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Forest biomass feedstock cost sensitivity to grinding parameters for bio-jet fuel production

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A B S T R A C T

Forest harvest residuals in the USA Pacific Northwest are a significant and largely underutilized source of renewable feedstock for "green" power. These forest harvest residuals are, however, not a uniform commodity and many choices can be made for source location, which tree parts to include in the harvest, how to comminute, transport, and process at a biofuels mill-site. Each of these many decisions can and should be informed by the overall impact on value chain costs, including all production costs and any impacts on the conversion process. The number of operational choices is large and the optimal solution not obvious. This paper explores the quantification of a number of the most likely significant operational choices in feedstock harvesting and preparation, and quantifies and ranks the main factors which can impact total value to the overall process of converting forest harvest residues to bio-jet fuel. Under the assumptions used here, total grinding costs are the largest cost impact factor, with a $26.12 per oven-dry tonne impact range. Higher bulk density (as long as moisture content is low enough) reduces hauling cost and is the second most powerful cost effect, having an impact range of $11.31 per oven-dry tonne.

1. Introduction

Energy security and greenhouse gases mitigation policies in the United States are increasing the interest in the development on renewable fuels such as bio-jet fuel. In the United States the airline industry is an important component of the economy reporting annual operating revenues of approximately 174 billion dollars in recent years [1,2]. As a result of the interest in renewable energy, different institutional efforts have been promoted between private, public and academic sectors to build a supply chain based on using softwood harvest residues to make aviation fuel [3]. These efforts are targeting increasing efficiency for each supply chain step from forestry operations to conversion processes. As with the costs of many cellulosic biofuels, the feedstock costs can be a very significant fraction of the total production cost [4,5]. A techno economical assessment in the Pacific Northwest (PNW), United States, has identified feedstock costs as the largest single element of the annual operation costs for potential bio-jet production from softwood harvest residues [19]; other operational costs are related to pretreatment, conversion, waste disposal and the use of other raw materials [29]. This prominence makes feedstock cost reduction a logical focus area to explore different process improvement methods. In this paper we analyze the forest biomass feedstock cost sensitivity to grinding parameters for bio-jet fuel production. Grinders compared to chippers can handle the processing of forest residues without being affected by contaminants, however, the processed material tends to be more heterogeneous in terms of particle size distribution [24], and therefore additional study is needed to understand how the material heterogeneity is translated into costs.

Feedstock preparation prior to conversion usually involves the harvesting, comminution and transport of forest residues from the forest to the conversion facilities. The harvesting process includes the collection of branches, tops, and pieces that do not meet the utilization standards for timber and pulp-paper production. The comminution of forest residues allows for particle size reduction to facilitate handling and transportation. In the PNW, harvest residues are comminuted using grinders that can be adjusted to provide finer and or coarser wood particles [6]. Screen size and bit type (hammer) are two grinding parameters that could affect particle size distribution and bulk density of the processed residue. Grinders using large screens yield a higher proportion in coarser

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particles. In contrast, using small screens reduces the proportion of oversized pieces but grinder fuel consumption could be affected since more power is needed to recirculate and re-cut bigger particles until they can pass though the small holes. The type of bit also affects particle size distribution depending on the type of edge. Processing with sharp-edged bits could help to increase bulk density and reduce fuel consumption because they tend to cut the material rather than only hammer it. On the other hand, hammer-carbide bits with blunt edges do not have the ability to cut the material and therefore more power and fuel would be required to break and reduce the size of the material [7].

Transportation of comminuted biomass in the form of grindings is mainly performed by truck-trailers of different capacities. Characteristically steep terrain in productive forest areas of the PNW limits the capacity of the trucks that can access the harvesting sites [8]. Since truck capacity is limited due to access, the maximization of trailer capacity is an important factor to consider. The management of bulk density through the adjustment of grinding parameters is one of the key factors to increase transportation efficiency [9]. In general, higher bulk densities are preferred to increase the capacity of the trailer during transportation as long as the material is dry enough to avoid being limited by volume rather than legal weight [10]. Increasing the kilograms per cubic meter of dry biomass could help to decrease transportation cost by hauling more material per trip.

In terms of bio-jet fuel the particle size distribution could have an impact on the conversion efficiency [27] and thus in the feedstock preparation cost. Specific guidelines for target particle size distribution are not completely developed for bio-jet production since there is still on-going research in the conversion of wood to liquid fuels. However, typical conversion processes to break hemicellulose sugars do not allow oversized particles of more than 50 mm and fine particles of less than 3.2 mm [11–13]; similar ranges apply for forest biomass boilers for electricity production [14]. Oversized pieces tend to clog the compartments of the equipment where the pretreatment and conversion processes take place [15]. Also, the breaking down process of the hemicellulose through fermentation may be longer with large pieces compared to smaller ones thus affecting pretreatment and conversion times [16]. However, oversized pieces can be reground at an additional cost to reduce their size to optimal ranges. Fines are often a problem since they usually contain higher proportions of contaminants such as sand, grit and bark that lead to low sugar yields. Prior work has shown the removal of fines could warrant some attention to avoid conversion problems and low yields [17,28]. Although previous literature have addressed many aspects of the effect of grinding in the bioenergy supply chain, they usually focus on observational studies of on-going industrial operations. This study is based on a controlled test to avoid confounding factors that could also affect bulk density and fuel consumption. Material was selected from the same site, separated in different piece sizes, and processed using the same machine under controlled grinding parameters.

Our main objective is to analyze the economic trade-offs of feedstock comminution by adjusting different grinding parameters such as screen size and bit type. Specifically we explore the effect of four different factors: (1) fuel usage on grinding cost; (2) oversize piece production on resizing cost; (3) fine particles production that degrades residue value to hog fuel; and (4) bulk density on transportation cost.

1.1. Material and methods

Douglas-fir (*Pseudotsuga menziesii*) harvest residues were collected from a 40-year-old stand in western Oregon, USA. Prior to comminution, residues were separated in three size classes: tops-limbs; pulpwood logs; and chunk-wood. The top-limbs size class consisted of pieces of less than 10 cm in diameter and variable lengths from 60 cm to 2 m. Pulpwood logs consisted of pieces with a diameter ranging between 10 and 20 cm and length between 2 and 8 m. The chunk-wood size class consisted of pieces with diameters greater than 20 cm and lengths of less than 1 m usually from the first (lowest) log in the tree. By the time of collection the pulpwood logs and chunk-wood had dried to about 24–26% moisture, while the tops and limbs were at about 15% moisture (wet basis). This was determined from 72 samples taken randomly and tested following ASTM-E871-82 procedures [25].

Six grinder parameter combinations to control particle size distribution were evaluated consisting of two bit types (knife-edge and hammer-carbide) and three screen size combinations (Table 1). The screen size consisted of a set of four screens located in the periphery of the cutting rotor, two smaller screens are combined with two larger screens to reduce the amount of spears (unusually elongated pieces) and oversized particles. The small screen combination consisted of two screens with 5 cm hexagon type openings and two larger screens had 7.6 cm openings. The medium screen size combination consisted of two 7.6 cm screens combined with two 10.2 cm screens. The large screen size combination consisted of 10.2 cm screens combined with a pair of 12.7 cm screens.

Residues were processed with a Peterson 4710B (570 kW) horizontal drum grinder. This machine is equipped with 20 bits that break the material and force it to pass through the screens. Grinder in-feed speed was set to 6 m min^{-1}. Cutting rotor speed was 3.3 Hz. Approximately eight tonnes of harvest residue was processed in each feedstock size class and grinder parameter combination. The key grinding response variables in the study were specific fuel consumption, material bulk density and particle size distribution. The controlled variables (Fig. 1) feedstock size category, grinder bit type, and grinder screen size. Methods on the experimental design of the controlled variables as well as results from the response variables were obtained from a previous study [18] (see also supplementary material file). Each of these responses has direct linkage to a cost component of the feedstock value chain.

Following the comminution of the residues for each grinding trial, samples of approximately 250 kg were collected and shipped to the Weyerhaeuser Technology Center in Federal Way, WA, USA, (WTC). Those samples were then subjected to simulated mill-site mechanical gyratory screening using a 4.4 cm round-hole perforated top deck to screen out "Oversize" material, and a 3.2 mm woven-wire bottom screen to remove "Fines". Gyratory screens are a form of vibratory screen that can provide strong control over particle size separation.

Since the absolute cost was not the main focus, all parameter combinations were indexed to a base scenario using hammer-carbide bits with 5 and 7.2 cm screens (medium), and feed piece class pulpwood (P-H-M). Cost variables used in the analysis are listed on Table 2.

1.2. Assumptions in the cost analysis

For the cost model, several assumptions were made in relation to the grinding and transportation operation. It was assumed that residue is located in piles roadside, which represent most of the cases for harvest units using cable or aerial systems. In ground-based harvested units, piles may not be located roadside but their location and distance from the road is highly variable and dependent on the operation techniques and personnel. For the grinder, an off-road diesel fuel price of \$0.93 l^{-1} was assumed given the forecast prices for 2014 [23]. It was also assumed that the grinder and loader system were running at 75% of full power each operating hour

Table 1
Grinder parameters evaluated for each of the feedstock size classes-tops and limbs (B), pulpwood (P) and chunk-wood (C).

Parameter code	Bit type	Screen size combination (cm)	Screen type
K-S	Knife-edge	5 and 7.6	Small
K-M	Knife-edge	7.6 and 10.2	Medium
K-L	Knife-edge	10.2 and 12.7	Large
H-S	Hammer-Carbide	5 and 7.6	Small
H-M	Hammer-Carbide	7.6 and 10.2	Medium
H-L	Hammer-Carbide	10.2 and 12.7	Large

using a constant fuel of 100 L of diesel per hour. In terms of particle resizing, it is assumed that all big particles will be resized to acceptable particles. Feedstock through-the-gate cost (cost of harvesting, processing and transporting the forest residues from the forest to the conversion facility) was assumed at $75 per oven-dry tonne [19]. For transportation, it was assumed that the moisture content is sufficiently low that the chip vans would fill volumetrically before reaching the gross vehicle weight (GVW) highway legal limit (for typical bulk densities and chip van configurations, the change-over between volume-limited and weight-limited trailer loads is around 35% moisture content, wet basis).

1.3. Comminution cost

To examine the cost sensitivity from grinder to plant, collection activities prior to comminution were not included. Residue is assumed piled at roadside. It is assumed the feedstock will be prepared by moving a mobile horizontal grinder to a residue pile at a truck-accessible landing in a forest harvest setting. At the hypothetical mill-site, the target specifications for particle size distribution to the conversion process are constant, and neither oversize pieces (particles>4.4 cm), nor fines" (particles<3.2 mm) are permitted to enter the bio-jet chemical-biological conversion process. This point in the chemical-biological process is often referred to as the conversion mouth.

Fuel usage was calculated on a per tonne basis. The liters of fuel used for each grinding parameter combination (Fc_i), were translated to a specific fuel consumption based upon total wet tons processed and moisture content, yielding liters per oven dry tonne (see supporting information file). As previously mentioned, it was assumed that the loader and grinder were kept running at 75% of full power each operating hour using a constant fuel (Fe), of 100 L of diesel per hour. Hourly operating average costs for grinding alone, not including fuel, were assumed to be on average \$216 h^{-1}, and the required separate loader to feed the grinder was assumed to cost \$102 h^{-1}. Similar costs are reported by Refs. [6,20,21]. Given a fuel consumption of 100 L per hour a total cost of \$93 h^{-1} was calculated. Adding up loader, grinder operating and fuel costs, it resulted in a total grinder hourly costs (Gh_i) of \$411 h^{-1} regardless of tonnes produced. The tonnes produced would vary by each parameter combination. Then for each parameter combination the total hourly costs of \$411 (including fuel) were allocated to the tonnes per hour that could be produced using the constant 100 L per hour. The fuel consumption per oven dry tone by grinder parameter combination (Fc_i) allowed us to calculate grinding cost differences (C_i) from the base scenario (Eq. (1)).

$$C_i = Gh_i\frac{Fc_i}{Fe} - Gh_i\frac{Fc_{baseCase}}{Fe} \quad (1)$$

After comminution and transport, the screening of the residues is needed to separate the oversize and fine particles fractions. In this study we assumed a cost of \$3.9 t^{-1} [29].

1.4. Oversize particles resizing cost

The oversize screening rejects would not be disposed of, but instead re-sized, typically in a hammer mill type hog. Using literature values for total re-sizing costs using an electrically powered

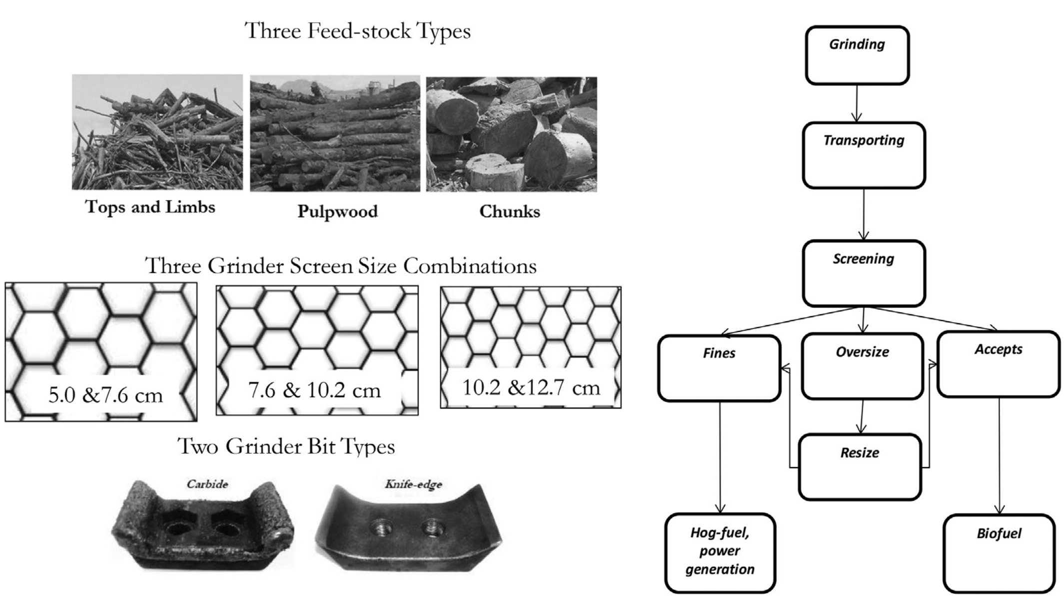

Fig. 1. Overview of the grinding trial controlled test variables, feed-stock type, screen size combination (5.0 & 7.6 cm; 7.6 & 10.2 cm; and 10.2 &12.7 cm) and bit type (hammer-carbide, and knife-edge) and system-processes flow.

Table 2
Variables and description for the cost analysis.

Variable	Description
$Bk_{basecase}$	Oven-dry bulk density for base scenario, kg m^{-3}
Bk_i	Oven-dry bulk density for parameter combination *i*, kg m^{-3}
C_i	Difference in grinding cost for parameter combination *i*, from base case, *\$ t^{-1}*
Cr	Resizing cost of oversized particles, *\$ t^{-1}*
Fc_i	Fuel consumption for parameter combination *i, l t^{-1}*
$Fc_{baseCase}$	Fuel consumption for base scenario parameter combination, *l t^{-1}*
Fe	Constant hourly fuel consumption for a grinder using 75% of available power, *l h^{-1}*
F_i	Fine particles cost for parameter combination *i*, from base case, *\$ t^{-1}*
Gh_i	Grinder hourly cost for parameter combination, *\$ h^{-1}*
Hp	Hog fuel price, *\$ t^{-1}*
O_i	Difference in oversize particles resizing costs for parameter combination *i*, from base case, *\$ t^{-1}*
$Pf_{baseCase}$	Proportion of fine particles for base scenario *i*, *%*
Pf_i	Proportion of fine particles for parameter combination *i*, *%*
$Po_{baseCase}$	Proportion of oversized particles for base scenario, *%*
Po_i	Proportion of oversized particles for parameter combination *i*, *%*
Pp	Through-the-gate feedstock price, *\$ t^{-1}*
Tc	Transportation costs per tonne per trip, *\$ t^{-1}*
T_i	Difference in transportation cost for parameter combination *i*, from base case, *\$ t^{-1}*

hammer mill in a centralized site including amortized capital, power costs, maintenance, etc. [14], we translated the total cost per oven-dry tonne of re-sized material (Cr) of \$3.83 t^{-1} into a differential cost based upon total feedstock. The cost differences (O_i) between each parameter combination and the base scenario are given by:

$$O_i = Po_i Cr \; - \; Po_{baseCase} Cr \tag{2}$$

1.5. Fine particles cost

The rejected fines would not be completely devalued (e.g., by sending to landfill), as they can be used as an energy source, either internally if the facility has a hog fuel boiler, or alternatively sold on the open market for power generation. Either way, the valuation can be set by market prices for hog fuel (Hp), which for the PNW region is around \$50 per oven-dry tonne [22]. The impact of fines rejects is then only the cost differential between the total assumed through-the-gate feedstock price of \$75 t^{-1} (Pp) and the hog fuel value, but only for the fraction rejected to hog fuel (Pf_i). This cost is then spread back over the total tonnes meeting specifications, expressing the cost change on a basis of feed tons, relative to the base case (Eq. (3)).

$$F_i = \frac{Pp - (Pf_i * Hp)}{1 - Pf_i} - \frac{Pp - (Pf_{baseCase} * Hp)}{1 - Pf_{baseCase}} \tag{3}$$

1.6. Transportation costs

To evaluate impacts on transportation costs, a 120 km one way haul using a 92 m^3 drop center chip van was used and the load carried adjusted according to the oven-dry bulk density of the material. Bulk density resulted from each parameter combination (Bk_i) was measured by loading one-half of a dump truck from an altitude of 1.2 m (see supporting information file). While these results do not give results corresponding exactly to fully loaded chip vans of normal height (2.6 m), the relative bulk density differences can be translated to full chip vans. Thus, by referencing the grinder parameter combinations against the chosen internal base scenario, the observed differences can be translated into truckload value differences for hauling costs. To translate these bulk density differences into a feedstock delivered cost change, it was assumed that the moisture content is below 35%. To achieve this level of moisture different management strategies are important to allow the residue to dry in the field. Transporting wet residue (<35% moisture content wet basis) makes transport cost inefficient since a great percent of the payload is water instead of dry matter. For the reference material, the round-trip transportation cost (Tc) for the 120 km trip was \$368 or about \$26.02 t^{-1}, similar costs are reported by Refs [6,20]. Changes in haul cost due to changes in bulk density were calculated by calculating the oven dry tonne in a 92 m^3 using the densities found in the trials.

$$T_i = Tc\left(\frac{Bk_{basecase}}{Bk_i}\right) - Tc \tag{4}$$

2. Results

2.1. Base scenario

We present the results for the base scenario that consisted of processing pulpwood size residue with hammer-carbide bits and a medium size screen combination (P-H-M). The results of the base case can be compared then with the cost differences (Table 3).

2.2. Grinding costs

Grinding costs between scenarios had high large relative differences due to fuel usage (Fig. 2). Lowest grinder cost per oven dry tonne was achieved by processing small pieces (tops and limbs), medium screen combination and knife-edge bits (\$8.82 t^{-1}). The highest grinder cost occurred with processing chunk wood with hammer-carbide bits and a small screen combination (\$34.94 t^{-1}).

Compared to the assumed typical total feedstock through-the-gate cost of \$75 t^{-1}, the total range of impact for grinding cost is large, nearly \$26.12 t^{-1} (between \$8.82 and \$34.94 t^{-1}), (Fig. 3). Most of the grinder parameters that used knife-edge bits resulted in lower costs compared to the base scenario (P-H-M) that used carbide-hammer bits because fuel usage is lower using the knife-edge bit compared to the carbide hammer bit [18].

2.3. Oversize Re-sizing cost

The conditions of the grinding parameter combinations, in particular the grinding screen size used, had a significant impact on the amount of oversize rejected above the 4.4 cm round-hole screen. There was nearly a factor of 10 difference between high and low cost combinations. (Fig. 4). Larger screen combinations allowed more oversized pieces to pass thorough the screens. Chunk-wood produced more oversized pieces due to the large cross section and relatively short length of these pieces that were difficult to either properly feed and/or cut during grinding.

Resizing oversize particles in a fixed, electrically powered hammermill is relatively inexpensive per unit processed. Resizing costs used here are PNW electricity rates of approximately 6.28 ¢ kW^{-1} [26], but could increase depending on the location and available power sources., Since only about 1%–10% of the feedstock needs to be resized, when expressed on the basis of feedstock to the conversion mouth, the economic impact is very small—the range is only \$0.42 t^{-1} feedstock through the gate (Fig. 5). This impact is dwarfed by the grinding cost effects shown earlier.

2.4. Fine particles downgrade to hog fuel cost

The fines reject levels can vary quite dramatically, in particular being high with the relatively dry tops and limbs when using hammer-carbide bits and a small grinder screen (Fig. 6). Logically, larger grinder screens produced more oversize and fewer fines, and vice-versa due to the increasing area of contact of small screens with wood residue.

The cost impact of fines downgrade to hog-fuel value is not very large, mostly due to the relatively small proportion that is downgraded, but also to the relatively small per-tonne value downgrade (Fig. 7). The total range of impact on a feed basis is \$3.05 t^{-1} feed (range between \$0.40 and \$3.45 t^{-1}).

2.5. Bulk density and hauling cost

The range in actual bulk density observed during the grinding tests suggest that bulk density is an important cost element for feedstock (Fig. 8). The results show that the tops and limbs gave higher bulk densities for all bit type and screen size conditions. This is likely due to both higher wood density of this material (which averaged 33% higher than pulpwood size class), and may also have been impacted by drier material and higher bark content, both of which could produce more fines. For larger piece sizes (pulp logs and chunks) the knife-edge bits gave consistently higher bulk density than hammer-carbide bits. The impact of bulk density had considerable cost impact with a total range of \$11.31 t^{-1} difference (Fig. 6).

3. Discussion

3.1. Total cost impact of all factors combined

Since the four factors described in the previous section are not independent of each other, and often are in counteracting directions, the net effect for any grinder parameter combination is not often obvious. For example, the use of smaller grinder screen combinations can increase fuel consumption thus increasing grinding cost, but also can increase bulk density, lowering transport costs, and reducing oversize and resizing costs, but increasing fines downgrade cost to hog fuel. Since the same reference base scenario was used for all relative comparisons, the net can be obtained by summing all impacts for each treatment. The range for total impact is \$35.77 t^{-1}, meaning that the cost for grinding, oversize particles resizing, fine particles downgrading and transportation will range between \$28.01 and \$63.78 t^{-1} depending on the grinding parameter combination and material size fed to the grinder (Fig. 9). This indicates that there is a large potential range of cost impact to the biofuels plant. If this cost range were applied to a large scale plant requiring 750,000 oven dry tonnes per year, it would change total costs by more than \$25 million dollars per year from one extreme to the other.

It can be seen in Fig. 9 that knife-edge bits are generally favorable in terms of lowering the total costs, and this arises from the combined effects of lower fuel consumption leading to lower grinding cost and higher bulk density giving lower hauling costs, the two most powerful effects measured here. In particular it would seem that hammer-carbide bits used on logs and chunks results in a particularly unfavorable cost condition. However it is important to consider that knife-edge wear off faster than carbide hammer bits, thus increasing downtimes that may affect grinder productivity and cost. Grinder screen sizes, seem to have little overall impact due to counteracting effects.

Table 3
Variables and cost for base scenario pulpwood, processed with a combination of hammer-carbide bits and 7.6–10.2 cm screen combination (P-H-M).

Item	Value
Oven-dry bulk density, kg m^{-3}	126.06
Fuel Consumption, l t^{-1}	5.51
Oversize Portion, %	6.70
Fine Portion, %	5.30
Grinding cost, \$ t^{-1}	21.24
Oversize Resizing cost, \$ t^{-1}	0.26
Fine particles downgrading cost, \$ t^{-1}	1.42
Transportation cost, \$ t^{-1}	26.03

3.2. Application of results

From a bioenergy-mill purchaser perspective, setting the oversize specification too low (e.g. using 5.0 and 7.6 cm screens) to decrease the percentage of oversize pieces will result in increasing grinding costs for the supplier due to increases in fuel consumption. Although, reducing the oversize proportion may have a positive effect reducing transportation and resizing costs, it will not compensate the grinding and fines downgrading costs. Instead it is more cost-effective to process the residue with a larger screen to reduce grinder fuel usage and resize the oversize particles proportion. For example, the cost of grinding, overs resizing, fines downgrading and transportation cost is \$2.19 t^{-1} higher using small screens (5.0 and 7.6 cm; 1.3% of oversize particles; and 12% of fine particles) compared to a large screen (10.2 and 12.7 cm; 9.7% of oversized particles; and 6.2% of fine particles).

4. Conclusions and recommendations

The lowest grinding power was achieved by: a) starting with smaller piece sizes, b) grinding to larger final sizes, and c) using (sharp) knife-edge bits instead of (blunt) hammer-carbide bits. Under the assumptions used here, grinding costs have the largest cost impact range (\$26.20 t^{-1}) as compared to transportation, resizing, or product downgrades. The highest bulk density was obtained with: a) smaller feed piece size class—tops-limbs, otherwise, with b) knife-edge bits compared to hammer-carbide bits. The reason for higher bulk density with tops and limbs here was probably due to the combination of higher wood density and greater fines production due to drier wood and higher bark content. Higher bulk density (as long as moisture is low enough) reduces transportation cost and is the second most powerful cost effect, having an impact range of \$11.31 t^{-1}. This factor is important given that larger trailers could not be used due to difficult access in steep roads and therefore increasing the capacity per trailer per trip

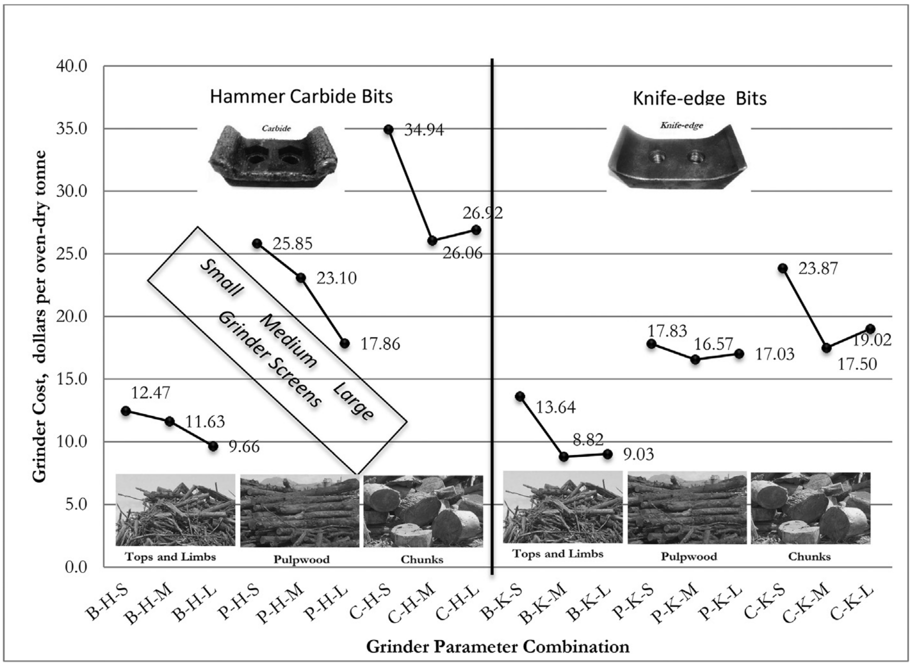

Fig. 2. Grinding cost per oven dry tonne for different parameter combinations: Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer carbide bits and screen size combination small 5.0–7.6 cm.

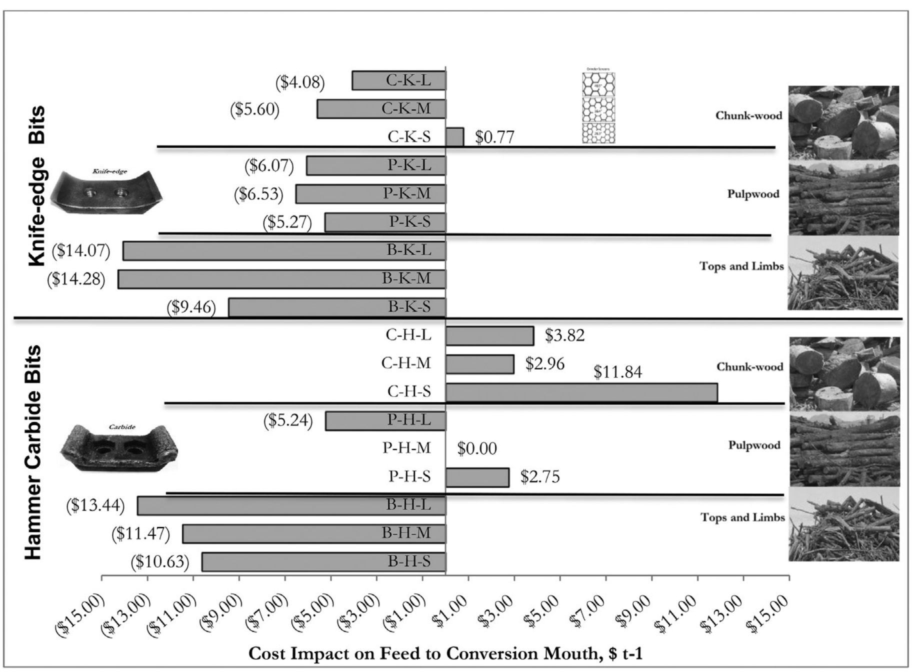

Fig. 3. Grinding cost differences from base scenario (P-H-M) vary significantly – a total impact range of \$23.70 t^{-1}. Control variable codes on y-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0–7.6 cm.

decreases significantly transportation cost. Oversize material production is, logically, almost totally controlled by grinder screen size. The cost impact of resizing oversize is very small; the impact range is \$0.42 t^{-1}. The fines downgrade to hog fuel is mostly related to grinder screen size, particularly for tops and limbs with hammer carbide bits. The cost impact of fines downgrade is relatively small; the impact range is \$3.05 t^{-1}. Overall, the total net impact of the variables assessed here can be quite large; the impact range is \$35.77 t^{-1}. Because both lower total grinding costs and higher bulk density was achieved consistently with tops and limbs, this feed piece size class was consistently favored for both bit types. For other feed class piece sizes (pulp logs and chunks), knife-edge bits were favorable to hammer-carbide bits, mostly due to lower grinding costs and higher bulk density for knife-edge bits.

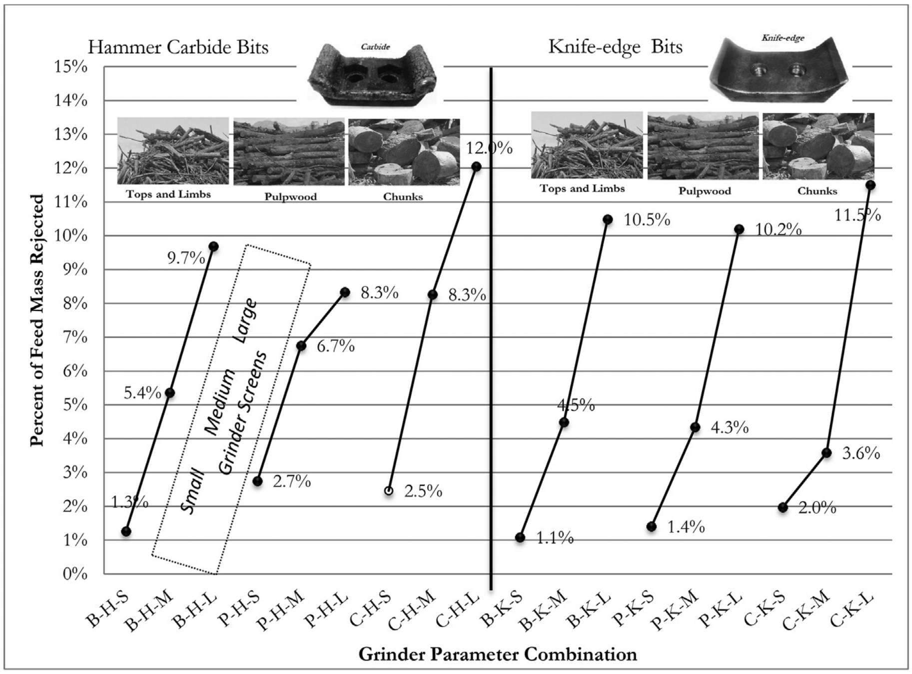

Fig. 4. Oversized particles for each of the grinder parameter combinations. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0–7.6 cm.

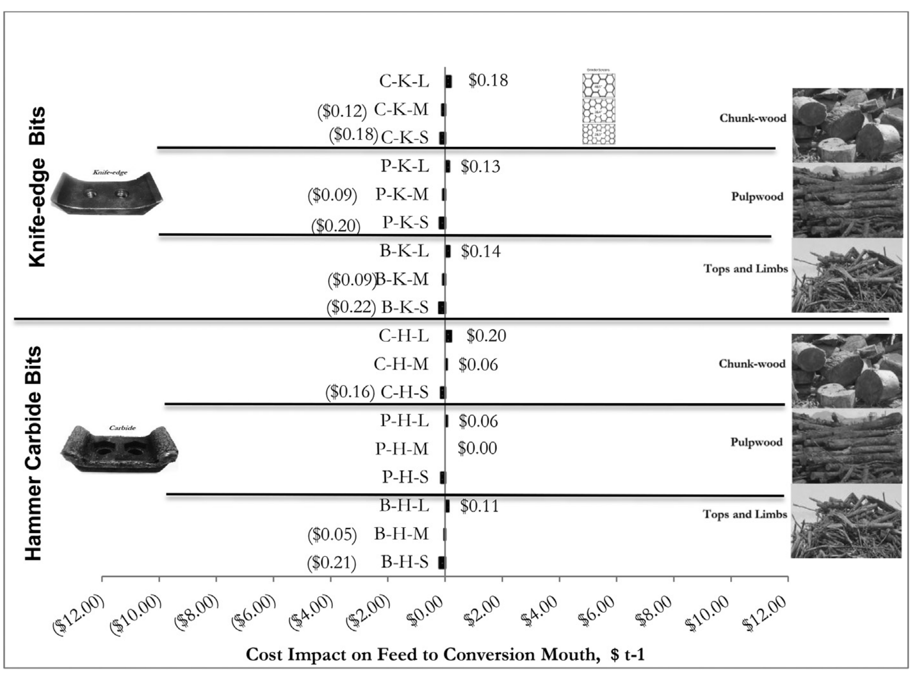

Fig. 5. Cost differences from base scenario (P-H-M) of oversize re-sizing costs as a function of the control variables. Control variable codes on y-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer carbide bits and screen size combination small 5.0–7.6 cm.

There are some caveats. Grinding cost differences assume that truck and residue availability permit the grinder to operate at 75% of maximum horsepower each hour. Lower truck availability would tend to reduce the range of grinding cost differences due to increased grinder waiting time. Knife-edge bits are somewhat more expensive and likely have higher maintenance costs and those could not be tested in this relatively short trial. Although it is possible to sort material size classes in practice, such as during delivery to the landing or during log processing on the landing, the materials that remain in residue piles are largely driven by pulp material and timber market demand. If pulp markets are not available and sufficient quantities of larger diameter pieces exist,

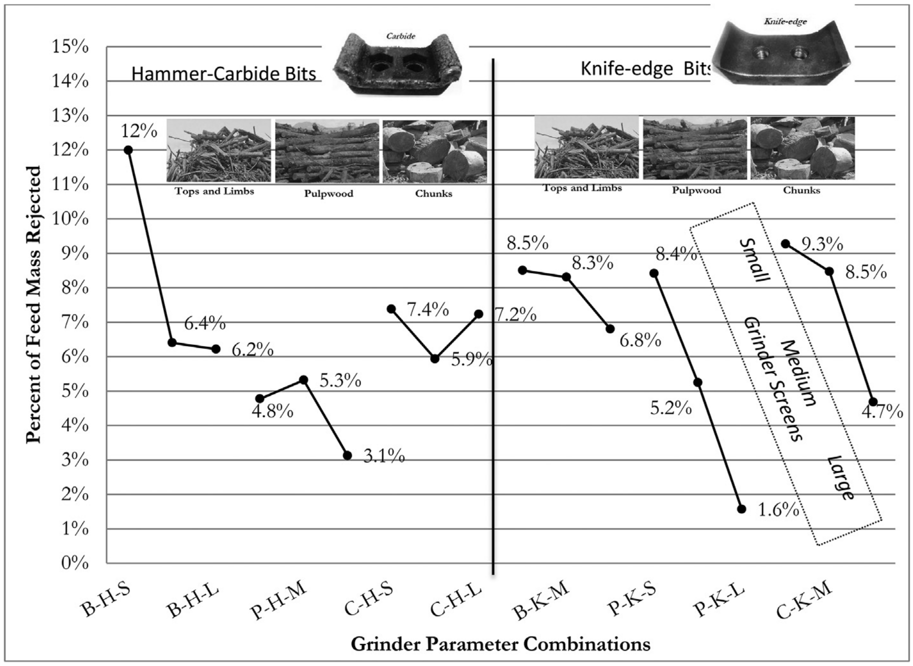

Fig. 6. Percent of fine particles rejected as a function of control variables. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0–7.6 cm.

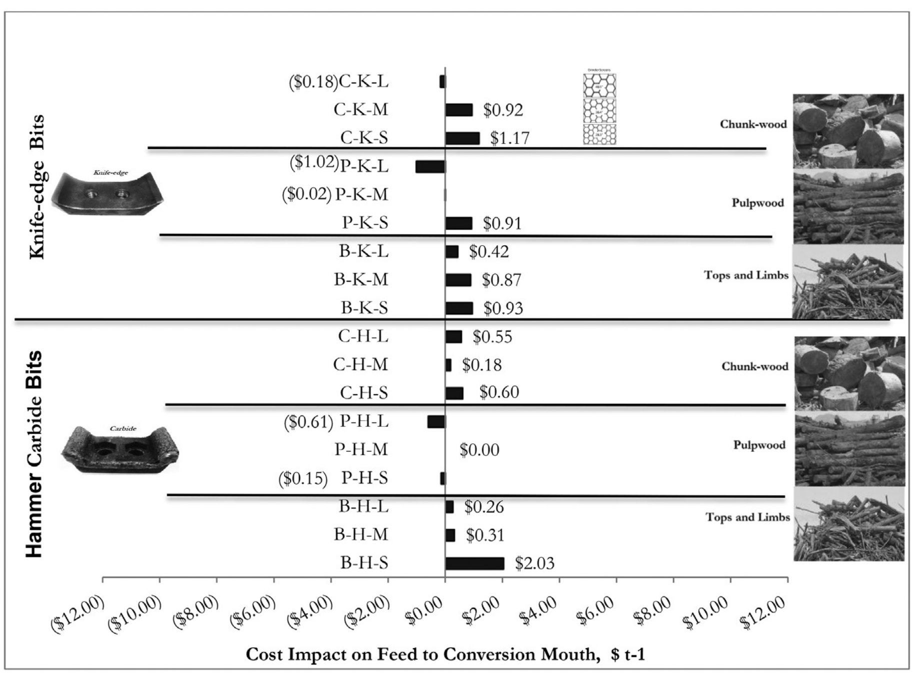

Fig. 7. The cost impact of fines downgrade to hog-fuel value as a function of feedstock size class, bit type and screen size. The maximum range of differences from the base scenario is \$3.05 t^{-1}. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0–7.6 cm.

then sorting and chipping the larger material, and grinding the smaller material is another material processing alternative that could be explored. Some of the bulk density benefit of tops and limbs is probably due to higher bark content creating more fines. Bark has lower conversion sugar yield and the lower conversion yield has not been explicitly accounted for here. Future work should test samples of each material type so that approximations of cost impacts of higher bark (lower total polysaccharides) can be quantified. While a "pulp chip" type size criteria was the assumed feedstock furnish, there is no disciplined analysis of optimum particle size distribution to conversion that trades added cost for preparing smaller particles against the presumed decreased conversion costs for reduced reaction/residence times. This optimization should be explored.

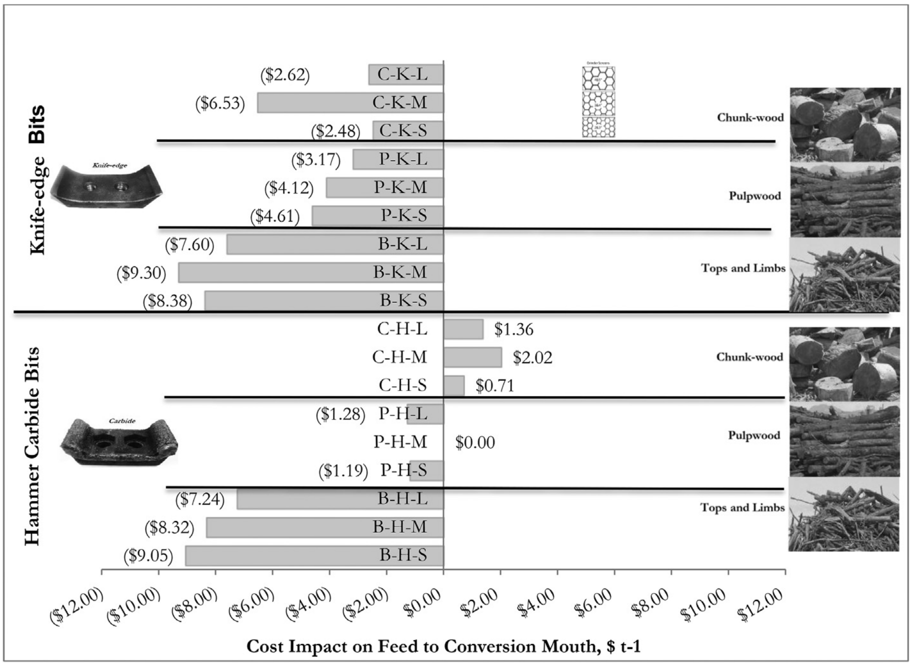

Fig. 8. Transportation cost differences from base scenario. The impact in cost range to \$11.31 t^{-1}. Control variable codes on y-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0–7.6 cm.

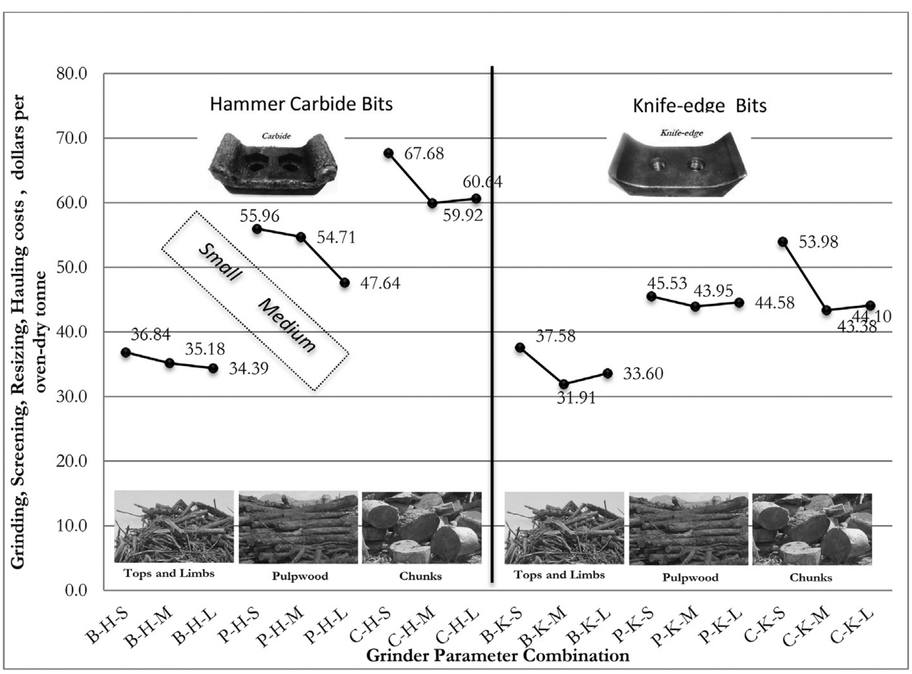

Fig. 9. Grinding, overs resizing, fines downgrading and transportation costs for each grinder parameter combination. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0–7.6 cm.

Disclosure policy

The authors of this manuscript, Gevan Marrs, Rene Zamora-Cristales and John Sessions declare that there is no conflict of interests regarding the publication of this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2016.07.071

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