FEEDSTOCK LOGISTICS (PART 5 OF 6)

TASK 4. EVALUATION OF CHIPPING AND GRINDING PRODUCTION TO MEET ALTERNATIVE FEEDSTOCK SPECIFICATIONS

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TASK 4. EVALUATION OF CHIPPING AND GRINDING PRODUCTION TO MEET ALTERNATIVE FEEDSTOCK SPECIFICATIONS

1. Introduction

Task 4 focuses on comminution of forest residues to meet specifications for pretreatment for liquid biofuels. Section 2 is an overview of the literature. Section 3 presents the experimental design and procedures for alternative methods of grinding forest residues, Sections 4 and 5 present results and conclusions. Section 6 focuses on increases to the bulk density of ground forest residues, and Section 7 evaluates the overall sensitivity to grinding parameters of feedstock cost. Section 8 describes a limited experiment to evaluate fuel consumption and particle distribution from grinding baled forest residues by Janna Loeppky, while a graduate student at Oregon State University. This document draws heavily from published peer reviewed manuscripts developed by investigators in the NARA project. In particular, we recognize:

Section 2-5.
Zamora-Cristales, R., J. Sessions, D. Smith and G. Marrs. 2015. Effect of grinder configuration on forest biomass bulk density, particle size distribution and fuel consumption. **Biomass & Bioenergy** 81 (2015): 44-54.

Section 6.
Zamora-Cristales, R., J. Sessions, D. Smith, and G. Marrs. 2014. Effect of high speed blowing on the bulk density of ground residues, **Forest Products Journal** 64(7/8): 290-299.

Section 7.
Marrs, G., R. Zamora and J. Sessions. 2016. Forest biomass cost sensitivity to grinding parameters for bio-jet fuel production**. J. of Renewable Energy** 99(2016):1082-1091.

2. Literature Review

Roadside forest biomass recovery operations from harvest residues require the use of processing machinery, such as grinders, to reduce the heterogeneity and increase the bulk density of the mixed residues to facilitate handling and transportation. Grinders, compared to chippers, are less susceptible to contaminants thus making them a feasible alternative for processing harvest forest residues (Hakkila, 1989; Spinelli et al., 2012). The grinding process reduces the size of the residues by hammering the material using bits (teeth) mounted in a cutting rotor. The residue is then forced to pass through screens until it is finally discharged onto a conveyor. The bit type and the opening size of the screens are two controllable factors that determine the particle size distribution and bulk density of the final product (Sang-Kyun et al., 2013). After processing, the grindings are usually dumped into chip vans that consist of a truck tractor and an open top trailer. Although larger trailers (>24 tons of capacity) are preferable in forest operations, low-standard roads, tight curves and adverse grades can limit access to sites where the residues are being comminuted (Sessions, et al., 2010; Angus-Hankin et al., 1995). Since using a larger trailer is often not feasible, other factors such as bulk density and moisture content must be managed to increase truck dry weight payload. Increasing the bulk density of the material in the trailer could reduce transportation cost by increasing the delivered dry wood per trip, thus decreasing the overall cost of the biomass operation. In addition to bulk density, the particle size distribution is important in terms of quality of the final product. In heating plants, oversize particles (>100 mm) can cause bridging problems that may stop the wood flow (Jensen et al., 2004). Fine particles may also cause a reduction in combustion and affect boiler performance (Badger, 2002; Naimi et al., 2006). The European Standard for fuel specification and classes of solid biofuels CEN/TS-14961 has defined different categories of wood chips and hog fuel based on the particle size (Alakangas et al., 2006). For liquid fuels production, the particle size distribution may influence how downstream processing will be configured to identify the fractions with high carbohydrate content and isolate portions with no sugar content such as soil particles. The amount of bark is also important to quantify, since it contains a lower amount of sugars and several inorganic and extractives components that reduce the energy yield (Zhang et al., 2012b).

In grinding operations, both bulk density and the particle size distribution of the final products can be influenced by adjusting the bit type and screens. Carbide hammer bits have dulled edges that are especially designed for processing dirty material due to their high abrasion wear-resistant capabilities. They are made of steel covered with carbide granules to increase abrasion during the cutting. Knife-edge bits do not contain a carbide cover. Knife-edge bits have knife type edges that cut/batter the material against the screens. Knife-edge bits are more suitable to process cleaner material and tend to produce a more homogeneous and denser product (Hurt, 2013). Increases in productivity and decreases in fuel consumption can be expected using knife-edge bits but their useful life is shortened by contaminants (Facello et al., 2014).

Screens are located in the cutting chamber in the periphery of the cutting drum. Since the area around the cutting rotor is large, several screens are needed to cover the different sections. Different screen pieces can be combined to reduce oversized particles and manage the particle size of the final product (Nati et al., 2010).

Previous studies have provided some insight about the effect of grinder configuration on forest biomass particle size and bulk density (Sang-Kyun et al., 2013; Dukes et al., 2013; Naimi et al., 2012), however, these studies are often based on observations of active industrial operations as compared to structured tests. In observational studies, uncontrollable and confounding elements can hide or affect the main effects of the factors under study such as bit type or screen size. From these studies some authors have reported that fewer oversized pieces were obtained when using small screens compared to larger ones (Jensen et al., 2004; Barmore, 2008). Fuel consumption tended to increase when using smaller screen sizes as compared to larger screens (Jensen, et al., 2004; Dukes et al., 2013), although other authors have reported increases in fuel consumption as screen size increases (Barmore, 2008). In Section 3 we performed a controlled test to decrease the variation of the system and isolate the effect of bit type and screen size on the particle size distribution and bulk density in order to understand potential trade-offs of some treatments in relation to fuel consumption. Understanding the grinding factors affecting bulk density will help to improve strategies to increase the amount of solid material per trailer per trip in order to decrease transportation costs.

Our hypothesis was that bulk density, particle size distribution and fuel consumption are affected by (a) grinder bit type; (b) grinder screen size; and (c) feedstock size class. The objectives of this study were to: (1) estimate the effect of two types of bits and three different screen sizes on the bulk density of the ground material, particle size distribution and fuel consumption for three feedstock size classes; and, (2) quantify the percentage of bark and other non-wood substances in each of the feedstock size classes. In this study we performed a controlled experiment with fully randomized treatments to minimize the effect of uncontrollable factors in our response variables (bulk density and fuel consumption) and to isolate the effect of the factors of interest (bit type and screen size) for 3 different feed piece classes.

3. Materials and Methods

3.1. Forest Harvest Residue Collection and Classification

We collected and transported approximately 180 tonnes of Douglas-fir (Pseudotsuga menziesii) wet residues from a harvest unit located 25 km north of Springfield, Oregon, USA (44°11’21”N, 122°59’15’’W). Residues came from a 40 year-old stand harvested between March and April 2013. Unprocessed residue was transported from the forest to a pulp and paper mill yard using an end-dump truck with a capacity of 76.5 m3. The study was conducted between July-August 2013. At the pulp and paper mill, residues were sorted in three different size classes using a John Deere 200 LC (104 kW) excavator loader.

The separation criteria of the residue were based on the size of collected residue (diameter of the piece and length) and its relation to the available markets for pulpwood and timber. In pulpwood markets with high demand, it is expected that logs with diameters greater than 10.0 cm and length of 3.6 m or longer would be removed from the logging site (Georgia-Pacific 2013, Perez-Garcia et al., 2012) and not available as harvest residues. In low pulpwood markets, logs with top diameter ranging from 15 cm to 20 cm may be left in the forest as residues. In addition to the pulpwood and non-pulpwood residue, large diameter butt log chunks can be available. These latter pieces are usually the result of the resizing process of the logs at the landing, particularly to meet export log requirements.

Based on these criteria and the available residue, we established three size classes to separate the residue material (Figure FL-4.1). The branches-and-tops size class consisted of limbs and tree tops with an average diameter of less than 10 cm and an average length of 1.0 m. This class represented the commonly available residue material in active pulpwood markets. The pulpwood size class was comprised of pieces with a diameter ranging from 10 to 30 cm with and an average length ranging from 1.2 to 4.3 m. In low demand pulp and paper markets this material would also be available as residue. The butt-log-chunks size class consisted of pieces greater than 30 cm with an average length of 50 cm. This class was comprised of pieces from the base of the tree and leftovers from the log manufacturing process. We analyzed the effect of bit and screen size combination in each of the three size classes.

Figure FL-4.1. Harvest residue classification by feedstock size. a) Branches-and-tops size class, typical residue with an average diameter of 6.3 cm and 1 m long; b) Pulpwood size class, medium size residue with pieces with an average diameter of 25 cm and 2.5 m long; c) Butt-log-chunks size class, large size pieces with an average diameter of 48 cm and 0.50 m long.

3.2. Experimental Design

A Peterson 4710B (570 kW) track-mounted horizontal grinder was used to process the residues. The cutting rotor of this machine was equipped with 20 bits to hammer the material and force it to pass through the screen area. The screen area consisted of four screens sections aligned next to each other. In this type of machine, the material is first compressed by an in-feed roll that permits a continuous feeding at a constant speed. Once the material is inside the cutting chamber, it is reduced to small pieces by the cutting rotor where the bits are mounted. The bits in the cutting rotor hammer/cut the harvest residue and force the particles to pass through the screens (Figure FL-4.2). The grinder in-feed speed was set to 6.1 m min^{-1}. Cutting speed was fixed to 33.3 Hz. The machine was remotely operated by the same operator in all the trials. We tested two different bit types, carbide hammer and knife-edge (Figure FL-4.3), and three different screen sizes of four hexagon-type grates with opening sizes of 5.0, 7.6, 10.2 and 12.7 cm respectively (Figure FL-4.4).

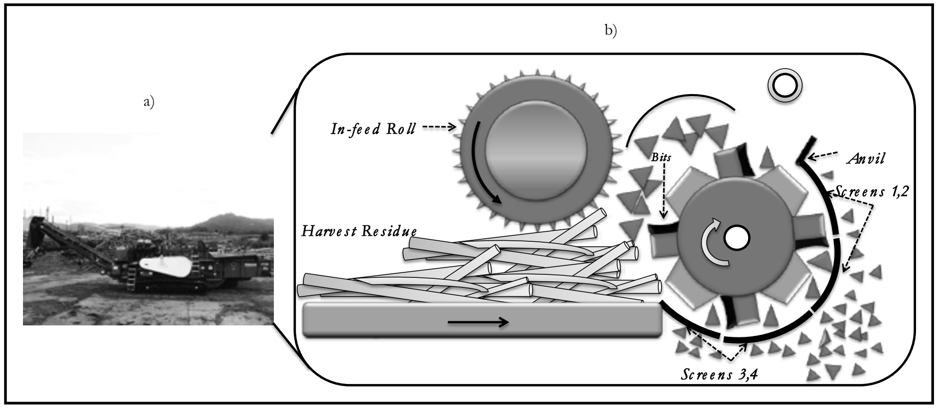

Figure FL-4.2. a) Horizontal grinder used in this study; b) diagram of the grinding process of harvest residue.

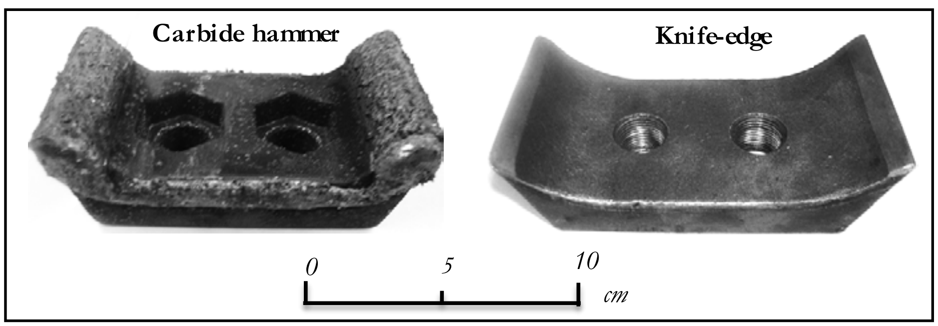

Figure FL-4.3. Examples of carbide hammer and knife-edge bits.

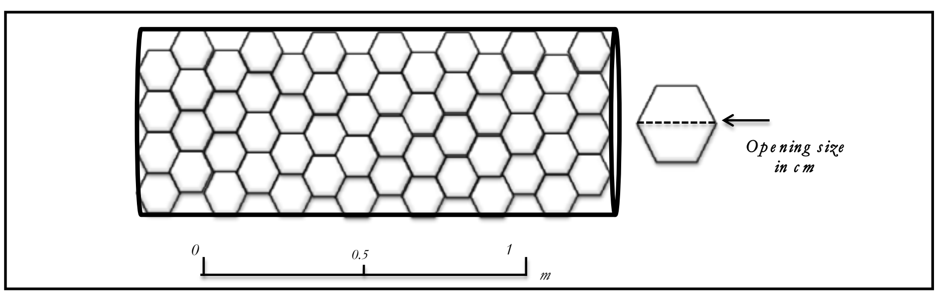

Figure FL-4.4. Hexagon type screen used in the experiment.

The machine utilized four screens, two at the top and two at the bottom of the cutting chamber. We tested three different screen size combinations 5.0-7.6 cm (small), 7.6-10.2 cm (medium) and 10.2-12.7 cm (large). The first number in each pair indicates opening size of the two screens that are set at the top of the machine. The second number indicates the screen opening size of the other two screens that are placed below the upper screens. In a combination of screens, the smaller section is usually placed at the top to reduce the proportion of long thin pieces (spears). The larger screens located below the top screens help to avoid significant decreases in productivity (Peterson Pacific Corporation, 2013).

The experiment consisted of two bit types and three screen sizes for a total of six treatments: (1) knife-edge-small; (2) knife-edge-medium; (3) knife-edge-large; (4) carbide-hammer-small; (5) carbide-hammer-medium; (6) and carbide-hammer-large. We performed 4 replications per treatment. Treatments were fully randomized and applied to each of the residue size classes under study (Table FL-4.1). For the branches-and-tops size class, we processed an average of 1.3 tonnes per trial. For the pulpwood and butt-log-chunks size classes we processed approximately 2.7 tonnes per trial to increase sample representativeness at each test.

Table FL-4.1. Randomized bit-screen treatments distributed in four replications.

Replication 1		**Replication 2**		**Replication 3**		**Replication 4**	
Screen size	***Bit Type***	***Screen size***	***Bit type***	***Screen size***	***Bit type***	***Screen size***	***Bit type***
Medium	Knife-edge	Medium	Carbide	Medium	Knife-edge	Small	Carbide
Large	Carbide	Large	Knife-edge	Small	Carbide	Medium	Knife-edge
Large	Knife-edge	Large	Carbide	Large	Knife-edge	Medium	Carbide
Small	Carbide	Small	Knife-edge	Medium	Carbide	Small	Knife-edge
Medium	Carbide	Small	Carbide	Small	Knife-edge	Large	Knife-edge
Small	Knife-edge	Medium	Knife-edge	Large	Carbide	Large	Carbide

After processing, the grindings were conveyor fed into a dump truck with a capacity of 11.7 m^3. The bin of the dump truck was divided in two compartments each with a capacity of 5.9 (front) and 5.8 m^3 (back) respectively. For the trials performed in branches-and-tops size class pieces, we filled the back compartment and for pulpwood and butt-log-chunks size classes we filled both compartments. After loading, the weight of the truck was recorded and the material was dumped for sample collection (Figure FL-4.5).

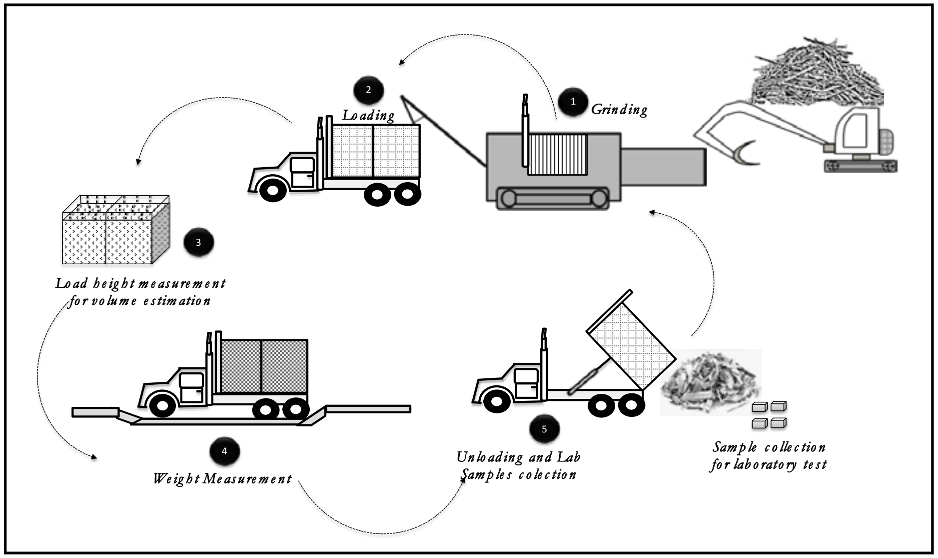

Figure FL-4.5. Field data and sample collection process.

We worked with a three-person crew. One person was operating the excavator loader, a second person was driving the bin truck and taking the weights at the scale and a third person was operating the grinder remotely, checking the loading process, recording the data and collecting the samples. After each trial, if a bit or screen change was required, the crew proceeded with the adjustment based on the randomized treatments. Each bit change required an average of 45 minutes. The screen change required approximately 50 minutes.

3.3. Bulk Density, Moisture Content and Particle Size Distribution

We ran laboratory tests to measure moisture content, particle size distribution, bark and other substances content, and lab bulk density. We collected approximately a 20 kg composite sample from each trial. The material was collected randomly from different places and depths after it was dumped from the truck. The samples were then transported using two 68-liter plastic boxes to avoid moisture loss.

Moisture content estimation was adapted from ASTM standard E871-82 for moisture analysis in particulate wood fuels (ASTM International, 2006). We dried approximately three 150 g samples per trial at 103 ± 1°C for 24 hours. We recorded the wet and dry weight and estimated the moisture content wet basis. Basic density was estimated adapting the procedures from the ASTM standard D2395 (ASTM International, 2008).

Bulk density was measured following the guidelines in ISO method 15103, 2011-10-12 (ISO, 2014). We filled to maximum capacity a 50-liter vessel by pouring the grindings from a height of 10.16 cm above the height of the container. After the container was filled with grindings, we dropped it three times from a height of 15 cm. Finally, we leveled to volume, recorded the weight and calculate the bulk density. We made three replications per sample for this test. Bulk density values were then converted to dry bulk density by using the moisture content. All bulk density values in this paper are reported in oven-dry kilograms per cubic meter.

Gross particle size distribution was quantified by pouring a homogenized 20 kg sample into a 50 x 127 cm Rotex oscillatory screen fitted with a 5.08 cm round hole top deck and 0.95 cm round hole bottom deck to separate the material in three gross size fractions: overs in the first deck, medium size “mids” in the second deck, and fines in the last deck. We recorded the weight of each fraction and estimated the percentage based on the sum of the total weight of the sample. Three replications per sample were made in this test.

A further, detailed size distribution was calculated for each of the categories estimated on the gross particle size analysis. For the overs and mids, we manually separated the sample into particles with a length of <7.62 cm; 7.62-15.24 cm; 15.24-30.48 cm; and >30.48 cm. We calculated the percentage in each of the four size fractions based on the total weight of all the fractions. For the fines we used a No. 6 Tyler screen (3.35 mm opening) and a vibrating screener set to 60% vibration to determine the percentage of 3.35 mm minus in the fines. We ran the screener for 4 minutes and weighed the fractions. We performed two replications per sample of this test.

Bark and other non-wood substances content was quantified by cone dividing the sample to isolate a representative volume of approximately 5 liters. We recorded the weight of this aliquot. Then we spread the material on to a table and manually separated all bark, needles, soil particles and other non-wood substances from the sample. We used a knife to strip bark from wood particles. We recorded the weight of bark and other substances and calculated the percent based on the total weight of the aliquot.

3.4. Fuel Consumption

Grinder fuel consumption was measured by adapting a 19 liter fuel tank to power the grinder. The main fuel and return lines were disengaged from the 1,135-liter main tank and plugged into the small tank. Since we were processing no more than 3 tonnes per run, the 19-liter fuel tank was sufficient. At each trial we turned on the grinder, processed the residues and turned off the engine. Before each trial, the tank was filled with diesel to a previously marked level. To avoid an over estimation in the fuel consumption measurement caused by starting and stopping the engine, we ran 15 independent tests to estimate fuel consumption for the engine starting and stopping process. This value was subtracted from the total fuel consumption per trial to accurately measure the fuel consumption during processing only. Diesel temperature was recorded using an Omega HH22 microprocessor thermometer type J-K thermocouple. After each trial we measured the temperature, and then we added diesel using a 1000 ml graduated cylinder until we reached the initial level. The amount of diesel added was recorded. Additionally, we recorded the theoretical fuel consumption from the engine computer of the grinder to compare with the manual calculation to evaluate the accuracy of the computer estimation. Temperature was recorded to compensate the potential changes in diesel volume due to the increase in the fuel temperature. We used a diesel expansion coefficient of 0.00083 per Celsius degree (Chevron Corporation, 2007). After an analysis of the temperature differences, we found little effect of temperature in the volume expansion within the small tank and thus, we considered the diesel thermal expansion negligible. Fuel consumption values were reported in the liters per oven-dry tonne of grindings.

3.5. Statistical Analysis

We performed individual two-way analysis of variance for each of the feedstock size classes using the measured bulk density and fuel consumption as dependent variables. The F-test for factorial effect consisted of two factors, bit type and screen size, each having two (carbide hammer and knife-edge) and three levels (small, medium and large opening size), respectively. The robustness of the F-test is dependent on several assumptions that we checked first in order to establish the applicability of this test. We assessed the normality assumption by creating Q-Q plots for each treatment and evaluating the dispersion pattern of the data. We also performed a Shapiro-Wilks test to ensure that normality assumption was met. The presence of outliers and variance were evaluated using side-by-side box plots of each treatment. We also tested the equal variance assumption using Levene's test and analyzing the dispersion pattern of the residual plots in each treatment. The assumption of independence was evaluated using residual plots. Data was ordered by the day that it was collected and treatment, and then residual plots were made to detect correlation or dependence among observations. The ANOVA test allowed us to analyze the effect of each factor and the interaction between them. We used a level of significance of 0.05. We performed pairwise t-test and multiple comparison analysis using the Bonferroni procedure when significant interactions between bit type and screen size were found. We also evaluated the effect of the two analyzed factors in the bark and other substances content. All the statistical analysis was performed in Statistical Package for Social Sciences (SPSS version 15), (SPSS, 2006).

4. Results

Results are presented by response variable (bulk density, particle size distribution and fuel consumption) in each of the feedstock size classes. Bulk density values are presented based on the oven dry weight and the wet volume. Fuel consumption values are presented in liters per dry tonne. Moisture content values are reported for each of the feedstock size classes.

4.1. Dry Bulk Density and Particle Size Distribution

The average moisture content for the branches-and-tops size class grindings was 15.3% (σ=3.2), wet basis. Basic density of grindings was 443.7 kg m^{-3}. For dry bulk density, resulting values per treatment in the branches-and-tops size class were normally distributed based on the dispersion pattern of the Q-Q plots and the Shapiro-Wilks test (p-values>0.05). The plot of residual over the time (days) did not show any serial effects. No significant difference in the variance among the treatments were found (p-value = 0.468 from a Levene's test). Results for the ANOVA test indicated that no significant effect of bit type was found (p-value=0.280). No evidence was found in relation to the screen size combination effect in the bulk density (p-value=0.104 for screen size combination). No interaction between the two factors was found (p-value=0.387). The small cross-section of the pieces in this piece size class could reduce the cutting capabilities of the knife-edge bit since the material was entangled and the cutting process could not be performed across the grain compared to pieces with larger diameter and longer. This also could decrease the effect of the screen size because particles could easily pass through the screen holes of all the screen sizes. Bulk density results for each bit and screen size are presented on Table FL-4.2.

Table FL-4.2. Dry bulk density for each of the treatments for the branches-and-tops size class.

Screen Size	Carbide hammer kg m^{-3}	Knife-edge kg m^{-3}
Small (5.0-7.6 cm)	162.2	166.7
Medium (7.6-10.2 cm)	147.6	167.0
Large (10.2-12.7 cm)	147.9	145.6

Particle size distribution was compared for all the treatments applied to the branches-and-tops size class. Using knife-edge bits, we found that between 76 to 91% of the particles were less or equal than 7.61 cm. In this group most of the particles had a size ranging between 0.95 to 7.61 cm (91.8, 85.6 and 76.8 % for each of the three screen sizes small, medium and large respectively). For both bit types, the amount of fine particles (<0.34cm) decreases as screen size increases. Small screen sizes have more contact area between the residue and screen, thus increasing the friction and producing more fine particles. Additionally, higher proportions of fines were produced using knife bits compared to carbide hammer bits. Larger screen sizes produced a higher proportion of oversized particles (>15.24 cm) for both bit types (Figure FL-4.6).

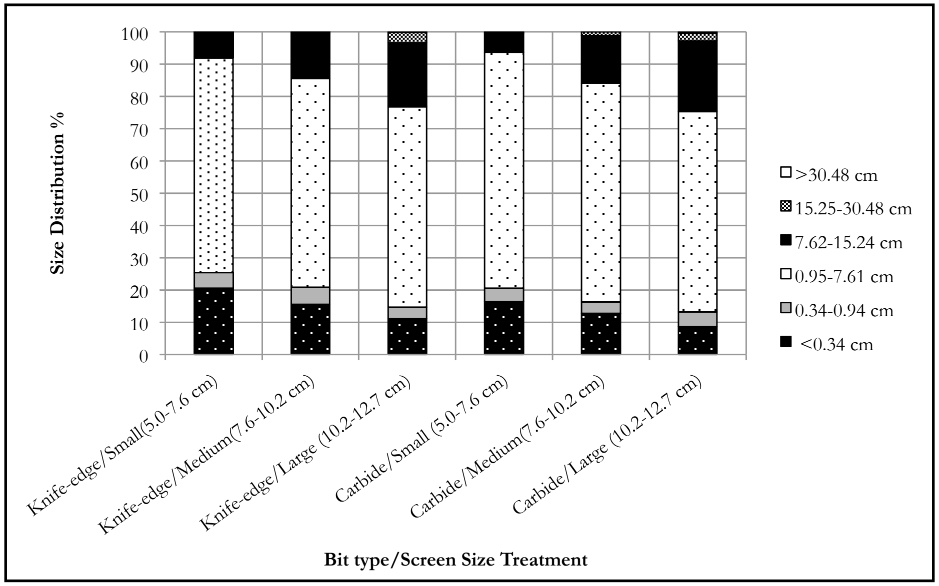

Figure FL-4.6. Particle size distribution per treatment for the branches-and-tops size class grindings.

Harvest residue in the pulpwood size class had an average moisture content of 24.8 % (σ=3.1), wet basis. Basic density of grindings was 401.9 kg m^{-3}. No outliers were found in any of the six treatments. Residuals from Q-Q plots indicated that the data is normally distributed. The visual interpretation of the residuals was supported by the Shapiro-Wilks test for each of the treatments that did not reveal any departures of normality. The equal variance assumption was confirmed after performing a Levene's test and also checking the side-by-side boxplots.

Results from the two-way ANOVA indicated that there was statistical significance of bit type and screen size on bulk density. No statistical significance was found in the interaction between bit type and screen size (Table FL-4.3). Knife-edge bits cut the material instead of typical hammering from carbide bits. The length of the pieces in this size class could facilitate the feeding process to produce the cut across the grain.

Table FL-4.3. Two-way ANOVA for the effect of bit type and screen size on dry bulk density for the pulpwood size class material.

Source	DF	Type III SS	p-value
Bit Type	1	2704.49	<0.0001
Screen Size	2	431.392	0.0260
Bit Type*Screen Size	2	0.219	0.9980

From the multiple comparisons Bonferroni test, we found significant differences in bulk density between the carbide hammer and knife–edge bits across all the screen sizes (Table FL-4.4). In general, materials processed with knife-edge bits have between 15.8 to 16.9% higher bulk density compared to grindings processed with carbide hammer bits.

Table FL-4.4. Differences in dry bulk density of the material processed in the pulpwood size class for each of the treatments.

Screen Size	Carbide hammer kg m^{-3}	Knife-edge kg m^{-3}	Difference kg m^{-3}	p-value	% Increase
Small (5.0-7.6 cm)	114.3	135.8	21.5±10.3	<0.0001	15.8
Medium (7.6-10.2 cm)	107.8	128.7	21.0±10.3	<0.0002	16.3
Large (10.2-12.7 cm)	104.2	125.5	21.3±10.3	<0.0003	16.9

Differences in bulk density across all screen sizes for carbide hammer and knife-edge bits only revealed statistical differences between the small and large screen. Using carbide hammer bits, bulk density was 16% higher using a small screen combination compared to a large screen combination. Using knife-edge bits to process the material, bulk density was 9% higher using a small screen combination compared to the large screen combination. No statistical differences were found for the comparison between the small-medium screen size combination for either knife-edge or carbide hammer bits.

Particle size distribution was evaluated for the pulpwood size class. In general, the proportion of particles with a length of 7.61 cm or less tended to decrease as larger screen combinations were used for both bit types. We found a slightly higher portion of larger pieces in material processed with carbide hammer bits compared to the material processed with knife-edge bits (Figure FL-4.7).

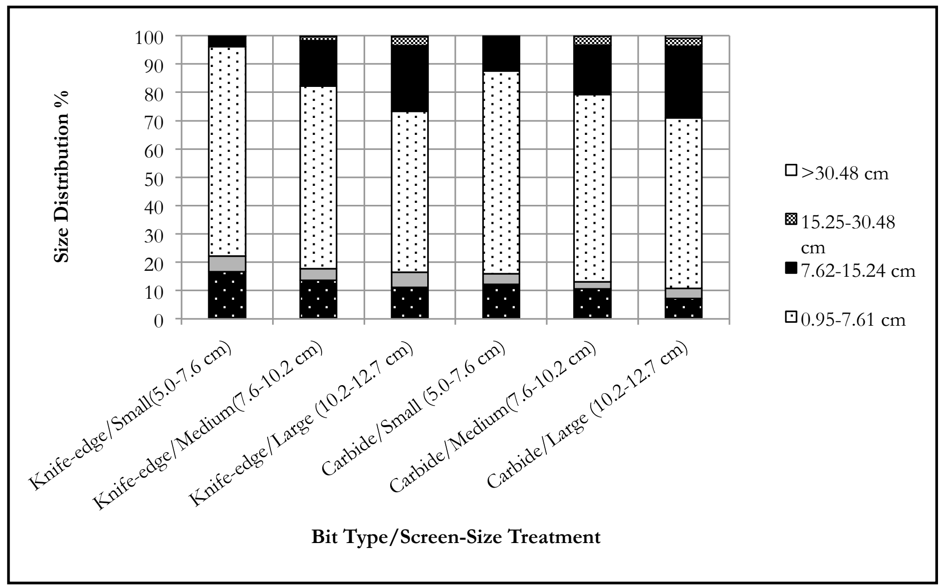

Figure FL-4.7. Particle size distribution per treatment for the pulpwood size class grindings.

Knife-edge bits produced a higher proportion of fine particles (pieces<0.95 cm) compared to carbide hammer bites as a product of the cutting process instead of only hammering. This could also help explain the increase in bulk density. Since the bits are cutting the wood, fine particles could be produced.

For the butt-log-chunks size class, no violations in the assumption for the ANOVA test were found. Resulting values per treatment in this size class were normally distributed based on the dispersion pattern of the Q-Q plots and the Shapiro-Wilks test (p-values>0.05). The plot of residuals over time did not show any serial effects. No significant difference in the variance among the treatments were found (p-value = 0.468 from a Levene's test. Harvest residue in the butt-log-chunks size class had an average 26.3 % (σ=4.6) moisture content. Basic density was 411.2 kg m^{-3}. Bulk density was strongly affected by bit type and screen size. The interaction between bit type and screen size was statistically significant for this type of material (Table FL-4.5).

Table FL-4.5. Two way ANOVA for the effect of bit type and screen size on dry bulk density for the butt-log-chunks size class material.

Source	DF	Type II SS	p-value
Bit Type	1	5690.30	<0.0001
Screen Size	2	720.41	0.0740
Bit Type*Screen Size	2	1361.69	0.0120

Dry bulk density was higher when using knife-edge bits compared to carbide hammer bits. The screen size effect on bulk density was mainly driven by differences in bulk density when processing with knife-edge bits (Table FL-4.6).

Table FL-4.6. Differences in dry bulk density per treatment in butt-log-chunks size class.

Screen Size	Knife-edge kg m^{-3}	Carbide hammer kg m^{-3}	Difference kg m^{-3}	p-value	% Increase
Small (5.0-7.6 cm)	132.2	107.5	24.7	0.0050	18.7
Medium (7.6-10.2 cm)	149.8	98.3	51.5	<0.0001	34.4
Large (10.2-12.7 cm)	119.0	102.8	16.1	0.0510	13.6

In terms of particle size distribution, the percentage of oversized particles ranged from 14 to 40%. The increasing amount of oversized pieces could be due to the larger pieces and the relatively short length (50 cm) that could affect the adequate feeding process to allow a cut across the grain (Figure FL-4.8).

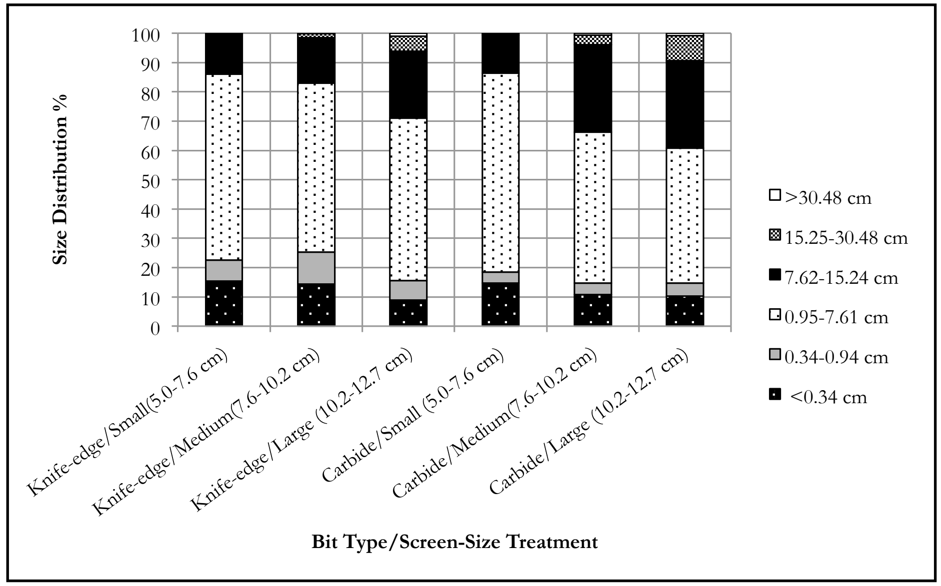

Figure FL-4.8. Particle size distribution for the butt-log-chunks size class grindings.

4.2. Fuel Consumption

For the branches-and-tops size class, fuel consumption values per treatment were normally distributed. No significant differences in the variance per treatment were found (p-value=0.399 from a Levene's test). We did not find any correlation between the fuel consumption variable and the time order of the data. There was evidence that screen size had an effect in the fuel consumption (p-value=0.022) potentially because it requires more energy to force pieces to pass through a small size screen compared to a larger one. From a multiple comparison test we found statistical differences in fuel consumption only when comparing the small versus large size screens. Fuel consumption increased from 1.8 $l\ t^{-1}$, using a large size screen to 2.5 $l\ t^{-1}$ using a small screen size (40% increase). No statistical significant effect was found for bit type or the interaction between bit and screen (Table FL-4.7).

Table FL-4.7. Fuel consumption in liters per dry tonne per treatment in the branches-and-tops size class.

Screen Size Combination	Carbide hammer $l\ t^{-1}$	Knife-edge $l\ t^{-1}$
Small (5.0-7.6 cm)	2.4	2.6
Medium (7.6-10.2 cm)	2.3	1.7
Large (10.2-12.7 cm)	1.9	1.7

For the pulpwood size class, the two way ANOVA test revealed that there was a statistical significant effect of bit type (p-value=0.002) and a moderate effect of screen size (p-value=0.057), on fuel consumption. The interactions between the two factors were not significant (p-value=0.113).

For bit type, fuel consumption was higher when the machine used carbide hammer bits compared to the knife-edge bits. Knife-edge bits may need less energy to process the material because they are cutting and not only hammering the residue (Table FL-4.8).

Table FL-4.8. Differences in fuel consumption per treatment in the pulpwood size class.

Screen Size Combination	Carbide hammer $l\ t^{-1}$	Knife-edge $l\ t^{-1}$	Difference $l\ t^{-1}$	p-value	% Increase
Small, 5.0-7.6 cm	5.1	3.5	1.6	0.003	47.9
Medium,7.6-10.2 cm	4.5	3.2	1.3	0.016	42.1
Large, 10.2-12.7 cm	3.5	3.3	0.2	0.620	-

The screen size had a moderately significant effect on the fuel consumption for material processed with carbide hammer bits but not with knife-edge bits. We found that fuel consumption decreases by 1.6±0.9 $l\ t^{-1}$, using a large screen size compared to a small screen size (p-value=0.004 from a pairwise t-test). For the medium-large screen size comparison, we found suggestive evidence of a difference indicating that fuel consumption decreases 1.0 $l\ t^{-1}$, when using the large screen combination compared to the medium screen size combination (p-value=0.051 from a pairwise t-test). For the small-medium screen size comparison, we did not found any statistical difference.

For the butt-log-chunks size class, fuel consumption values per treatment were normally distributed and no significant violations to the ANOVA assumption were found. Also we did not find any correlation between the fuel consumption variable and the time order of the data. Bit type has a significant effect on fuel consumption (p-value<0.001). Fuel consumption increased using carbide hammer bits comparing to knife-edge bits (Table FL-4.9). A significant difference in fuel consumption between the different screen sizes was also found when processing with carbide hammer bits (p-value=0.004).

Table FL-4.9. Differences in fuel consumption per treatment in the butt-log-chunks size class.

Screen Size Combination	Carbide hammer $l\ t^{-1}$	Knife-edge $l\ t^{-1}$	Difference $l\ t^{-1}$	p-value	% Increase
Small, 5.0-7.6 cm	6.9	4.6	2.3	0.001	49.2
Medium,7.6-10.2 cm	5.1	3.4	1.7	0.009	51.9
Large, 10.2-12.7 cm	5.3	3.7	1.6	0.013	44.3

4.3. Effect of Feedstock Size

For all treatments, we found significant statistical differences in dry bulk density between the different size classes (p-value<0.0001 from a one way ANOVA). From a multiple comparison test, we identified a statistical difference between the dry bulk densities in the branches-and-tops size class compared to the pulpwood and butt-log-chunks size classes. No statistical differences were found between dry bulk density results in the pulpwood size class compared to the butt-log-chunks size class. Dry bulk density for the branches-and-tops size class was 37.0 ± 12.2 kg m^{-3} higher compared to the pulpwood size class and 38.1± 12.2 kg m^{-3} compared to the butt-log-chunks size class. The branches-and-tops size class residue produced denser material compared to the other classes. This was caused in part by the higher basic density of these grindings compared to the other size classes. The known presence of reaction wood in branches can be related to this increase in basic density (Hakkila, 1989). In terms of screen size, a smaller screen size produced denser material compared to larger screen sizes, however the effect was not as evident as with the bit type. As feedstock size increased we observed stronger differences especially between the small screen compared to the medium and large screen combination.

Fuel consumption increased as feedstock size increased showing a similar trend to chippers that indicate that for larger pieces more energy is required to process them to pass a given screen hole size (Assirelli et al., 2013). Processing branches-and-tops size class material consumed 1.7±0.8 $l\ t^{-1}$ less fuel compared to processing pulpwood size class residues. Similarly, the grinding of branches-and-tops size class residue consumed 2.7 ±0.8 $l\ t^{-1}$ less fuel than processing residue in butt-log-chunks size class. Grindings from the pulpwood size class consumed 1.0 ±0.8 $l\ t^{-1}$ compared to butt-log-chunks size class grindings. Bulk density and fuel consumption for each of the treatments are shown on Figure FL-4.9.

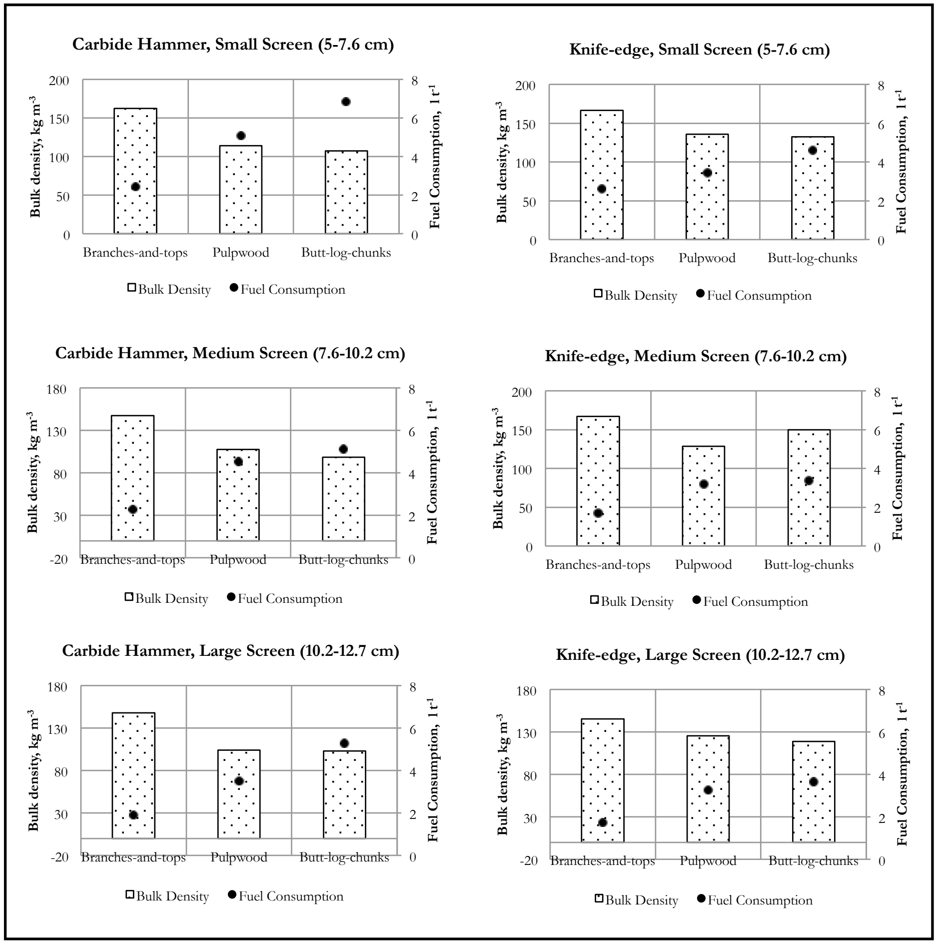

Figure FL-4.9. Dry bulk density and fuel consumption for each of three feedstock size classes.

4.4. Bark and Other Non-wood Substances Content

We estimated the proportion of bark and other non-wood substances content for the three size classes. No significant effects of bit type or screen size were found in the proportion of bark and other substances content. Significant statistical difference was identified between the amount of bark and other substances content in the branches-and-tops size class compared to the pulpwood and butt-log-chunks size classes (p-value<0.0001 from a one way ANOVA). Bark and other non-wood substances content in the branches-and-tops size class was 7.5±3.2 % higher than in the pulpwood size class and 7.9±3.2 % higher than in the butt-log-chunks size class (Figure FL-4.10).

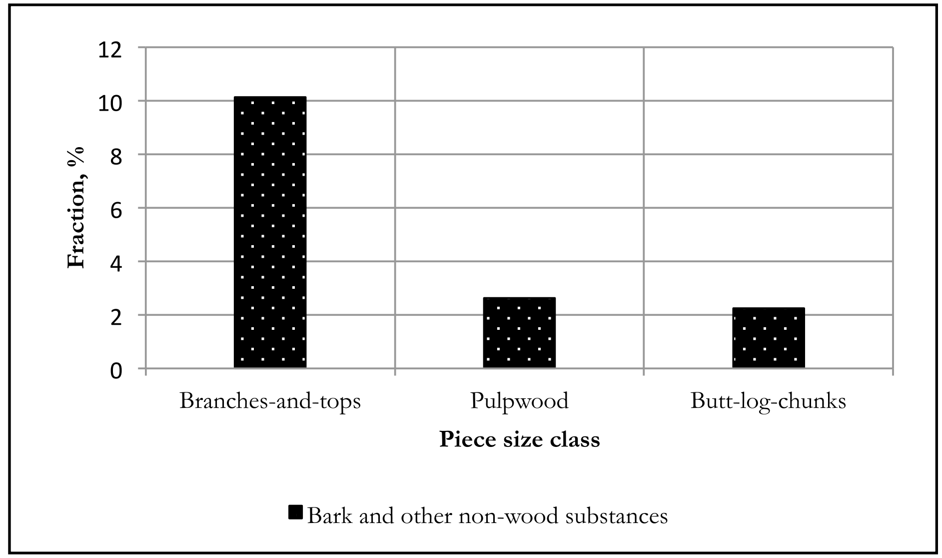

Figure FL-4.10. Bark and other non-wood substances content fraction in each of the three feedstock size classes.

We did not observe a higher amount of bark and other substances in pulpwood and butt-log-chunks size classes compared to the branches-and-tops size class, because those pieces were probably debarked by the log processor when the log manufacturing was performed at the landing during the harvesting. Also bark is loosest in the spring (Murphy and Pilkerton, 2011). Additionally, smaller pieces have a higher surface-volume ratio, thus greater proportions of bark and other non-wood substances (Spinelli et al., 2011).

5. Discussion

In general, knife-edge bits produced denser grindings compared to carbide hammer bits. The sharp-edge of the knife-edge bits tended to cut the material across the grain instead of the normal hammering process of the carbide hammer bits however the cut in direction across the grain could not be performed equally well in all the feedstock size classes. The other measurable benefit we found using knife-edge bits was the reduced fuel consumption. This effect was statistically significant in pulpwood and butt-log-chunks size classes but not in the branches-and-tops size class. Although several benefits can be obtained by using knife-edge bits, they are more susceptible to wear from dirt and they initially cost approximately 17 % more compared to carbide hammer bits (Peterson Pacific Corporation, 2013). We did not measure tool wear, but the shorter tool life may increase machine downtime and affect the benefits of using this type of bit. In general, using small screens may increase fuel consumption since more energy is required to pass the pieces through the screen compared to larger size screens. Although the effect of screen in dry bulk density did not show the same trend for all the treatments, we found that fuel was impacted by the screen size especially when using carbide hammer bits.

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Since carbide hammer bits lack of the ability to cut the material, they depend on the hammering of the residue, and thus they are more affected by a reduction in the screen size than knife-edge bits. The screen size also affected the proportion of oversized particles. In general, we found a higher proportion of oversized particles when processing the material using large screen compared to the small screen combination. On the other hand we found higher proportion of fines when using small size screens compared to the large size ones.

6. Opportunities to Increase Bulk Density

Transportation by truck-trailer comprises a large portion of the total delivered cost of comminuted forest harvest residues and the load quantity is dependent on the moisture content and dry bulk density of the residues. Dry bulk density is the mass of dry material in a unit of volume, and as long as the truck is below legal weight limits increasing dry bulk density will allow an increase in dry weight carried per truckload, reducing unit transportation costs. Dry bulk density is the dry weight of the wood per unit load volume (Briggs, 1994). It is affected by the comminution system, trailer loading method, particle size distribution and the specific gravity of the processed biomass that for residues is typically a mixture of wood, bark, dust, and needles (Hakkila, 1989). In this section, the effect of the loading method on the bulk density is analyzed.

Commonly, grinders dump the material into the truck through a discharge conveyor. After leaving the conveyor, grindings fall into the truck by gravity. Alternatively, the comminuted material can be accelerated and loaded into the trailer horizontally or vertically using a blower (Figure FL-4.11). The difference between these two loading methods is related to the speed of the particles when loading. In a typical conveyor-fed method, particles are accelerated by the force of gravity only. In a blower loading system, the particles are mechanically accelerated at specific speeds and therefore each particle contains more kinetic energy that tends to increase the particle settlement. Many commercial chippers have high speed fans or chip accelerators to force the chips into the trailers (Bruks, 2017; Morbak, 2017). Horizontally blown chips have been tested in the pulp and paper industry with good results in increasing the payload, however the longer the trailer, the more difficult to pack the chips especially in the front of the container (Thompson et al., 2012). The use of pneumatic blowers is also common when loading railcars for train transportation (Adler, 1978). In grinding operations, horizontal blowing has been tested to load trailers by adapting centrifuge blower devices to the grinder (Rawlings et al., 2004). Prior work from Uuscaara and Vekasalo (as cited in Hakkila, 1987) has also been done in testing density comparing different loading methods. Although extensive research has been found in the horizontal blowing of chips, few studies were found applied directly to grinding operations and no research was found in relation to high speed blowing of grindings in a vertical orientation during loading. Grindings differ from chips in being less uniform in terms of particle size distribution and usually have a lower bulk density compared to chips (Smith et al., 2012). Grindings usually have a higher proportion of bark and contaminants compared to chips because chipping most often takes place in log-like material that has been processed by delimbers that remove a percentage of the bark. Tests on pulp chips have usually been done at higher moisture contents for the pulpwood market (~50 percent wet basis). Here the interest is in lower moisture content material, both to improve transport efficiency, and to improve energy value for combustion. Moisture management strategies to improve forest harvest residue values by reducing moisture content have been proposed by Acuna et al. (2012), and Rogers (1981).

Figure FL-4.11. a) Conveyor-fed loading method into a chip van in a grinding operation; b) Horizontal blowing of wood chips into trailers.

In the United States, forest products including forest biomass are predominantly transported using trucks (Angus-Hankin et al., 1995; Schroeder et al., 2007; Forest Resources Association, 2006). Low bulk density of processed woody residues often results in a lower utilization of the truck legal load weight capacity (Thompson et al., 2012). Truck capacity can be measured in terms of volume and weight of the trailer (or trailers in double trailer configurations). A truck limited by weight indicates that the maximum allowable legal weight of the truck has been reached. The maximum legal weight capacity is measured as a function of the number and distance between axles and the specific road regulations. A truck is limited by volume when the volumetric capacity of the trailer is reached before reaching the legal weight limit. In such a case the truck is carrying less than an allowable weight load and if bulk density could be increased transportation cost would be reduced. Volume-limited trailer condition is often characterized by transporting dry material that is lower than approximately 35% moisture content wet basis. In conveyor-fed loading, the material may not be well packed in the trailer (Figure FL-4.12), and therefore the truck becomes volume limited (Schroeder et al., 2007). Various methods have been explored to increase bulk density. McDonald et al. (1994) summarize mechanical compression and vibration methods. In this paper we explore the effect of near-vertical high speed blowing during loading on bulk density, and further the interaction with grinder bit configuration and piece size.

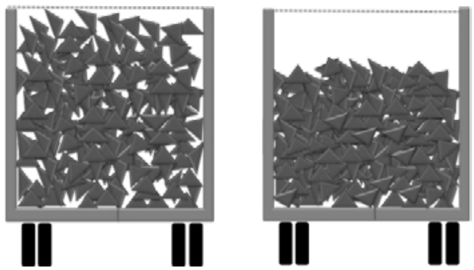

Figure FL-4.12. Diagram illustrating the potential increase in truck volumetric capacity by increasing bulk density of the comminuted material, as long as the material is dry enough such that the truck is not at legal weight limit, more material can be added to the more compacted load.

In the Pacific Northwest, USA, harvest forest residues are typically processed using horizontal grinders that reduce the size of the harvest residues by hammering them against an anvil until the particles are reduced to pass through peripheral exit screens. Grinders are favored over chippers due to the contamination of the forest residues (with soil particles) that reduce the productivity of chippers due to frequent downtimes to replace dull knives (Peterson Pacific Corp., 2013; Ryans, 2009). The comminuted material is then loaded into trailers and transported to a bioenergy conversion facility. The hammering-cutting process is performed by bits attached to a cutting rotor. Carbide coated hammer bits have relatively blunt edges that are highly abrasive and tend to hammer-shred the material. Knife-edge bits tend to cut-shred the residue using the sharp edge of the bit. Carbide hammer bits tend to produce less dense material compared to knife-edge bits but they are less susceptible to contaminants (Hurt, 2013).

The main objective of this study was to assess the effect on the bulk density of low moisture content grindings by high speed blowing in a near-vertical direction compared to the usual conveyor-fed trailer loading method. We were also interested in: (1) estimating the combined effect of feed piece size and loading method on bulk density; and (2) estimating the influence of bit type and loading method on bulk density. This research was based on a controlled experiment that allowed us to isolate the effects of the high speed blowing loading method on bulk density. Our aim is to increase the understanding of comminution and transportation processes in order to evaluate strategies to decrease cost of processing and transport of low moisture forest harvest residues. Biomass from forest residues is a low value product and therefore any decrease in cost will help to improve cost efficiency and contribute to the long-term success of this relatively new supply chain.

6.1. Materials and Methods

A total of 150 green metric tons of Douglas-fir (*Pseudotsuga* menziesii) harvest residues were transported from an active forest operation (44°11’21”N, 122°59’15’’W) to a pulp paper facility located in Springfield, Oregon USA (44°3’7”N, 122°57’7’’W). The primary objective of the timber harvesting was the extraction of sawlogs for export markets. During these logging operations, no pulpwood had been transported from the harvest unit due in part to the low demand and imports affecting North America in the last years (UNECE-FAO, 2012). At the pulp-paper facility, the harvest residues were sorted into two feedstock size classes. The harvest residue material class that is commonly available in typical forest biomass operations consisting of branches and tree tops was separated from the total residue collected. This residue had an average diameter of 6.3 cm (σ=0.77 cm) and average length of 1 m. This size class was called “branches-and-tops”. The remaining residue was comprised of small logs with a diameter ranging from 10 to 30 cm (σ=6.5 cm) with an average length ranging from 1.2 to 4.27 m. In high demand pulpwood markets this would be considered suitable material for chipping. This size class was called this residue size class “pulpwood”.

The test was performed during August and September, 2013 and took 10 days to complete. The material was comminuted using a Peterson 4710B (570kW) horizontal grinder equipped with a 20-bit cutting rotor. Hexagon type screens were used consisting of two grates with an opening size of 7.62 cm, followed by two grates with an opening size of 10.16 cm each. This configuration was selected as it is commonly used in current forest residue harvesting operations in the Pacific Northwest, USA, and it follows recommendations made by the manufacturer of the equipment to maintain productivity while decreasing the proportion of overlength pieces. Two types of bits were tested in three different configurations: (1) carbide hammer bits; (2) knife-edge bits; (3) combo bits which consisted of 12 knife-edge bits in the center of the cutting rotor and 8 carbide hammer bits placed in the outer edge of the cutting rotor.

Harvest residues were loaded into the grinder using a John Deere 200 LC track-mounted loader (104 kW). The high speed near-vertical blowing of the grindings was tested using a Peterson BT-40 blower truck equipped with a live floor and a blower system capable of blowing the material at a speed of 54.4 m/s at 2700 blower RPM (with a discharge hose diameter of 15.2 cm). The blower had a theoretical output of 46 m^3/h. Material processed through the horizontal grinder was conveyor-fed into the blower-truck. The material in the blower truck was then blown from the blower truck by manually holding the discharge hose directly into a dump truck at an approximately vertical angle (Figure FL-4.13). The dump truck was equipped with a rectangular bin with a capacity of 11.7 m^3 divided in two compartments of 5.8 m^3 (back) and 5.9 m^3 (front).

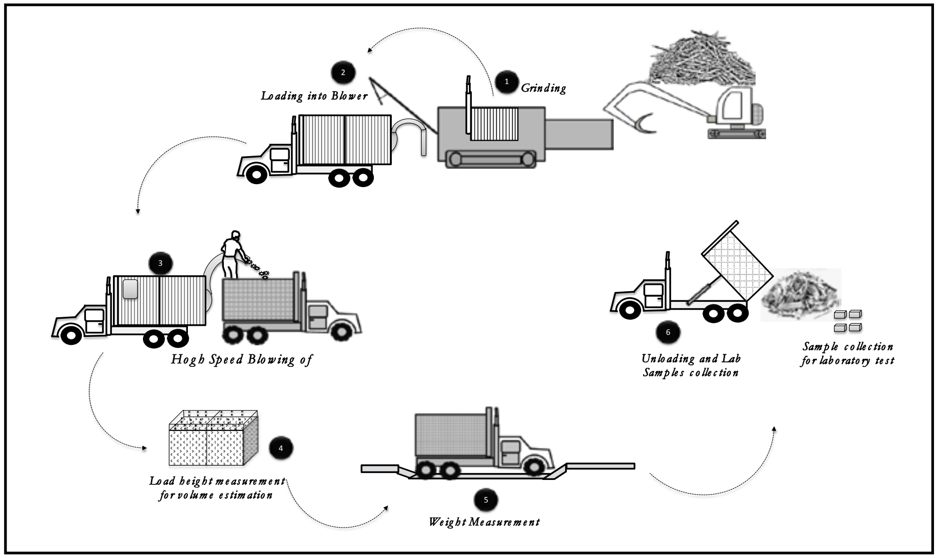

Figure FL-4.13. High speed blowing test procedure.

Bulk density was measured by weighing the truck on a scale. Truck empty weight was recorded at the beginning of each testing day or if the truck was refueled during the day. The grindings volume was estimated by measuring the height of the load in systematic sample points located 50 cm apart. An average height was derived and the material volume was calculated based on the width and the length of the rectangular bin.

The crew was composed of a truck driver who operated the dump truck, a blower-truck operator who manually directed the blower hose vertically into the dump truck, one person in charge of the excavator loader operation and a grinder operator who was in charge of the grinding process and the recoding of the field data.

In the conveyor-fed loading tests, the material was conveyed and dumped directly from the horizontal grinder into the dump truck as typically occurs when loading chip-vans in the field. A shroud was used to control the grindings flow and to direct fine particles under windy afternoon conditions. Bulk density was measured in the same way as it was using during the high speed blowing experiments. The different loading methods are shown in Figure FL-4.14.

Figure FL-4.14. a) Near-vertical high speed blowing of grindings during truck loading; b) conveyor-fed truck loading.

A fully randomized test was done with two factors: (1) bit type with three levels, carbide hammer, knife-edge and combo bits; and (2) loading method with two levels, high speed blowing, and conveyor-fed (gravity drop). In total, six different treatments with four replications per treatment were tested. The randomized treatments and replications are shown in Table FL-4.10. The randomized treatments were applied to the two feed size classes corresponding to the branches-and-tops and pulpwood residue. At each trial, an average of 1.3 metric tons of branches and tops and 2.7 metric tons of pulpwood residues were processed. The amount of processed material in each residue type varied because a limited amount of branches and tops was found after sorting, but the experimental design consisting of four replications per treatment was desired to favor the robustness of the statistical model. Processed material from branches and tops was loaded into the back compartment of the dump truck and pulpwood residue was loaded in both front and back compartments.

Table FL-4.10. Randomized treatments of bit type and loading method distributed in four replications.

Replication 1	Replication 2	Replication 3	Replication 4
Knife-edge/Blower	Combo/Conveyor	Carbide/Blower	Combo/Blower
Combo/Conveyor	Carbide/Conveyor	Knife-edge/Conveyor	Knife-edge/Blower
Combo/Blower	Combo/Blower	Knife-edge/Blower	Knife-edge/Conveyor
Knife-edge/Conveyor	Knife-edge/Blower	Carbide/Conveyor	Carbide/Conveyor
Carbide/Blower	Carbide/Blower	Combo/Blower	Combo/Conveyor
Carbide/Conveyor	Knife-edge/Conveyor	Combo/Conveyor	Carbide/Blower

After each trial, a sample of approximately 36 liters was taken and transported for testing in the laboratory. Lab tests included moisture content determination adapted from the ASTM E871-82 standard (ASTM, 2006), and particle size distribution. The moisture content of each sample was used to calculate the oven dry weights for the bulk density. The basic density of the grindings was also calculated following standard ASTM D2395 (ASTM, 2008). The basic density allowed us to calculate the solid fraction using Eq. 1 from Hakkila (1989). The solid fraction is the number of solid wood cubic meters that will produce a cubic meter of grindings. The basic density of the grindings provided information to assess if the differences in bulk density were due to variances in wood basic density between samples rather than other factors. Variability in basic density can occur due to locations within a tree, between trees, and between species.

$$Sf = \frac{Bk(100 - Mc)}{100\rho} \qquad \text{(Eq. 1)}$$

Where:

Sf Solid fraction

Bk Bulk density of the load (kg/m^3)

Mc Moisture content of the grindings wet basis (%)

ρ Basic density of the grindings (kg/m^3)

Particle size distribution was measured to investigate the effect of bit type and blowing on the bulk density. Particle size distribution was measured using a 50 x 127 cm Rotex oscillatory screen with two decks with round openings. The opening size of the upper and middle decks was 0.95 and 5.08 cm, respectively. An 18-liter sample was poured into the oscillatory screen and divided into three particle sizes: oversized pieces, medium size pieces and fine pieces. Collected fractions were weighed and the percentage of each size calculated. After weighing the fractions, the sample was homogenized again and two more replications were performed. Oversized and medium size pieces were further classified into a detailed particle size distribution test consisting of manual separation into four fractions based on the length of the particle: (a) <7.62 cm; (b) 7.62-15.24 cm; (c) 15.24-30.48 cm; and (d) >30.48 cm. Two replications of the detailed particle size procedure were made. Fine particles were classified using a No. 6 Tyler screen with an opening size of 3.35 mm. The sample was placed on a screener vibrator for four minutes and the percentage of particles that passed the 3.35 mm screen was determined. Two replications of this test were performed and the average was reported. The fine fraction was of interest as others have reported that it contains a significant proportion of the potential contaminants in the grindings (Zhang et al., 2012a).

Forest residues contain bark, foliage and soil. The percentage of bark and other substances was estimated in order to provide more information about the particle size distribution and bulk density results. The bark and other substances content was estimated by manually isolating needles, bark, rocks and other contaminants from a 5-liter sample. Bark that was still attached to the wood was removed with a small knife. All bark and other substances content was weighed and the percentage calculated as a function of the total sample weight.

For the statistical test, a factorial analysis of two factors (bit type and loading method), and one dependent variable, (oven dry bulk density) was performed. The two-way ANOVA was performed in each size class: branches-and-tops and pulpwood. The normality assumption was checked by visually checking Q-Q plots in conjunction with Shapiro-Wilks tests. The equal variance assumption per treatment was analyzed using side-by-side box plots. This also helped us to check for outliers. Levene's test was performed to support the visual interpretation of boxplots in relation to the equal variance assumption. The time correlation of the data was tested since field data was collected on different days in order to evaluate independence. Residuals were plotted for each treatment by time as an independent variable. Multiple comparison tests using Bonferroni's correction were made where appropriate to explain the individual factor significance at each of their levels. Our statistical significance was based on the p-values. For values close to 0.05 it was concluded that a strong statistical significance occurred. For p-values around 0.10 it was concluded that moderate but inconclusive statistical significance existed.

An economic analysis was also developed to estimate the potential transportation cost savings of increasing trailer payload through the use of a specific bit type and/or loading method. Transportation costs were obtained from consultation with trucking companies in Oregon and Washington, USA, and direct estimation based on the power needed to overcome air and rolling resistance traveling loaded and unloaded. A cost of $100.1/h traveling unloaded and $121.7/h loaded was used in the cost estimations. Additionally a cost of $37.62/h was used when the truck was not traveling, that is, either loading or unloading. For the truck load capacity, the assumption included a truck (335 kW) equipped with a single drop center trailer with a capacity of 100 m^3 and a maximum allowable legal weight (truck-trailer) of 40,823 kg. Cost and average life of carbide hammer and knife-edge bits were obtained directly from the manufacturer of the machinery. Average hourly cost of carbide bits was $4/productive hour with life of 150 hours. Knife-edge bits cost $14/productive hour with an expected life of 50 hours.

6.2. Results

6.2.1. Branches-and-Tops Residue Size Class

The branches-and-tops piece size class had an average moisture content of 17.3 percent (σ=3.3), wet basis. Basic density of the grindings was 444 kg/m^3. Bark and other substances content were estimated as 15.7 percent (σ=11.2). No significant departures from normality or violation of the equal variance assumption or time dependence of the data per treatment were observed. Results from the ANOVA test indicate that vertical high speed blowing had a statistically significant effect on the oven dry bulk density. Bulk density increased between 24.3 to 27.8 percent by loading the truck using vertical high speed blowing compared to conveyor-fed loading. The bit type effect resulted in no statistical significance in the oven dry bulk density (Table FL-4.11).

Table FL-4.11. Two-way ANOVA results for the bit type and loading method effect on bulk density.

Source	DF	Type III SS	*p*-value
Bit type	2	154.3	0.7870
Loading method	1	14459.5	<0.0001
Bit type*loading method	2	25.9	0.9602

Branches-and-tops processed with knife-edge bits and loaded using the vertical high speed blowing method had an average increase in oven dry bulk density of 51.66 kg/m³ (27.8 percent) more than the conveyor-fed loading method. For residue processed with a combination of carbide hammer and knife-edge bits, the material blown into the testing truck had an average increase of 49.03 kg/m³ (25.3 percent). Material processed with carbide hammer bits had an average increase of 46.57 (24.3 percent higher) (Table FL-4.12). All differences were statistically significant (p-value<0.002 from a multiple comparison Bonferroni test).

Table FL-4.12. Effect of loading method and bit type on average oven dry bulk density for branches-and-tops size class residue.

Bit type	High speed blower, average bulk density kg/m³	Conveyor-fed, average bulk density kg/m³	Bulk density difference and 95% confidence interval kg/m³	*p* - value	Percent increase
Carbide hammer	238.1	191.5	46.58±26.48	0.001	24.32
Combo	242.5	193.5	49.03±26.48	0.001	25.34
Knife-edge	237.6	186.0	51.66±26.48	0.002	27.78

Particle size distribution had a slight increase of fines fraction (<0.3 cm) when the material was blown into the truck compared to the conveyor-fed method (Figure FL-4.15). The proportion of particles greater than 7.62 cm was higher when the material was conveyor fed.

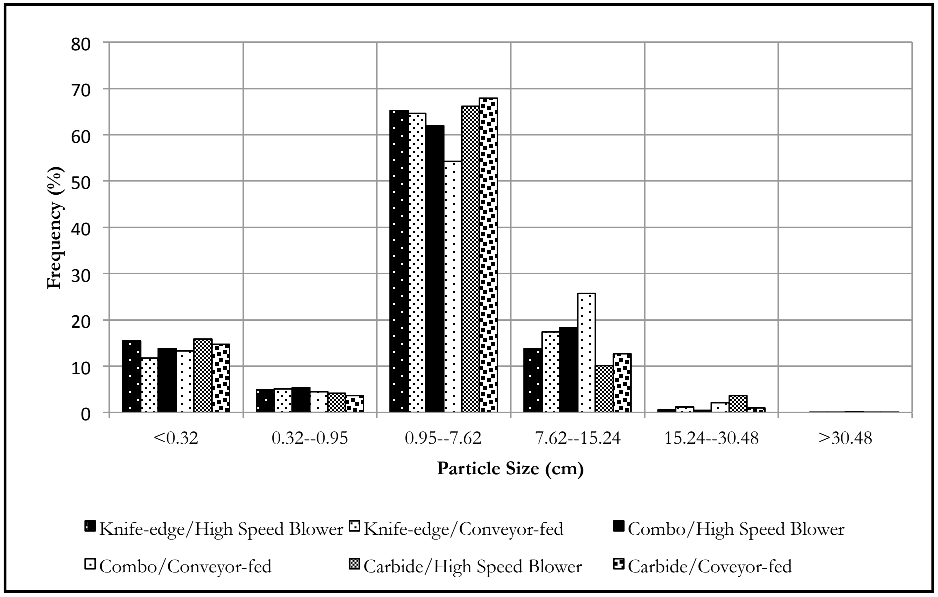

Figure FL-4.15. Particle size distribution per treatment (bit type-loading method) for standard residue size class.

6.3. Pulpwood Size Class

Grindings processed from the pulpwood size class had an average moisture content of 20.12 percent (σ=2.44). Basic density was 401 kg/m³. The percentage of bark and other substances content in this size class was 4.44 percent (σ=4.68). The analysis of the assumptions for the ANOVA test did not reveal any violation. Strong evidence was found of the effect of bit type and loading method on the oven dry bulk density however the effect of loading method is greater than the effect of bit type. No statistical significance was found in the interaction between the two factors (Table FL-4.13).

Table FL-4.13. Two-way ANOVA results for the bit type and loading method effect on bulk density for pulpwood size class.

Source	DF	Type III SS	*p*-value
Bit type	2	363.9	0.0271
Loading method	1	13998.3	<0.0001
Bit type*loading method	2	21.2	0.7751

The effect of the bit type factor is mainly driven by the difference between the bulk densities of the grindings processed with knife-edge bits compared to carbide hammer bits for both loading methods. Knife-edge bits produced grindings that were 13.1 kg/m³ denser (8 percent), on average compared to carbide hammer bits (Table FL-4.14). Statistical differences between the combo configuration and the other two configurations were not significant.

Table FL-4.14. Effect of loading method and bit type on oven dry bulk density for pulpwood size class.

Bit type	High speed blower, average bulk density kg/m^3	Conveyor-fed, average bulk density kg/m^3	Bulk density difference and 95% confidence interval kg/m^3	*p*-value	Percent increase
Carbide hammer	182.51	137.47	45.04±13.44	<0.0003	32.76
Combo	193.41	145.09	48.32±13.44	<0.0002	33.30
Knife-edge	198.89	147.34	51.55±13.44	<0.0001	34.98

In terms of the loading method, high speed blowing increased the oven dry bulk density between 32.7 to 34.9 percent. Maximum bulk density was achieved using knife-edge bits and decreased for combo and carbide only bit types.

Particle size distribution for the pulpwood size class exhibited a slight increase in the percentage fines (<0.3 cm) for material processed with knife-edge bits compared to carbide hammer bits. Combo bits produced a greater amount of these fine particles compared to the other two types of bits tested. Slightly higher fines were found when the material was blown compared to conveyor-fed. A higher percentage of particles larger than 7.62 cm in length were found when processing the residue with combo and carbide bits compared to knife-edge bits. For all treatments with the pulpwood size, fine particles (<0.32 cm in length) constituted 11 percent; particles with a length ranging between 0.32 to 7.6 cm in length represented 67 percent and oversized pieces larger than 7.6 cm constituted the remaining 22 percent (Figure FL-4.16).

6.4. Comparison between Residue Feed Size Classes

The effect of the treatments between the two material size classes was compared. For all the treatments, the grindings processed from branches-and–tops type residues had an average bulk density of 47.4 kg/m^3 higher (25 percent) compared to grindings from pulpwood size class. As was shown before, no statistical differences were found in bulk density between the different bit types tested. On the other hand, the loading method showed a significant effect on the bulk density. For all the treatments, the high speed blower loading method increased bulk density 25.8 and 33.7 percent for branches-and-tops and pulpwood size classes respectively (Figure FL-4.17).

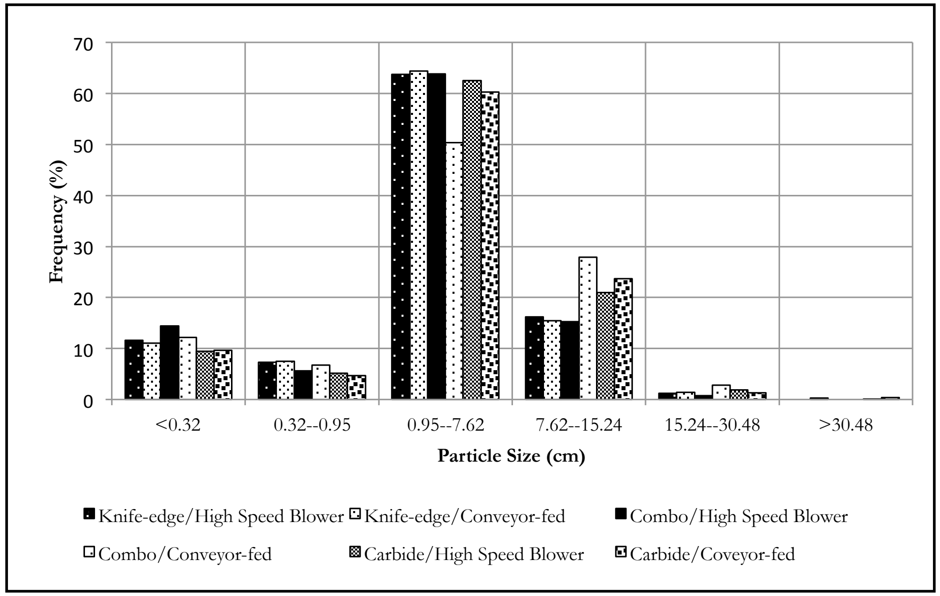

Figure FL-4.16. Particle size distribution for each treatment on pulpwood size class residue.

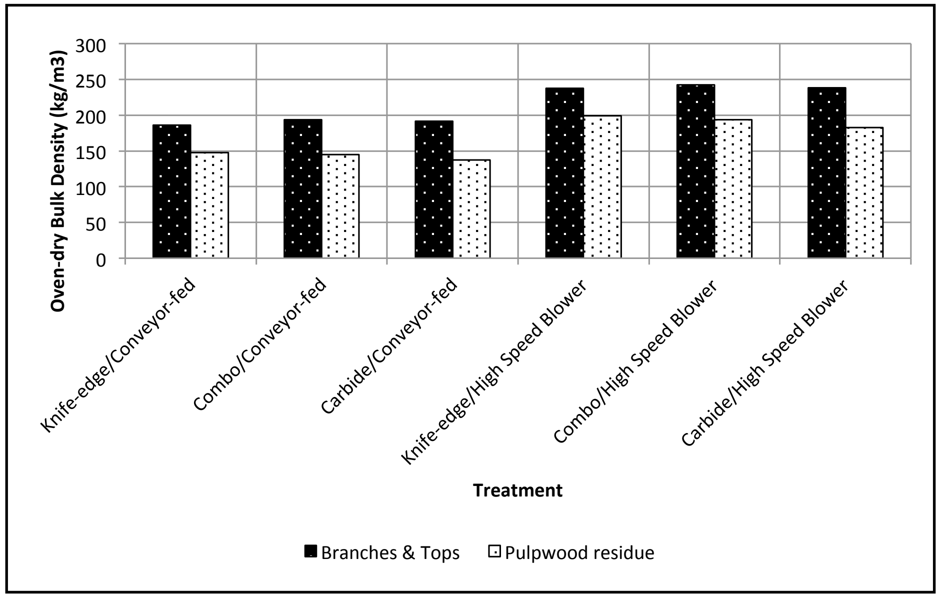

Figure FL-4.17. Effect of the treatment bit type-loading method on the bulk density for material processed from branches-and-tops and pulpwood size classes.

The average solid fraction for each of the treatments in the two size classes was calculated. The solid fraction was based on the moisture content, basic density and the actual bulk density measured in the field. Values are reported in Table FL-4.15. For all the treatments, solid fraction was 13 percent higher for the branches-and-tops size class compared to pulpwood class when high speed blowing was used to load the truck.

Table FL-4.15. Solid fraction of the different grinding combinations for each treatment.

Bit type	Branches-and-tops size class		Pulpwood size class	
	Solid fraction High speed blower	Solid fraction Conveyor-fed	Solid fraction High speed blower	Solid fraction Conveyor-fed
Carbide hammer	0.45	0.37	0.39	0.29
Combo	0.46	0.37	0.41	0.31
Knife-edge	0.45	0.35	0.42	0.31

6.4.1. Economics Implications in Transportation

Based on the results, significant increases in oven dry bulk density can be achieved by vertically blowing the processed material into the truck. The potential increase in payload derived the transportation cost per oven dry metric ton (ODMT) was estimated. Transportation costs are a function of the distance from the harvest unit to the bioenergy conversion facility. Therefore, a sensitivity analysis was performed to illustrate the effect of the blower loading method when one-way distance is varied (Figure FL-4.18). The use of the high speed blowing system on branches-and-tops feedstock can decrease transportation cost from $1.2/ODMT (20 km one way trip) to $8.3/ODMT (200 km one way trip).

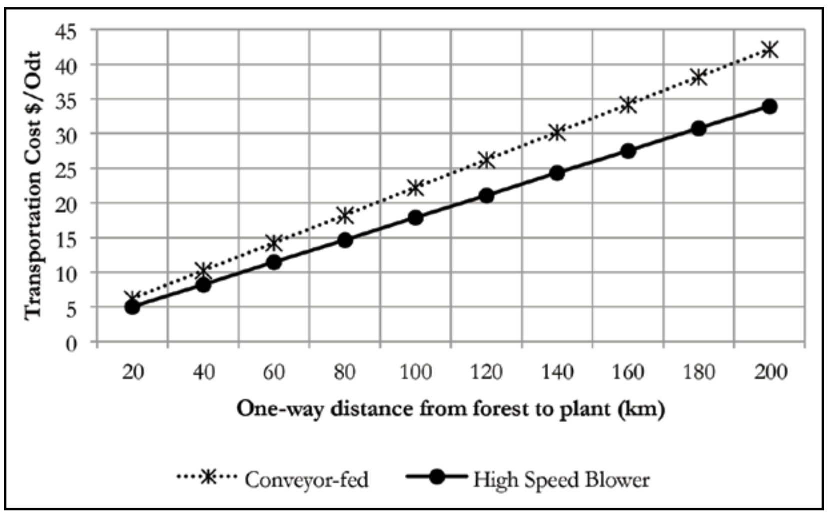

Figure FL-4.18. Transportation cost for each of the two loading methods on branches-and-tops size class material.

On pulpwood type material, a combination of knife-edge bits and blower loading produced denser loads compared to the other treatments. The combined effect of high-speed blowing and knife-edge bits have the potential to reduce the cost from $2.2/ODMT (20km one way trip) to $14.7/ODMT (200 km from forest to bioenergy facility) (Figure FL-4.19).

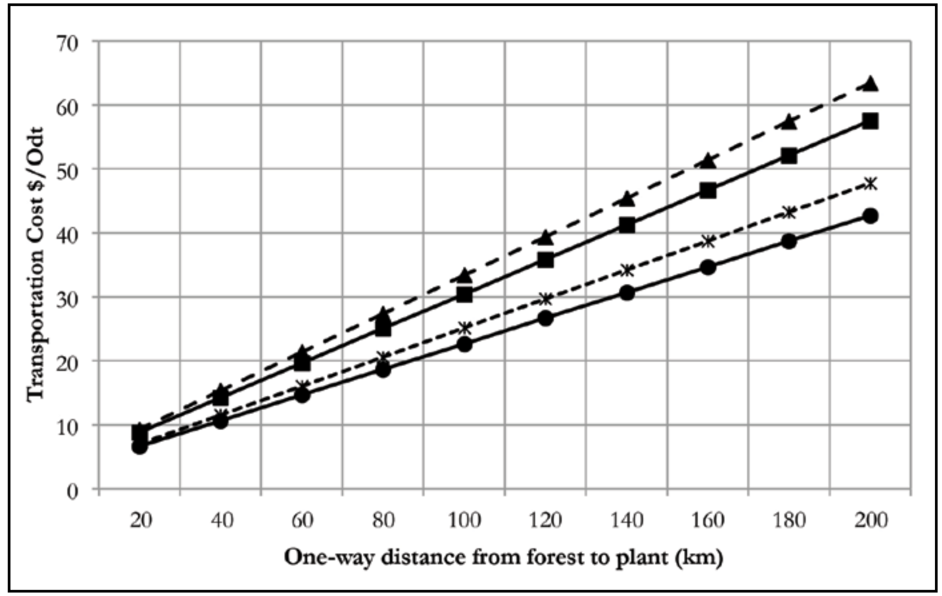

Figure FL-4.19. Transportation cost for each of the two loading methods on pulpwood size class residue.

6.5. Discussion

The use of high speed blowing during loading in a trailer demonstrated promising results in increasing bulk density of the low moisture content grindings and permitted more uniform packing. The uniform packing was achieved during the blowing operation because the operator could manually move the hose side to side to distribute the load uniformly into the trailer. Few problems were found associated with blowing grindings. A few hose obstruction problems were found when processing larger pieces but in general the testing was not significantly affected by this problem. For the branches-and-tops material, high speed blowing led to significant increases in oven dry bulk density. It would seem to be intuitive that the force with which particulate material impacts the loaded mass would have an impact on the resulting packing of the material, and thus the measured bulk density. For example, conveyor-fed gravity dropping of residues into a 2.5 m deep trailer might have an average drop height of about 2.5 m. Given acceleration due to gravity of 9.8 m/s, residues would only be traveling at about 7 m/s. Compare this to the exit velocity of the blower tested here, rated at 54 m/s. Since material would begin slowing after discharge from the high-speed blower, the terminal velocity before impacting appears to be the key factor. Terminal velocity of wood chips and bark before impacting in horizontal blowing (an average of 7.5 m flight path) have been reported to be in the range of 4.3 and 6.5 m/s (Sturos, 1972), however in near-vertical high speed blowing flight distance shorter flight paths can be expected resulting in a higher impact velocity producing better packing and higher bulk density.

In terms of feed piece size, the processing of branches-and-tops resulted in higher bulk density compared to pulpwood. This effect is in part due to the higher basic density of grindings from the branches-and-tops size class (10 percent higher) compared to the pulpwood size class. The lower initial moisture content, higher basic density, and higher bulk density of the branches and tops resulted in a higher solid fraction than for the pulpwood residue. The moisture content of the two materials was different and friction mechanics may play a role in explaining the effect of moisture content on compressibility, but that was outside the scope of this study. The amount of reaction wood in branches and tops may be the cause of this higher bulk density. Also, the branches-and-tops size class had a higher percentage of bark and other substances. The particle size distribution and bark and other substances content may also explain, in part, the higher bulk density in branches and tops. Bark can be easily broken into fine pieces and also contains soil particles and other contaminants that could cause an increase in the amount of fines. The amount of fines in grindings from the branches-and-tops size class was 14 percent compared to 11 percent of those coming from the pulpwood size class. The proportion of oversized pieces increased when processing pulpwood type residue. The fraction of oversized pieces larger than 7.6 cm increased 4 percent in pulpwood grindings compared to the branches-and-tops size class.

Bit type did not appear to have any effect on increasing bulk density; the small diameter of the material may not have fully exploited the knife-edge bit capabilities. Potentially, the directional feed across the grain when processing branches and tops cannot be properly done due to the different size and characteristics of the material mixture. This is an important conclusion given that bit type has been considered a key factor for affecting bulk density, however for the study conditions, no significant statistical effect was found.

For the pulpwood size residue, a significant effect of bit type and loading method was found on oven dry bulk density, although the effect of bit type was mainly driven by differences between grindings processed with knife-edge bits compared to carbide hammer bits. Knife-edge bits cut the material instead of just breaking it by brute force. During the cross-cutting more fines are produced that may lead to increases in bulk density of the load. Additionally, pulpwood compared to branches-and-tops residue is easier to load into the grinder favoring the cut across the grain. A higher oven dry bulk density was achieved using a combination of knife-edge bits and high speed blowing when loading, however knife-edge bits tend to wear more quickly than carbide hammer bits as they are more susceptible to contaminants. This may increase the grinder downtime and reduce productivity. A productivity analysis must be done to properly test the economic efficiency of this combination.

In terms of transportation, the increase in the amount of material per trailer per trip can led to potential savings that are proportional to the travel distance. If the demand of forest biomass from harvest residues increases, longer hauling distances could be expected to supply the demand. Based on the result of this study, high speed blowing can increase bulk density about 30% suggesting significant potential reductions in transportation cost could be achieved by developing vertical high speed blowers on grinders that can both increase packing by impacting with greater force and also evenly load the trailer. The experiment compared high speed blowing to conveyor-fed loading into a dump truck. In actual operations, the trailer height is up to 2 m higher so the grindings fall farther and are packed deeper than in the dump truck container, therefore different bulk densities may be expected when loading truck-trailers. The actual mechanism involved in the increase in bulk density is related to the high velocity of the particles, but this variable was not measured directly. Future studies can test the effect of blower speed on bulk density.

In August, 2014, we conducted tests using a prototype chip flinger designed by BCI, Cary, North Carolina at the Lane Forest Products Yard in Eugene, Oregon. Twenty trailer loads of dry primarily Douglas-fir grindings were first loaded by conventional gravity loading, then reloaded using a prototype chip flinger under a range of discharge velocities. Laboratory results of grinding samples indicated 11-15% increases in bulk density for low moisture grindings. Maximum increases in bulk density were achieved at about 75 miles per hour. A manuscript is in preparation. The results of this study indicate that increasing truck capacity by loading with a high-speed blower would lead to reduction in transportation cost. However, other factors that could affect the total costs were not part of this study and should be addressed in future work. These include: (1) the effect of dense packing on the unloading process at the plant; (2) trade-offs of installing the blower on grinders and providing the mobility to evenly load a trailer; (3) blower power requirements; (4) manpower and operator skills to properly operate the grinder and blower; and, (5) equipment costs and potential increases in equipment fuel consumption.

7. Sensitivity of Cost to Grinding Parameters

A techno economic 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 (Marrs et al., 2016). This prominence makes feedstock cost reduction a logical focus area to explore different process improvement methods. In this section 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 (Smith et al., 2012), 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 (Zamora-Cristales et al., 2015b). 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 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 force larger particles to pass through the small holes or recirculate them until all residues have passed through the screen 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 (Hurt, 2013).

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 (Angus-Hankin et al., 1995). 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 (Zamora-Cristales et al., 2014). 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 (Roise et al., 2013). 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 (Hosseini and Shah, 2009) 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 (Zhang et al., 2012b; Biermann, 1996; SP, PBTC, 2001); similar ranges apply for forest biomass boilers for electricity production (Naimi et al., 2006). Oversized pieces tend to clog the compartments of the equipment where the pretreatment and conversion processes take place (APA, 2004). Also, the breaking down process of the hemicellulose through fermentation may be longer with larger pieces compared to smaller ones thus affecting pretreatment and conversion times (Carvalheiro et al., 2008). 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 (Zhang et al., 2012b; Spinelli et al., 2012).

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.

7.1. 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 to 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 (ASTM International, 2006).

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 FL-4.16). 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.

Table FL-4.16. 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

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 (Figure FL-4.20) were feedstock size category, grinder bit type, and grinder screen size. Methods used for the experimental design of the controlled variables, as well as results from the response variables, were obtained from a previous study (Zamora-Cristales et al., 2015b). Each of these responses has direct linkage to a cost component of the feedstock value chain.

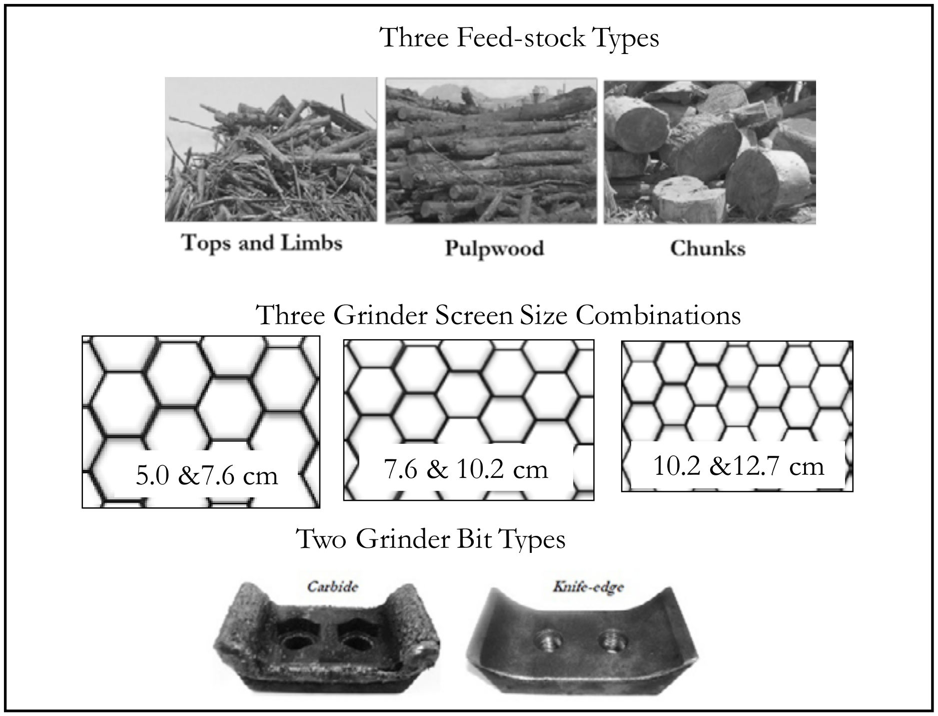

Figure FL-4.20. Overview of the grinding trial controlled test variables, feed-stock type, screen size combination (5.0 and 7.6 cm; 7.6 and 10.2 cm; and 10.2 and12.7 cm) and bit type (hammer-carbide, and knife-edge).

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 FL-4.17.

Table FL-4.17. 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}*

7.2. 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.

For fuel consumption impacts, an off-road diesel fuel price of \$0.93 l^{-1} was assumed given the forecast prices for 2014 (USEIA, 2014), and 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. Further, since more than just fuel costs vary with specific power usage, 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 liters of diesel per hour. Hourly operating average costs for grinding alone, not including fuel, were assumed to be an 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 (Zamora-Cristales et al., 2015a; Anderson et al., 2012; Harrill and Han, 2009). Given a fuel consumption of 100 liters per hour, a total cost of $93 h^{-1} was calculated. Summing the loader and grinder operating and fuel costs resulted in a total grinder hourly cost (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 cost of $411 (including fuel) was allocated to the tonnes per hour that could be produced using the constant 100 liters per hour. The fuel consumption per oven dry tonne by grinder parameter combination (Fc_i) allowed us to calculate grinding cost differences (C_i) from the base scenario (Eq. 2).

$$C_i = Gh_i \frac{Fc_i}{Fe} - Gh_i \frac{Fc_{baseCase}}{Fe} \qquad \text{(Eq. 2)}$$

After comminution and transport, 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} (Humbird et al., 2011).

7.3. 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 hammer mill in a centralized site including amortized capital, power costs, maintenance, etc. (Naimi et al., 2006), 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. We assumed that all oversize pieces will be resized to acceptable particles. The cost differences (O_i) between each parameter combination and the base scenario are given by (Eq. 3):

$$O_i = Po_i Cr - Po_{baseCase} Cr \qquad \text{(Eq. 3)}$$

7.4. 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 (Sessions et al., 2013). 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 (Marrs et al., 2016). 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. 4).

$$F_i = \frac{Pp-(Pf_i*Hp)}{1-Pf_i} - \frac{Pp-(Pf_{baseCase}*Hp)}{1-Pf_{baseCase}} \qquad \text{(Eq. 4)}$$

7.5. 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 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). Moisture management strategies in the field are important to allow the residues to dry. Transporting wet residue (>35% moisture content wet basis) makes transport cost inefficient since a large fraction 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 on (Zamora-Cristales et al., 2015a; Chung et al., 2012). 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.

$$T_i = Tc\left(\frac{Bk_{basecase}}{Bk_i}\right) - Tc \qquad \text{(Eq. 5)}$$

7.6. Results

7.6.1. 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 FL-4.18).

Table FL-4.18. 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

7.6.2. Grinding Costs

Grinding costs between scenarios had high large relative differences due to fuel usage (Figure FL-4.21). 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}).

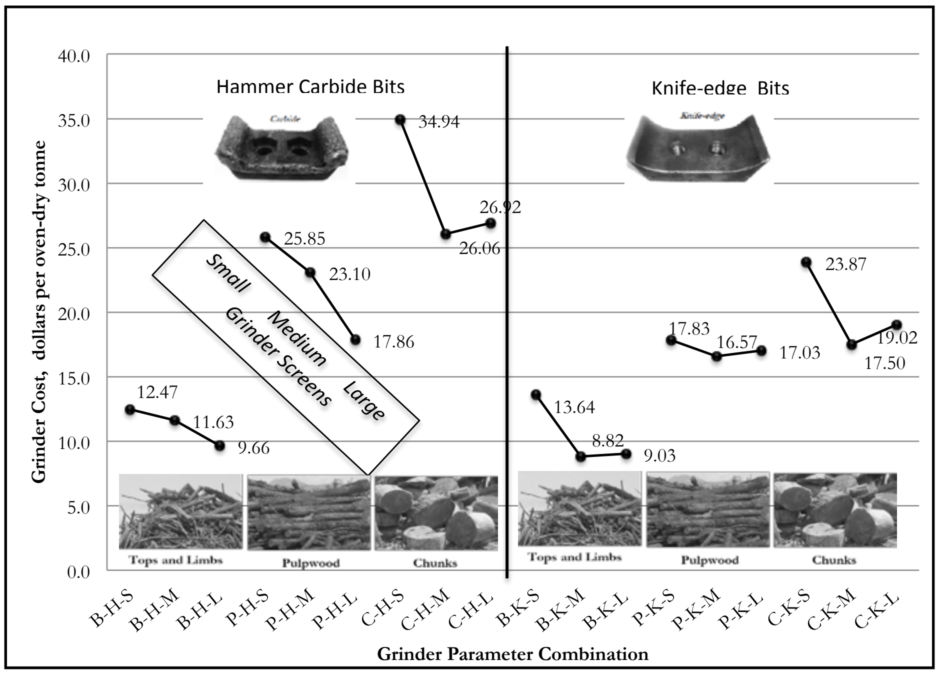

Figure FL-4.21. Grinding cost per oven dry tonne for different parameter combinations: Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer- carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example, B-H-S is size class tops and limbs, hammer carbide bits and screen size combination small 5.0-7.6 cm.

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}), (Figure FL-4.22). 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 (Zamora-Cristales et al., 2015b).

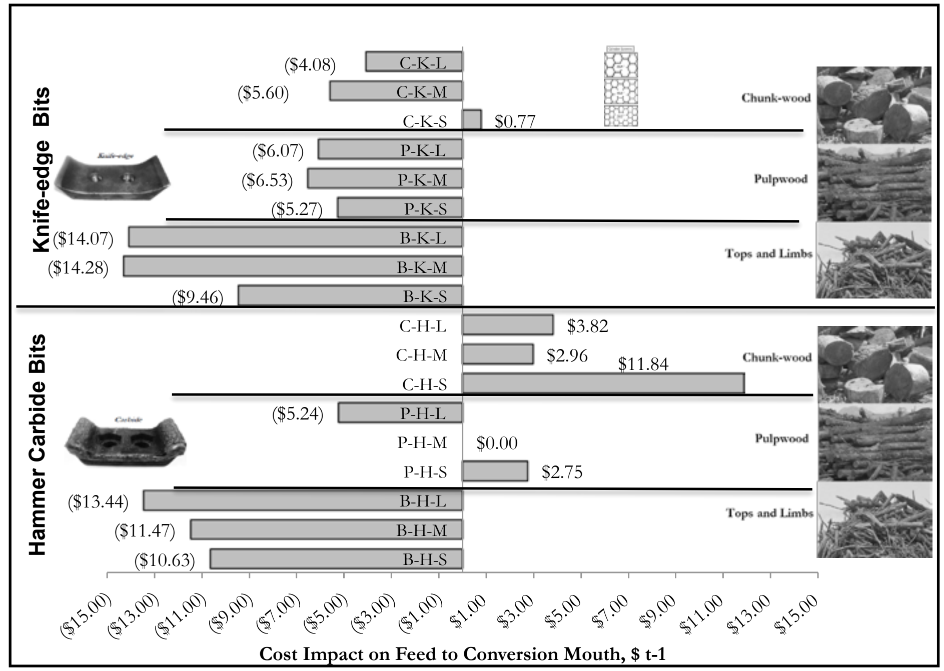

Figure FL-4.22. Grinding cost differences from base scenario (P-H-M) vary significantly – a total impact range of \$23.70 t-1. Control variable codes on y-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (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.

7.6.3. 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 (Figure FL-4.23). 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.

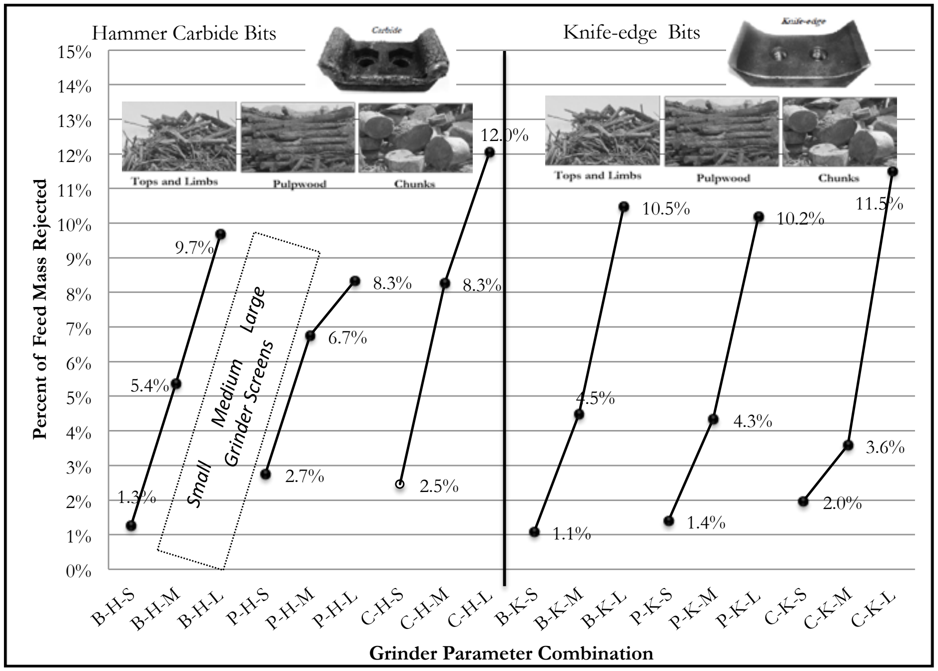

Figure FL-4.23. Oversized particles for each of the grinder parameter combinations. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example, B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0-7.6 cm.

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} (USIA 2015), but could increase depending on the location and available power sources. Since only about 1% to 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 \$0.41 t^{-1} feedstock through the gate (Figure FL-4.24). This impact is dwarfed by the grinding cost effects shown earlier (Figure FL-4.22).

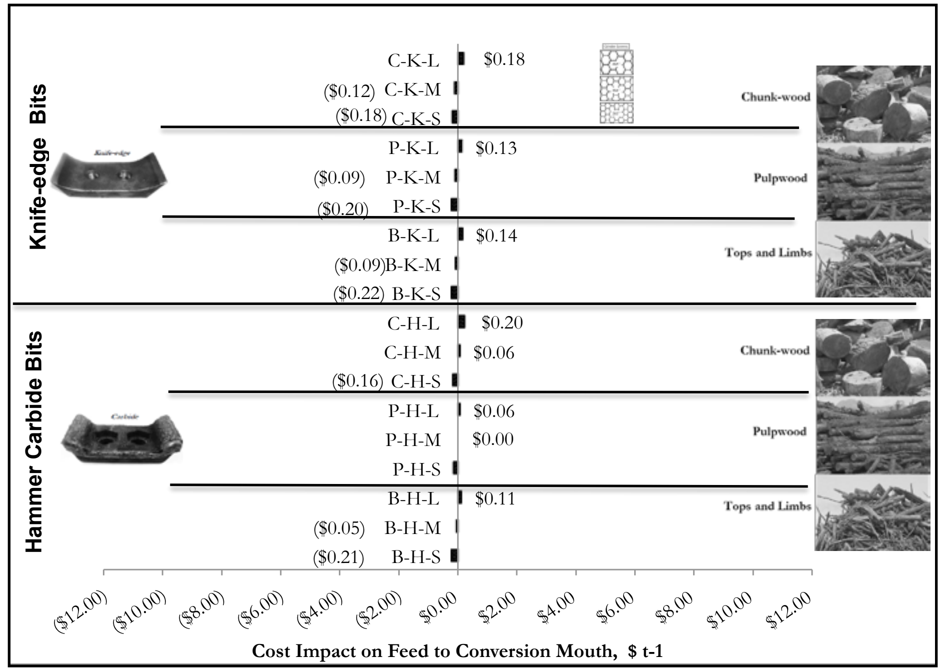

Figure FL-4.24. Cost differences from base scenario (P-H-M) of oversize re-sizing costs as a function of the control variables. Control variable codes on y-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (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.

7.6.4. 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 (Figure FL-4.25). 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.

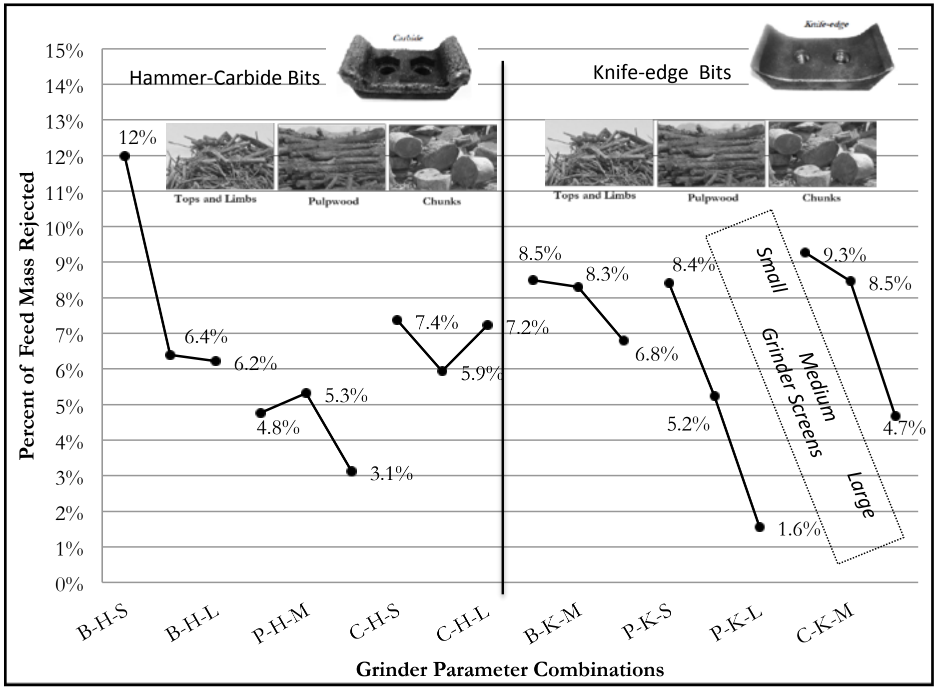

Figure FL-4.25. Percent of fine particles rejected as a function of control variables. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example, B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0-7.6 cm.

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 (Figure FL-4.26). The total range of impact on a feed basis is \$3.05 t^{-1} feed (range between \$0.40 and \$3.45 t^{-1}).

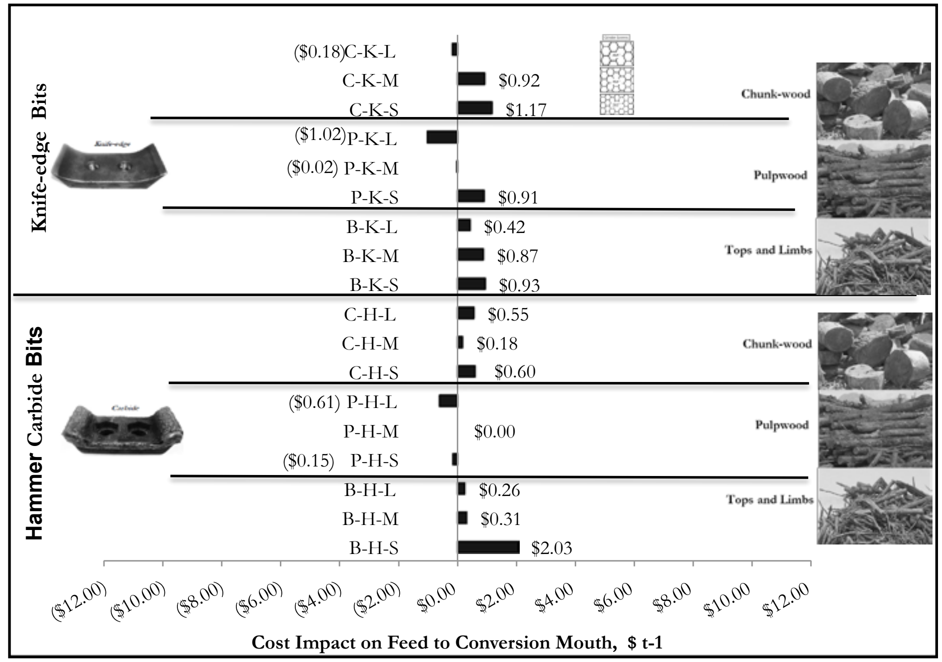

Figure FL-4.26. The cost impact of fines downgrade to hog-fuel value as a function of feedstock size class, bit type and screen size. The maximum range of differences from the base scenario is \$3.05 t-1. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); 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.

7.6.5. 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 (Figure FL-4.27). 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 (Figure FL-4.28).

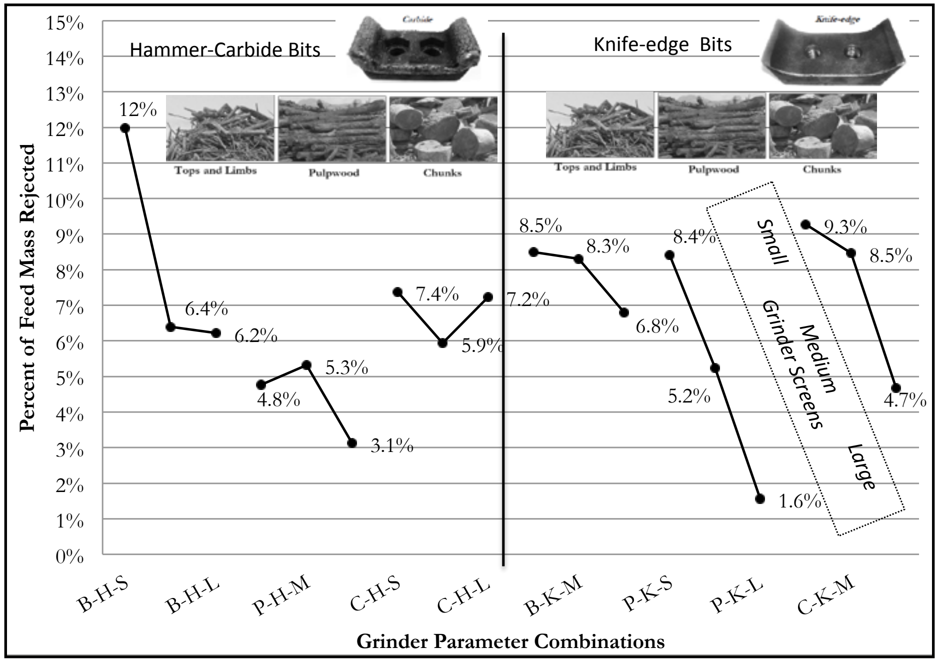

Figure FL-4.27. Percent of fine particles rejected as a function of control variables. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; M: medium; L: large). For example B-H-S is size class tops and limbs, hammer-carbide bits and screen size combination small 5.0-7.6 cm.

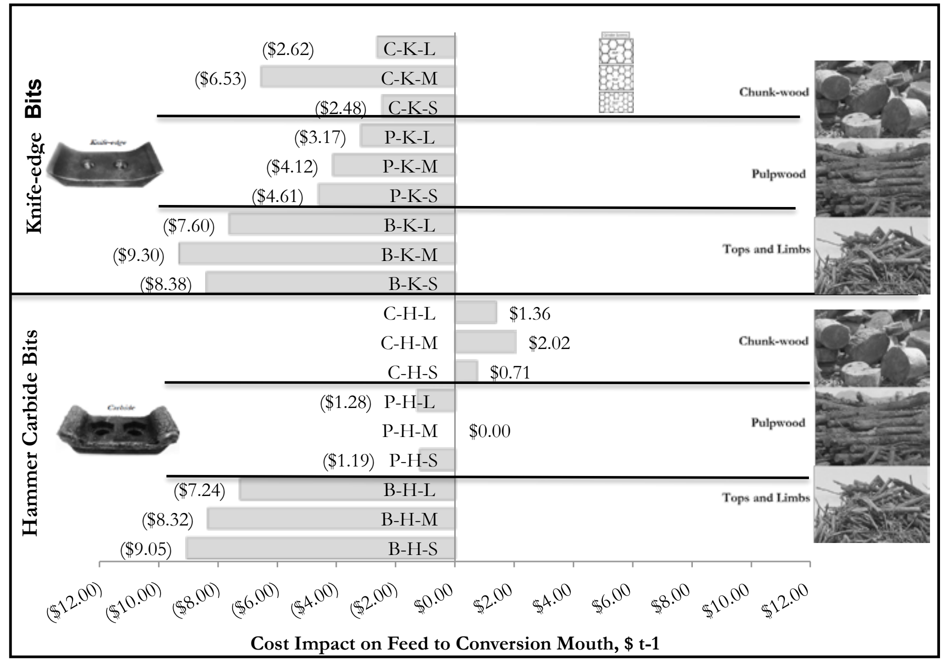

Figure FL-4.28. Transportation cost differences from base scenario. The impact in cost range to \$11.31 t-1. Control variable codes on y-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (S: small; 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.

7.7. Discussion

7.7.1. 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 (Figure FL-4.29). 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.

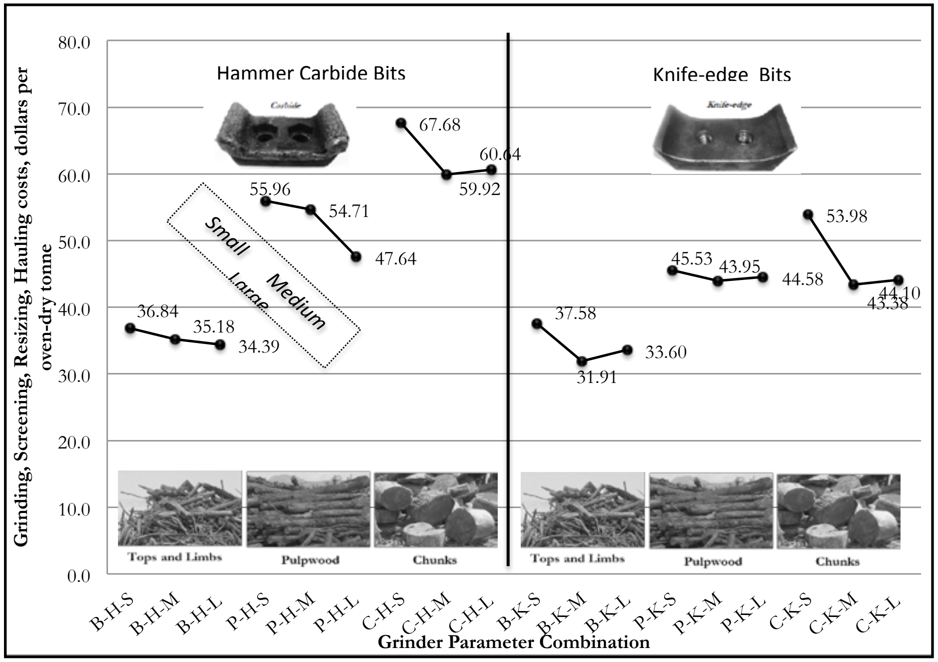

Figure FL-4.29. Grinding, overs resizing, fines downgrading and transportation costs for each grinder parameter combination. Control variable codes on x-axis are: feedstock size class (B: tops and limbs; P: pulpwood; C: chunk-wood); bit type (H: hammer-carbide; K: knife-edge); and screen size combination (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.

It can be seen in Figure FL-4.29 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 the knife-edge bits wear faster than carbide hammer bits, thus increasing downtime that may affect grinder productivity and cost. Grinder screen sizes seem to have little overall impact due to counteracting effects.

7.7.2. 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).

7.7.3. 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 on steep, narrow roads and therefore increasing the capacity per trailer per trip significantly decreases 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.

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, 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 of each 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.

8. Baling

Baling densifies residues through compression into a form that can be transported by trailer from landings before comminution. It permits grinding of forest residues on electricity that is much lower in cost in the Pacific Northwest compared to diesel. Additionally, baling increases the potential for improving storage both at the mill and at the landing. It also increases the accessibility to more remotely located residues. In doing so, standard trailers can be used with the baler as opposed to using bin trucks or large chip vans. We conducted a limited test of baling to measure the consumption of baled and unbaled treatments, the gross particle size distribution of baled and unbaled treatments, and to determine the results of energy consumption differences for the two treatment types.

8.1. Study Design

The study design was composed of a 2x2x2 factorial design. This refers to having two treatment types, two screen sizes and two bit types. Treatment types used (baled material and loose material) were then processed with the use of a commercial grinding machine. The machine used for the baling portion of residues in this experiment was designed and constructed by Jim Dooley of Forest Concepts (Figure FL-4.30). Originally intended for use in suburban and urban forest areas, this street-legal baler utilizes an on-board loader attachment to lift piles of distinctly sized woody biomass into a compression chamber. The compression chamber used approximately 3,000 psi when creating the bales as well as a range of 11-52 gal/min of fuel. Once the material was compressed, bales were wrapped with either static (fixed or stationary) or dynamic (flexible) baling twine to maintain its structural form. The bales were then weighed using a portable scale and stacked along the testing site prior to use. After residue collecting and baling was completed, a Peterson 4701B horizontal grinder was used for grinding bales. Powered by a Caterpillar C18 diesel engine (700-765 hp), this track-mounted machine also featured a three-stage grinding process with an up turning rotor and a changeable grate and bit area. It had an in-feed opening size of 60"x 37.5" (Peterson Pacific, 2012).

Figure FL-4.30. Producing bales utilizing a small baler provided by Forest Concepts.

Once forest residues were processed, samples for further lab tests were taken and later tested to document variability in particle size distribution. Multiple replications of various treatments include changes in grate sizes and bit types. Samples were selected at random and were randomly allocated a bit type and grate type (Table FL-4.19). Approximately 4 test samples were allocated to each replication. These replications include grate sizes of 3" & 4" inches as well as 4" & 5" inches with both hammer and knife-edge bits. In total, this equates to 32 bales (16 trials) and 16 piles of loose residues (16 trials).

Table FL-4.19. Replication structure for testing.

Replication 1					
Test	Bit Type	Grate	Tons/Bale	Bales	Total Tons
1	Hammer	3&4	1	2	2
2	Knife-edge	3&4	1	2	2
3	Knife-edge	4&5	1	2	2
4	Hammer	4&5	1	2	2

Approximately 189 tons of residue material (95% Douglas-fir) was collected and transported to the Weyerhaeuser TOPS facility at International Paper located in Springfield, OR. Residues originated on private lands near Dexter Reservoir, 15 miles south of the mill facility. Residues were loaded into trucks and transported to the testing site located at the TOPS facility. In order to keep large material out of the machines, operators removed any material larger than 6 inches in diameter. The residues were then divided using a hydraulic excavator loader to control (residues that would be ground unbaled) those that would be baled. Employees from Forest Concepts in Auburn, WA cut the residues to be baled by chainsaw to fit into the feed-in opening of the baler. The baling unit was mounted to a trailer attached to the back of a truck. Cut material was then lifted with a small Forest Concepts loader head attached to the baling unit. Thirty-seven bales were made by the baling device with a compression chamber size of 64 inches x 48 inches x 32 inches (Figure FL-4.31). Of these 37 bales, 32 were to be tested with a remainder of 5 to serve as a safety buffer in the event one or more bales proved to be inadequate for testing. After each bale was created, it was wrapped in 1-inch metal straps to ensure material would not break apart. Due to the heavy influence of rain, the weight of each bale was measured on the day it was created, two days later after heavy rain and on the day of grinding.

Figure FL-4.31. Loading bales tangentially into grinder at International Paper site, Springfield, OR.

After grinding a Rotex oscillating screen was fitted with a 2-inch round holed top deck and a 3/8- inch round holed bottom deck. This was completed in order to separate material into three size fractions consisting of overs, mids and fines. Overs were >3 inches, mids were between 3 and 3/8 inches and fines were < 3/8 inches. Material was poured at a steady rate onto an in-feed deck careful not to overflow or unload the screen. Each size fraction was divided into piles and weights were recorded. Material was then remixed and the process was repeated 3 times. Eventually, processed samples were reported and values were averaged for each size class (based on the sum of total weight) (Smith et al., 2012). Calculated values were then used in R and RStudio in order to conduct a statistical analysis.

8.2. Results

Mean fuel consumption of baled residues was 0.12 gallons per bone dry ton more than the mean fuel consumption of loose residues (95% confidence interval of 0.08 to 0.17 gallons/bdt). This increased consumption could have also been due to the fact that baled material was placed tangentially (against the grain) into the grinder. Although it is uncertain whether or not this played crucial role in fuel consumption, it still remains a factor. Knife-edge bits used in the grinder consume less diesel fuel as opposed to hammer bits. Mean fuel consumption when using knife-edge bits was 0.08 gallons per bdt less than mean fuel consumption when using hammer bits (95% confidence interval of 0.03 to 0.12 gal/bdt). Overall, knife-edge bits were shown to use significantly less fuel during grinding operations. Screen size 3" & 4" consumes more diesel fuel between both baled and unbaled residues overall, as opposed to screen size 4" & 5". Mean fuel consumption when screening with size 3" & 4" was 0.11 gallons per bone dry ton greater than mean fuel consumption when screening with size 4" & 5" (95% confidence interval of 0.06 to 0.15 gal/bdt). By using the smaller grate size (3" & 4"), more fuel was consumed during grinding operations.

Baled and knife-edge treatments produced more class size overs and fines while screen size 3" & 4" produced less percent overs sizes and greater percent fines sizes (Table FL-4.20). Overall, there was no significant evidence suggesting an interaction between these three variables.

Table FL-4.20. Least-squares means contrasts results for the estimate of ratio of medians and corresponding 95% confidence interval of gross particle size distribution.

	Ratio of Medians	Three-Way ANOVA 95% CI
Overs, Baled-Loose	1.84	1.59, 2.14
Overs, 3"&4"-4"&5"	0.49	0.43, 0.57
Overs, Hammer-Knife-edge	0.85	0.73, 0.98
Fines, Baled-Loose	1.04	0.85, 1.26
Fines, 3"&4"-4"&5"	1.15	0.95, 1.40
Fines, Hammer-Knife-edge	0.95	0.78, 1.17

The size 4" & 5" screens produced a greater percentage of particles for size class overs ($F_{1,24} = 97.26$, $p < 0.001$). The corresponding 95% confidence interval for size overs was (0.43, 0.57). There is some evidence to show a difference in the median percent of particle size overs or size fines when using knife-edge bits ($F_{1,24} = 5.02$, $p = 0.03$) with a confidence interval of (0.73, 0.98) and a ratio of medians between hammer and knife-edge of 0.85.

Overall, baling consumed slightly more fuel as compared to grinding loose material. Using a larger screen size will produce a greater percentage of overs particles while reducing the amount of fuel consumed. Depending on the objectives for an operation, it may be more economical to use larger screens as well as knife-edge bits in order to reduce fuel. If transport is of concern, baling could be considered a viable option as the benefits of fitting more on a truck may outweigh the slight increase in fuel economy. Although the compact weight of baled material should be greater as compared to that of a chip van, a more detailed weight comparison should be completed in order to provide stronger evidence for using the baled method. The small sample size of this study could have played a limiting factor in the analysis of the data. Further studies would be necessary to determine if baling shows strong evidence to suggest a significant change in energy consumption when using an electric grinder.

Additional studies may give reason to suggest a statistical difference in fuel consumption caused by the tangential placement of baled material in the grinder. Results from additional testing might also provide stronger evidence as to whether or not baling could be considered a more economical method of grinding forest residues in terms of fuel consumption and gross particle size distribution for a larger and more commercial operation. However, it would take a more complete economic evaluation from the landing to a plant or processing facility in order to determine costs and benefits of a baling operation.

9. Future Work

This task (Task 4) focused on grinding of forest harvest residues from branches and small tops typically left from operations in western Oregon and Washington industrial forests where strong pulpwood markets typically exist. The effect of grinder configuration on forest biomass bulk density, particle size distribution and fuel consumption was examined and forest biomass cost sensitivity to grinding parameters for bio-jet fuel production was evaluated. The impact of residue freshness on grinding energy and sugar yield was also evaluated under Task 2: Develop Moisture Management Strategies and Models.

When the NARA project began, PNW pulp markets were considerably stronger than currently. If increasing amounts of pulpwood become available, direct shipment of pulp logs to chip yards or on-site chipping of pulpwood should be considered. Pulp logs are cleaner than slash and can be chipped with less energy than by grinding. And, if electrical energy is available at a chip yard, the cost of electricity is much lower than the cost of diesel. Chip packing densities are higher than ground material due to a more uniform shape and they are usually blown into vans rather than conveyed. Chip size has been optimized for pulp. Both larger and smaller chip sizes could be tested for the NARA pretreatment process and to evaluate where size reduction should economically occur.

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