# Effects of Grate Size on Grinding Productivity, Fuel Consumption, and Particle Size Distribution

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## Abstract

Matching the right feedstock quality to a biomass conversion technology effectively facilitates the energy conversion process and improves the economic feasibility of forest biomass for energy production. In this study, we conducted a controlled experiment on a horizontal grinder to evaluate the effect of three different grate size combinations on grinding productivity, fuel consumption, and particle size distribution for two different biomass types (mixed conifer slash and hardwood whole trees). Mixed conifer slash resulted in higher grinding productivity (39.0 to 45.1 bone dry US tons/h) and a lower fuel consumption rate (0.57 to 0.90 gal/h) than hardwood whole trees. Small grate size configurations (2-, 3-, and 3-in. holes) in the grinder had low grinding productivity and higher fuel consumption rates compared with large grate size configurations (3-, 4-, and 4-in. holes). High grinding productivity and low fuel consumption rates were accomplished by using a new anvil type that is manufactured with holes in the plate. The study also showed that production of small feedstock particles (length, $<$2 in.) from logging slash was operationally feasible by using small grates and a newly designed anvil. Additional research is needed to further control oversized materials and improve our knowledge about the effect of moisture content on grinding productivity, especially with a wide range of grate size combinations.

Biomass derived from forests can come from materials removed in mechanical thinning and as residues from conventional sawtimber harvesting operations. They produce a wide variety of feedstock types (unmerchantable trees, small-diameter trees, tops, limbs, and chunks) with varying moisture contents (25% to 60%). These materials are highly variable in shape and size and are characterized as loose, low-density materials. In-woods chipping or grinding, referred to as ''comminution,'' is used to process these materials into uniformly sized biomass feedstocks for energy production. The comminution process also facilitates efficient transportation, which is one of the most expensive components in a biomass feedstock supply chain (Han and Murphy 2012). These factors may influence the quality of the feedstock and the productivity of different comminution processes.

The primary machinery used for biomass comminution are chippers (disc and drum) and grinders (horizontal and tub). Each machine type has its advantages and disadvantages. Chippers are better designed to process larger-diameter materials, such as whole trees, large limbs, and chunks, by cutting woody material with a slicing action and producing relatively uniform chips (Assirelli et al. 2013). Unlike chippers, grinders reduce the size of woody biomass particles by repeatedly pounding them into smaller pieces through a combination of tensile, shear, and compressive forces. They will accept a wider range of grinding material types, including whole trees, stumps, tops, brush, and large forked branches. In addition, grinders are not as sensitive to contamination, but bit and grate life may improve with clean material. The ''hog fuel'' produced from biomass is highly variable in size.

Emerging biomass conversion technologies, such as gasification, pelletization, and torrefaction, aim to reduce the cost of transportation by further densifying the material. However, hog fuel is not commonly used in these biomass

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Forest Prod. J. 65(5/6):209–216.
doi:10.13073/FPJ-D-14-00072

conversion technologies. One challenge is meeting the desired material specifications for each technology. The important feedstock specifications for biomass conversion systems are particle size distribution, moisture content, tree species, contamination level, and ash content. Particle size distribution is one of the most important issues in forest biomass energy because it especially affects transportation costs and combustion efficiency at the end-use location. It also affects energy value and durability during storage in the biorefinery (Nati et al. 2010). In addition, particle size affects the energy requirement of the hydrothermal pretreatment needed for the conversion of woody biomass into liquid biofuels (Hosseini and Shah 2009). Larger particles also have greater combustion time than smaller particles, which reduces the net utilization of the fuel. For energy production, the optimal particle size of biomass feedstocks depends upon the type of burners used and the biomass conversion system. In Canada, a particle size of less than 1 inch is required for small boilers (<1 MW), while a particle size of less than 2 inches is suitable for large boilers (>1 MW; Naimi et al. 2006). In the US Pacific Northwest, most biomass energy plants generally require their fuels to have a particle size of 3 inches or smaller. In addition, several fast pyrolysis biofuel facilities simply specify that the ideal feedstock should be 2 inches or less because long particles can clog auger mechanisms feeding the conversion reactor (Wechsler et al. 2010).

Particle size distribution in the grinding process is influenced by a number of factors, such as machine type, raw material, moisture content, knife/bit setting, and grate/screen sizes used. Chippers usually produce highly uniform particle sizes compared with grinders. For whole trees and treetops, chippers are often used to produce uniform sizes. Grinders are generally used to process forest residues, such as limbs and chunks, into hog fuel, which is typically characterized by having material in a wide range of sizes. Grinders are also capable of handling material with a higher amount of contamination in the form of soil aggregates.

Another factor that directly affects particle size distribution during the comminution process is moisture content of biomass feedstocks. Suadicani and Gamborg (1999) examined the size distribution of chips from freshly felled and summer-dried trees in western Denmark. They found that summer-dried trees produced less fine (1/8-in.) fractions and a more homogeneous size distribution of chips than freshly felled trees. However, more coarse (oversize) chips were produced from summer-dried trees compared with chips from freshly felled trees.

Feedstock species (hardwood or conifer) and types (limbs, tops, stems, etc.) also have an influence on the particle size distribution of fuel. Many hardwoods, such as oak (*Quercus* spp.), beech (*Fagus* spp.), ash (*Fraxinus* spp.), and sycamore (*Platanus* spp.), have stiff branches that produce long particles, and small birch trees have pliable branches that give many thin, overlong particles (Kofman 2006). Nati et al. (2010) investigated the effect of different tree species (poplar vs. pine) and tree parts (branch vs. log) on chipping productivity and particle size distribution. They found that poplar chips tend to be larger than pine chips and contain a higher proportion of oversized particles. Chips produced from logs contained a smaller proportion of oversized particles and a higher proportion of acceptable-size particles.

The different equipment options, such as knives, bits, anvils, and screen sizes, can also have a significant impact on particle size distribution, machine productivity, and fuel consumption rates. Chippers generally require clean (little contamination with soil aggregates) wood to get a satisfactory knife life. Dull or damaged knives in chippers usually result in increased and inconsistent particle sizes. Additionally, knife wear after chipping 215 green tons of wood caused a significant reduction in chipping productivity of up to 15 percent—and a remarkable increase of fuel consumption of up to 60 percent—compared with when new knives were used (Nati et al. 2010). Smaller screen sizes tend to reduce the particle size of chipped or ground materials compared with larger screen sizes, but the installation of smaller screen sizes causes a significant reduction of machine productivity and increase of fuel consumption.

Each biomass conversion technology requires certain material specifications to produce high-quality and sustainable bioenergy and useful biobased products from forest residues. However, literature on how to achieve specific feedstock particle sizes for different forest biomass conversion systems is limited. Therefore, the aim of this study was to investigate the effect of three different grate size combinations on grinding productivity, fuel consumption, and particle size distribution for two different biomass types (mixed conifer slash and hardwood whole trees).

## Materials and Methods

Field studies were conducted in June and September of 2012 on private industrial timberland in northern California. A track-mounted horizontal grinder (Peterson Pacific 5710C) was used to comminute forest residues, including limbs, chunks, tops, and small-diameter trees of mixed conifer and whole-tree hardwoods. The grinder was powered by a Caterpillar C13 engine with 1,050 horsepower and a drum rotor (diameter, 32 in.; width, 59¾ in.; 20 sets of bits) designed for land clearing, logging slash, and scrap board. The grinder was fitted with a solid anvil, one grate with 3-inch holes, and two grates with 4-inch holes, to produce hog fuel for local power plants. The loader (Linkbelt 3400) used to feed the grinder had a rotating, seven-tine grapple that placed material onto the grinder's horizontal infeed conveyer. After processing, the hog fuel was fed via conveyor into a positioned chip trailer.

Grinding operations were carried out on two different feedstock types: mixed conifer slash and hardwood whole trees (Fig. 1; Table 1). Two different material ages (2 mo and 1 y) were included for each feedstock type. Mixed conifer slash was collected from two different clearcut harvest units. The stand composition of both units ranged from 51 to 61 percent redwood (*Sequoia sempervirens* (D. Don.) Endl.), 18 to 30 percent Douglas-fir (*Pseudotsuga menziesii* Mirb.), 1 to 7 percent western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and 7 to 13 percent tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.). Two additional units were selected for testing hardwood whole trees. These consisted of tanoak (46% to 68%), Douglas-fir (26% to 34%), redwood (8% to 13%), and western hemlock (3% to 5%). For each feedstock type, the 1-year-old materials were felled in May 2011 and used for our grinding study in June 2012. The 2-month-old materials were harvested in July 2012 and comminuted using the same grinder in September 2012. The raw material composition

*Figure 1.—Mixed conifer slash (top) and hardwood whole trees (bottom) piled in the unit: 2 months old (left) versus 1 year old (right).*

used in this study varied with feedstock type and date (i.e., age) of sawtimber harvest (Table 1). Moisture content was also different at grinding operation times. Freshly felled trees generally have higher moisture content than trees that are felled and left for 1 year or for summer drying (Suadicani and Gamborg 1999). In our study, however, the 1-year-old mixed confer slash had higher moisture content than the 2-month-old slash because the former received significant rain over the winter and held the moisture in the pile of slash while the latter was felled and left on the ground for 2 months in dry summer conditions (Table 1).

In this study, four different types of feedstock (2-mo-old and 1-y-old materials of conifer slash and hardwood whole trees) were comminuted separately using the same grinder with the same operators. For each feedstock type, three different treatments were applied with three different grate size combinations: solid anvil with 3-, 4-, and 4-inch grates (SA-3-4-4); solid anvil with 2-, 3-, and 3-inch grates (SA-2-3-3); and holed anvil with 3-, 4-, and 4-inch grates (HA-3-4-4; Fig. 2). Five replications (~125 bone dry US tons [BDT] in total) were applied for each treatment. Each replication represents a van load (~25 BDT) of comminuted materials. In each replication, a time-motion study was conducted to measure the grinding time that corresponded to the time required to fill up a standard chip van with a maximum payload capacity of 25 BDT. Load weights were taken from scale tickets recorded at a local power plant. Average fuel consumption rates for each treatment were calculated using fuel level differences between the start of the first replication and end of the fifth replication.

Samples of hog fuel were taken to determine particle size distribution and moisture content. From each truck load, three subsamples (~2.2 lb) were collected from the top of the front, middle, and rear of a filled chip van container. All three subsamples were mixed, weighed, and sealed in a plastic bag. The bags were tagged to identify the slash type and the treatment applied to each sample. In the laboratory, the samples were placed in brown paper bags and allowed to dry in a dry oven at 221°F for 24 hours and then reweighed. Moisture content was determined using a wet-based method.

Each dried sample of hogfuel was screened roughly by length using a BM&M Chip Classifier with six screen trays (2-, 1-, 1/2-, 3/8-, 1/4-, and 1/8-in. holes) and a fines tray to

*Table 1.—Age, raw material composition, and moisture content of feedstock types used.*

| Feedstock | | Raw material composition (%)[a] | | | |
|---|---|---|---|---|---|
| Type | Age[b] | Conifer limbs and chunks | Conifer stems (>4-in. diam.)[c] | Hardwood whole trees[d] | Moisture content (%) |
| Mixed conifer slash | 2 mo | 64–71 | 29–36 | — | 28 |
| | 1 y | 43–71 | 29–57 | — | 42 |
| Hardwood whole trees | 2 mo | 13–15 | — | 85–87 | 27 |
| | 1 y | 10–18 | — | 82–90 | 23 |

[a] Data were collected by ocular measurement when the loader fed raw material into the grinder.
[b] Time elapsed after trees were felled and left on the harvest site.
[c] Average diameter at breast height was 10.1 inches in mixed confer stand.
[d] Average diameter at breast height was 12.7 inches in hardwood stand.

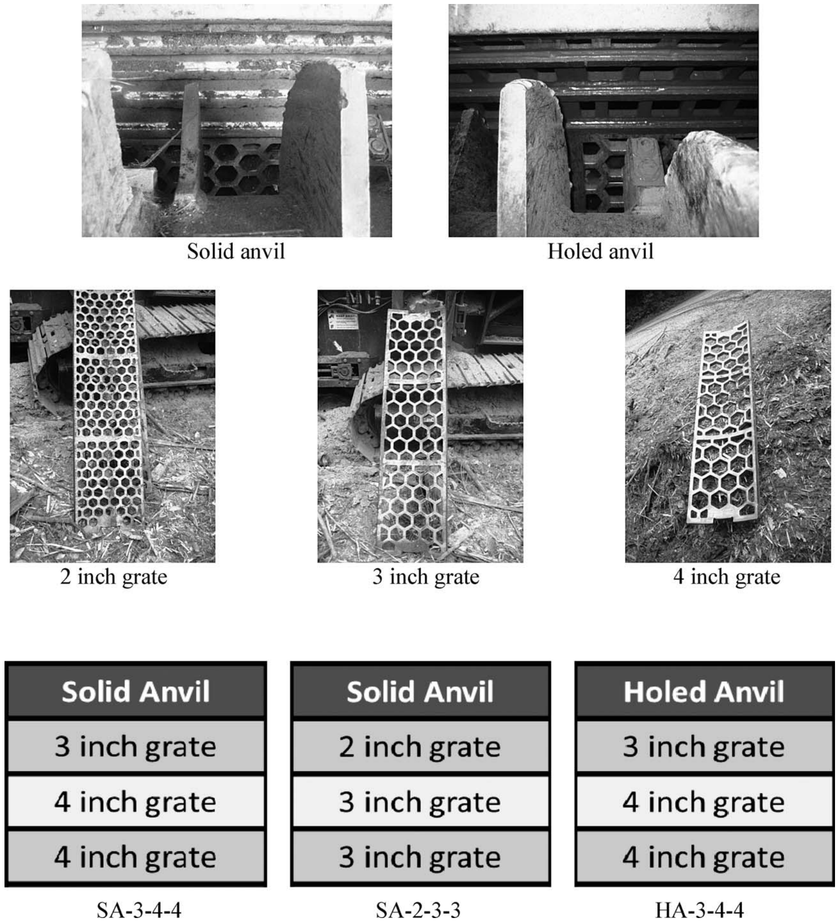


*Figure 2.—Two types of anvil and three different grate size combinations used in this grinding study.*

obtain five size classes (<0.5, 0.5 to 1.0, 1.1 to 2.0, 2.1 to 3.0, and >3.0 in.). Each size class for every sample was hand-sorted using digital calipers to measure the longest dimension of the particle. The five classes of the sorted hog fuel were then weighed separately. In the size distribution analysis, the particle size of each class was weighed and expressed as a percentage of the total mass of all five classes combined.

Data analysis was performed using Statistical Analysis System (SAS Institute Inc. 2001) and Statistical Package for the Social Sciences (SPSS Inc. 1998). Data were evaluated for normality before running the analysis. The effect of feedstock types on grinding productivity was tested using a one-way analysis of variance. Regression analysis was conducted to find the effects of feedstock type, age, and grinder grate size on particle size distribution (Olsen et al. 1998). The significance level was set to 5 percent ($\alpha = 0.05$).

## Results and Discussion

### Grinding productivity

Grinding productivity was significantly influenced by feedstock type (mixed conifer slash or hardwood whole tree) and by grinder grate size ($P < 0.001$; Table 2). The effect of feedstock age (freshness), however, had little statistical significance ($P > 0.05$), because there was no difference in moisture content between the 2-month-old and the 1-year-old hardwood whole trees. Therefore, we could not reject the hypothesis that the productivity obtained when grinding freshly felled feedstock was the same as that obtained when grinding 1-year-old feedstock.

For both feedstock ages and for all grate size combinations, the grinder was able to fill a chip van with mixed conifer slash significantly faster (21 min) than with hardwood whole trees (28 min; $P < 0.001$). Mixed conifer slash resulted in consistently higher grinding productivity by up to 52 percent (HA-3-4-4 with 1-y-old feedstock) compared with hardwood whole trees (Table 2). The average productivity for grinding mixed conifer slash was 42.7 BDT/h, and the average productivity when grinding hardwood whole trees was 34.1 BDT/h. The grinder had more difficultly comminuting hardwood whole trees due to its higher wood density and larger diameter. Similar results were reported by Spinelli et al. (2011). They investigated the effect of feedstock species on chipping productivity and found that softwood had a higher chipping productivity than hardwood because of the high density of hardwood.

Different grate size combinations significantly affected grinding productivity in both feedstock types ($P < 0.05$) with the exception of 1-year-old mixed conifer slash (Table 2). Grinding productivity (BDT/h) was dramatically decreased by up to 30 percent with a smaller grate size combination (SA-2-3-3). Arthur et al. (1982) also found substantial increases in grinding productivity that resulted from increasing the size of the holes in screens. Grinder anvil type also influenced grinding productivity. The use of

Table 2.—Average moisture content, productivity in bone dry US tons (BDT) per productive machine hour (PMH), and fuel consumption rate (gallons per BDT) of a grinder for different feedstock types, ages, and grinder–grate combinations.

| Feedstock | | | Average | | |
|---|---|---|---|---|---|
| Type | Age | Grinder–grate combination[a] | Moisture content (%)[b] | Grinding productivity (BDT/PMH)[b] | Fuel consumption rate (gal/BDT) |
| Mixed conifer slash | 2 mo | SA-3-4-4 | 26.8 A (5.53) | 43.0 A (4.20) | 0.74 |
| | | SA-2-3-3 | 27.1 A (4.19) | 39.0 B (2.03) | 0.80 |
| | | HA-3-4-4 | 25.9 A (1.11) | 45.3 A (3.63) | 0.69 |
| | 1 y | SA-3-4-4 | 41.4 A (2.63) | 42.6 A (3.40) | 0.69 |
| | | SA-2-3-3 | 40.9 A (5.02) | 41.1 A (4.01) | 0.90 |
| | | HA-3-4-4 | 42.9 A (3.59) | 45.1 B (3.91) | 0.57 |
| Hardwood whole tree | 2 mo | SA-3-4-4 | 24.8 A (2.93) | 38.2 A (4.32) | 1.03 |
| | | SA-2-3-3 | 26.0 A (2.40) | 27.2 B (1.21) | 1.72 |
| | | HA-3-4-4 | 25.2 A (4.42) | 39.5 A (2.69) | 0.84 |
| | 1 y | SA-3-4-4 | 21.6 A (3.73) | 37.2 A (3.76) | 0.96 |
| | | SA-2-3-3 | 20.8 A (3.80) | 31.7 B (2.68) | 1.57 |
| | | HA-3-4-4 | 22.6 A (1.57) | 29.7 B (2.54) | 1.02 |

[a] SA = solid anvil; HA = holed anvil. Numbers refer to inches for the grate combinations.

[b] Different letters within a column indicate significant differences between values within each feedstock type and age ($P < 0.05$). The value in parentheses is the standard deviation of each measurement.

holed anvils produced slightly higher productivity than the use of solid anvils in all treatments except the 1-year-old hardwood whole trees, but the differences in productivity were not statistically significant ($P > 0.05$). We had limited replications on different anvil types in our study, and additional experimental studies are needed to determine the effect of grinder anvil type on machine productivity.

## Fuel consumption rates

Fuel consumption rate was influenced by feedstock type, grate size, and anvil type (Table 2). In this study, however, no statistical analysis was performed to find the effect of these variables on fuel consumption rates, because the average fuel consumption rate for each treatment was determined by dividing the total fuel consumed by the total feedstock weight produced during each of the five replications per test, resulting in the same fuel consumption per process.

For both feedstock ages, hardwood whole trees had higher fuel consumption rates than mixed conifer slash. The average fuel consumption rate for grinding hardwood whole trees was approximately 64 percent higher than for grinding mixed conifer slash (Table 2). Similar results were also reported by Spinelli et al. (2011). They investigated fuel consumption rates when chipping softwood stems and hardwood stems and reported that hardwood stems had 7 to 14 percent higher fuel consumption rates than softwood stems. These results can be attributed to the physical properties of hardwoods, such as high bending strengths, stiffness, specific gravity, and hardness. These properties vary with species and region, but hardwoods generally are more dense, fibrous, and harder than softwoods (Haygreen and Bowyer 1982). Therefore, hardwood takes more energy to grind and requires more fuel to comminute.

Grinder grate size and type also affected fuel consumption rates in all of the feedstock types (Table 2). As expected, fuel consumption rate increased with smaller grate sizes. The SA-2-3-3 combination had 20 to 65 percent higher fuel consumption rates than the SA-3-4-4 combination. The differences between both grate combinations were especially high in hardwood whole trees (65%) compared

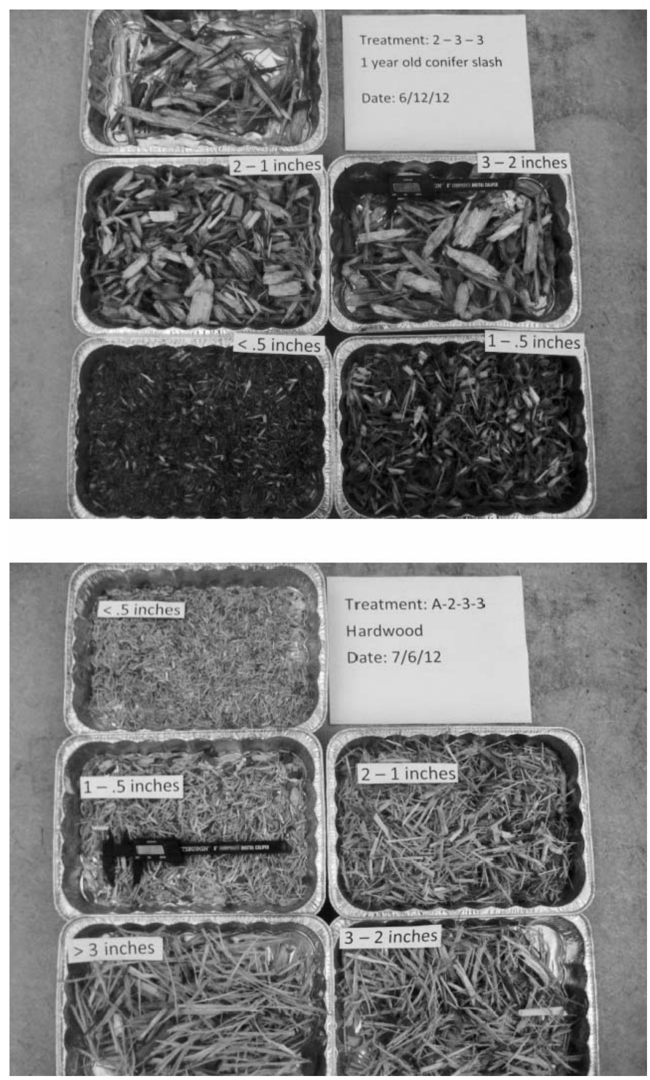


Figure 3.—Example of particles in classified 1-year-old mixed conifer slash sample (top) and hardwood whole-tree sample (bottom).

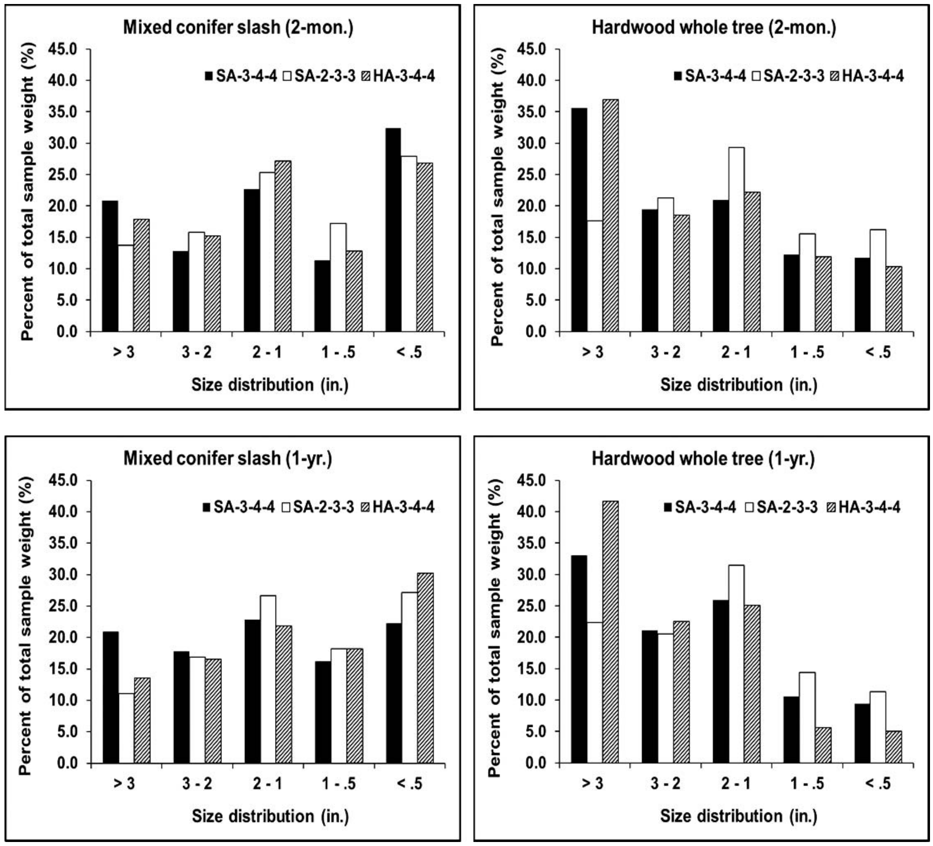


*Figure 4.—Particle size distribution as a percentage for different feedstock types, ages, and grinder grate combinations. SA = solid anvil; HA = holed anvil.*

with mixed conifer slash (20%). In different anvil treatments, the use of a holed anvil resulted in less fuel consumption than the use of a solid anvil in all treatments except the 1-year-old hardwood whole tree. Conversely, the solid anvil had slightly lower fuel consumption rates than the holed anvil in the 1-year-old hardwood whole tree.

## Particle size distribution

On average, all treatments produced different percentages of acceptable-size particles (<3 in. for US Pacific Northwest applications), which varied from 51 to 89 percent of the total sample weight (Figs. 3 and 4). Mixed conifer slash produced a higher proportion of acceptable particle sizes (84%) than hardwood whole trees (69%) for all treatments. In addition, the smaller grate size increased the proportion of the acceptable particle size to as much as 89 percent in mixed conifer slash. However, the results of our grinding study show a lower proportion of acceptable particle sizes compared with a past chipping study. Nati et al. (2010) found that pine logs and limbs had a high percentage of acceptable-size (≤3 in.) chips, up to 95 percent of total chip size distribution.

Regression analysis was conducted to investigate the significance of different feedstock types and grate sizes on particle size distribution. The results of the regression analysis are presented in Table 3. Only variables with $P < 0.05$ were included in the regression equations. Mixed conifer slash produced smaller particles than hardwood

*Table 3.—Regression equations relating the percentage of a given particle size class in different feedstock types and ages and grinder–grate size combinations.*[a]

| Particle size class (in.) | Intercept | Mixed conifer slash[b] | 1-y-old material[c] | SA-2-3-3 combination[d] | Adjusted $R^2$ | $F$ value | $P$ value |
|---|---|---|---|---|---|---|---|
| >3 | 34.9 | −14.9 | No effect | −11.3 | 0.70 | 32.3 | <0.0001 |
| 3–2 | 19.6 | −4.8 | 2.0 | 0.4 | 0.46 | 11.7 | <0.0001 |
| 2–1 | 24.2 | −1.4 | No effect | 4.1 | 0.24 | 4.4 | <0.005 |
| 1–0.5 | 10.0 | 3.9 | No effect | 4.2 | 0.29 | 5.6 | <0.005 |
| <0.5 | 11.2 | 17.1 | −3.4 | 2.6 | 0.76 | 43.7 | <0.0001 |

[a] Only variables with a significance level of $P < 0.05$ were included in the regression equations.

[b] Indicator variable for mixed conifer slash equals 1 if feedstock type is mixed conifer slash and 0 if hardwood whole tree.

[c] Indicator variable for 1-year-old material equals 1 if feedstock age is 1 year and 0 if 2 months.

[d] Indicator variable for the combination of a solid anvil (SA) with 2-, 3-, and 3-in. grates (SA-2-3-3) equals 1 if the combination is SA-2-3-3 and 0 if SA-3-4-4 or holed anvil (HA)-3-4-4.

whole trees. Oversized particles (>3 in.) were significantly more frequent in hardwood whole trees ($P < 0.01$). The quantity of fine particles (<0.5 in.) was significantly higher in mixed conifer slash than in hardwood whole trees ($P < 0.05$). Similar results have been reported in past chipping studies (Kofman 2006, Nati et al. 2010, Spinelli et al. 2011).

The moisture content of feedstocks in grinding operations has significant effects on particle size distribution. In general, the content of fine material decreased with increasing moisture content, and a more coarse size distribution was produced from summer-dried trees compared with freshly felled trees (Suadicani and Gamborg 1999, Spinelli et al. 2011). In our study, the age (freshness) of feedstock did not have any significant additional effect in the oversized class because the 1-year-old material had similar or higher moisture content than the fresh material. The effect of feedstock age was only observed in large (2 to 3 in.) and fine (<0.5 in.) particle classes. As expected, fresh feedstock showed a tendency to produce a smaller proportion of large particles and a larger proportion of fine particles.

The effect of different grate size combinations on particle size distribution was apparent in all of the feedstock types. The smaller grate size combination significantly reduced the proportion of oversize particles and produced a higher proportion of acceptable particle sizes. Contrary to our expectations, the HA-3-4-4 combination did not have a significant effect on size class distribution ($P > 0.05$). However, the holed anvil tended to reduce the amount of oversized particles and increase the amount of particles that were 1 inch or less when grinding mixed conifer slash ($P < 0.05$).

## Conclusions

Currently, several biomass conversion technologies (e.g., gasification, pelletization, and torrefaction) have been developed for biomass energy production, and most have fuel feedstock specifications (e.g., size, moisture content, and contaminants) that are unique to each technology. Therefore, matching the right feedstock quality to the appropriate conversion technology may improve utilization of forest residues for bioenergy and biobased product development. In this study, controlled experiments using a horizontal grinder were conducted to evaluate the effect of three different grate size combinations on machine productivity, fuel consumption, and particle size distribution with two different biomass types (mixed conifer slash and hardwood whole trees).

Grinding productivity was significantly influenced by the feedstock type and grinder grate size. Mixed conifer slash had a higher grinding productivity than hardwood whole trees. The average productivity for grinding mixed conifer slash was 42.7 BDT/h, and the average productivity when grinding hardwood whole trees was 34.1 BDT/h. Grinding productivity also dramatically decreased by up to 30 percent when a smaller grate size combination was used. The use of a holed anvil produced slightly higher productivity than the use of a solid anvil. Additional directed studies including various slash types with different moisture content levels are needed to determine the effect of grinder anvil type on machine productivity.

Fuel consumption rate was influenced by feedstock type, grinder grate sizes, and grate type. Hardwood whole trees had higher fuel consumption rates than mixed conifer slash. Fuel consumption rate increased with smaller grate sizes; the SA-2-3-3 combination had a 20 to 65 percent higher fuel consumption rate than the SA-3-4-4 combination.

In the particle size distribution analysis, mixed conifer slash produced a higher proportion of acceptable-size particles (<3 in.) than hardwood whole trees. The smaller grate size combination significantly reduced the proportion of oversize particles while producing a higher proportion (89%) of acceptable particle sizes in mixed conifer slash. The use of a holed anvil tended to reduce the amount of oversized particles and increased the amount of particles that were 1 inch or less when grinding mixed conifer slash. However, this was not statistically significant. Therefore, further experiments are needed to find stronger evidence for the effect of holed anvils on particle size reduction. If our results are supported by future research, the use of a holed anvil will be the most efficient grinding method, because the test conducted with a holed anvil had higher grinding productivity and lower fuel consumption rates with efficient size reduction of particles.

Moisture content of forest biomass is often considered to be a critical factor affecting grinding productivity, fuel consumption, and particle size distribution. In our study, however, the effect of moisture content on grinding productivity, fuel consumption, and particle size distribution was not examined because the moisture content of freshly felled trees had been quickly reduced, by up to 25 percent, within 8 weeks of summer. Therefore, further research is needed to determine the effect of moisture content on grinding operations.

## Acknowledgments

The research was funded by the Biomass Research and Development Initiative of the US Department of Agriculture's National Institute of Food and Agriculture, with additional support from Green Diamond Resource Co., Steve Morris Logging, Peterson Pacific Corporation, and the R&D Program for Forestry Technology (Project No. S211314L020110) provided by Korea Forest Service, South Korea.

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