respectively. The stand inventory estimated basal area (square meter/ha), and species composition . ANOVA showed that there was no significant difference in tree dbh for the different units (*p-value*= 0.90, 0.21 and 0.83). However, Unit 1 had less than 8% of hardwood trees, therefore this replicate unit was considered as conifer, while Units 2 and 3 were regarded as mixed stands.

4.2.Operational phase

Felling: A total of 2,566 observations were taken from the three units. Travel empty constituted the longest time component within the feller-buncher's delay-free cycle and ranged between 36 to 52%. The average delay-free cycle time for all the units was 42 and 31 seconds for sawlogs and biomass trees, respectively, and there was no specific trend observed among treatments. The cost of felling was influenced by the average number of trees cut per turn, which averaged 1.1 and 1.8 trees for sawlogs and biomass trees, respectively. The average distance between trees and bunching distance was 5.2 and 7.8 m, respectively.

Bunching of biomass trees separately from the sawlogs started right from felling, however, during shoveling both sawlog and biomass were combined together as they were hauled to the landing in order to maximize the volume for each grapple. This suggests that sorting of sawlog and biomass components could have started during the shoveling operation at the landing rather than during felling, which would have further lowered the cost of felling.

Shovel yarding: A total of 1,009 delay-free cycle times were captured from the three units. The average delay-free cycle time for each swing was approximately 31 seconds. The swing loaded time had the largest share in the cycle (approximately 37%) and was highly influenced by the orientation of trees within the bundle. On average, 3.6 trees were moved in a single swing and the average swing distance was approximately 18 m for all the units. The external yarding distance from the unit to the roadside ranged from 16 to 137 m (Table 1). For Unit 1, 51% of the logs were downhill shoveled and the remaining uphill. Most of the sub-units in Unit 3 were downhill shoveled (68%), and all but two decks in Unit 2 were yarded downhill.

The regression model showed that the cost and productivity of the shovel operation was highly influenced by distance loaded, and swing distance. Distance loaded and walking distance being functions of the average yarding distance (AYD); sensitivity analyses were done to understand the influence of the AYD and the swing distance (SD) on the cost. Results showed that a 15 m increase in AYD corresponded to a 9.81 $ m^{-3} increase in the total shoveling cost (SD =17 m) (Fig. 5). Shovel cost (AYD =30 m) decreased an average of 1.65 $ m^{-3} for every 2 m increment of SD between 15 and 27 m (Fig. 6).

Shovel yarding was commonly planned to have the trees reach the landing within two or three swing turns. Sensitivity analyses showed the importance of maximizing the swing distance (SD) for shovel logging, as increasing SD (on an operational level) could counteract the increase in external yarding distance, which itself was a function of the stand and road layout. The swing distance is usually maximized by the shovel operator and is highly dependent on presence of tree stumps, slope, terrain features, and the size of the logs being shoveled [19].

 The cost of shovel logging is higher than regular skidding operation [20]; but is found to have lower impact on the forest floor due to one time machine pass (Fig. 3). Therefore, using conventional ground-based skidders could have potentially further reduced the total cost of operations.
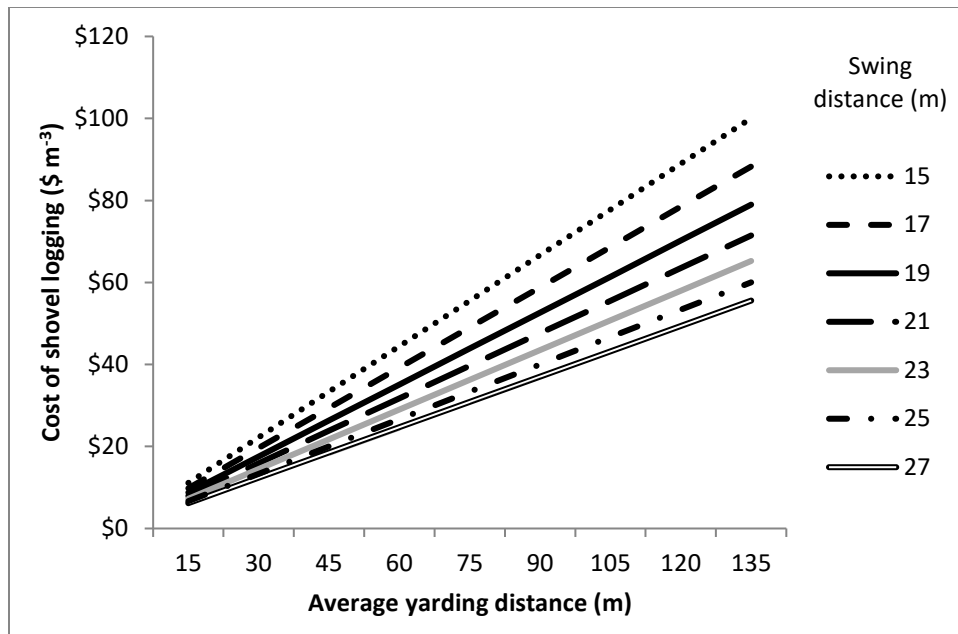
Figure 5. Effects of average yarding distance (AYD) on the cost of shovel logging at different swing distances (SD).
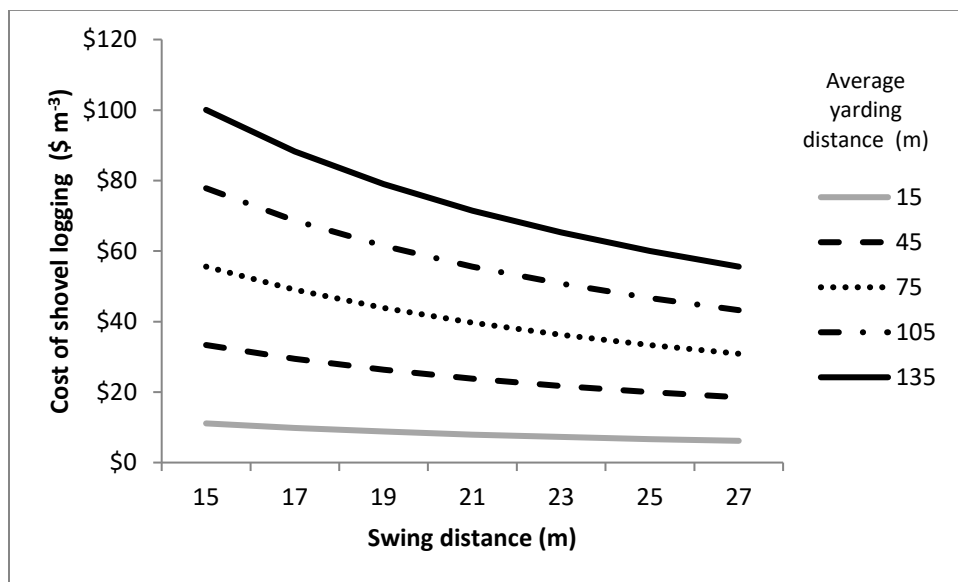

Figure 6. Effects of swing distance (displacement distance of wood in each swing movement) on the cost of shovel logging at different average yarding distances (AYD).

Processing: The processor being the focus of the study, a total of 1,583 valid observations were taken from the three units. The delay-free cycle time averaged 34, 38 and 43 seconds for no, moderate and intensive sorting treatments, respectively (Fig. 7) The average number of sawlogs generated per cycle was 1.63.

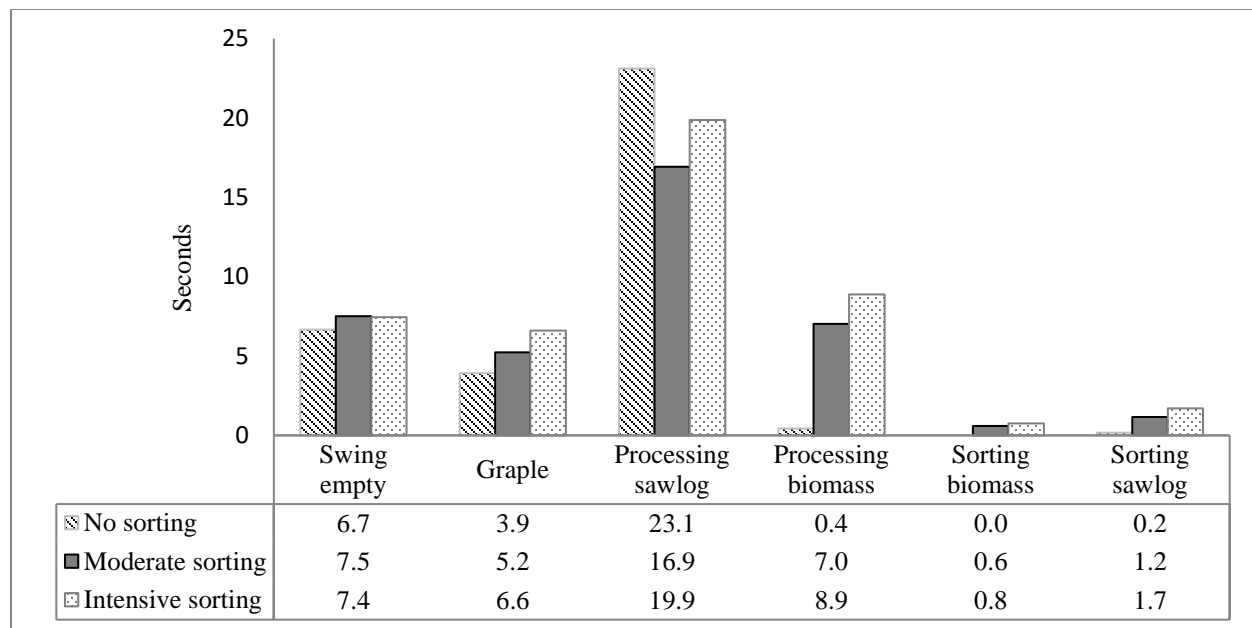|	Swing empty	Graple	Processing sawlog	Processing biomass	Sorting biomass	Sorting sawlog
No sorting	6.7	3.9	23.1	0.4	0.0	0.2
Moderate sorting	7.5	5.2	16.9	7.0	0.6	1.2
Intensive sorting	7.4	6.6	19.9	8.9	0.8	1.7

Figure 7. Average delay free cycle time component for the processor activities (both sawlog and biomass components) in forest residues processing and sorting study.

The high cost of processing for the sorting treatment was primarily due to the extra time required to process and sort the biomass materials into different piles. In no sorting treatment, all forest residues generated during sawlog processing were stacked into a single pile. However, the hardwood (biomass component) was processed for energy feedstock in the no sorting treatment sub-units. The sorting treatment further required extra space at the landing for decking the biomass materials in addition to the sorted logs. As observed in other studies, it generally took more time to process hardwoods (tanoak) compared to conifers [21,22]. Between the units, the cost difference was greater for the mixed units (Units 2 and 3) compared to the conifer unit (Unit 1) where more space was required to pile both conifer and hardwood forest residues separately. Additionally, processing cost differed between conifers and mixed units for the no sorting treatment averaging 4.09 and 4.75 $ m^{-3}, respectively.

Loading and sorting of sawlogs: The delay-free cycle averaged 30 seconds for loading and 21 seconds for sorting. On average, it took 14 minutes for the loader to load a sawlog truck. Swinging loaded was the largest component in the delay-free cycle and constituted between 35 to 53% of the cycle. The time to load a sawlog truck varied with the number of logs and the orientation of logs in the pile. For units 2 and 3, which had two additional biomass piles from hardwood, more time was spent on sorting.

The study was intended to reflect a regular integrated harvest operation in northern California by incorporating aspects of sorting and processing forest residues while harvesting sawlogs. The differences in total cost of operations between the three treatments could be mainly attributed to processing, as other phases including felling, shoveling, sorting and loading, did not show any such trend (Table 4). The overall cost of the three forest residue treatments showed that there was a gradual increase from the non-sorting (41 $ m^{-3}) to intensive sorting (45 $ m^{-3}) (Table 4).

The additional time to process and sort the tree tops increased cost by 1.25 $ m^{-3} (approximately 30% increase in the processing cost) from non- to intensive sorting treatments. For the same scenario, the cost difference for the biomass component was around 3.50 $ ODMT^{-1}. Although there was an increase in total cost attributed to processing, results showed that 30 -59% of the total cost for all the sub-units were actually from the shovel operation. This indicates that primary transport was still the greatest influencing factor in the total cost, not processing. For the biomass component, the processing constituted about 45 to 51% of the total cost and was the most expensive component of the operation.

Table 4. Cost and productivity of the various phases in the integrated timber harvesting operation focused at processing and sorting forest residues. Sawlog components are conifer trees ≥ 20 cm diameter at breast height (dbh), utilized down to a small-end diameter of 15 cm, eventually sent to sawmills for producing sawlogs. Biomass components are trees between 8 and 20 cm dbh for conifers and all hardwood species from 8cm upwards.

Sawlog	No sorting		Moderate		Intensive	
	Cost	Productivity	Cost	Productivity	Cost	Productivity
	$ m^{-3}	m^3 PMH^{-1}	$ m^{-3}	m^3 PMH^{-1}	$ m^{-3}	m^3 PMH^{-1}
Feller-buncher	$ 5.63	31.4	$ 5.28	33.5	$ 6.54	27.1
Shovel[a]	$ 19.36	5.4	$ 20.10	5.2	$ 19.62	5.3
Processor	$ 7.90	20.9	$ 9.14	18.1	$ 10.84	15.2
Loader(loading)	$ 5.30	25.6	$ 5.16	26.2	$ 5.20	26.1
Loader(sorting)	$ 2.62	51.7	$ 2.57	52.6	$ 2.55	53.1
Total	$ 40.81		$ 42.25		$ 44.75	

Biomass	No sorting		Moderate		Intensive	
	Cost	Productivity	Cost	Productivity	Cost	Productivity
	$ ODMT^{-1}	ODMT PMH^{-1}	$ ODMT^{-1}	ODMT PMH^{-1}	$ ODMT^{-1}	ODMT PMH^{-1}
Feller-buncher	$ 6.67	26.5	$ 6.27	28.2	$ 5.66	31.3
Shovel[a]	$ 4.73	1.3	$ 4.91	1.3	$ 4.79	1.3
Processor	$ 15.30	10.8	$ 16.30	10.1	$ 18.96	8.7
Total	$ 26.70		$ 27.48		$ 29.41	

[a]cost evaluated by joint product allocation, m^3- cubic meter, ODMT- oven dry metric ton, PMH-productive machine hour

In general, the standardized comparison model was able to predict the delay-free cycle time for each machine more effectively for the sawlog component compared to biomass. The R^2 values ranged from 0.10 to 0.63 (Table 5). The harvesting units and species were found to be significant predictors for most of the regression models, suggesting that species composition and stand condition within the units influenced the delay-free cycle time.

Table 5. Regression models developed for predicting delay-free cycle time (DFC) in centi-minutes using standardized comparison. All units are in cm for dbh and in m for distance. Dummy varibales were used for harvesting unit and species.

	Component	R^2	Standardized models predicting delay-free cycle time (DFC)
Feller-Buncher			
No sorting	Sawlog	LogDFC 0.15	1.26 +0.07(trees/cycle) –0.02(unit 2) –0.00(unit3) +0.01(dbh) +0.10(Douglas fir) +0.15(redwood) +0.09(western hemlock)
Moderate		LogDFC 0.19	1.27 +0.04(trees/cycle) –0.27(unit 2) –0.21(unit 3) +0.01(dbh) –0.03(redwood) –0.03(western hemlock)
Intensive		LogDFC 0.41	1.36 +0.11(trees/cycle) –0.27(unit 2) –0.21(unit 3) +0.00(dbh) -0.08(redwood) –0.13(Douglas fir) – 0.18(western hemlock)
No sorting	Biomass	LnDFC 0.10	3.42 –0.12(trees/cycle) –0.09(unit 2) –0.06(unit 3) +0.01(dbh) +0.05(redwood) –0.01 (western hemlock) +0.00(tanoak)
Moderate		LnDFC 0.12	3.15 +0.12(trees/cycle) –0.09(unit 2) –0.06 (unit 3) + 0.01 (dbh) –0.0(tanoak) –0.05(redwood) –0.01(western hemlock)
Intensive		Ln DFC 0.39	3.58 –0.00(trees/cycle) +0.70(unit 1) +0.43(unit 3) – 0.22(distance between trees) –0.01(dbh) +0.007(Douglas fir) –0.12(redwood) –0.07(western hemlock)
Shovel			
No sorting	Combined [a]	LnDFC 0.59	3.84 +0.01(walking distance) +0.01(swinging distance) +0.02(distance loaded) –0.02(sawlog pieces/cycle) +0.01(biomass pieces/cycle) +0.28(unit 1) –0.22 (unit 3)
Moderate		LnDFC 0.63	3.75 +0.03(walking distance) +0.01(swinging distance) +0.01 (distance loaded) –0.04(sawlog pieces/cycle) – 0.03(biomass pieces/cycle) +0.00(unit 1) –0.36(unit 3)
Intensive		LnDFC 0.39	3.84 +0.01(walking distance) +0.01(swinging distance) +0.01(distance loaded) +0.05(sawlog pieces/cycle) – 0.03(biomass pieces/cycle) –0.01(unit 1) –0.19(unit 3)
Processor			
No sorting	Sawlog	LnDFC 0.27	3.70 –0.21(unit 1) –0.28(unit 3) +0.19(logs/cycle) +0.01(dbh) +0.07(redwood) +0.08(western hemlock)
Moderate		LnDFC 0.28	3.66 +0.04(unit 1) –0.24(unit 3) +0.19(logs/cycle) +0.01(dbh) +0.03(redwood) +0.15 (western hemlock)
Intensive		LnDFC 0.26	3.70 –0.04(unit 3) +0.20(logs/cycle) –0.02(dbh) – 0.01(redwood) –0.09(western hemlock)
No sorting	Biomass	LnDFC 0.42	2.73 +0.13(pieces/cycle) +0.12(dbh) +0.07(unit 3) +0.23(processed pieces) +0.02(unprocessed pieces) – 0.42(redwood) +0.16(tanoak)

Moderate		LnDFC	0.33	3.43 +0.05(dbh) +0.07(unit 3) +0.12(processed pieces) +0.19(unprocessed pieces) –0.04(redwood) +0.21(tanoak)
Intensive		DFC	0.29	46.75 +0.60(dbh) +0.04(weight/load) +6.41(processed pieces) –5.51(unprocessed pieces)
Loader (loading)				
No sorting	Sawlog	LogDFC	0.20	1.51 +0.11(unit 1) +0.02(unit 3) +0.05(logs/cycle)
Moderate		LogDFC	0.23	1.55 +0.13(unit 2) +0.00(board feet) –0.01(logs/cycle)
Intensive		LnDFC	0.17	3.59 –0.02(unit 1) +0.35(unit 1) +0.02(logs/cycle)
Loader (sorting)				
No sorting	Sawlog	LnDFC	0.26	3.83 –0.25(unit 3) +0.02(logs/cycle)
Moderate		LnDFC	0.38	3.91 –0.20(unit 1) –0.38(unit 3)
Intensive		LnDFC	0.18	3.40 +0.11(unit 1) +0.23(unit 3) +0.05(logs/cycle)

Where LnDFC is the natural log of DFC, logDFC is the log to the base 10 of DFC
[a]sawlog and biomass

4.3. Implication on management and the timber harvesting operation

Processing and sorting forest residues are common in regions where strong markets exist. However, in northern California there is limited demand and interest for woody biomass except as feedstock to power plants. Conventionally, harvested biomass trees are spread within the unit and are used as a slash mat for the harvesting machines to minimize soil compaction [23]. Even though these slash mats are recoverable, the biomass can be contaminated.

In general, any biomass recovery operations leaves about 30 - 40% of the forest residues on the floor [5]. For this study, the biomass trees were brought and processed at the landing. When forest residue treatments (sorting and processing) were incorporated to regular timber harvesting, communition via chipping can be facilitated. The increase in cost due to processing and sorting of forest residues was estimated at around 1,150 $ ha^{-1}. This figure was calculated by dividing the cost increase due to sorting and processing by the area of the sorting treatment units combined (i.e., intensive and moderate sorting). As these products are of higher value, it is possible that the additional cost incurred by treating forest residues could be offset by the income generated from selling the materials as dowels and pulp woods if local markets are available.

The increased value for the high quality feedstock can also substantiate increasing the secondary transportation distance; thus, opening new timberlands for biomass recovery operation. Currently, the procurement regions are limited to less than 130 km to the final utilization point (power plants) due to the low price offered for conventional feedstock making the cost of secondary transportation beyond that not feasible [6].

The small-end diameter and length of tree tops averaged 17 cm and 7 m, respectively, ensuring they could be shipped using short log trucks instead of the modified dump trucks used commonly to transport unprocessed forest residues in the region [24]. In Humboldt County, biomass recovery operations are seasonal (roughly 100 days per year) due to the closure of roads during rainy seasons for these dump trucks. This is in contrast to the year-round timber harvest for cable logging and at least six months for shovel logging. Therefore using short log trucks could

extend the biomass operation window throughout the year. Further on, short log trucks are more productive than the dump truck [25].

For the landowner, treating forest residues can potentially reduce the cost of site preparation for replanting by utilizing the forest residues which are burned at a cost of around 1,000 $ ha^{-1}. Additionally, the loader cost around 150 -200 $ ha^{-1} for piling the scattered residues. Even at this price, the quality of piled stand is not suitable for re-planting [19]. Therefore, the cost of biomass recovery (including sorting and processing) can be substantiated as an alternative to slash pile burning, and weed treatment. From an operational point of view, forest residues are easier to handle when sorted than when piled together.

Conclusions

It is very common leave forest residues unutilized (on site) in regions that does not have a strong woody biomass market. However, this practice can lead to increased fuel load on the floor resulting in repercussion such as, increasing the cost for replanting purpose, risk of fire, and pest spread. Sorting and processing the forest residues can facilitate the production of quality of feedstock via chipping tree tops, instead of grinding a mix of tops, limbs and branches. This study showed that the cost of treating biomass trees and tree-tops increased around 10% of the overall cost of the timber harvest operation, compared to the usual practice of piling and open burning all the forest residues. However, this additional sorting of tree tops cost-effectively facilitate increased utilization of forest residues to more lucrative markets and thereby enhancing the financial potentials as well as avoiding open burning and facilitating tree replanting tasks.

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