QUALITY OF FEEDSTOCK PRODUCED FROM SORTED FOREST RESIDUES

Waste to Wisdom: Subtask 2.3.1

Project Management

Prepared By:
Joel A Bisson and Han-Sup Han

March 2018

This material is based upon work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297.

U.S. DEPARTMENT OF ENERGY HUMBOLDT STATE UNIVERSITY

For more information please visit WasteToWisdom.com

Quality of Feedstock Produced from Sorted Forest Residues

Joel A Bisson and Han-Sup Han

Abstract

Emerging biomass conversion technologies, such as small scale mobile biochar or pyrolysis/torrefaction machines, aim to use forest residues left after extracting merchantable timber from timber harvest or fuel reduction thinning operations. The residues generated from these operations typically produce low quality feedstock which may not be suitable for new biomass conversion technologies. In an effort to increase feedstock quality, our study separated sub-merchantable trees and tops from piled limbs during the timber harvest. A portion of the separated material was further processed to remove limbs to create five material types: processed and unprocessed, conifer and hardwood stem wood, and slash (stems, limbs and chunks). These materials were comminuted with a disc-chipper or a grinder. The quality of the feedstock produced was characterized by moisture content, particle-size distribution, bulk density, and ash content. Moisture content of sample collected ranged from 19 to 29%. The mean geometric lengths for unprocessed hardwood, unprocessed conifer, processed hardwood, processed conifer, and slash were 20.60, 18.27, 18.16, 17.41, and 47.47 mm, respectively. The bulk density of the five material types ranged from 137.20 – 322 kg/m3. The least amount of ash were observed in processed conifer samples (0.27%) and greatest in ground slash (1.5%). The results showed that a high quality feedstock can be produced by separating stem wood from other residues during a harvest.

Keywords: Biomass Utilization; Forest Residues; Chipping; Grinding; Particle Size; Ash Content

1. Introduction

Nationwide, 89 million bone dry metric tons (BDmT) of woody biomass in the form of residues from timber harvest and fuel reduction treatment operations are produced annually (Perlack et al., 2011). Despite the abundance, forest residues remain underutilized due to economic and operational barriers related to the cost of collecting, processing, and transporting a product with low market value (Han et al., 2010). The cost of transportation, which ranges from US$0.11 to US$0.32 per tonne per km, remains to be the greatest challenge as it severely limits the range in which residues can be collected (Perlack et al., 2005).

A potential solution to increase transportation efficiency is to reduce moisture content and densify the biomass close to its source. This can be achieved by using different biomass conversion technologies (BCT), such as pyrolysis, e.g., torrefaction and biochar, or physical densification, e.g., briquetting (Van der Stelt, 2011; Picchio et al., 2012). Providing a quality feedstock for these BCTs can be problematic, as they each have their own specific requirements for particle size, moisture content, and ash content. Meeting these requirement can be difficult when considering the utilization of forest residues.

Typically, forest residues are comminuted, or reduced in size, using grinders. The output, commonly called “hog fuel”, is highly variable is size, low in bulk density, and is often contaminated with rock and soil (Han et al., 2015). For these reasons, hog fuel may not be a preferable feedstock for BCTs. Another option is to comminute with a chipper. This machine utilizes knives to slice through woody material creating chips that are relatively uniform in size. They are very effective when chipping whole trees and stems, but lack when fed loose materials such as limbs and chunks. Furthermore, the knives are susceptible to wear and damage from soil and rock contamination requiring relatively clean material. Despite these limitations, the chipper’s ability to control particle size makes it more preferable when considering feedstock requirements of a BCT.

To facilitate the use of chippers, whole stems and tops would need to be separated out from other residues during a timber harvest operation. The extra handling would provide a preferred feedstock with less contamination, but would come at a cost (Kizha and Han, 2015). Therefore, understanding the amount of feedstock quality improvement through sorting and processing is warranted.

Particle size is one of the greatest considerations when evaluating feedstock quality for BCTs. Particle size can influence fuel conveyance and the efficiency of machines by having an effect on drying and reaction time (Picchio et al., 2012). Research suggests that there are many factors that influence the size of particles generated from chipping. Of them, material type (i.e. tree part and species) and moisture content have shown to have significant effects. Spinelli et al. (2005) found that delimbing stems produced the highest-quality chip (i.e., the largest proportion of acceptably sized chips) when compared to chips generated from whole trees with limbs. Similar results were found by Nati et al. (2011) who experimented with chipping different tree parts, specifically logs and branches. Furthermore, they found that species also had an effect on size distribution. Poplar chips tended to be larger than pine chips and contained a higher proportion of oversized particles. Spinelli et al. (2011) produced more uniform chips with fewer oversized particles when chipping larger sized stem wood (e.g., small-diameter trees or tops from sawlog processing) compared to smaller-diameter materials (e.g., branches) which tended to produce more oversized (i.e. > 50 mm) particles. They went further to note that moisture content also had a strong effect on the resulting particle size distribution of chips. Fresh branches produced the lowest proportion of acceptable chips.

Moisture content not only effects particle size distribution, but also BCT efficiency. The moisture content of freshly felled trees can range from 30% to more than 200% (Ross, 2010). At these levels, thermochemical conversion efficiency is decreased, as moisture must first be evaporated resulting in higher processing costs (Acharjee et al., 2011). Management strategies to reduce moisture content of residues, such as harvest timing, air drying, and transpiration drying have proven to be effective methods (Rogers, 1981; Stokes et al., 1993; Brand et al., 2011). Moreover, the practice of bark removal has also shown decreases in moisture content of residues (Nurmi and Hillebrand, 2007; Röser et al., 2011). Nurmi and Lehtimaki (2011) further investigated the amount of moisture reduction in Pinus sylvestris and Betula pubescens after partial bark removal from processing. They found that partial debarking only resulted in a marginal reduction.

Ash content is another characteristic to consider when providing feedstocks for BCTs. The presence of ash in feedstock reduces thermochemical conversion efficiencies in processes, such as gasification and pyrolysis (Lacey et al., 2015). Research on methods to reduce ash content in feedstocks have suggested better material handling techniques to minimize contamination (i.e., soil and sand) and mechanical screening to sort out smaller fractions in "hog fuel" which are typically heavier in contamination (Dukes et al., 2013; Greene et al., 2014). In addition to contamination, bark has been found to be a contributor to ash content (Lehtikangas, 2001; Flibakk et al., 2001; Picchio et al., 2012).

Bulk density, although a less consequential feedstock characteristic, can still influence transportation efficiencies when providing a feedstock to BCTs. Low bulk density can result in the underutilization of transport equipment and an increase in hauling cost (Hakkila, 1989). It is affected by moisture content and comminution method. Chips differ from "hog fuel" in that they are more uniform in terms of particle-size distribution and usually have higher bulk densities (Mozammel et al., 2006; Smith et al., 2012). This supports the idea of sorting to facilitate chipping. However, the difference in bulk density of chips generated from whole-trees with limbs compared to chips from stems with no limbs is not well understood.

The aim of this study was to determine the improvement in feedstock quality as a result of sorting forest residues. We used a controlled experimental design to evaluate particle size distribution, moisture content, ash content, and bulk density of five material types produced from forest residues during a timber harvest. We hypothesized that sorting out stem wood from other forest residues would facilitate a chipping operation and provide a higher quality product compared to grindings. In addition, we hypothesized that further processing (delimbing) the sorted stem wood would have an effect on moisture content, bulk density, and ash content of the feedstock generated. The results from this work will provide land managers strategies to increase feedstock quality when comminuting forest residues.

2. Methods

2.1. Field Operations

2.1.1. Preparing Material for Chipping and Grinding Experiment

The forest residues used in this study were produced and collected from three experimental study units located on commercial timberlands owned by Green Diamond Resource Company in northern California. The harvested units were characterized as second growth mixed conifer forest, comprised of *Sequoia sempervirens, Pseudo-tsuga menzesii, Tsuga heterophylia, Notholithcarpus densiflorus, and Chrysolepis chrysophylla*. The terrain was uneven with ground slopes up to 48%.

Three subunits (2.43 - 3.64 hectares) were selected from three replicate even-aged timber harvest units (7.69 – 8.50 hectares). Within each subunit, sawlog trees (> 20.3 cm diameter at breast height (DBH)) and small-diameter, non-merchantable biomass trees (< 20.3 cm DBH) were cut and piled with a feller-buncher (John Deere 959K with a Quadco disc saw head) and shovel logged to the roadside using a Cat 568 with a standard log grapple. A dangle-head processor (John Deere 2454D with a Waratah 623 harvester head) processed (i.e., delimbed) and sorted sawlog and hardwood trees (> 25.4 cm DBH) in preparation for transportation to the mill or energy plant, respectively. In addition, the operator also separated out small-diameter conifer and hardwood trees and further processed a portion of these stems to produce processed conifer (PC), processed hardwood (PH), unprocessed conifer (UC), unprocessed hardwood (UH), and slash. Long stems were cut into 7.6 to 9.1 m sections to facilitate transportation to a centralized chipping/grinding site. The slash pile consisted of stem wood, limbs, bark, and chunks, i.e., off-cuts from processing sawlogs and energy wood.

Prior to chipping, each material type (PC, PH, UC, UH) was characterized by size, volume, and bark and foliage coverage. The length and diameters of the small- and large-end tops were measured to estimate volume. Stems that ended in a natural tip were assumed to have a 2.54 cm small-end diameter. The amount of bark covering each sampled piece was ocularly estimated by a single observer and recorded as a percentage. Species and the presence of attached foliage (needles or leaves) were also noted. Each slash pile was observed and a visual estimate of the percentage of limbs, chunks, and bark were recorded.

2.1.2. Chipping and Grinding of Sorted Forest Residues

Material sorted and piled during the timber harvest operation was later collected with a loader and placed into modified dump trucks for transport to the chipping and grinding location. One material type was chipped or ground at a time until a 12-m chip trailer was filled. This was done for all five material types and then replicated with material from the two other study units (Table 1).

Table 1 Number of 18.9 liter samples collected for each material type.

Comminution machine	Material type	Number of samples / Chip trailer		
		subunit 1	subunit 2	subunit 3
Chipper	Unprocessed hardwood	0[1]	15	15
	Unprocessed conifer	16	16	12
	Processed hardwood	0[1]	15	9
	Processed conifer	17	11	15
Grinder	Slash[2]	5	5	5
Total		38	62	56

[1] Pre-harvest estimations indicated there wass not enough of this material type for sampling.
[2] Slash was a mixture of conifer and hardwood stems, limbs, and chunks left from processing sawlogs, energy wood.

The processed and unprocessed conifer and hardwood material was chipped using a 632.5 kW Mobark 76 cm disc chipper. The chipper was equipped with four sets of key knife disposable blades set to produce 19.05 mm chips. In an effort to control confounding variables, all machine configurations and operating speeds remained constant during the entire chipping operation. To eliminate knife wear as a variable, knives were changed every replicate subunit or approximately every 90 BDmT production of wood chips. Slash material was comminuted using a Peterson Pacific 772.3 kW 5710C horizontal grinder. The grinding rotor was equipped with 11 knife bits in the center and seven carbide hammer bits on the outer edge. The grinder was also equipped with a pair each of 7.62 and 10.16 cm screen plates to help control output size.

Collecting representative samples of output material from the two different machines was done using a systematic method to avoid bias. A collection tube made from 15.24 mm, 90 degree elbow attached to a 15.24 mm by 3.05 m PVC pipe was held in front of the chipper's discharge spout to redirect a portion of the chips down to a 19 L collection bucket (Mitchell and Gallagher, 2007). A sample was collected approximately every two minutes for the length of time it took to fill the collection bucket. The contents of a bucket were placed into a plastic garbage bag and marked with a sample identification number. A 1.9 L subsample was taken from each bag before being sealed. This subsample was immediately weighed with a portable balance, marked with the corresponding sample identification number, and placed in a cooler. The samples and subsamples collected were transported to the lab for analysis.

2.2. Laboratory Analyses

2.2.1. Determining Moisture Content of Samples

The wet basis moisture content of samples collected during the chipping and grinding operation were determined using ASTM E871-82 standard test methods deigned for green tree chips and hog fuel (ASTM, 2006). For this study, all samples were placed in paper bags and dried at 103°C for 48 hours to streamline analysis.

2.2.2. Subsampling

During the experiment, 156 samples were collected from the chipping and grinding operation (Table 1). These sample, were further separated into smaller subsamples to conduct particle size, bulk density, and ash content analysis. The separation process involved dumping the collected sample into a 19 L bucket, which was inverted over a large clean surface. The bucket was lifted vertically to allow the content to spill out forming a cone. A 30.5 x 61 cm piece of sheet metal was used to systematically divide the pile into halves, quarters, and eighths for subsampling.

2.2.3. Evaluating Particle Size Distribution

Methods to evaluate particle size distribution for each sample were done using ANSI/ASAE S424.1 standard (ANSI, 1992). A subsample of approximately 2.5 L was poured onto a stack of six, 30.5 cm diameter sieves and a bottom pan. The sieve stack and sample were shaken with a sieve shaker for two minutes. The shaking motion fractioned the samples into seven size classes (Table 2). The contents of each sieve were removed, oven-dried for 48 hours, and weighed to calculate the mean geometric length and standard deviation for each sample. The 15 hog fuel samples required manual rescreening in order to address the issue of long, narrow particles diving down through screens.

Table 2 Sieve sizes and size classes used in the study.

Sieve size (mm)	Size class (mm)
50.8	>50.8
38.1	38.1 – 50.8
25.4	25.4 – 38.1
19.05	19.05 – 25.4
12.7	12.7 – 19.05
6.35	6.35 – 12.7
Bottom pan	< 6.35

2.2.4. Measuring Bulk Density of Samples

The bulk density of wood chip and hog fuel samples were determined using a modified version of ISO 15103 (Cen/TS, 2006). A plastic bucket with a volume of 21.55 L, a height-to-diameter ratio of 1.26, and a taper of 9.7 cm/m was used instead of the suggested 50 or 10 L vessel. Material from two random samples of the same material type and replicate (e.g., two processed conifer chip samples both from Unit 1) were thoroughly mixed together and used to get a set of bulk density measurements. The average of the two samples and their moisture contents were used to calculate bulk density at their current moisture content.

2.2.5. Evaluate Ash Content of Samples

The procedure used to evaluate ash content was consistent with protocol established by the National Renewable Energy Lab (Sluiter, 2008). A 1.9 L subsample further processed with a 16.4 cm3 laboratory Wiley mill running at 800 rpm with a 2 mm screen. Approximately 6.5 g of finely milled material was randomly scooped into a ceramic crucible and oven dried for 48 hr at 103°C. The standard method was modified by igniting the sample by placing the crucible and sample above a Bunsen burner in a vented laboratory hood. The sample was heated until spontaneous combustion and then allowed to burn above the burner until there was no visible flame. Desiccant chambers were used to control moisture absorption after oven drying and ashing in the muffle furnace. The standard procedure was followed for the muffle furnace without a ramping program. Three samples were prepared and analyzed for each sample of wood chips and hog fuel.

2.2.6. Statistical Analysis

The data collected from the different analyses were statistically tested using R Statistics (R Core Team, 2013). ANOVA was used to check the statistical significance of the eventual differences between treatments. Alpha was set at 0.05. Residual plots were examined to ensure test assumptions were not violated. Shapiro-Wilk tests were used to confirm normality and post-hoc tests were conducted using Tukey HSD test method.

3. Results and Discussion

3.1. Characteristics of Forest Residues Produced for the Study

A characterization of the material used in the study prior to chipping provided information about the size and volume of material fed into the chipper and grinder. The average volume for unprocessed and processed stems were 0.08 and 0.15 m3, respectively (Table 3). The average percent bark cover across all species for unprocessed and processed stems were 92.8 and 66.7%, respectively (Table 4). An average pile of slash was estimated to have 82, 12, and 6 % of limbs, stems and chunks, and bark, respectively.

Table 3 Average cubic meters of processed and unprocessed biomass material by species: *Sequoia sempervirens (sese), Pseudo-tsuga menzesii (psme), Tsuga heterophylia (tshe), and Notholithcarpus densiflorus (node).*

	Unprocessed				Processed			
Unit	psme	sese	tshe	node	psme	sese	tshe	node
1	0.076	0.067	0.096	NA	0.184	0.136	0.153	NA
2	0.079	0.071	NA	0.062	0.125	0.133	NA	0.147
3	0.059	0.102	NA	0.082	0.127	0.127	NA	0.150
Avg	0.071	0.080	0.096	0.072	0.145	0.132	0.153	0.149

Table 4 Average percent bark cover on processed and unprocessed biomass material by species: *Sequoia sempervirens (sese), Pseudo-tsuga menzesii (psme), Tsuga heterophylia (tshe), and Notholithcarpus densiflorus (node).*

	Unprocessed				Processed			
Unit	psme	sese	tshe	node	psme	sese	tshe	node
1	96	96	93	NA[1]	49	84	56	NA[1]
2	88	92	NA[1]	93	64	71	NA[1]	70
3	87	91	NA[1]	97	71	82	NA[1]	73
Avg	90	93	93	95	61	79	56	71

[1] Species was not available (NA) in that particular unit.

We determined that there was not enough hardwood material in Unit 1 to conduct our experiment prior to timber harvest operations. Therefore, processed and unprocessed hardwood material was excluded from the experiment reducing sample sizes for those material types.

The average piece size of processed material was found to be greater in volume compared to unprocessed. This is because unprocessed conifer and hardwoods were exclusively tops from processing, whereas processed material was made from either stem wood of non-merchantable trees, or the stem portion of the tree cut before the top (Figure 1). The difference in material size may have had an effect on the size of particles produced after chipping. The difference in material size certainly increased the volume per load which may be important when considering transport from the landing to a centralized processing location. The 26% difference in bark coverage between processed and unprocessed material was a direct result of processing. The top and bottom knives used to delimb and the forces from the 3 feed rollers on the processing head caused bark to sluff off. This may be significant, if we consider its contribution to fine particles as it breaks up during chipping or the amount of ash in samples, as bark is higher in ash content compared to wood (Lehtikangas, 2001; Filbakk et al., 2011; Picchio et al., 20012).

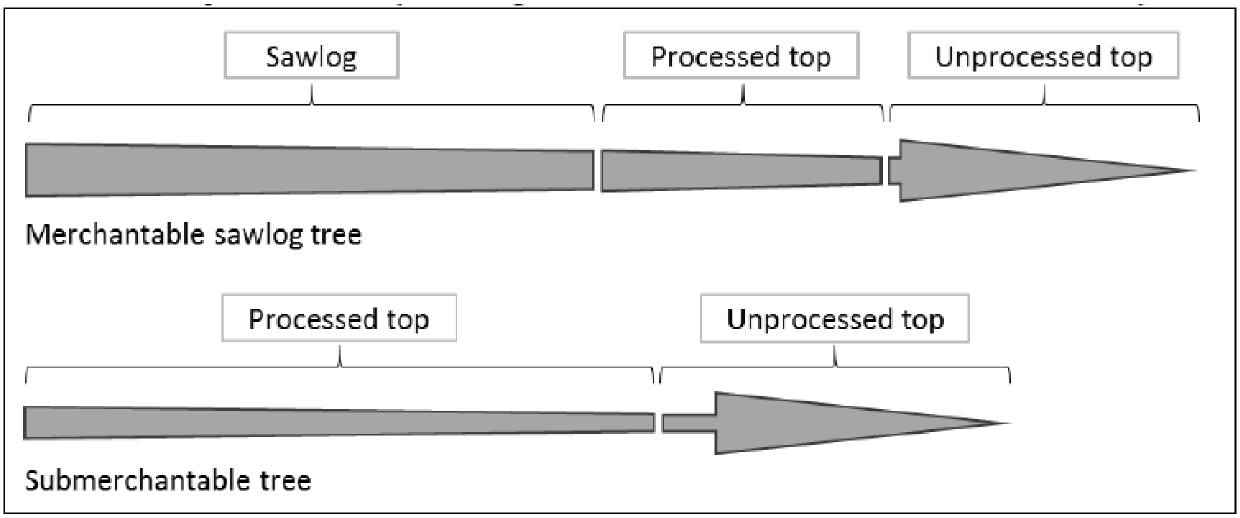

Fig. 1. Sections of merchantable sawlog and submerchantable trees used to produce processed and unprocessed materials in this study.

3.2. Moisture Content of Feedstock

A total of 156, 19 L samples were collected from the chipping and grinding operation (Table 1). The average moisture content of the sampled chips and hog fuel collected from the five different material types ranged from 19 to 29% (Table 5). A one-way ANOVA was conducted to compare mean moisture content between material types. The means were found to be statistically different at the $p<.05$ level between material types [$F(4,151) = 8.585$, $p = 2.862e-6$]. Post hoc multiple comparison using Tukey HSD test indicated that slash (i.e., ground hog fuel) was the only material type that was significantly different in mean moisture content compared to other material types ($p < .05$).

A noticeable reduction in moisture content of the four material types was observed during the two month period between harvest and chipping. However, after chipping there was no statistical difference in means. This implies that partially removing bark may not have an effect on moisture content. This is consistent with results by Nurmi and Lehtimaki (2011). Further research will be needed to determine if bark loss has an effect on moisture content over a longer period of time.

3.3. Particle Size Distribution

The mean geometric length of particles sampled from the four chipped material types (PC, PH, UC, and UH) were 17.41, 18.27, 18.16, and 20.60 mm, respectively (Figure 2). There was a statistically significant difference between geometric means of the different material types determined by one-way ANOVA $F(3,132) = 7.041$, $p = 0.0002$. A multiple comparison determined that UH was the only material type significantly different from the others (p-value < 0.05).

Table 5 Average moisture content of five different material types sorted out from the material generated from processing sawlogs and non-merchantable trees.

Material type		Percent moisture content (SD)[1]	n
Processed conifer	(PC)	26 (±5)	43
Processed hardwood	(PH)	29 (± 4)	24
Unprocessed conifer	(UC)	27 (± 5)	44
Unprocessed hardwood	(UH)	27 (± 3)	30
Slash		19 (± 4)	15

[1]Moisture content evaluated on percent wet basis and reported with standard deviation (SD).

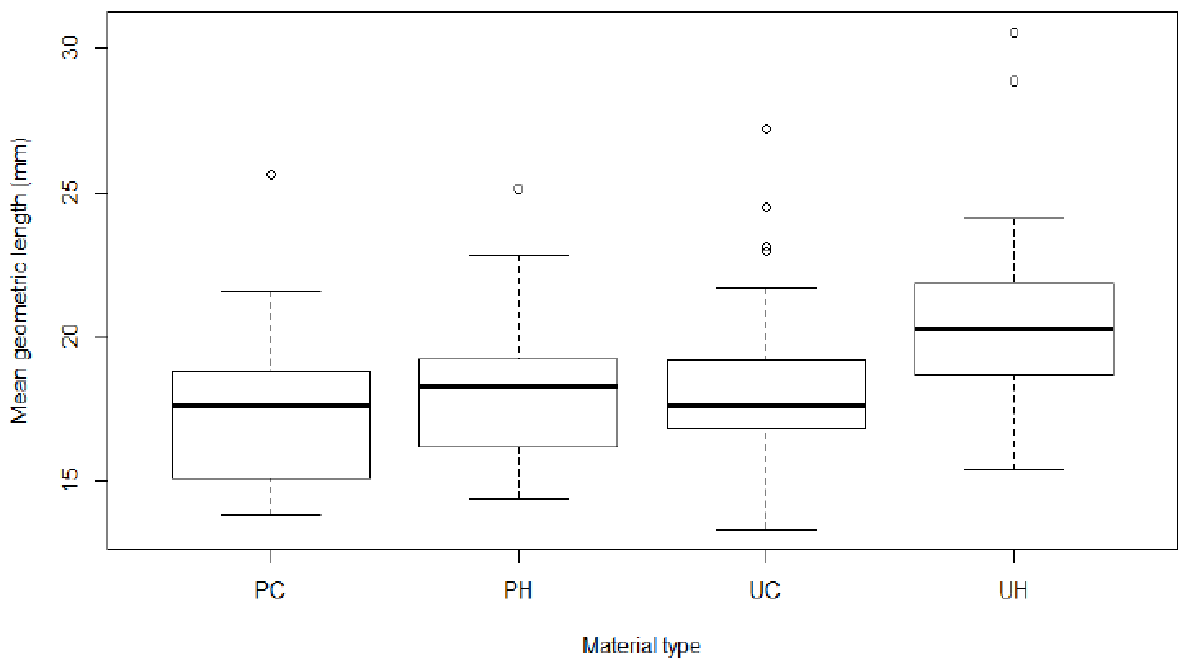

Fig. 2. Mean geometric length of sampled chips of four different material types: processed conifer (PC), processed hardwood (PH), unprocessed conifer (UC), unprocessed hardwood (UH). The mean geometric length varied between the different material types.

We noticed a number of outliers in the all four materials types (Figure 2). Further investigation revealed that these outliers were long, conifer and hardwood, branch segments typically found in our unprocessed material samples or dense branch collars in the processed material samples. For this reason these observations were not screened from the data. This was consistent with observations made during the sample collection. The collection tube would occasionally get clogged with long, branch segments leading us to believe that the chipper tended to pull flexible branches through without actually cutting it into small pieces.

The cumulative size distribution by percent mass of wood chips passing through screening sieves can be seen in Figure 3. The size distribution of wood chip particles revealed some interesting findings. Unprocessed hardwood and conifer chips were significantly different from processed chips. On average, we found a 6% increase in the amount of processed material chips passing through the 25.4mm sieve compared to the unprocessed material. The 19.1 – 25.4 mm size class, which was the target size range set by the chipper, had approximately the same percentages for all material types. There was more noticeable variation in the smaller and especially the larger size particles within the distribution. Based on the data, we can recommend processed when oversized (> 25.4 mm) are undesirable and unprocessed hardwood if smaller particles (< 6.35 mm) are not wanted.

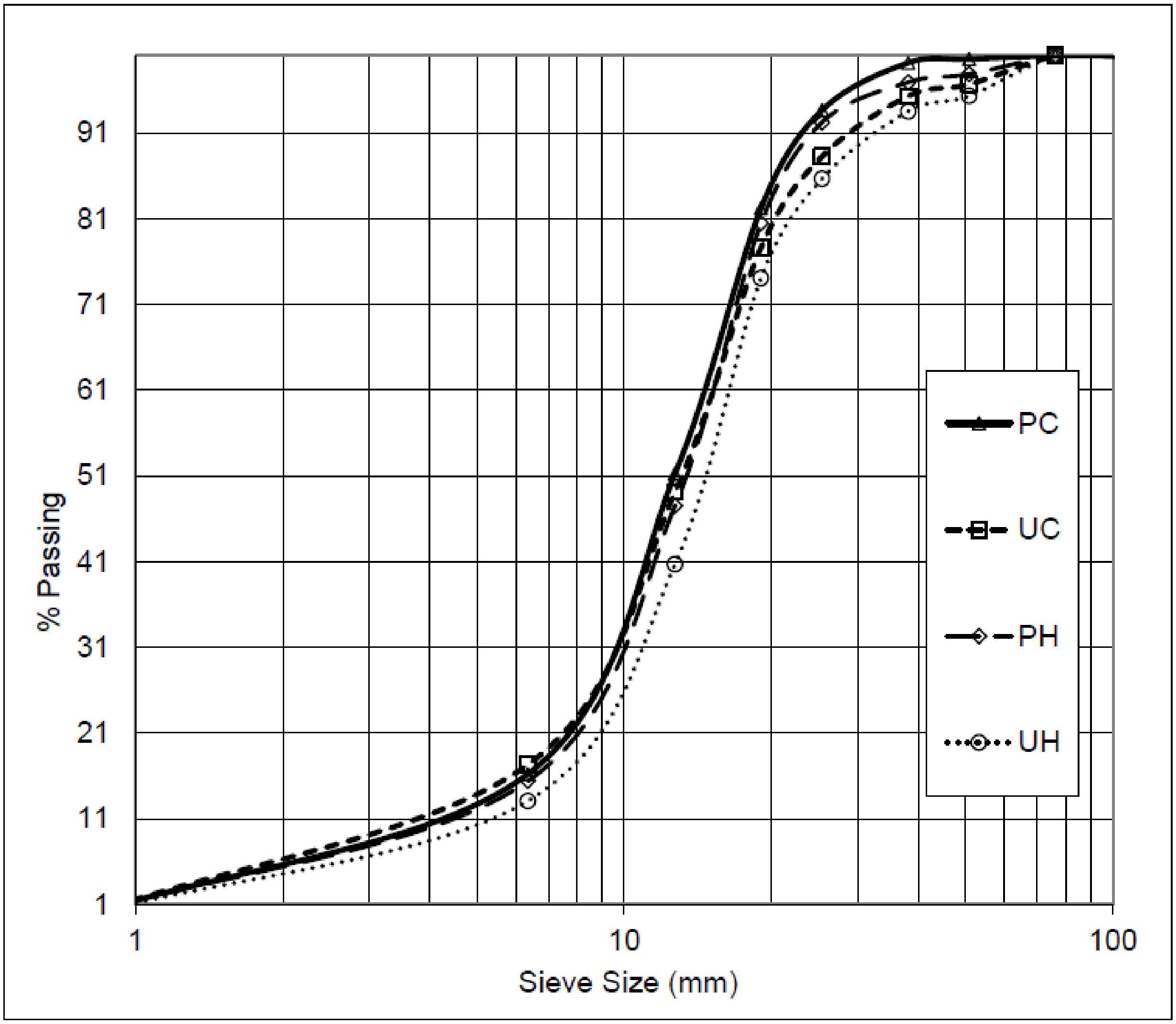

Fig. 3. Cumulative size distribution of % processed conifer (PC), unprocessed conifer (UC), processed hardwood (PH), and unprocessed conifer (UC) wood chip mass passing through screening sieves.

The influence the different variables had on particle size distribution can be seen in Table 6. Smaller size classes (< 6.35 to 19.05 mm) were mainly influenced by species, whereas the larger size classes (25.4 - >50.8 mm) were influenced by treatment.

Table 6 ANOVA table of particle size distribution.

Particle size class (mm)	Effect	DF	SS	MS	F-Value	P-Value
< 6.35	Treatment	1	0.0004	0.0004	0.1490	0.7006
	Species	1	0.0185	0.0185	6.9240	0.0095
	MC	1	0.0000	0.0000	0.0050	0.9439
	Treatment*Species	1	0.0114	0.0114	4.2640	0.0409
	Residuals	134	0.3575	0.0027		
6.35 - 12.7	Treatment	1	0.0545	0.0545	17.0420	0.0001
	Species	1	0.0432	0.0432	13.5130	0.0003
	MC	1	0.0000	0.0000	0.0080	0.9307
	Residuals	135	0.4319	0.0032		
12.7 - 19.05	Treatment	1	0.0049	0.0049	1.7320	0.1904
	Species	1	0.0363	0.0363	12.7670	0.0005
	MC	1	0.0086	0.0086	3.0290	0.0841
	Residuals	135	0.3840	0.0028		
19.05 - 25.4	Treatment	1	0.0013	0.0013	0.5280	0.4690
	Species	1	0.0011	0.0011	0.4300	0.5130
	MC	1	0.0025	0.0025	1.0010	0.3190
	Residuals	135	0.3336	0.0025		
25.4 - 38.1	Treatment	1	0.0215	0.0215	14.9830	0.0002
	Species	1	0.0002	0.0002	0.1260	0.7235
	MC	1	0.0002	0.0002	0.1040	0.7472
	Residuals	135	0.1940	0.0014		
38.1 - 50.8	Treatment	1	0.0026	0.0026	10.9240	0.0012
	Species	1	0.0007	0.0007	2.8680	0.0927
	MC	1	0.0000	0.0000	0.0220	0.8835
	Residuals	135	0.0325	0.0002		
> 50.8	Treatment	1	0.0251	0.0251	18.7340	0.0000
	Species	1	0.0071	0.0071	5.2910	0.0230
	MC	1	0.0010	0.0010	0.7430	0.3901
	Species*MC	1	0.0125	0.0125	9.3260	0.0027
	Residuals	134	0.1795	0.0013		

Note: Treatment = processed or unprocessed; Species = conifer or hardwood; MC = moisture content; DF = degrees of freedom; SS = sum of squares; MS = mean square.

During the analysis, we observed a difference in moisture content between samples of different size classes, i.e., chips greater than 50.8 mm had a higher moisture content compared to chips less than 6.35 mm. We were concerned that these differences would influence mass used to make comparisons between size classes. To minimize this effect, fractions created during the shaking process were bagged and dried in an oven for 48 hr and then re-weighed.

The mean geometric length of the ground slash material (limbs and chunks) from processing was 47.47 mm. The particle size distribution of the 15 hog fuel samples showed that a majority (55%) of the particles were > 25.4 mm (Figure 4). It should be noted that manual sorting, in addition to the mechanical separation done by the shaker and sieves was done to obtain fractions represented by their maximum length. This was because long, "spear-like" particles would tend to dive down the sieve stack and rest on a sieve measuring its second longest dimension.

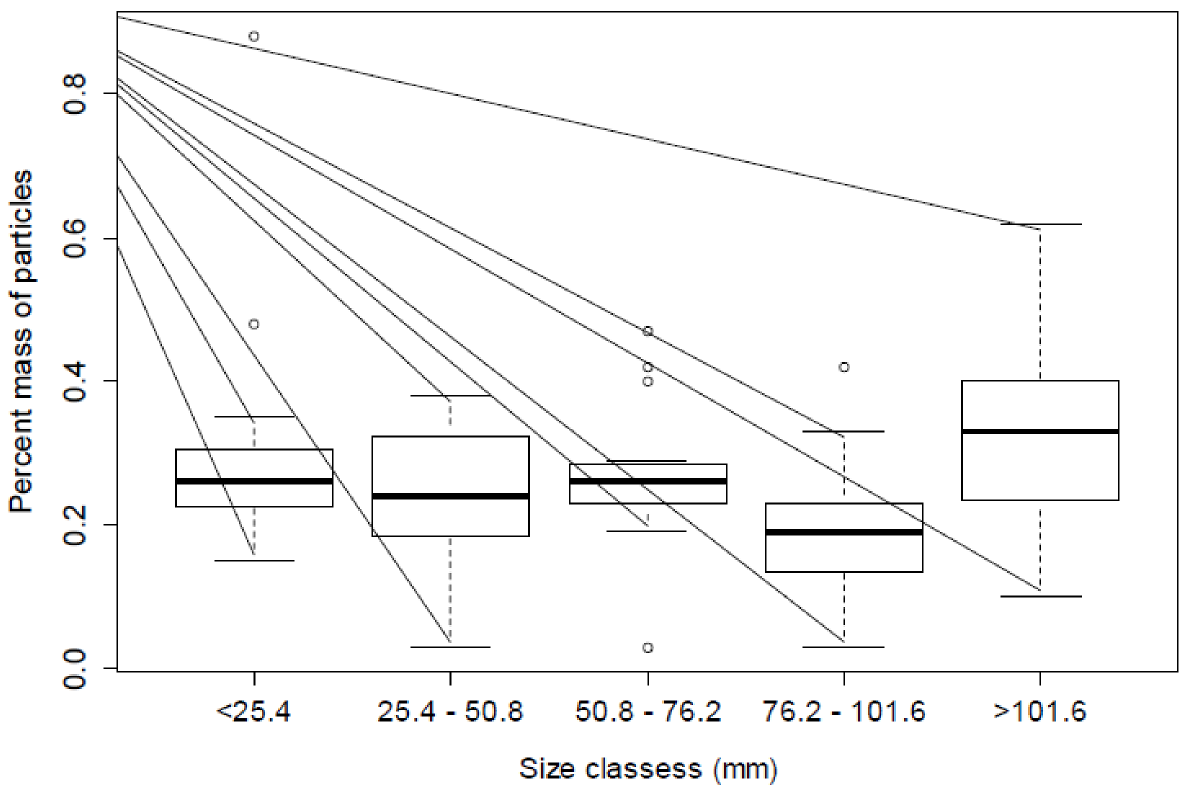

Fig. 4. Size distribution of hog fuel samples collected from grinding slash material (i.e., stems, limbs and chunks left after processing sawlogs). The percentage of total dry weight retained on 25.4, 50.8, 76.2, and 101.6 mm sieves and a bottom pan. Samples were further separated manually to achieve an accurate distribution analysis.

3.4. Bulk Density

The bulk density of the five material types ranged from 137.20 – 322.17 kg/m3 (Table 7). There is a statistically significant difference between material types determined by one-way ANOVA $F(4,148) = 530.5$, $p = <0.0001$. A post hoc multiple comparison test determined that all were statistically different from each other except processed and unprocessed hardwood.

Table 7 Mean bulk density of five material types produced from sorting forest residues generated from a timber harvest operation.

Material type		Average bulk density (kg/m^3)	n	SD
Processed conifer	(PC)	228.13	36	12.70
Processed hardwood	(PH)	322.17	22	11.82
Unprocessed conifer	(UC)	239.09	37	15.76
Unprocessed hardwood	(UH)	309.84	28	14.21
Slash		137.20	15	25.84

We hypothesized that unprocessed materials would have greater proportions of larger sized particles resulting in significantly different bulk densities compared to processed material. We found that there was no significant difference between the bulk density of PH and UH; $t(48)=-0.18$, $p=0.86$. There was however, a significant difference between PC and UC; $t(71)=-6.54$, $p < 0.0001$. Interestingly, the mean bulk density of the unprocessed conifer was greater than processed, which is contrary to what we expected. The most reasonable explanation for this was a 19 day time lag between PC and UC analysis. Even though samples were sealed in a plastic bag, there may have been some moisture loss. Our suggestion for future research is to quickly analyze all samples when using this method. The other, less practical solution is to oven dry all samples before analysis.

3.5. Ash Content Analysis

Ash content for the five different material types ranged from 0.24 and 1.50% of the oven-dry sample weight (Table 8). There was a significant difference between all material types except for processed and unprocessed hardwoods as determine by a one-way ANOVA $F(4,198) = 51.88$, $p = < 0.001$. The results from the ash content analysis were within reported ranges of 0.4 and 0.8 wt% (dry basis) and 1.0 and 1.3 wt% (dry basis) for softwoods and hardwoods, respectively (Obernberger and Thek, 2004). The highest ash content results were from the slash samples. Visually, these samples looked “dirty” by containing soil and leaves. There was a 58% reduction in ash content between PC and UC which might be a result of bark removal during processing. However, this reduction was not observed between the PH and UH samples. Other factors such as bark thickness, bark adhesion, or difference in inorganic materials within the bark of the different species may have influenced our results. More investigation is needed to determine what specifically influenced ash content.

3.6. Feedstock Quality and Implications for Management

In a typical timber harvest operation, biomass in the form of unmerchantable trees, tops, branches, and chunks from processing sawlogs, are piled together. This forces contractors to comminute with machines such as grinders which can handle mixed residues. A study looking at grinding mixed conifer slash and hardwood whole trees found the percentage of particles < 2.54 cm was only 45 and 33%, respectively (Han et al., 2015). Another study that ground branches and tops, and pulpwood using knife-edge bits and a small screen size configuration found that

91.8 of the particles were < 7.61 cm in length (Zamora-Cristales et al., 2015). In both studies a majority of the comminuted material was too large for current BCT operation. The results of this study showed how separating biomass stems from other residues during a timber harvest or fuel reduction operation can facilitate the use of a chipper instead of a grinder, which can greatly improve the ability to produce quality feedstock that meets the specifications for BCTs.

Table 8 Ash content of five material types generated from sorting forest residues generated from a timber harvest operation.

Material type		Ash content (%)[1]	n	SD
Processed conifer	(PC)	0.27	31	0.07
Processed hardwood	(PH)	1.03	43	0.24
Unprocessed conifer	(UC)	0.64	45	0.68
Unprocessed hardwood	(UH)	1.07	39	0.21
Slash		1.50	45	0.40

[1] The weight of the ash divided by the original oven-dried sample weight multiplied by 100.

Sorting residues was also influential on the amount of ash contained in samples. Our findings showed that slash material had a significantly higher ash content compared with the other material types. Dukes et al. (2013) analyzed the ash content of two residue types: larger residues from delimbing with a pull-through delimber and branches, and bark removed from a chain flail machine. They found a 4 and 11.9% ash content for the two material types, respectively. This further suggests that sorting out stem wood from branches is an important tool in improving feedstock quality. And even though moisture content nor bulk density were influenced by the additional step of processing biomass stems when sorting, the results of this study showed that it has the potential to further reduce ash content.

4. Conclusion

Processed and unprocessed, conifer and hardwood tops were chipped and slash (stems, limbs and chunks) generated from processing sawlogs were ground in a study to evaluate their differences in moisture content, particle size distribution, bulk density, and ash content. The moisture content ranged from 19 – 29% with evidence that slash was significantly drier than other material types. Bark removal from processing or delimbing stems did not have an effect on moisture content within a two month period. The use of a chipper increased the ability to control particle size compared to material comminuted in similar studies with a grinder. We found that additional processing prior to comminution decreased the amount of material greater than one inch in length by an average of 6%. The results of the particle-size distribution analysis suggest that processing stems is recommended to control the amount of particles greater than 25.4 mm. Furthermore, species selection can control the amount of particles less than 19.05 mm in length. The bulk density of the hardwood was significantly greater than conifer with no difference between processed and unprocessed hardwood. The ash content was found to be greatest in the ground slash material and the least in the processed conifer. A 58% reduction was noticed between processed and unprocessed conifer which may be due to the reduction in bark during processing.

Our findings have shown that sorting and processing forest residues during a timber harvest can facilitate the use a chipper and provide a high quality feedstock for biomass conversion technologies. The results also illustrate the potential feedstock that can be derived from processed and unprocessed conifer and hardwood stems of the Pacific Northwest.

5. References

1. Acharjee, T. C., Coronella, C. J., & Vasquez, V. R. (2011). Effect of thermal pretreatment on equilibrium moisture content of lignocellulosic biomass.Bioresource technology, 102(7), 4849-4854.
2. ANSI/ASAE Standard S424.1, 1992 (R2007) Method of Determining and Expressing Particle Size of Chopped Forage Materials by Screening American Society of Agricultural and Biological Engineers (1992) pp. 663–665
3. ASTM E871–82 Standard Test Method for Moisture Analysis of Particulate Wood Fuels American Society for Testing and Materials (ASTM), USA (2006)
4. Brand, M. A., de Muñiz, G. I. B., Quirino, W. F., & Brito, J. O. (2011). Storage as a tool to improve wood fuel quality. Biomass and Bioenergy, 35(7), 2581-2588.
5. CEN/TS. 15103: 2006. Solid biofuels – methods for the determination of bulk density. European Committee for Standardization, Brussels, Belgium (2006) p. 9
6. Dukes, C. C., Baker, S. A., & Greene, W. D. (2013). In-wood grinding and screening of forest residues for biomass feedstock applications. Biomass and Bioenergy, 54, 18-26.
7. Filbakk, T., Jirjis, R., Nurmi, J., & Høibø, O. (2011). The effect of bark content on quality parameters of Scots pine (Pinus sylvestris L.) pellets. Biomass and Bioenergy, 35(8), 3342-3349.
8. Greene, W. D., Cutshall, J. B., Dukes, C. C., & Baker, S. A. (2014). Improving woody biomass feedstock logistics by reducing ash and moisture content. BioEnergy Research, 7(3), 816-823.
9. Hakkila, P. (1989). Utilization of residual forest biomass. Springer-Verlag, Berlin. 568 pp.
10. Han, H. S., Halbrook, J., Pan, F., & Salazar, L. (2010). Economic evaluation of a roll-off trucking system removing forest biomass resulting from shaded fuelbreak treatments. biomass and bioenergy, 34(7), 1006-1016.
11. Han, S. K., Han, H. S., & Bisson, J. A. (2015). Effects of grate size on grinding productivity, fuel consumption, and particle size distribution. *Forest Products Journal*.
12. Kizha, A., and Han, H. S. (2015). Cost and productivity for processing and sorting forest residues. Proceeding for the Council of Forest Engineering’s Annual Conference, in Lexington, Kentucky on July 19-22.
13. Lacey, J. A., Aston, J. E., Westover, T. L., Cherry, R. S., & Thompson, D. N. (2015). Removal of introduced inorganic content from chipped forest residues via air classification. Fuel, 160, 265-273
14. Lehtikangas, P. (2001). Quality properties of pelletised sawdust, logging residues and bark. Biomass and bioenergy, 20(5), 351-360.
15. Mitchell, D., & Gallagher, T. (2007). Chipping whole trees for fuel chips: a production study. Southern Journal of Applied Forestry, 31(4), 176-180.

16. Mozammel, H., S. Shahab, B. Tony, M. Sudhagar, J. Ladan, J. Lim, & M. Afzal. (2006). Interaction of Particle size, Moisture content and Compression Pressure on the Bulk density of Wood chip and Straw. *ASABE Paper*, (06-100).
17. Nati, C., R. Spinelli, & P. Fabbri. (2010). Wood chips size distribution in relation to blade wear and screen use. Biomass and Bioenergy. 34(5), 583-587.
18. Nurmi, J., & Hillebrand, K. (2007). The characteristics of whole-tree fuel stocks from silvicultural cleanings and thinnings. Biomass and Bioenergy, 31(6), 381-392.
19. Nurmi, Juha, and Jani Lehtimäki. (2011). Debarking and drying of downy birch (Betula pubescens) and Scots pine (Pinus sylvestris) fuelwood in conjunction with multi-tree harvesting. Biomass and Bioenergy 35(8): 3376-3382.
20. Obernberger, I., & Thek, G. (2004). Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass and bioenergy, 27(6), 653-669.
21. Perlack, R. D., Wright, L. L., Turhollow, A. F., Graham, R. L., Stokes, B. J., & Erbach, D. C. (2005). Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Lab TN.
22. Perlack, R. D., Eaton, L. M., Turhollow Jr, A. F., Langholtz, M. H., Brandt, C. C., Downing, M. E., ... & Lightle, D. (2011). US billion-ton update: biomass supply for a bioenergy and bio-products industry.
23. Picchio, R., Sirna, A., Sperandio, G., Spina, R., & Verani, S. (2012). Mechanized harvesting of eucalypt coppice for biomass production using high mechanization level. Croatian Journal of Forest Engineering, 33(1), 15-24.
24. R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.
25. Rogers, K. (1981). Pre-harvest drying of logging residues. Forest Products Journal. 31(12):32-36.
26. Röser, D., Mola-Yudego, B., Sikanen, L., Prinz, R., Gritten, D., Emer, B., ... & Erkkilä, A. (2011). Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. biomass and bioenergy, 35(10), 4238-4247.
27. Ross, Robert J. (2010). Wood handbook : wood as an engineering material. Centennial ed. General technical report FPL ; GTR-190. Madison, WI : U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, 2010: 1 v.
28. Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., & Templeton, D. (2008). Determination of ash in biomass. National Renewable Energy Laboratory, 1-5.
29. Smith, D., Sessions, J., Tuers, K., Way, D., & Traver, J. (2012). Characteristics of forest-derived woody biomass collected and processed in Oregon. Forest Products Journal, 62(7), 520-527.
30. Spinelli, R., B. R. Hartsough, & N. Magagnotti. (2005). Testing mobile chippers for chip size distribution. International Journal of Forest Engineering. 16(2), 29-35.
31. Spinelli, R., N. Magagnotti, G. Paletto, & C. Preti. (2011). Determining the impact of some wood characteristics on the performance of a mobile chipper. Silva Fennica. 45(1), 85-95.
32. Stokes, Bryce J.; McDonaStokes, Bryce J.; McDonald, Timothy P.; Kelley, Tyrone. (1993). Transpirational drying and costs for transporting woody biomass - a preliminary review. In: Proceedings of IEA/BA Task IX, Activity 6: Transport and Handling; 1994 May 16-25; New Brunswick, Canada. Aberdeen, UK: Aberdeen University: 76-91.

33. Van der Stelt, M. J. C., Gerhauser, H., Kiel, J. H. A., & Ptasinski, K. J. (2011). Biomass upgrading by torrefaction for the production of biofuels: a review.*Biomass and bioenergy*, *35*(9), 3748-3762.
34. Zamora-Cristales, R., Sessions, J., Smith, D., & Marrs, G. (2015). Effect of grinder configuration on forest biomass bulk density, particle size distribution and fuel consumption. Biomass and Bioenergy, 81, 44-54.