Title: Removal of introduced inorganic content from chipped forest residues via air classification

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1. Introduction

Biomass feedstocks are gaining recognition as the renewable resource with the greatest potential to contribute to the energy demands of modern society [1, 2]. The wide availability of biomass offers the potential to reduce the dependence of national economies on the importation of conventional energy resources, including coal, petroleum and natural gas. As conventional resources continue to be depleted, biomass is expected to gain importance as an alternative energy source world-wide, but will be especially important for developing countries whose economies are heavily based upon agriculture and forestry [3].

Specific to the availability of forest resources, a 2006 study estimated that there were about 36.2 million dry tons (US short tons) of recoverable logging residues available in the US each year, with more than half of that material located in the Southeast and Southcentral regions of the US. [4]. The Billion-Ton Update released by the US Departments of Energy (DOE) and Agriculture (USDA) in August 2011 predicts that forest residues will be a significant source of biofuels [5, 6]. According to projections, the logging residue supply curve plateaus with 47 million dry tons potentially available from all forest lands at \$40 per dry ton or less. The estimated quantity of forest thinnings is approximately 37 million dry tons per year at a roadside price of \$100 per dry ton or less [5, 6]. Such resources may provide a significant amount of feedstock for energy conversion pathways.

The ash content of biomass is known to have significant effects on thermochemical processes, including combustion (see Table 1). The primary thermochemical conversion processes are gasification, pyrolysis and hydrothermal liquefaction [7]. The following paragraphs briefly summarize the effects of inorganic species in each of these processes, starting with pyrolysis. Pyrolysis is thermal decomposition of biomass into solid char, liquid oil or tar, and gaseous products in the absence of oxygen. Pyrolysis processes that incorporate rapid biomass heating rates to moderate temperatures in the range 480-550 °C and short vapor residence times are referred to as fast pyrolysis and are known to maximize the production of liquids. Fast pyrolysis (FP) is gaining interest as a potentially versatile, efficient, economical and environmentally favorable process for converting biomass to liquid fuels [7, 8]. During pyrolysis, some ash forming elements, even at trace levels (<0.1%), can alter both the thermal degradation rate and chemical pathways [9]. The alkali metals potassium (K) and sodium (Na), and the alkaline earth metals calcium (Ca) and magnesium (Mg), are known to catalyze the thermal degradation of biomass to light gases rather than the preferred liquids [10, 11]. Other studies have demonstrated negative effects of higher bulk ash content on the pyrolysis process yield [12, 13]. These studies have compared the process yields of various biomass sources before and after different leaching processes and have demonstrated a negative correlation between total ash content and bio-oil yield.

In addition, studies have impregnated clean biomass or biomass constituent samples with various inorganics, including K, Mg, Ca, iron (Fe), and phosphorous (P) or salts containing those elements. In general, liquid yield was found to increase for demineralized biomass and decreased with increasing salt impregnation [14]. In another study, potassium was found to promote depolymerization/fragmentation reactions to form lower molecular weight oxygenates at the expense of levoglucosan and other anhydrosugars [15]. However, other ash forming elements had only minor effects, except for P, which resulted in a simpler product distribution dominated by levoglucosenone and furfural. Another study reported that K significantly

enhanced the rate of lignin pyrolysis and char production, but with minimal change in the product distribution [16]. Fast pyrolysis of cellulose with varying concentrations of added alkali and alkaline metal chlorides and anions revealed that char formation was strongly enhanced by alkali and alkaline earth metal addition [17].

Hydrothermal liquefaction (HTL) converts biomass in the presence of a solvent at moderate temperatures (250–550 °C) and pressures (5–25 MPa) to solid, oil, aqueous, and gas fractions [18]. Although HTL has longer residence times and higher capital costs than fast pyrolysis, HTL does not require drying of the feed materials, making it suitable for wet grasses and algal resources. In addition, bio-oils from HTL usually have lower moisture and oxygen content compared to oils from fast pyrolysis [19].

Elevated ash content has also been shown to be deleterious to the combustion of biomass for energy generation. The inorganic species silicon (Si), K, Na, sulfur (S), chlorine (Cl), P, Ca, Mg, and Fe contribute to reactions that lead to fouling and slagging [20, 21]. The primary sources of problems are reactions of alkalis with silica that form alkali silicates with low melting or softening temperatures and also reactions of alkalis with sulfur to form alkali sulfate deposits that impede heat transfer on reactor surfaces. Chlorine, a minor constituent in virtually all coals and biofuels, contributes to the corrosion of boiler surfaces depending upon concentration and appears to facilitate the transport of alkalis from fuel to surfaces [22, 23]. Jenkins et al. has noted that the amount of alkali vaporized during combustion often depends as strongly upon chlorine concentration as it does the alkali concentration [21, 24].

Because of the published results discussed above, ash removal prior to conversion processes will become more important as forest residues and other high ash content feedstocks are used alone or in higher blend ratios in conversion processes. There are many ways to remove ash forming elements from biomass; however none of them are without associated costs. Disposal costs will rise as quantities of ash rise [25]. The key to efficient and economical biomass conversion processes will be to remove the ash forming elements from the biomass

effectively, inexpensively, and in a manner that removes as little biomass from the process as possible.

Soil contamination is known to be a major contributor to the total ash content in typical forest residue samples [26], and some of this contamination can be concentrated in the smallest size fractions of the biomass [26, 27]. Effective ash reduction methods in forest residue samples include improved harvest and collection systems [28], and fine particle removal after initial size reduction using sieving [25] or trommel screens [26, 28, 29]. The removal of fine particles from the biomass can lead to improved ash concentrations; however the high-ash biomass that is removed must either be disposed of and replaced with on-spec feedstock, or treated to remove the ash forming elements so it can be used in the conversion processes [29]. Leaching can be used to effectively remove many of the soluble ash forming elements; however, this process typically requires that the biomass be dried prior to conversion, and potentially large volumes of waste leachate will need to be treated prior to disposal. It has been shown that ash removal can be achieved through the use of different field processing systems, although at a much higher delivered cost [28, 30].

Pine trees are known to have an uneven distribution of inorganic elements throughout their tissues [31, 32], with needles and bark containing higher concentrations of ash than wood. The concentration of some inorganic elements is highest in the cambium, the metabolically active boundary between the sapwood and bark [33]. Cambium concentrations of K, P, Ca, and Mg were found to be an order of magnitude higher than the concentrations found in sapwood, while most inorganic elements were lowest in the heartwood [33]. In addition to chemical differences between plant tissue types, there are also density differences, including measurable differences between bark, needles, heartwood, and sapwood [34-38]. These differences may be useful in separating these tissues into distinct fractions using methods that rely on material density, particle shape, and surface area. Air classification is a well understood separation technology used in a wide variety of industries that separates materials based upon particle size and

particle density [39]. Air classification has the potential to take advantage of the natural physical characteristics of biomass feedstocks to isolate fractions of feedstocks that have different chemical compositions, such as specific anatomical fractions or low or high ash content fractions. This work describes air classification methods to isolate high- and low-ash content fractions in loblolly pine forest residues to prepare these materials for thermochemical conversion processes.

2. Materials and Methods

2.1. Material Supply and Formatting

Loblolly pine forest thinnings and loblolly pine logging residues, chipped to 5.8 cm (2 inches), were supplied from Verdant BioSciences (Denver, CO). The material was dried to approximately 4.3% moisture and stored in super sacks. Two super sacks for each material (approximately 200 kg dry weight each) were homogenized and divided into smaller samples by completing successive passes through a custom eight-way rotary splitter.

2.2. Anatomical Fractionation

Anatomical fractions were separated by hand and included needles, bark, whitewood, branches, twigs, and cambium. Cambium was defined as a wood chip with no bark that originated from the outermost layers of the tree, identified by a smooth surface that was once attached to the bark. Twigs were defined as full round branches that were small enough to go through the chipping process with all bark attached. Branches were similar to twigs but were larger and broken along their axis during the chipping process, causing loss of some bark. White wood originated from an interior portion of the tree, with no attached bark or smooth surfaces where bark was once attached. There were no visible differences in the color of the white wood chips, so separation of heartwood from sapwood was not possible in any of these experiments. A minimum of 200g of each anatomical fraction was collected.

The amount of each major anatomical component was quantified in three separate splits of both logging residues and forest thinnings. Anatomical components included needles, bark,

whitewood, and bark attached to whitewood. In each sample, there was a certain quantity of material that was either unidentifiable, or too small to be manually separated. This fraction was referred to as “fines.” The mass of each collected fractions was recorded.

2.3. Air Classification

A 2x Air Cleaner (Key Technologies, Walla Walla, WA) equipped with an Iso-flo dewatering infeed shaker (Key Technologies) was used in all air classification experiments. Fan speeds on the air classifier were optimized for separation of fractions of the chipped pine residues. The fan speeds were set using an electronic controller, and the speeds used in separations were (in Hz): 10, 12, 15, 18, 22, 28, 32 and 40. Air velocity measurements were recorded at fan speeds from 10Hz to 25Hz at distances of 15.4, 30.5, 47.5 cm (6, 12, and 18 inches, respectively) above the air cleaner blower screen (Figure 1). To begin each separation experiment, the air classifier was set for the lowest fan speed (10Hz). A bag (3-5kg) of chipped logging residues or forest thinnings was manually fed onto the infeed shaker at a rate that ensured that material was not more than one layer thick as it passed through the air classifier. As the material passed over the blower screen of the air classifier it was separated into two fractions by the upward flow of air. Particles that were blown out of the flow of material were considered the light fraction, and particles that passed through the air current were considered the heavy fraction. The heavy fraction was passed through the air classifier two additional times at the same air velocity before the light fraction was collected from the hopper of the air classifier and placed in plastic bags. After the light fraction was collected, the fan speed was incrementally increased, and the remaining material (heavy fraction) was processed through the air cleaner at the increased fan speed three times. This was repeated for all specified fan speeds. After processing the material through the air classifier at all fan speeds, the final heavy fraction was also saved. Throughout the experiment, some of the smaller and denser particles fell through the blower screen and into the fan ducting. This fraction, referred to as the “below screen” or “BS” fraction, was collected from the ducting after each experiment was completed. The mass of each collected fraction was

recorded. These experiments were completed in triplicate with both chipped logging residues and chipped forest thinnings.

2.4. Sample Analysis

Air classified fractions were size reduced to 200 μm prior to total ash analysis and elemental ash analysis, which was done by Huffman Laboratories (Golden, CO). The procedure used is described here briefly. Ground samples were placed in platinum crucibles and analyzed with a LECO TGA701 Thermogravimetric Analyzer (St. Joseph, MI) for moisture and total ash content. The apparatus was heated to 107°C under a flow of 10 liters per minute ultra-high purity nitrogen and maintained at that temperature until a constant mass was reached to measure the moisture content. The temperature was then increased to 750°C and held until a constant mass was reached for total ash measurement. Following the analysis for total ash, the samples were well mixed with lithium metaborate in the original platinum crucible and fused for a fixed time at 950°C. The cooled crucible was placed into a new polypropylene bottle containing 100.0 mL of dilute acid and shaken for several hours on a mechanical shaker until the fusion bead completely dissolved from the crucible. The resulting solution was analyzed by inductively coupled plasma – atomic emission spectroscopy for major and minor ash forming elements. Sample concentrations for individual elements were calculated based on molecular weight.

2.5. Economic Modeling

Aspen Plus process simulation software (version 8.6) was used to estimate costs associated with air classification of pine forest residues. A flow of 25 US short tons per hour was assumed. The wood in the model has an ash composition similar to the logging residue of this report, but with only the major components included. The total ash content is 1.25 wt%, with that total being composed of silica 65 wt% (representing all of the soil elements) and the carbonate salts of calcium (14.4 wt%), magnesium (5.6 wt%), potassium (13.3 wt%), and sodium (1.7 wt%). Budgetary quotes of air classifiers were received from the manufacturer, Key Technologies.

3. Results

3.1. Anatomical Fractionation

Results from the anatomical fractionation can be seen in Table 2. The mass distribution among anatomical fractions was very similar between the two pine residue sources. The only noticeable difference was that the logging residues had nearly twice the amount of needles as the forest thinnings; however at quantities ranging from 0.69% to 1.26% of the total biomass, this is unlikely to have a major impact on whole sample composition. Total ash content of the anatomical fractions (Table 3) was similar to other values reported in the literature [40-42]. Whole ash concentrations were highest in the needles (2.21%) and lowest in the white wood (0.31-0.38%). The elemental analysis of the anatomical fractions is also shown in Table 2. Needles contained relatively high concentrations of K (0.39%), sulfur (S, 0.042-0.047%), P (0.094-0.116%), Si (0.35-0.38%) and halogens (primarily Cl, 340-395 µg/g). Levels of Al (aluminum) and Mg were highest in the bark fraction.

3.2. Air Classification

The air classified fractions obtained from the 2" wood chips contained some visually distinctive characteristics. While the "below screen" fraction was not intentionally created, its impact on ash concentrations is important as it contained a large proportion of sand, dirt, and small rocks (heavy fines). The 10 Hz fraction contained mostly dirt, dust, and small thin pieces of bark or wood, but contained no needles. Nearly all of the needles came out in the light fractions collected at 12, 15, and 18 Hz. These fractions contained both bark and white wood, with particle size increasing as the fan speed increased. As the fan speed increased further (22-32 Hz), there was less bark and more white wood. The 40 Hz and the Heavy samples consisted primarily of large pieces of wood, knots, full round twigs, branches, and some cambium. There were very few wood chips that had originated from the interior portion of the trunk in these heaviest two fractions.

Figure 2 shows how the mass was distributed throughout the air classified fractions. In the 2" chips of both biomass types, around 75% of the biomass was contained in the heaviest 4

fractions (28 Hz, 32 Hz, 40 Hz, Heavy). The total ash content of each air classified fraction, along with the relative mass distribution, is shown in Table 4. The fractions with the highest ash content contained very little mass.

3.3. Elemental analysis of air classified fractions.

The elemental analyses of the whole material and air classified fractions are shown in Table 5 for both forest thinnings and logging residues. All elemental concentrations are reported as a percentage of whole biomass, with the exception of the halides (primarily Cl) which is reported as $\mu\text{g}/\text{gram}$ of whole biomass. Notice that the concentrations of some inorganic species, including K, Mg, Ca, and S are higher in the heavier fractions.

4. Discussion

4.1. Anatomical classification

Due to their high calorific values, needles have received increased attention as a potential higher value feedstock [43, 44], but they also contain higher concentrations of ash. Needles were found to be most concentrated in the 12Hz, 15Hz, and 18Hz fractions, so collecting this fraction is a possibility; however their selective removal would provide little impact to overall ash content due to their low quantities in this biomass. Bark was found in every air classified fraction collected, so its removal from this feedstock via air classification is not straightforward.

4.2. Air classification for ash reduction

Because the BS fraction and lightest fractions contain considerably more ash than the heavier fractions (primarily Si), these fractions were mathematically removed from the bulk of the material, and the resultant ash content of the remaining sample was recalculated. Figures 3 and 4 show the changes in total ash concentration when different groups of high-ash content air classified fractions are removed from the forest thinnings and logging residues, respectively. The abscissa in these graphs shows the collection of samples that were removed from the bulk of the material. For example, "BS-15Hz" would indicate that fractions collected from BS, 10Hz, 12Hz, and 15Hz conditions were removed from the bulk of the sample. The left ordinate shows

the amount of biomass or ash that was removed with these fractions and the right ordinate shows the resultant ash content of the remaining biomass. As an example, Figure 3 shows that for forest thinnings, the removal of the two highest ash content fractions (BS and 10Hz) results in the removal of about 41% of the ash forming elements in the original biomass while only removing 6.7% of the total biomass, or a ash selectivity factor of 6.1 (calculated by dividing the % of total ash removed by the % of total mass removed). As a result, the ash content of the remaining biomass decreased from 1.69% to 1.07%. Logging residues showed a similar pattern with 42% of the total ash forming elements being contained in the same two fractions, representing only 6.7% of the biomass (ash selectivity factor of 6.3). The removal of these two fractions resulted in an ash content reduction from 1.09% to 0.68%. In both cases, the ash concentration was reduced considerably by removing less than 7% of the total biomass.

4.3. Removal of specific elements of ash

While the actual concentrations of all ash forming elements tended to decrease in the fractions as fan speed increased, two distinct patterns of ash element concentrations were observed. The first group of elements are common soil elements that may have been introduced to the pine residues during harvest and collection and will be referred to as “exogenous” or introduced elements. These elements include Si, Al, Fe, Na, and titanium (Ti). These elements are highly concentrated in the lighter fraction and make up a larger proportion of the ash forming elements in these fractions (>90% in some). Silicon concentrations decrease rapidly with the sequential removal of fractions with the highest ash concentrations. The comparison of biomass removed, silicon removed, and resulting silicon concentration is shown in Figure 5. Aluminum, Fe, and Na also follow this same removal pattern. Larger quantities of these elements are removed with the lighter fractions, and their concentrations rapidly decrease in the heavier fractions. This finding indicates that exogenous elements are more easily removed by air classification, and likely consist primarily of introduced ash forming elements that are either loose in the sample or lightly adhered to the surface of the biomass. Sodium was found to

behave like the exogenous elements, and is a common element in many fertilizers and clays; however it is also known to be an important biological element. Based on its behavior, it is likely that most of the Na that was concentrated in the lightest fractions was part of the introduced ash, and not of biological origin. The second group of elements are common in biological processes and will be referred to as “physiological” elements. These elements include Ca, K, Mg, S, manganese (Mn), and P. Figure 6 shows the effects on calcium concentrations from the sequential removal of the highest ash concentration samples. These elements are more uniformly distributed throughout the air classified fractions, so their removal is nearly proportional to the total biomass removed from the sample. In the light fractions, they represent a smaller proportion of the total ash content; however these physiological elements represent a majority of the total ash forming elements in the heavier fractions. The physiological elements are more likely to be of biological origin and contained inside the biomass. Physiological elements would likely require more intensive treatment strategies, such as leaching or significant size reduction, to reduce their concentrations in the biomass.

In a series of comprehensive reviews of the chemical composition of a variety of biomass types, Vassilev et al. [42, 45-47] reported some of the same observations that were found in this study. They reported that natural biomass is enriched in Mn, K, P, Cl, Ca, Mg, and Na. With the exception of Na, these elements in our study were found to be associated with the biomass itself, and not the easily removed contamination. They also reported that biomass was naturally depleted in Al, Fe, S, Si and Ti, similar to our observations of exogenous elements (with the exception of S), as these elements were likely only present in elevated concentrations due to contamination from soil or dust. They also found strong positive correlations between many physiological elements, including: Ca and S; K, Mg, and S; and Ca, Mg, and Mn; and positive correlations between exogenous elements including: Si, Al, and Ti; and Al, Ti, and Fe. They summarized that the sum of Si, Al, Fe, Na, and Ti likely originated from both the biomass itself and from soil introduced during harvest and collection, while Ca, Mg, Mn, K, P, S, and Cl were

likely to be of biological origin and not a result of contamination. Tao et al. [48] also found a similar pattern of correlation between ash elements, finding that ash elements grouped into three distinct groups: 1) Si, 2) Ca, Mg, P, K, and S, and 3) Al, Fe, and Na. These conclusions obtained through a thorough analysis of available data agree with the conclusions found in this study of air classification.

4.4. Preliminary economic analysis of air classification

The air classifier is a free-standing machine supplied fully assembled. Key Technology (Walla Walla, WA), the manufacturer of the unit used in this testing, provided budgetary quotes for three sizes of similar equipment. The largest unit, Model #16, can process approximately 1400 cubic feet of solids per hour. Assuming wood chips with a density of 40 pounds for cubic foot of wood and a 50% void fraction in bulk, this is equivalent to 14 US short tons per hour. The target processing rate for this study is 25 tons per hour as that capacity has been determined appropriate for a biomass collection depot (Thermochem SOT, INL). Although two machines could provide the needed capacity, three machines were costed to allow time out of service for setup, cleanup, and maintenance. The facility as a whole is assumed to have, as a result of other external factors, a 90% stream factor that is not improved by having a third train available.

The quoted price per machine was \$56,440. Feed and product hoppers and a conveying system between them and the classifier will be needed; and the cost and complexity of these items are expected to be similar to those the classifier. The total purchase cost of three classifier trains is then approximately \$339,000. Taking the final installed cost, including foundations, electrical, plumbing, painting and instrumentation, to be four times the purchase price gives a total system cost of \$1.36 million. Assuming a 12% capital charge leads to a yearly capital charge of \$0.83 per ton of biomass processed. A complete breakdown of operational costs is shown in Table 6.

Approximately 90% of the operating cost comes from the assumed yield loss of discarding the light fraction of biomass (the Below Screen through 12 Hz fractions). Alternatively, the lights

fraction might be used as fuel. Considering that dried pine has a heating value of approximately 10 GJ/dry ton and a fuel value of \$3/GJ (less than natural gas to reflect transport, handling, and ash disposal costs), the value of the separated fraction is worth approximately \$30.00/dry ton. Note that although high ash content is undesirable for most dry thermochemical and combustion conversion applications, there are other conversion processes under development, including biochemical and hydrothermal liquefaction, which will likely have higher tolerance for feedstocks with high ash content. A further consideration is that there are technologies, such as chemical leaching, that can remove additional ash content from the separated fraction, potentially improving its conversion performance in thermochemical or combustion processes. The cost of an example wet chemical leaching method has been estimated to \$30-40/dry ton (manuscript in preparation). The actual value that can be obtained from the separated high ash content fraction is likely between \$10 and \$40/ dry ton, depending upon regional demand for biomass feedstock. Assuming that the initial value of the forest residue material is \$40/dry ton and that a credit of \$30/dry ton can be obtained for separated material with high ash content, the net operating cost of air classification is \$1.33 per dry ton resulting in an estimated total cost of \$2.23 per dry ton (including the capital charge), making it a very attractive technology for ash content removal from forest residues.

5. Conclusions

The quality of many feedstocks suffers from the inclusion of soil during the harvest and collection process. Air classification is an effective, economically viable tool for creating high- and low-ash content fractions, and to reduce whole ash forming element concentrations in pine forest residues. Introduced ash, or soil elements, are easily concentrated from biomass using air classification. Given the successful removal of introduced ash elements from pine chips demonstrated in this study, additional work should be performed to determine how effective air classification can be at removing introduced ash from other feedstocks to improve their quality. However, it should be recognized that air classification does not appear to be an effective

method for isolating any of the biologically derived (or associated) elements found in pine forest residues as they seem to be more uniformly distributed throughout the biomass tissue, and are likely located inside the biomass itself. More intense and costly physical or chemical processing methods will need to be employed if concentrations of these elements need to be reduced to meet quality specifications. Further development of these extraction methods will be required if they are to be economically feasible.

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Table 1: Effects of ash content in thermochemical conversion processes

Ash content/composition	Soluble ash forming elements affect fuel acidity/quality; lower oil yields; char composition and disposal; transportation costs
Potassium & sodium	Alkali metals with greatest catalytic effect for thermal degradation of lignin to increase the yield of reaction water
Calcium & magnesium	Lesser catalytic effect for thermal degradation of lignin; CaO can reduce bio-oil oxygen; ash utilization
Chlorine & sulfur	Corrosion generally; upgrading catalyst poisons
Phosphorus	Strong catalytic effect, increased char, promotes different, simplified product distribution than alkali metals

Table 2: Anatomical distribution among loblolly pine forest residues. Reported values are mean weight percent $\pm$ 1 standard deviation, $n = 3$.

	% White	% White with bark attached	% Bark	% Needles	% Fines	% Rock
Forest Thinnings	57.9% $\pm$ 1.6%	17.6% $\pm$ 1.0%	3.6% $\pm$ 0.1%	0.7% $\pm$ 0.1%	20.2% $\pm$ 2.6%	0.0%
Logging Residues	59.6% $\pm$ 2.4%	12.2% $\pm$ 0.5%	4.5% $\pm$ 0.4%	1.3% $\pm$ 0.2%	22.3% $\pm$ 2.6%	0.1% $\pm$ 0.2%

Table 3: Ash content and elemental ash content of anatomical fractions of loblolly pine forest residues. Values are reported as weight percent.

Forest thinnings	Ash Content	Si	Al	Fe	Na	Ti	Ca	K	Mg	S	Mn	P	Halogens (µg/g)
Needles	2.21%	0.377%	0.061%	0.045%	0.004%	0.001%	0.147%	0.393%	0.093%	0.047%	0.023%	0.116%	340
Bark	1.42%	0.093%	0.090%	0.025%	0.004%	0.001%	0.239%	0.255%	0.126%	0.031%	0.017%	0.051%	95
Twigs	1.09%	0.063%	0.028%	0.015%	0.003%	0.001%	0.218%	0.301%	0.119%	0.031%	0.018%	0.057%	122
Branch	0.57%	0.047%	0.015%	0.017%	0.002%	0.001%	0.096%	0.110%	0.044%	0.010%	0.010%	0.017%	50
Cambium	0.38%	0.028%	0.006%	0.010%	0.001%	0.001%	0.061%	0.076%	0.027%	0.007%	0.008%	0.008%	33
White Wood	0.31%	0.014%	0.004%	0.003%	0.001%	0.000%	0.059%	0.071%	0.025%	0.006%	0.008%	0.006%	17
Logging Residues	Ash Content	Si	Al	Fe	Na	Ti	Ca	K	Mg	S	Mn	P	Halogens (µg/g)
Needles	2.21%	0.345%	0.046%	0.017%	0.004%	0.001%	0.146%	0.394%	0.087%	0.042%	0.023%	0.094%	395
Bark	1.73%	0.123%	0.087%	0.009%	0.006%	0.001%	0.243%	0.281%	0.127%	0.034%	0.016%	0.052%	143
Twigs	1.26%	0.053%	0.029%	0.005%	0.004%	0.001%	0.256%	0.210%	0.075%	0.022%	0.016%	0.038%	123
Branch	0.64%	0.027%	0.021%	0.003%	0.001%	0.000%	0.102%	0.119%	0.048%	0.011%	0.009%	0.017%	70
Cambium	0.39%	0.026%	0.007%	0.002%	0.001%	0.000%	0.056%	0.078%	0.025%	0.008%	0.007%	0.007%	41
White Wood	0.38%	0.035%	0.008%	0.002%	0.002%	0.001%	0.055%	0.074%	0.024%	0.006%	0.008%	0.005%	19

Table 4: Mass distribution and ash content of air classified fractions of loblolly pine forest residues. Reported values are mean weight percent $\pm$ 1 standard deviation, $n = 3$.

	Forest Thinnings		Logging Residues	
Fan Speed	% Total Mass	% Ash	% Total Mass	% Ash
Below Screen	1.9% $\pm$ 0.6%	15.1% $\pm$ 1.7%	2.2% $\pm$ 0.1%	8.9% $\pm$ 4.34%
10Hz	4.8% $\pm$ 0.5%	8.5% $\pm$ 1.1%	4.5% $\pm$ 0.3%	5.8% $\pm$ 0.2%
12Hz	2.4% $\pm$ 0.4%	3.6% $\pm$ 0.9%	2.5% $\pm$ 0.5%	3.4% $\pm$ 0.7%
15Hz	3.1% $\pm$ 0.3%	1.9% $\pm$ 0.2%	3.7% $\pm$ 0.5%	1.9% $\pm$ 0.2%
18Hz	3.8% $\pm$ 0.3%	1.6% $\pm$ 0.1%	4.3% $\pm$ 0.2%	1.0% $\pm$ 0.4%
22Hz	7.5% $\pm$ 0.9%	1.3% $\pm$ 0.1%	8.1% $\pm$ 0.4%	0.7% $\pm$ 0.5%
28Hz	19.9% $\pm$ 0.7%	1.1% $\pm$ 0.04%	21.3% $\pm$ 0.8%	0.5% $\pm$ 0.3%
32Hz	16.0% $\pm$ 0.2%	0.7% $\pm$ 0.1%	16.8% $\pm$ 0.1%	0.4% $\pm$ 0.3%
40Hz	20.9% $\pm$ 0.4%	0.8% $\pm$ 0.1%	19.9% $\pm$ 0.4%	0.5% $\pm$ 0.3%
Heavy	19.7% $\pm$ 2.0%	1.0% $\pm$ 0.1%	16.8% $\pm$ 1.9%	0.6% $\pm$ 0.5%

Table 5: Elemental ash analysis. Top: whole material from forest thinnings and logging residues. Bottom: air classified fractions from forest thinnings and logging residues. Values are reported as mean weight percent ± 1 standard deviation, *n* = 3.

Whole Material

	Ash Content	% Si	% Al	% Fe	% Na	% Ti	% Ca	% K	% Mg	% S	% Mn	% P	Halogens µg/g
Forest Thinnings	1.27% ± 0.06	0.302% ± 0.016	0.056% ± 0.002	0.051% ± 0.004	0.016% ± 0.001	0.002% ± 0.000	0.098% ± 0.001	0.106% ± 0.000	0.033% ± 0.000	0.006% ± 0.000	0.043% ± 0.002	0.012% ± 0.000	28.7% ± 1.5
Logging Residues	1.11% ± 0.10	0.233% ± 0.037	0.051% ± 0.003	0.039% ± 0.010	0.012% ± 0.002	0.002% ± 0.000	0.106% ± 0.006	0.112% ± 0.004	0.036% ± 0.001	0.007% ± 0.000	0.043% ± 0.003	0.013% ± 0.001	28.7% ± 1.5

Air Classified Material

Forest Thinnings	Ash Content	% Si	% Al	% Fe	% Na	% Ti	% Ca	% K	% Mg	% S	% Mn	% P	Halogens µg/g
Below Screen	15.13% ± 4.33	4.913% ± 1.410	0.866% ± 0.272	0.506% ± 0.183	0.294% ± 0.101	0.016% ± 0.003	0.398% ± 0.010	0.458% ± 0.137	0.058% ± 0.007	0.016% ± 0.001	0.017% ± 0.001	0.037% ± 0.004	64.3 ± 22.0
10Hz	8.46% ± 0.22	2.728% ± 0.141	0.494% ± 0.025	0.220% ± 0.006	0.188% ± 0.045	0.019% ± 0.002	0.273% ± 0.018	0.277% ± 0.0241	0.064% ± 0.009	0.019% ± 0.002	0.018% ± 0.001	0.040% ± 0.005	936.0 ± 843.5
12Hz	3.55% ± 0.69	1.070% ± 0.275	0.181% ± 0.035	0.074% ± 0.020	0.067% ± 0.021	0.006% ± 0.001	0.183% ± 0.008	0.168% ± 0.020	0.049% ± 0.002	0.017% ± 0.003	0.016% ± 0.000	0.036% ± 0.001	418.0 ± 306.6
15Hz	1.91% ± 0.21	0.457% ± 0.071	0.087% ± 0.011	0.039% ± 0.013	0.028% ± 0.014	0.003% ± 0.000	0.144% ± 0.005	0.150% ± 0.008	0.046% ± 0.002	0.018% ± 0.004	0.016% ± 0.000	0.036% ± 0.002	268.0 ± 157.4
18Hz	1.59% ± 0.40	0.309% ± 0.083	0.077% ± 0.019	0.028% ± 0.004	0.027% ± 0.021	0.003% ± 0.001	0.174% ± 0.037	0.142% ± 0.030	0.054% ± 0.013	0.019% ± 0.003	0.016% ± 0.003	0.026% ± 0.007	209.7 ± 215.1
22Hz	1.27% ± 0.50	0.145 ± 0.057	0.055% ± 0.025	0.025% ± 0.014	0.011% ± 0.006	0.002% ± 0.001	0.195% ± 0.071	0.169% ± 0.069	0.069% ± 0.027	0.020% ± 0.004	0.020% ± 0.007	0.026% ± 0.013	68.3 ± 39.2
28Hz	1.13% ± 0.30	0.144% ± 0.068	0.046% ± 0.015	0.026% ± 0.016	0.011% ± 0.008	0.002% ± 0.000	0.149% ± 0.045	0.150% ± 0.044	0.058% ± 0.020	0.015% ± 0.003	0.018% ± 0.006	0.021% ± 0.003	66.0 ± 45.9
32Hz	0.72% ± 0.25	0.038% ± 0.012	0.017% ± 0.006	0.006% ± 0.002	0.003% ± 0.002	0.001% ± 0.000	0.126% ± 0.052	0.129% ± 0.041	0.048% ± 0.017	0.016% ± 0.004	0.016% ± 0.006	0.014% ± 0.006	35.7 ± 23.0
40Hz	0.76% ± 0.29	0.047% ± 0.026	0.017% ± 0.008	0.008% ± 0.002	0.003% ± 0.001	0.001% ± 0.000	0.118% ± 0.049	0.137% ± 0.048	0.049% ± 0.019	0.019% ± 0.008	0.017% ± 0.006	0.015% ± 0.007	32.3 ± 9.1
Heavy	1.02% ± 0.47	0.088% ± 0.108	0.032% ± 0.029	0.009% ± 0.004	0.007% ± 0.009	0.001% ± 0.000	0.173% ± 0.067	0.161% ± 0.048	0.059% ± 0.016	0.017% ± 0.002	0.019% ± 0.006	0.021% ± 0.005	38.7 ± 1.2
Logging Residues	Ash Content	as SiO2	as Al2O3	as Fe2O3	as Na2O	as TiO2	as CaO	as K2O	as MgO	as SO3	as MnO	as P2O5	Halogens µg/g
Below Screen	8.90% ± 1.66	2.913% ± 0.600	0.550% ± 0.104	0.196% ± 0.044	0.166% ± 0.035	0.014% ± 0.003	0.317% ± 0.036	0.318% ± 0.039	0.056% ± 0.005	0.018% ± 0.001	0.017% ± 0.000	0.038% ± 0.003	93.0 ± 23.4
10Hz	5.79% ± 1.05	1.793% ± 0.393	0.345% ± 0.062	0.133% ± 0.034	0.100% ± 0.023	0.014% ± 0.003	0.245% ± 0.022	0.227% ± 0.026	0.058% ± 0.003	0.020% ± 0.002	0.018% ± 0.001	0.043% ± 0.003	211.0 ± 60.9
12Hz	3.35% ± 0.90	0.945% ± 0.284	0.172% ± 0.048	0.059% ± 0.010	0.045% ± 0.014	0.007% ± 0.002	0.191% ± 0.015	0.203% ± 0.026	0.053% ± 0.003	0.022% ± 0.003	0.021% ± 0.001	0.047% ± 0.006	201.7 ± 15.3
15Hz	1.90% ± 0.24	0.419% ± 0.094	0.085% ± 0.018	0.033% ± 0.011	0.017% ± 0.006	0.003% ± 0.002	0.159% ± 0.001	0.197% ± 0.007	0.054% ± 0.001	0.022% ± 0.003	0.021% ± 0.001	0.046% ± 0.003	177.7 ± 22.0
18Hz	0.97% ± 0.06	0.151% ± 0.009	0.045% ± 0.004	0.016% ± 0.001	0.007% ± 0.001	0.002% ± 0.000	0.127% ± 0.007	0.123% ± 0.006	0.040% ± 0.002	0.014% ± 0.002	0.014% ± 0.001	0.022% ± 0.002	62.3 ± 7.4
22Hz	0.69% ± 0.06	0.069% ± 0.020	0.029% ± 0.005	0.016% ± 0.004	0.004% ± 0.001	0.001% ± 0.000	0.112% ± 0.003	0.103% ± 0.005	0.038% ± 0.002	0.011% ± 0.003	0.012% ± 0.000	0.015% ± 0.001	37.0 ± 5.2
28Hz	0.52% ± 0.04	0.034% ± 0.009	0.017% ± 0.004	0.007% ± 0.003	0.002% ± 0.001	0.001% ± 0.000	0.084% ± 0.002	0.094% ± 0.010	0.036% ± 0.003	0.010% ± 0.003	0.011% ± 0.001	0.011% ± 0.001	36.3 ± 6.7
32Hz	0.44% ± 0.05	0.027% ± 0.009	0.011% ± 0.003	0.005% ± 0.001	0.002% ± 0.000	0.000% ± 0.000	0.077% ± 0.007	0.085% ± 0.007	0.031% ± 0.001	0.009% ± 0.002	0.011% ± 0.001	0.009% ± 0.001	23.7 ± 3.2
40Hz	0.47% ± 0.05	0.026% ± 0.008	0.011% ± 0.003	0.004% ± 0.001	0.002% ± 0.000	0.000% ± 0.000	0.083% ± 0.011	0.088% ± 0.008	0.032% ± 0.004	0.009% ± 0.002	0.010% ± 0.001	0.010% ± 0.003	28.7 ± 7.2
Heavy	0.62% ± 0.06	0.024% ± 0.004	0.012% ± 0.001	0.018% ± 0.026	0.002% ± 0.001	0.000% ± 0.000	0.110% ± 0.010	0.115% ± 0.009	0.042% ± 0.005	0.013% ± 0.003	0.012% ± 0.003	0.016% ± 0.004	38.0 ± 6.6

Table 6: Cost components for air classification of pine forest residues

<u>Cost component</u>	<u>Usage</u>	<u>Unit cost</u>	<u>Cost per ton biomass</u>
Equipment	12%/year of capital	\$1.36MM capital	\$0.83
Electricity for blowers	2 @ 15 HP usage	\$0.10/kWh	\$0.09
Yield loss	9%	\$10 - \$40/ton	\$0.90 - \$3.60
Maintenance and operations	6%/year of capital	\$1.36 MM capital	\$0.41
TOTAL			\$2.23 - \$4.93

Figure 1: Air velocities of the air cleaner at select fan controller settings. Values represent mean $\pm$ 1 standard deviation, $n = 3$.

Figure 2: Mass distribution of air classified, 2" loblolly pine chips. Values represent mean $\pm$ 1 standard deviation, $n = 3$.

Figure 3: Comparison of fractions for biomass removed, ash removed, and remaining biomass ash concentrations in forest thinnings.

Figure 4: Comparison of fractions for biomass removed, ash removed, and remaining biomass ash concentrations in logging residues.

Figure 5: Comparison of fractions for biomass removed, silicon removed, and remaining biomass silicon concentrations in logging residues.

Figure 6: Comparison of fractions for biomass removed, calcium removed, and remaining biomass calcium concentrations in logging residues.