Impact of Screening on Behavior during Storage and Cost of Ground Small-Diameter Pine Trees: A Case Study

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Abstract

Whole comminuted trees are known to self-heat and undergo quality changes during storage. Trommel screening after grinding is a process that removes fines from the screened material and removes a large proportion of high-ash, high-nutrient material. In this study, the trade-off between an increase in preprocessing cost from trommel screening and an increase in quality of the screened material was examined. Fresh lodgepole pine (*Pinus contorta*) was comminuted using a drum grinder with a 10-cm screen, and the resulting material was distributed into separate fines and overs piles. A third pile of unscreened material, the unsorted pile, was also examined. The three piles exhibited different characteristics during a 6-week storage period. The overs pile was much slower to heat. The overs pile reached a maximum temperature of 56.8°C, which was lower than the maximum reached by the other two piles (65.9°C and 63.4°C for the unsorted and fines, respectively). The overs also cooled faster and dried to a more uniform moisture content and had a lower ash content than the other two piles. Both piles of sorted material exhibited improved airflow and more drying than the unsorted material. Looking at supply system costs from preprocessing through in-feed into thermochemical conversion, this study found that trommel screening reduced system costs by over $3.50 per dry matter ton and stabilized material during storage.

The biofuels industry is rapidly expanding to meet an increasing demand for infrastructure-compatible liquid transportation fuels. To meet this demand, the industry will require a diversity of feedstock sources, including agricultural and forest products or by-products. Incorporating the most economical feedstock that is compatible with the conversion technology is key to reducing biofuels production cost. Although a variety of factors influence harvest and collection cost of woody biomass (e.g., stand density, haul distance to the landing, season, tire/track characteristics, clear-cut vs. thinning, and terrain conditions; Beardsell 1983, Leinonen 2004), larger trees (e.g., 25 to 40 cm diameter at breast height [DBH]) are generally more economical than smaller trees (e.g., 5 to 15 cm DBH) and slash. As industry demand exceeds the supply of economically available larger trees, the large quantity of underused feedstocks, such as smaller-diameter (i.e., <20 cm) trees and residues, will become important feedstocks. However, the drive to minimize supply chain costs remains. Sources of these additional woody feedstocks may include fire suppression thinnings, precommercial thinnings, or slash (Perlack et al. 2005). This may also shift industry trends away from storing only debarked woodchips to storing whole-tree chips or different mixtures of cleaned and whole-tree chips.

Integration of various mixtures of trees as feedstocks requires an improved understanding of the behavior of these materials during storage, including such considerations as heating, dry matter loss, and ash content. While there has been extensive work done on the behavior of woody materials during storage (e.g., Bergman 1974, Weiner et al. 1974, Springer 1979, Fuller 1985, Jirjis 1995), most focus on cleaned, paper-quality chips, with a limited number of studies looking at whole-tree chips or hog fuel. Physical and chemical properties of biological materials have a major impact on their behavior during storage, such as how the

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temperature of the material changes. Therefore, the impact of bark, leaves/needles, and dirt present in whole-tree chips and hog fuel that are not found in large amounts in paper-quality chips requires further study. Examples of these physical and chemical properties include moisture, ash content, particle size distribution, and nutrient content.

Cellulosic biomass, such as wood chips, with moisture contents between 25 and 50 percent (wet basis [w.b.]) is more conducive to microbial growth that results in heat production and dry matter loss. Self-heating can go so far as to cause autoignition and fire (Pottie and Guimier 1985, Hall 2009). The small particle size created by chipping and grinding leads to an enormous increase in the exposed surface area available for microbial growth, results in reduced airflow and heat diffusion through the pile, and makes the material more susceptible to self-heating. Below a moisture content of 20 percent, microbial activity and self-heating are limited (Springer 1979, Pottie and Guimier 1985, Hall 2009). Also, storage of material with increased particle size provides improved airflow through the pile and experiences less degradation (dry matter loss) during storage (Pottie and Guimier 1985, Jirjis 1995, Nurmi 1999, Wihersaari 2005, Nordic Innovation Centre 2008). Understanding the interaction between moisture, self-heating, and particle size allows researchers to design techniques that stabilize biomass during storage.

A possible strategy for stabilizing ground wood is the removal of leaves/needles, bark, and other fine material by screening after grinding. It is believed that piles of larger particles (i.e., over 5 cm) from screening may have sufficiently increased air movement to reduce heating while allowing moisture to move through and out of the pile as the material dries. Also, removal of fines will reduce ash content in the overs material, and the residual fines may have alternative uses, such as for cofiring with coal or other fuels or nutrient replacement to forests (Heninger et al. 1997, Schoenholtz et al. 2000). The potential advantages of screening are weighed against the cost added by the process.

This study compares self-heating and changes in feedstock moisture, density, heating value, and ash of three different piles of ground small-diameter pine trees and the costs associated with each of the piles. Recognizing that long-term storage (i.e., over 3 mo) of woody biomass can be avoided because of an almost year-round harvest season in many regions, mixtures stored uncovered for 6 weeks starting in late September 2010 near Ririe, Idaho, were compared. Whole trees were comminuted with a hammer mill and separated to construct three piles of material: one of woody biomass that passed through a 10-cm trommel screen (fines), another of larger material that remained on the screen (overs), and a third of woody biomass that had not been screened (unsorted).

Materials and Methods

Pile construction and deconstruction

Small-diameter lodgepole pine trees (*Pinus contorta*) from natural growth forest in Island Park, Idaho, were clear-cut harvested at an average DBH of 10 cm. They were skidded to the landing with a wheeled skidder that carried the small trees with minimal contact with the ground, reducing dirt entrapment in the trees. The trees were hauled whole to Ririe, Idaho, where truck weights were taken both loaded and empty within 8 hours of harvest. The trees were comminuted the following day using a mobile grinder with hot saw teeth on a hot saw rotor with a 10-cm screen. The comminuted material was discharged directly into a trommel screen with a 1-cm screen, after which initial sampling was performed for each material mixture. The material that passed through the screen is referred to as the fines, the material too big to pass through the screen is referred to as overs, and the material taken directly from the grinder (and not passed through the screen) is termed the unsorted. Each mixture of material (fines, overs, and unsorted) was conveyed directly into trailers and again weighed at a grain elevator.

The material mixtures were stored on-site in piles. As the piles were built on September 15, 2010, temperature and humidity sensors were placed in each pile and set to log readings every hour. Three were placed in the center of each pile at 1, 2, and 3 m above the ground surface. After settling for 2 days, two additional sensors where inserted in each pile 3 m up and 45 cm deep on the north and south flanks. One additional sensor was placed in a prominent moisture vent once air circulation within the piles was clearly established (about 2 wk). The pile heights at that time (initial pile heights) were 3.7, 3.2, and 3.7 m for the overs, fines, and unsorted piles, respectively. The starting angles of repose were likewise 45°, 38°, and 42°, respectively. Photographs of the piles were taken at various stages of deconstruction. Photographs were overlaid with a grid to estimate surface areas of wet and dry zones, and surface areas of the piles at various stages of deconstruction were combined to approximate pile volumes. Photographs were also used to estimate angle of repose.

A quantitative approximation of resistance to air movement or permeability of each of the piles was obtained by applying air pressure to a perforated sonde inserted into the pile (Ernstson and Rasmuson 1992). The sonde consisted of a 100-cm-long, 5-cm-diameter pipe with a sharp pointed conical tip. Perforations extended for 10 cm at the pointed end and accounted for 40 percent of the surface in that length.

After 6 weeks of storage (on November 3, 2010), the sensors were retrieved, and the piles were deconstructed by carefully removing material from one side of the pile until a vertical face was formed in the pile center. Samples were obtained using a shovel from various pile locations to measure moisture and bulk density. They were then placed in plastic bags, sealed, and stored in coolers prior to analysis. Pile materials were again loaded onto trucks and weighed to obtain a final mass. Analyses performed are described below.

Analyses and weather conditions

Laboratory analyses.—The moisture content was measured according to the National Renewable Energy Laboratory analytical procedure ‘‘Determination of Total Solids in Biomass’’ (Sluiter and Sluiter 2005), which is based on ASTM E1756-01 (ASTM International 2001). Briefly, samples were dried in an oven at 105°C to a constant weight. The reported values are an average of two measurements. Loose and tapped bulk density was measured for wood chip samples by Hazen Research, Inc. (Golden, Colorado) according to ASTM E1109-86 (ASTM International 2009a). Calorific value was measured for all woody samples using a Leco AC600 bomb calorimeter according to ASTM D5865-07 (ASTM International

2007b). Thermogravimetric analysis (TGA) was performed at Idaho National Laboratory (INL) using a Leco TGA 701. Moisture, volatile, and ash content were measured according to ASTM D5142-09 (ASTM International 2009b), and fixed carbon was determined by difference. Crucibles containing ground sample were placed in the TGA and heated to 107°C under an N_2 atmosphere until a constant weight was reached for moisture measurement. Prior to measurement of volatiles, crucibles were capped; samples were then heated to 950°C under N_2, and the temperature was held constant for 25 minutes. For ash determination, caps were removed from crucibles, and samples were cooled to 600°C and then heated to 750°C until a constant weight was reached. Fixed carbon was determined by weight difference between volatiles and ash. Particle size distribution was determined by ASTM standard method D4749-87 (ASTM International 2007a). Bulk density was measured for both loose and compacted material using the standard ASTM E1109-86.

Weather conditions.—Weather data were obtained from the Rexburg weather station, located approximately 15 km northwest of the study site. The average precipitation in Rexburg from 1977 to 2005 for September, October, and November was 2.1, 2.7, and 2.8 cm, respectively (Western Regional Climate Center 2010), indicating that this is generally a dry climate. There was less than 2.5 cm of total precipitation throughout the study, with no single occurrence being more than 0.6 cm. All precipitation fell between October 4 and November 1. Humidity averaged less than 58 percent.

Results and Discussion

Figures 1 through 3 show final moisture readings along with graphical representations of the observed regions of differing moisture concentrations (labeled A, B, and C). Samples from the interior of each pile were analyzed and reported in Table 1.

The piles had settled and had a lower final height of approximately 3 m. The final angles of repose were 41°, 37°, and 37° for the overs, fines, and unsorted, respectively. This decrease in angle was a product of the material settling. Little or no material slid to the base of the pile, as the pile diameters remained unchanged throughout the study. These angles are consistent with those reported in literature for similar materials (Danielsson 1990). The volumetric flow rate of air, when measured at an applied pressure of 50 Pa, was highest in the overs pile (425 liters/min), followed by the unsorted pile (312 liters/min), and was lowest in the fines pile (297 liters/min).

Bulk density

Bulk density was measured for both loose and compacted material. Bulk densities in all zones in both the fines and overs piles decreased during storage (Table 1), for example, from an initial density of 254 kg/m^3 to a final density of 230 kg/m^3 in Region A of the fines pile, likely due to a decrease in moisture content. Bulk density in the unsorted material increased in the upper regions of the pile (the wet Region A in Fig. 1) and remained unchanged or decreased in the lower regions of the pile.

Moisture

Initial moisture content of the fines ranged from 45 to 54 percent moisture (w.b.) and averaged 52 percent. Overs ranged from 47 to 53 percent, with an average of 51 percent, and finally the unsorted material had moisture content between 48 and 53 percent, with an average of 52 percent. Final moisture content varied on the basis of location within the pile (Figs. 1 and 2). For example, moisture measurements in Region C of the fines pile were below 30 percent, while moisture measurements in Region A of the unsorted pole were over 60 percent. In general, moisture migrated within all three piles with visibly distinct zones occurring in the fines and unsorted piles. Only the moisture measurements of the fines and overs piles suggested pile moisture loss, whereas the unsorted pile showed moisture migration.

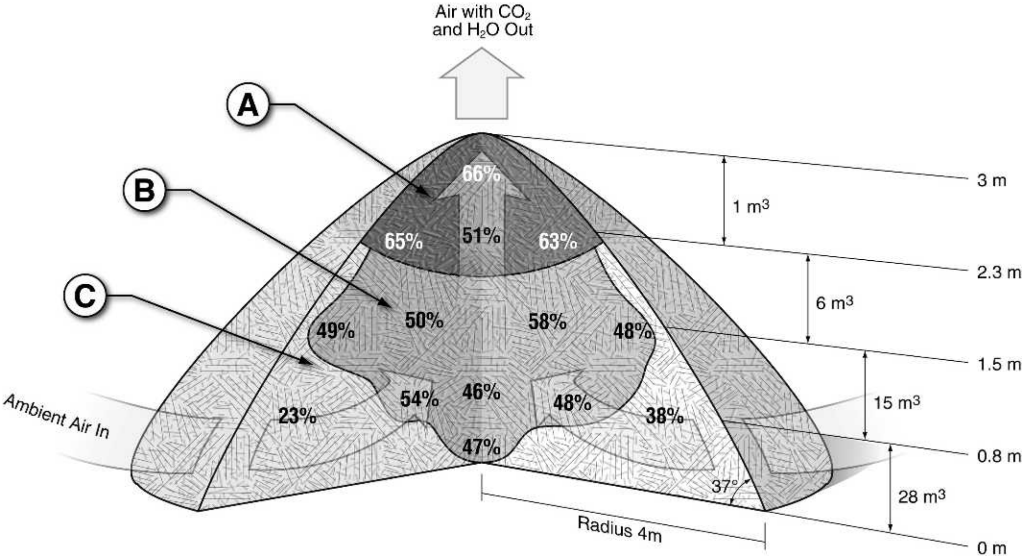

Figure 1.—Schematic showing approximate contour lines of moisture distribution in the unsorted pile after 6 weeks of storage. This pile had a large area of material that increased in moisture during the study (Region A, approximately 60% moisture content [MC]), a larger area of medium to high moisture (Region B, approximately 51%), and a region of material on the flanks, which lost moisture (Region C, approximately 46% MC).

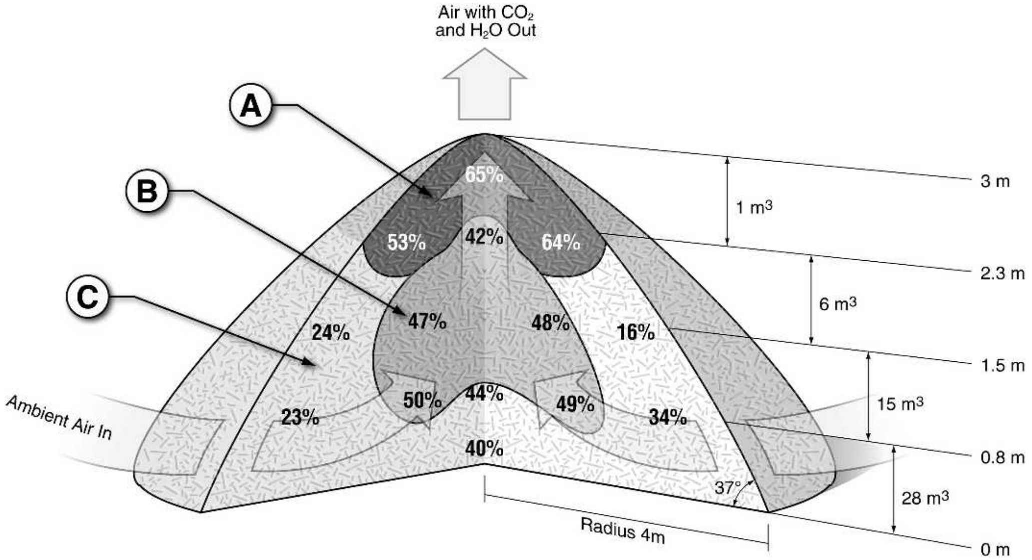

Figure 2.—Schematic showing approximate contour lines of moisture distribution in the fines pile after 6 weeks of storage. The area of increased moisture (Region A, approximately 56% moisture content [MC]) is smaller in this pile than in the unsorted pile. The area of medium moisture (approximately 47%) is indicated by Region B, and a relatively large region of material on the flanks, which lost moisture (approximately 28% MC), is shown in Region C.

By volume, around 80 percent of each pile was located from the ground up to 1.5 m. Moisture averages from this zone suggest drying in all piles, with the overs pile being the driest. Moisture measurements indicate that both the overs and the fines piles lost more moisture than the unsorted pile. Because temperature profiles were similar in the unsorted and fines piles, other factors likely contributed to the increase in drying in the fines. Possible mechanisms for increased drying include shorter distance for water to diffuse out of the wood particles, enhanced capillary movement of water in the fines due to smaller average particle size, and decreased thermal conductivity of the fines pile causing less condensation to occur while water vapor was still inside the pile. Even though the piles settled during storage, changes in bulk density were likely driven primarily by movement of water in the piles.

Particle size

The unsorted pile had the most even distribution of particle sizes at the time of pile constriction, ranging from 10 percent in the 13-mm fraction to 24 percent in the 2-mm fraction (Fig. 4). As expected, the overs pile contained the highest proportion of larger particle sizes. The overs and unsorted pile had nearly the same proportion of 20-mm pieces; however, the overs pile had a much lower portion of smaller particle sizes than the unsorted pile. The fines did not contain any particles above 6 mm, with the majority of the fines being 2 mm. Although particle size distribution

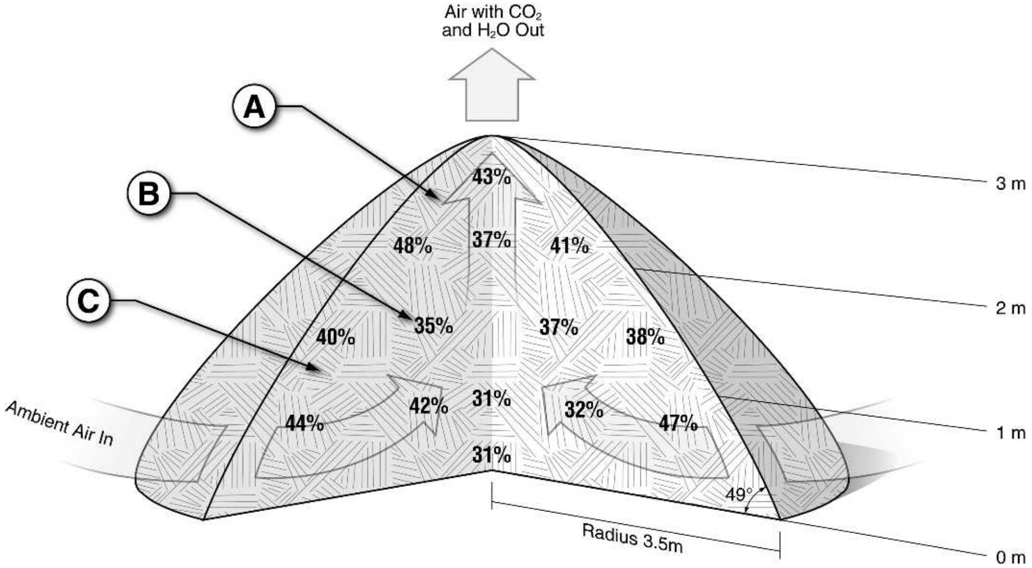

Figure 3.—Schematic showing approximate contour lines of moisture distribution in the overs pile after 6 weeks of storage. The pile dried to relatively uniform moisture with no regions of varying moisture visible (ranging from approximately 36% to 42% moisture content).

Table 1.—Synopsis of initial and final data for all three piles, with letters A, B, and C corresponding to regions in Figures 1 through 3.[a]

	Moisture content, mean ± SD (%)	Ash content, mean ± SD (% w.b.)	HHV, mean ± SD (kJ/kg)	Density (kg/m^3)		Minimum/maximum temp (°C)	Pile weight (wet kg)
				Loose	Packed		
Unsorted							
Initial	52.32 ± 1.36	0.83 ± 0.49	9,766 ± 368	274	354	—	21,673
Final							15,749
A	60.2 ± 6.9	1.28	10,101	294	381	11.3/65.9	—
B	51.3 ± 4.0	0.94	10,245	266	314	11.3/64.7	—
C	45.9 ± 6.9	0.83	11,123	229	315	12.8/56.6	—
Fines							
Initial	51.85 ± 2.65	0.88 ± 0.21	10,134 ± 546	254	339	—	22,008
Final							16,239
A	56.1 ± 9.6	1.43	12,260	230	302	20.2/63.4	—
B	47.4 ± 4.4	0.95	11,099	243	310	20.1/63.2	—
C	28.2 ± 8.1	1.31	11,724	234	290	18.8/53.3	—
Overs							
Initial	51.43 ± 1.35	0.52 ± 0.11	10,136 ± 284	229	291	—	16,629
Final							12,002
A	42.1 ± 4.1	0.82	13,197	150	190	0/41.4	—
B	37.5 ± 1.8	0.82	12,897	144	205	0/56.8	—
C	36.6 ± 6.8	0.97	14,554	139	171	2.1/45.2	—

[a] w.b. = wet basis; HHV = higher heating value.

was determined from samples taken at various pile heights during pile deconstruction, distribution remained consistent throughout the piles.

The trees comminuted for this study were still green and had high moisture content (approximately 51%). Grinders tend to be less effective at comminuting wetter material (e.g., Pottie and Guimier 1985), but in this study, a large proportion of fine particles were produced. Visual observation suggested that much of the bark ended up as fines, most likely because of its friable nature, and a large proportion of the fines were also needles and small particulates. The overs material had a large amount of wood chunks, as expected, but also a surprising amount of needles. Because the trees were comminuted while fresh, the needles were still firmly attached to the branches, causing many branch tips to remain on the screen, and these needle-covered branch tips ended up in the overs pile.

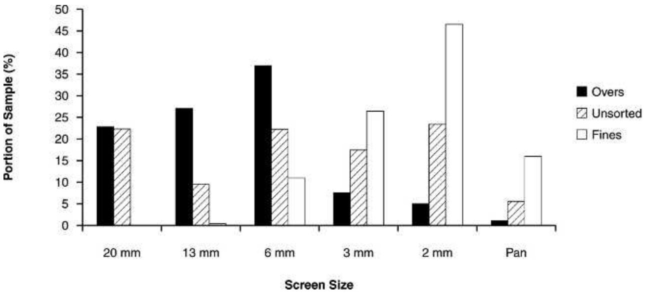

Figure 4.—Particle size distribution at the time of pile construction in three piles of comminuted pine trees studied. The fines had a high percentage of small particles, whereas the overs have a large percentage of large particles. As expected, the overs had a more even particle size distribution than the other piles.

HHV and ash

The energy content, expressed as higher heating value (HHV), was approximately the same for each fraction at the start of the study, which is a reflection of the similarities in carbon and moisture content. Loss of moisture in the overs and fines piles increased the HHV in these materials.

The initial ash content was lowest in the overs pile, which is as expected, as much of the ash is in the bark and needles. The trommel screen reduced the initial ash content in the overs to 0.52 percent (w.b.), raising the ash content in the fines to 0.88 percent (Table 1), while the initial ash content of the unsorted material was 0.83 percent (w.b.).

The trommel screen was effective at reducing the ash content of the overs. A number of factors contributed to the low (i.e., <1%) level of ash in the parent material, including minimizing ground contact of the trees during skidding (high-ash dirt can become embedded in the bark, raising the ash content; Harkin and Rowe 1971, Phanphanich and Mani 2010). Woody materials with elevated ash due to entrained soil may show an even greater decrease in ash due to the effectiveness of trommel screening at removing small particles (Hubbard et al. 2007).

Elevated ash measurements in the upper zones of the fines and unsorted fractions may be caused by microbial degradation in these high-moisture zones that release carbon (in the form of CO_2) and retain the inorganic materials as a result of dry matter losses. Increases in ash in stored wood as a result of biological degradation and resulting dry matter loss has been reported by other researchers (Thörnqvist 1985, Jirjis 2005).

Temperature

Temperature sensors indicated that all three piles underwent self-heating during storage. Figure 5 is a plot of temperature fluctuation within the three storage piles

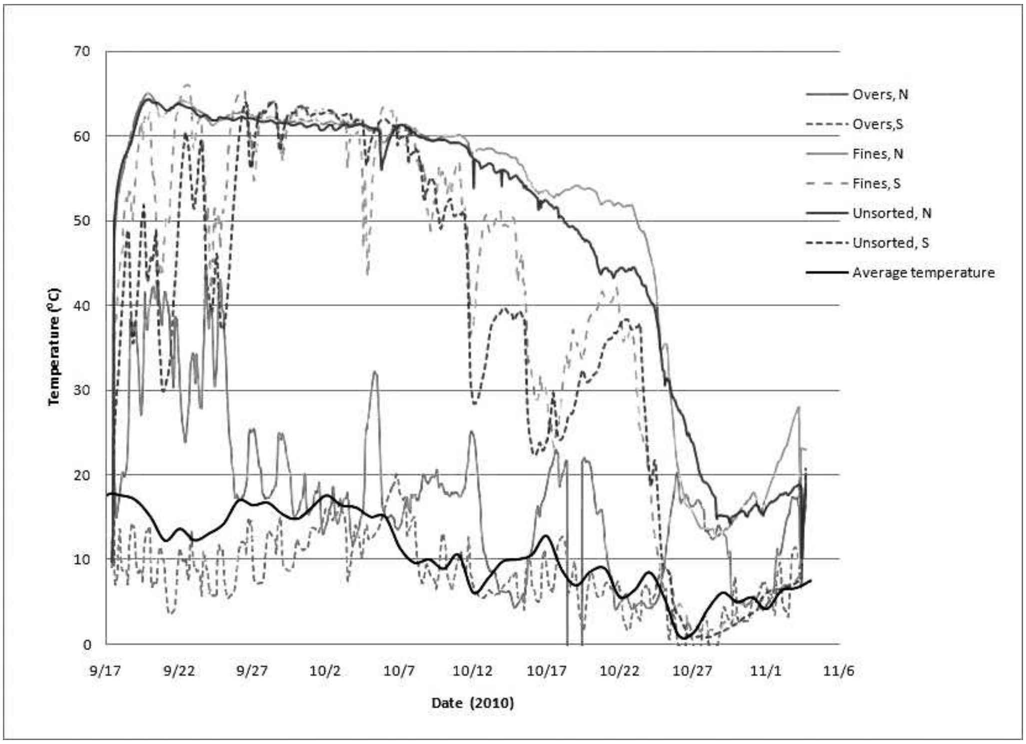

Figure 5.—Temperature profiles observed in each of the three piles. Note conditions in the fines and unsorted piles grew sufficiently hot that some sensors stopped working because of battery failure. Average ambient temperature is indicated with a black line.

during storage at the upper, middle, and lower portions of each pile.

There was a difference in the temperature profiles of the three piles. The fines and unsorted piles heated up faster and to higher temperatures than the overs pile regardless of the location of the sensor. The fines and unsorted reached maximum temperatures at approximately the same time; however, the unsorted heated to a higher temperature than the fines. The fines pile remained relatively constant at approximately 64°C for about 35 days, at which point the temperature decreased slowly to about 60°C. The overs pile took longer to heat up and heated to a much lower temperature than both the fines and the unsorted piles, which reached their maximum temperatures within a week of construction; the unsorted pile took about 12 days before a steady increase in heating was observed. The maximum temperature reached in the overs pile was 56.8°C, as opposed to the 63.4°C and 65.9°C reached in the fines and unsorted piles, respectively. The overs pile was more sensitive to changes in ambient temperature (Fig. 6).

Sensors placed in the surface vents for each of the piles revealed different temperatures in each of the three piles at the vents. High temperatures in the vents were 44°C, 48°C, and 46°C, and low temperatures were 0°C, 6°C, and 6°C in the overs, fines, and unsorted piles, respectively.

Although there was some fluctuation for all the piles, the top of the overs pile generally experienced less heating than the bottom and center of the pile (Fig. 5). This is again consistent with the overs being more vulnerable to changes in ambient conditions. The bottom of the overs piles was frequently warmer than the center. However, for the unsorted pile, the top heated slightly more than the center, which in turn heated more than the bottom of the pile. For the fines pile, the top of the pile again heated up faster than the center of the pile, although the two areas were within 5°C after about 2 weeks. Both the top and the center of the fines pile stayed warmer than the bottom of the pile. Thermal images were taken of all three piles at the end of the study, confirming the results shown in Figure 5.

The north side of the overs pile had higher temperature readings than the south side. Prevailing southerly winds likely caused the internal plume of water vapors to drift toward the north as it rose, resulting in vents and elevated temperature readings on the north side. Although the same was noted for the unsorted and the fines, the difference was less dramatic. These declines in temperature may be due to increased porosity, allowing heat to escape the pile, consumption of easily accessible organic compounds by microbes, and/or moisture reduction (Springer 1979, Pottie and Guimier 1985, Hall 2009).

The high temperature of the fines vent may be a sign of increased transportation of moisture out of the pile due to reduced condensation occurring in the upper levels of the pile. The data show the transient nature of the surface vents and the sensitivity of the vents to diurnal changes in temperature and wind speed. The temperature readings of the 45-cm-deep sensors in the unsorted and fines piles indicated that the region of self-heating may have been very large. This was verified by thermal images.

Both the unsorted and the fines piles experienced a rapid decline in temperature followed by a slow rise in temperature near the end of the study (Fig. 6). The drop and subsequent rise corresponds to ambient temperatures during the study, and the drop was preceded by the largest occurrence of precipitation. It is likely that the combination of low ambient temperatures and evaporative cooling on the flanks of the piles cause very cool air to be drawn into the piles, resulting in quick cooling.

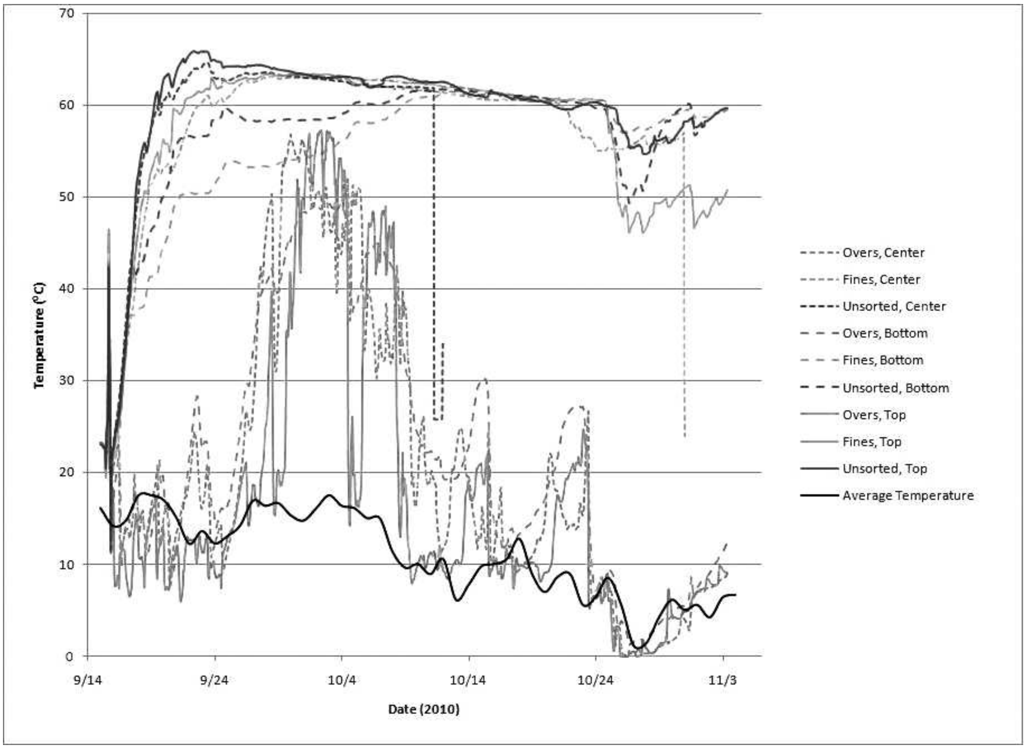

Figure 6.—Differences in self-heating in piles in north and south faces, 2.5 m up and 45 cm deep. Average ambient temperature is indicated with a black line. High temperatures of the fines and unsorted piles at a 45-cm depth indicate the expanse of the heated area in the pile.

Dry matter loss

The dry matter loss, which is a combination of mechanical and biological losses, was estimated from the volume of regions shown in Figures 1 through 3, combined with the starting and end weights of the truck. Estimated losses are 10, 24, and 12 percent for the overs, unsorted, and fines pile, respectively. However, the heterogeneity of moisture distribution in the fines and unsorted piles poses a challenge to estimating dry matter loss in the piles, as small differences in moisture concentrations and/or moisture zone volumes, as well as the assumption of average moisture content for an entire volumetric region, cause large swings in weight calculations. In addition, piles are conical, and the volume of a cone is greatly affected by height and radius. For example, the difference in whole-pile volume between a 3-m pile that is 4.0 m (13 ft) in diameter and 4.3 m (14 ft) in diameter is around 8 m^3. To estimate pile volume, it was assumed that the bases of the piles were a perfect circle; however, this was unlikely the case. Any small deviation from that assumption impacts the calculation of pile volume. The relative uniformity of moisture levels in the overs pile facilitates a more accurate calculation of total dry matter loss, which is the sum of mechanical and biological losses.

Impact of screening on heating and quality

Other researchers examining how compaction and particle size distribution and therefore permeability to airflow affect wood storage have obtained conflicting results (Thörnqvist 1985, Ernstson and Rasmuson 1992, Nurmi 1999). A reduced permeability to airflow may have limited self-heating in the fines pile by reducing oxygen levels, thereby limiting microbial metabolism (Fuller 1985). Limited permeability measurements suggested that the overs pile had the highest permeability, which is as expected, as the fine material that would fill spaces in the wood and inhibit airflow had been sifted out with the trommel screen. This higher permeability would allow air to move more freely through the pile and therefore water vapor to escape. It would also allow the pile to cool down and therefore limit the formation of hot spots, which was confirmed with temperature measurements (Fig. 6). In the unsorted pile, there was still a large portion of large particles (Fig. 4) to promote airflow; however, a large percentage of fine particles restricted air movement. Limited permeability measurements also suggested that the unsorted pile had lower permeability than the overs pile. This restriction may have contributed to an increase in heating over the other two piles. Finally, airflow in the fines pile was most restricted, as there were no larger voids facilitating airflow.

Although the initial moisture in all piles was very similar (Table 1), elevated temperatures in the unsorted and fine piles caused moisture to migrate within the pile, resulting in heterogeneous distribution. During self-heating, the hot air rises from the pile center toward the surface, drawing air in through the flanks (Hall 2009). Increased temperatures also cause water evaporation that is then transported toward the center and higher in the pile, resulting in drying in the flanks and condensation, increasing moisture in the upper regions (Figs. 1 and 2). Anecdotal evidence suggests that some moisture is transported completely out of the pile and is visible as vapor on cold mornings. The venting of the hot air through the top of the pile was clearly observed for the fines and unsorted piles and for a short time the overs pile. The overs pile heated less, and the moisture content measured was more homogeneous. Even after cooling, increased porosity would allow water to evaporate and escape the overs pile.

The fines pile is more likely to experience dry matter loss. Previous work has shown that the material composition of fines, with a higher percentage of needles and bark, increases decay (Springer 1979, Pottie and Guimier 1985), as these particles are rich in nutrients that promote the growth of fungi and bacteria (Gislerud and Gronlien 1977, 1978; Springer 1979; Hall 2009). Heated air moving through the pile becomes saturated with water, and heat is lost from the top of the pile because of conduction and convection (Lynch et al. 1997). Cooling humid air causes condensation, explaining the water and high moisture concentrations at the top of the fines and unsorted piles. However, it is suspected that the fines have reduced conduction and convection, allowing more water to stay in the vapor phase and escape the pile, resulting in decreased moisture content.

Cost impact

Although there may be quality improvements related to screening, there is an associated cost. To examine the cost impact of screening woody biomass intended for thermochemical conversion, costs of relevant portions of the supply chain were extracted from a woody supply system model developed by INL. The woody biomass supply system model incorporates a combination of values and relationships obtained from other national laboratories, publications, consultation with academics and staff from the US Department of Agriculture Forest Service, and published and unpublished INL data. There are many inputs into the model, including but not limited to ownership costs (e.g., depreciation, interest, and insurance), operating costs (e.g., repair and maintenance, fuel, and labor), dry matter losses, biomass yield, machine capacity and efficiency, machine speed, moisture content, and so on. Costs for the relevant portions of the supply chain are shown in Table 2.

Equipment used to determine costs presented in Table 2 is consistent with that described in the section ''Pile construction and deconstruction.'' The base case shown in Table 2 is a scenario wherein whole trees are ground, piled, and then transported to the biorefinery without storage. The material is handled the same as the unsorted material after transport. Initial grinding occurs at the landing for all cases; however, for the overs and fines scenarios, the cost of a trommel screen is added. As the mass of the screened and unscreened material is approximately equal (Table 1), the trommel screen cost is also assumed to be equal. Moisture content and bulk density during transport are taken from Table 1, and these values are used to determine transport and plant handling costs. Two drying scenarios are considered: drying the material to 10 percent moisture content using (1) waste process heat and (2) a natural gas–fired rotary drum dryer. Finally, a hammer mill is added after the dryer for the base case, unsorted, and overs scenarios to account for the difference in particle size between the different materials. Note that elevated levels of ash are problematic in most biomass conversion facilities (Phillips et al. 2007, Jones et al. 2009) and that differences in ash content of the different materials were not taken into account.

Looking at the costs in Table 2, the fines pile has the lowest cost when using the waste heat dryer or the natural gas dryer (the difference being greater with the waste heat dryer). The average of the fines and overs costs was also lower than the unsorted cost for these scenarios. If hammer milling is not a consideration (i.e., particle size does not matter for conversion process in-feed), then the unsorted pile has the lowest cost when a waste heat dryer is used. The fines had a lower cost when the natural gas dryer was used. For this case, the overs and fines costs are nearly identical for this scenario, and therefore the average of fines and overs is slightly higher than the fines. Passive drying during storage decreased transportation and handling costs for all three piles over the base case. Therefore, the additional investment in the trommel screen operation at the landing has savings that carry throughout the supply chain.

Conclusions

Trommel screening resulted in piles with heating and drying characteristics that are different from the unsorted material. As suggested by observations of the behavior of

Table 2.—Differences in system costs for the three piles studied.[a]

	Base case (unsorted, no in-field drying)	Unsorted	Overs	Fines
Cost for preprocessing at landing ($)				
Grinding only	5.95	5.95	—	—
Grinding and screening	—	—	7.50	7.50
MC during transport (%)	52	51	38	43
Density during transport (wet kg/m^3)	354	322	184	296
Cost for transportation and in-plant handling (80 km) ($)[b]	12.80	12.20	12.40	11.50
Cost to dry material to 10% MC ($)[c]				
Waste heat dryer	3.35	3.35	2.75	2.95
Natural gas rotary drum dryer	12.35	11.95	9.7	10.50
Cost to grind to 6 mm using hammer mill ($)	4.6	4.6	4.6	—
Cost savings over base case ($)				
Natural gas	—	1.00	6.10	6.20
Waste heat dryer	—	0.60	(0.55)	4.75

[a] Costs do not include stumpage fee or harvest and collection costs. Costs are in 2007 US dollars per dry matter ton. MC = moisture content.

[b] Assuming that piles are stored at landing.

[c] Natural gas dryer modeled is an Anko Eaglin, waste heat dryer based on 160°C retention dryer design. Waste heat dryer costing does not include any preparation required for heat.

the overs pile over the 6-week storage period, trommel screening can be used to lower ash content and self-heating while increasing moisture loss in storage piles. It is unexpected that the fines fraction would also have improved drying and self-heating characteristics, indicating that factors other than permeability to airflow play a role in self-heating and drying in these piles. In addition, passive drying at the landing lowers transportation and facility drying costs and improves conversion economics. Understanding the relationships between these factors is crucial to optimizing storage parameters that improve biomass quality and storage characteristics.

Although the relationship between permeability to airflow, pile size, particle size, and moisture content have all been previously studied, the comparison presented herein suggests that using a trommel screen on comminuted woody biomass prior to screening can be beneficial by reducing self-heating, increasing drying, and decreasing ash content (all of which were observed in the overs pile). Improving the understanding of the behavior of new biomass feedstocks during storage and the potential implication of these behaviors in subsequent supply chain operations is an important component of expanding the integration of these feedstocks in a growing biofuels industry.

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