IN-WOOD SCREENING OF WOOD GRINDINGS FOR BIOMASS FEEDSTOCK APPLICATIONS

by

CHARLES CORY DUKES

(Under the Direction of W. Dale Greene)

ABSTRACT

Logging residues present a substantial near term opportunity as a bioenergy feedstock, but contaminants can be introduced during collection. We studied the use of a trommel screen to reduce ash levels in ground forest harvest residues at time of production. Treatments of initial harvest type, grinder size, debris age, and screen usage were applied to southern pine residues in the coastal plain of South Carolina. After screening, the average ash levels of roundwood and clean chipped residues were reduced from 4.0% to 1.4% and from 11.9% to 6%, respectively. Average energy density was improved with screening, but not significantly. Large grinder utilization with roundwood residues was reduced when screening. Screened roundwood residues were consistently more costly to produce than unscreened roundwood or screened clean chipped debris with either grinder size. Financially, the screened clean chip systems and the unscreened roundwood material provided the most competitive residue on an energy basis.

INDEX WORDS: Logging residues, Grinding, Screening, Biomass, Ash

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CHARLES CORY DUKES

BSFR, UNIVERSITY OF GEORGIA, 2010

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial

Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2012

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CHARLES CORY DUKES

Major Professor: W. Dale Greene

Committee: Pete Bettinger
Laurie Schimleck

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
May 2012

## DEDICATION

This work is dedicated to all of my family, friends, and colleagues who have offered endless encouragement and support throughout this project.  Thank you.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Dale Greene, for his constant direction and guidance in completing this project. Many thanks also to my advisory committee, Dr. Pete Bettinger and Dr. Laurie Schimleck, for their input and assistance. Finally, I would like to thank Jason Cutshall for his assistance in the field and the office, as well as Shawn Baker for his technical help and advice. Funding for this work was provided by the Sun Grant Initiative.

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# CHAPTER 1

## INTRODUCTION AND LITERATURE REVIEW

Current energy consumption in the U.S. is primarily centered on fossil fuels. Over three quarters of total annual consumption is comprised of petroleum, natural gas, and coal [1]. These statistics are at the heart of concerns about national energy security and the global effects of carbon emissions. Indeed, only 8% of annual U.S. energy consumption is considered "renewable" – including biomass, hydroelectric, geothermal, solar, and wind [1]. Certainly, considerable policy and debate has attempted to increase the amount of renewably sourced energy. Of course, every energy feedstock has inherent limitations relative to factors such as cost, efficiency, or geography. In this regard, potential renewable energy sources are often dictated by local circumstances. In the U.S. South, there exists an abundant forest resource along with an established infrastructure for utilization. Woody biomass has the greatest near term potential to contribute to energy demands by direct combustion or co-generation with coal in boilers to produce steam or electricity [2].

Forest harvesting methods have improved dramatically over the past 50 years, and in most cases are increasingly mechanized, highly productive systems. However, partial utilization of the above ground biomass is the norm with low value components typically removed from trees and left on site. These logging residues are typically comprised of two components – logging slash (limbs, tops, defective pieces, etc) and unmerchantable stems left standing [3]. Studies have indicated an immediate availability of logging residues and also the economic hurdles associated with their utilization. With potential increases in demand for biomass feedstocks, logging residues will be more fully utilized, particularly across the entire US South [4]. This is aided by the widespread use of roadside tree length logging systems in that region. Approximately 90% of current logging crews in the South use this system [5]. Tree length systems have the advantage of collecting debris and residue in a centrally located logging deck that is at, or near, roadside. Thus, there is no additional cost to recover and collect residues from across the site and the potential of further soil damage is reduced without additional site entries [4]. Additional benefits of biomass collection to a site include subsequent reductions in site preparation costs, reduced risk of wildfire and forest health issues, as well as improved aesthetic values [6, 7].

Limitations of residue use have been observed and documented for decades. Primary concerns have centered on processing and transportation issues of such a highly variable, low value product. Hakkila discusses the need for "comminution" of residue materials – simply reducing the size to a homogenous state via mechanical means [3]. Comminution has the benefit of improving handling of the feedstock while producing a denser product (important in light of transportation costs). Equipment to achieve these goals has been available for decades and can be grouped into two main categories – chippers and grinders. Hakkila provides a detailed explanation of disk chippers and drum chippers [3]. Both are similar in that knives are used against an anvil to cut woody material into chips. Alternatively, grinders (also known as shredders, mulchers, and hogs) utilize hammers against an anvil to shred woody material into strips. Previously, tub grinders have been studied for use in forest residue applications [8], but horizontal grinders have recently gained interest [9]. In many cases, the feeding characteristics of horizontal grinders are desired due to limitations experienced with tub grinders [8]. In all cases, grinders are operationally desired for processing residual materials as chippers can experience increased knife wear from contaminants and have difficulty processing materials other than intact stems [3].

Studying these systems, Aman [9] examined the costs, utilization rates, and resulting product characteristics for grinder and chipper systems producing biomass for energy. Horizontal grinders were observed while processing residue material from clearcut harvests of southern pine stands using conventional roundwood systems as well as residues produced from the first thinnings of pine plantations using clean chipping systems. These results were compared with a whole tree chipping system. Elevated ash levels were seen in both grinder systems, particularly with clean chipping residues. All three systems demonstrated similar delivered costs on a wet weight basis.

Patterson et al. [10] presented case studies for five systems capturing forest residues. Two of these case studies used a chipper, one with thinning material and one with thinning residues. The remaining three case studies examined horizontal grinder systems, all with roundwood residue material. While no statistical comparisons were made, the ground residue studies demonstrated lower average energy contents (BTU's per oven dried pound) than their chipped counterparts – 7,785 and 8,168 respectively.

Grinders also demonstrated greater average ash content than seen with chipped material (4.5% and 1.2%).

Physical characteristics such as moisture content and ash content of wood and other cellulosic materials being used for direct combustion in boilers affect their performance. Fouling and slag formations within the boilers of many biomass fired energy facilities due to aluminosilicate contaminants such as sand and soil are well documented [11-13]. This issue is of increased concern with logging residue, as it is frequently piled for extended periods and handled multiple times, increasing contamination. Consequently, direct combustion of some forms of biomass may be limited due to these issues [14]. Proposed solutions have included the use of additives such as kaolin and limestone to reduce the size of ash deposits [12].

A more direct approach, however, would be to reduce the amount of fine material contaminants before the fuel is introduced to the boilers of an energy producing facility. A number of sifting or screening options exist that can be used to separate the desired wood fuel from any fine material. Badger [15] explores several practical concerns and solutions, from a feedstock purchaser's perspective, while presenting potential system configurations for a wood to energy conversion facility. A number of screening technologies are considered at such a facility including an oscillating screen, a scalping disc screen, and also a rotary trommel screen.

However, not all purchasers of wood fuel have the ability to screen at the facility, thus limiting the materials that can be purchased and reducing markets for forest residues. With this in mind, screens can be used in the woods between a grinder and a hauling truck to improve feedstock quality. Patterson et al. [10] included in their study the idea of removing fine material from residues after comminution and before transport to a purchaser to improve the value of the feedstock. After manually separating their samples in the lab, increases in energy content and reductions in ash content were reported by removing the fine material.

Spinelli et al [16], demonstrated mobile chip screening technology for Italian wood energy uses employing a bench-style screen with rectangular steel panes. The primary purpose was to control the size characteristics of chipped wood fuels (both under- and over-sized) for small energy plants with tighter quality specifications. The cost of screening was shown to be offset by the improved price from increased commercial standards.

As mentioned previously, trommel screens provide another screening option. These machines tumble the feedstock material through a cylindrical screen. Rejected materials that fall through the screen are then conveyed from the machine separately from the feedstock. While trommel screens are often utilized in fixed locations, mobile versions are available and can be used in the woods to improve the quality and marketability of ground forest residues. Unfortunately, this solution has not been well tested, and no examples could be found in the literature. Consequently, this system has not been widely accepted by the forest products community.

In this study we quantified the effectiveness and cost of operating several horizontal grinder/trommel screen systems with residual forest materials. These configurations were examined in capturing primarily loblolly pine (*Pinus taeda L.*) residues in the coastal plain of South Carolina.

# CHAPTER 2

# IN-WOOD SCREENING OF WOOD GRINDINGS FOR BIOMASS FEEDSTOCK APPLICATIONS

To be submitted to *Biomass & Bioenergy*

C. Cory Dukes, W. Dale Greene, Jason B. Cutshall, and Shawn A. Baker

## 1. INTRODUCTION

Political mandates and social pressures are continually increasing the need for renewably sourced energy fuels. Some regions, particularly the U.S. South, are well equipped to immediately provide woody biomass for energy applications [17]. There are numerous environmental benefits of biomass use for energy production [18]. Specifically, “woody biomass” is a suitable replacement for fossil fuels that can provide an additional offset of greenhouse gas emissions [19] and reduce $SO_2$ and $NO_x$ emissions relative to coal use [20]. Work has already been done to develop co-firing systems that are operationally proven and have a number of environmental and economic benefits [18].

With such potential for woody biomass use in renewable energy processes, much work has gone into developing methods for harvesting and collecting this material. Numerous studies have examined the use of logging residue as a primary source of biomass fuel in energy and biofuel production [21, 22]. Yet, in many cases logging residue is currently not utilized as a part of normal forest management regimes. There is a demonstrated need to “pretreat” residue before it is transported to an energy facility [21]. Objectives of pretreatment typically include resizing and densifying the material to facilitate improved transportation to a facility, storage at a facility, and eventual processing for energy applications [23]. A number of in-woods options have been developed and tested, with research focusing on chippers and tub grinders [8]. However, there is not a substantial body of literature examining the use of horizontal grinders in energy applications with forest residues. Yet, horizontal grinders could prove useful in this setting, since they allow for a varied and versatile feedstock [24]. This advantage has been observed with logging contractors that have demonstrated a greater ability to process limbs and branches with grinders as opposed to chippers [25].

Despite the potential benefits of using residual logging material as an energy feedstock, challenges must be addressed. There are well-documented concerns of fouling and slag formations within the boilers of many biomass fired energy facilities due to aluminosilicate contaminants such as sand and soil [11-13]. This issue is of increased concern with logging residue, as it is frequently piled for extended periods of time, increasing contamination. Consequently, direct combustion of some forms of biomass may be limited [14]. Proposed solutions have included the use of additives such as kaolin and limestone to reduce the size of ash deposits [12].

A more direct approach, however, would be to reduce the amount of fine material contaminants at the source, before the fuel is transported to an energy producing facility. A number of sifting or screening utilities exist that can be used to separate the desired wood fuel from any fine material. Specifically, trommel screens can be used between a grinder and a hauling truck in this capacity. Trommel screens tumble the feedstock material through a cylindrical screen. Rejected materials that fall through the screen are then conveyed from the machine separately from the feedstock. Unfortunately, this solution has not been well tested, and consequently has not been widely accepted by the forest products community.

In this study we quantified the effectiveness and cost of operating several horizontal grinder/trommel screen systems with residual forest materials. These configurations were examined in capturing primarily loblolly pine (*Pinus taeda L.*) residues in the coastal plain of South Carolina.

## 2. MATERIALS AND METHODS

This study was conducted by monitoring and collecting samples from a number of active fuelwood removal operations where a logger utilized a trommel screen to remove fine materials from the grinding streams of piled logging residue (tops, limbs, etc.). Field trials were held in conjunction with active operations by a small sawmill owner in southern South Carolina. The operator currently uses a grinder/trommel screen system fed by a front-end loader to capture residue debris following both roundwood clear-cuts and clean chipping of first thinnings. Two grinder sizes were included in the study - a large 780 Hp Peterson 4600 and a small 460 Hp Peterson 2400. Both grinder sizes were fed by a 225 Hp John Deere Model 644J front-end loader. In addition, a 174 Hp McCloskey Model 621 trommel screen fitted with 0.5 inch screen openings was used for some of the treatments.

A total of 8 treatments were examined consisting of a number of variables including initial harvest type, time since harvest, grinder size, and use of trommel screen. The original treatment design was a balanced design as seen in Table 2.1. Sites were selected to reflect similar stand conditions and reduce biological and geographical variance. Sites were also targeted that had an estimated minimum of 30 loads of residual material. All sites were located in the upper coastal Plain of South Carolina.

Table 2.1. Original treatment block

| System | Harvest Type | Weeks Since Harvest |
|---|---|---|
| Large Grinder (Screened) | Roundwood (Clearcut) | 4 |
| Large Grinder (Screened) | Roundwood (Clearcut) | 8 |
| Large Grinder (Screened) | Chipping (First Thin) | 4 |
| Large Grinder (Screened) | Chipping (First Thin) | 8 |
| Small Grinder (Screened) | Chipping (First Thin) | 4 |
| Small Grinder (Screened) | Chipping (First Thin) | 8 |
| Small Grinder (Screened) | Roundwood (Clearcut) | 4 |
| Small Grinder (Screened) | Roundwood (Clearcut) | 8 |

## 2.1 Product Analysis

Samples were taken from each load of each treatment to facilitate analysis of physical traits. Three material streams were sampled – between the grinder and the screen, after screening (acceptable material), and after screening (rejected, fine material). One sample of acceptable materials from the screen was taken for every load. The other two material streams were sampled once every four loads. In all cases, composite samples were taken to produce a representative sample of each truck load. This was accomplished by combining several small samples from throughout each load and mixing these into one large composite sample. From each of these composite samples, a 1 Kg sample was bagged, labeled and immediately weighed on-site to determine the green weight. These bagged samples were returned to the lab for further analysis.

All samples were oven dried in the lab at 105$^{o}$ Celsius for 48 hours. Dry weights in comparison with the corresponding green weights allowed for moisture content calculation on a wet basis. Samples were further processed by the UGA Agricultural & Environmental Services Laboratory for measures of caloric value, ash content, and nutrient composition.

ANOVA and Least Squares Means testing were processed in the SAS statistical package and used to determine significant differences between treatments.

**2.2 Production Analysis**

Daily progress was timed and tracked for production and utilization estimates. Work day length and time for each load were recorded in addition to the state of the system at two minute intervals, i.e. what each machine is doing at that point in time (idling, loading, grinding, etc.). Additionally, the total number of loader bites required to fill each load was also recorded. The time interval data demonstrates the efficiency of each machine throughout each treatment and also shows the effects of one machine on any other.

Net tonnage of each loaded truck was recorded at delivery to a production facility. Additionally the rejected, fine material was fed into a live-bottom chip van that was also weighed at a production facility. These data allowed for calculation and direct comparison of production per ton for each treatment.

Again, Least Squares Means testing was utilized to determine significant differences of production measures among each of the treatments.

## 2.3 Cost Estimation

A new harvesting system must be shown to demonstrate favorable economics before it will be adopted in the woods. A number of cost assumptions were measured and analyzed to understand the feasibility of such grinder/screen operations. Purchase price, depreciation and salvage rates, and worker cost assumptions were estimated from the manufacturer and existing literature. Fuel consumptions were measured daily on-site with the use of an in-line flowmeter. Machine utilization rates were calculated as described above in Production Analysis. These inputs were used with the Auburn Harvesting Analyzer to develop a sensitivity analysis around the expected costs and utilization rates for each system [26]. Additionally, trucking costs were estimated to understand the effects of the trommel screen on load weights and loading times.

# 3. RESULTS

Early in the study it became obvious that our original treatment design did not appropriately reflect operational results and limitations encountered when grinding harvest residues. We improved the study design after observing the low production levels of roundwood debris with the large grinder and the production of the small grinder. With these observations, we anticipated the roundwood debris with the small grinder to provide unacceptable rates of production. We replaced both small grinder with roundwood treatments with an unscreened large grinder system with roundwood (Table 2.2). This adaption created an unbalanced treatment design, but it allowed for direct production comparisons between a screened and unscreened system, a major focus of the study.

Table 2.2. Modified treatment block

| System | Harvest Type | Weeks Since Harvest | Number of Trucks Sampled |
|---|---|---|---|
| Large Grinder (Screened) | Roundwood (Clearcut) | 4 | 25 |
| Large Grinder (Screened) | Roundwood (Clearcut) | 8 | 25 |
| Large Grinder (Screened) | Chipping (First Thin) | 4 | 26 |
| Large Grinder (Screened) | Chipping (First Thin) | 8 | 28 |
| Small Grinder (Screened) | Chipping (First Thin) | 4 | 30 |
| Small Grinder (Screened) | Chipping (First Thin) | 8 | 30 |
| Large Grinder (Unscreened) | Roundwood (Clearcut) | 4 | 21 |
| Large Grinder (Unscreened) | Roundwood (Clearcut) | 8 | 20 |

### 3.1 Product Analysis

Treatment variables for product quality analysis were initial harvest type, time since harvest, and grinder/screen system. Statistical significance at a p-level of 0.05 indicated product differences for a number of categories between treatments. These differences can be used to understand the effects of each treatment on the physical characteristics of the feedstock produced. Before harvest residues are removed from a site, the initial harvest type and time since harvest affect, in many ways, the moisture content of residues that are left on site.

Moisture content on a field weight basis as measured after grinding and before screening was calculated for both residue types at four and eight weeks (Figure 2.1). Four and eight week roundwood material was not significantly different (30% and 32%

respectively). Likewise, there was no significance between the four and eight week clean chipped debris (38% and 42%). However, significance was shown between roundwood and clean chipped debris at four weeks (30% and 38%) and between the roundwood and clean chipped debris at eight weeks (32% and 42%). We expect the moisture variations between debris piles to be a function of the physical characteristics of the different piles. Clean chipped debris piles tended to be more densely packed with greater levels of foliage present, as opposed to the more loosely stacked roundwood residues. Air flows within the roundwood debris could explain lower moisture levels.

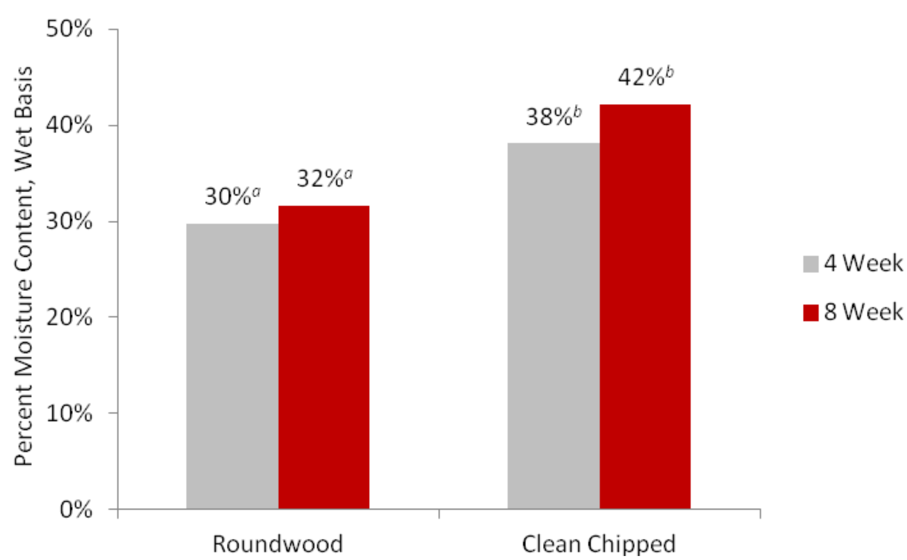


Figure 2.1. Moisture content on a field weight basis for two levels of time since harvest and initial harvest type.

Additional significance testing was performed within each of the debris types (roundwood or clean chipped) for the three material streams - unscreened, screened, and fines (Table 2.3). Of primary concern are the ash levels that correspond to each debris type and screening level. Roundwood debris showed no significant reduction in ash content from screening even though the average was reduced from 4% to 1.4%. This was due to the variability of measurements taken. The ash content of clean chipped debris, however, was significantly reduced from 11.9% to 6%. The high ash levels seen with clean chipped debris fall within the upper range of the literature, and is likely a product of contaminants introduced during processing and handling [27]. It should be noted that the screened, clean chip debris did not differ greatly in ash content from the unscreened roundwood debris.

Reducing ash levels has the added effect of increasing the caloric values of residual feedstocks as a greater percentage of the residues are fully combusted. Thus, the energy content observed followed similar statistical patterns as the ash levels. Screened, clean chipped debris were shown to contain more energy on a dry ton basis then the unscreened, clean chipped materials. Roundwood debris, while on average slightly greater for the screened samples, were not significantly so. Again, however, the energy content of the screened, clean chipped debris did not differ greatly from the unscreened, roundwood (Table 2.3). Reported values for harvest residue energy density as measured in BTU per oven dried ton range from 7700 up to 9000 [9, 10, 27, 28]. Our reduced values appear to be a function of increased ash and contaminant levels as compared to other studies.

Nutrient analyses were also performed for each of the material streams (Table 2.3). Within the roundwood residues, the carbon percentage of the fine material was statistically less than the screened and unscreened. Likewise, the carbon percentage of the clean chipped fines was also significantly less than the other material streams. This reduction could be explained by the reduced wood component in the fine material after screening. The fine material also demonstrated an elevated nitrogen component for both the roundwood and clean chipped residues.

Table 2.3. Moisture, ash, nutrient, and energy contents of a screened residue grinding operation processing roundwood and clean chipped debris.

| | Roundwood | | | Clean Chipped | | |
|---|---|---|---|---|---|---|
| | Unscreened | Screened | Fines | Unscreend | Screened | Fines |
| Moisture Content (%) | 30.8*a* | 28.1*a* | 31.6*a* | 40.2*B* | 38.5*BC* | 35*C* |
| Ash Content (%) | 4.0*a* | 1.4*a* | 14.7*b* | 11.9*A* | 6.0*B* | 29.7*C* |
| Nutrient Content | | | | | | |
| C (%) | 47.3*a* | 48.5*a* | 44.2*b* | 45.1*A* | 47.9*B* | 37.3*C* |
| N (ppm) | 2034*a* | 2180*a* | 2968*b* | 2944*A* | 2796*AB* | 3313*AC* |
| S (ppm) | 149*a* | 157*a* | 214*b* | 191*A* | 191*A* | 226*A* |
| K (ppm) | 951*a* | 1012*a* | 1019*a* | 990*A* | 1042*A* | 994*A* |
| P (ppm) | 231*a* | 272*a* | 308*a* | 200*A* | 215*A* | 235*A* |
| Energy Content | | | | | | |
| BTU/o.d. lb | 7710*a* | 7880*a* | 6987*b* | 7338*A* | 7714*A* | 5978*B* |

Different letters within each row indicate significantly different values by debris type ($p<0.05$).

### 3.2 Production Analysis

Production rates for this study were largely a function of the harvest type and age of the residue processed. First, the interaction between each harvest treatment system and debris age was tested (Table 2.4).

Table 2.4. Field tons per load, tons per productive machine hour, and load times for four harvest treatment systems at two debris age classes.

| Harvest Treatment System | Debris Age (Weeks) | Truck Payload (Field Tons) | Load Time (Minutes) | T/PMH |
|---|---|---|---|---|
| Screened, Clean Chipped, Large Grinder | 4 | 20.2*a* | 17.8*a* | 70.1*a* |
| | 8 | 23.5*b* | *16.9a* | *84.7b* |
| Screened, Roundwood, Large Grinder | 4 | 11.7*c* | 47.2*b* | 15.3*c* |
| | 8 | 15.2*d* | 46.1*b* | 21.3*d* |
| Screened, Clean Chipped, Small Grinder | 4 | 21.2*a* | 29.0*c* | 44.6*e* |
| | 8 | 20.5*a* | *28.4c* | 44.9*e* |
| Unscreened, Roundwood, Large Grinder | 4 | 17.7*e* | 30.0*c* | 35.9*f* |
| | 8 | *20.2a* | 31.0*c* | 41.6*ef* |

Different letters within each column indicate signficantly different values ($p<0.05$).

The effect of debris type on overall production can be easily seen by comparing the screened, large grinder systems for each of the debris types (roundwood vs. clean chipped) at both age classes. Both ages of the clean chipped material averaged considerably greater payloads than the two roundwood treatments, significantly so. This was seen as an effect of the different physical piece sizes that were produced by the grinder for each treatment. The solid, roundwood pieces tended to produce larger, more loosely packed pieces than the smaller clean chipped debris which would load much more densely. Loads of roundwood debris were processed in this system at 47.2 and 46.1 minutes for four and eight week material, while the clean chipped material required only 17.8 and 16.9 minutes. Tons per productive machine hour (T/PMH) is a measure of the potential output of the system on an hourly basis. Being a function of payload tonnage and time per load, it is unsurprising that the clean chipped system produced at a rate of 70.1 and 84.7 tons per productive machine hour for the four and eight week material compared to the roundwood systems at 15.3 and 21.3 tons per productive machine hour.

Another useful comparison is that of the grinder size – screened, clean chipped with the large grinder versus the screened, clean chipped with the small grinder. In this case, both systems processed clean chipped debris resulting in comparable payloads – 20.2 and 23.5 tons with the large grinder and 21.2 and 20.5 tons with the small grinder. However the machines resulted in very different load times – 17.8 and 16.9 minutes for the large grinder compared with 29.0 and 28.4 minutes with the small grinder. The load times between these two machines were significantly different. Again, this translated to improved T/PMH for the large grinder system – 70.1 and 84.7 as opposed to 44.6 and 44.9 with the small grinder. Within the large grinder system, the greater payloads observed for the eight week material (23.5 tons) did translate to a significant difference when compared to the four week debris (20.2 tons).

The final comparison to be made here is that of the screened and unscreened systems of roundwood with the large grinder. Payloads for the screened system were 11.7 and 15.2 tons for four and eight week materials while unscreened payloads were 17.7 and 20.2 tons. These significantly greater payloads can be attributed to the additional weight of fine materials that remained in the material streams without screening. The addition of the screen also significantly increased the average load times – 30.0 and 31.0 minutes for the unscreened system and 47.2 and 46.1 minutes after adding the screen. For these reasons, adding a screen to the system effectively halved the T/PMH for both age classes - a result of smaller payloads combined with longer processing times.

**Fuel Consumption**

Fuel consumption data were also recorded to allow for a comparison by each machine and for the system as a whole (Table 2.5). Fuel averages were not calculated on a per load basis, but data were recorded whenever the machines were refueled (typically at the end of each day). Thus, the sample size was not great enough to allow for statistical means comparisons between systems.

Table 2.5. Fuel consumption as expressed in mean gallons of fuel per each ton produced for four harvest treatment systems at two debris age classes.

| | | Mean Field Gallons/Ton | | | |
|---|---|---|---|---|---|
| Harvest Treatment System | Debris Age | Fuel Grinder | Fuel Loader | Fuel Screen | Total System |
| Screened, Clean Chipped, Large Grinder | 4 | 0.4 | 0.1 | 0.1 | 0.6 |
| | 8 | 0.4 | 0.1 | 0.1 | 0.5 |
| Screened, Roundwood, Large Grinder | 4 | 1.6 | 0.4 | 0.3 | 2.3 |
| | 8 | 1.0 | 0.6 | 0.2 | 1.8 |
| Screened, Clean Chipped, Small Grinder | 4 | 0.4 | 0.2 | 0.1 | 0.7 |
| | 8 | 0.4 | 0.2 | 0.2 | 0.7 |
| Unscreened, Roundwood, Large Grinder | 4 | 0.7 | 0.2 | - | 0.9 |
| | 8 | 0.6 | 0.2 | - | 0.8 |

Residue debris type had an effect on the total fuel economy of the system. The system total fuel consumption for roundwood with the large grinder, screened system was 2.3 and 1.8 gallons per ton (at four and eight weeks) as compared to the clean chipped debris with the large grinder, screened system producing at a rate of 0.6 and 0.5 gallons per ton.

Screening ground residues increases the fuel consumption per ton as compared with unscreened residues. The screened roundwood with the large grinder required, on average, 2.3 and 1.8 gallons per ton; whereas, the unscreened roundwood required only 0.9 and 0.8 gallons per ton. The longer load times observed with the addition of the screen could account for these differences.

Grinder size had a much different effect on the total fuel consumption. While the small grinder system was not as productive hourly as the large grinder equivalent, the fuel usage on the gallon/ton basis was very similar. Averages for the screened large grinder with clean chipped debris were 0.6 and 0.5 gallons per ton at four and eight weeks as opposed to the same system with the small grinder – 0.7 gallons per ton for both age classes.

**Machine Utilization**

Machine time was categorized as follows: productive, mechanical delay, non-mechanical delay (Table 2.6). Non-mechanical delays included categories such as waiting on trucks, waiting on the loader, grinder, or material, wait-off (extended delays), idle, and miscellaneous delays.

Productive rates for the grinder were highest, at 58.4%, with the unscreened roundwood debris processed with the large grinder. Comparing directly with the screened roundwood debris, large grinder system, productive rates decreased to 47.3% and 41.1% for the grinder and loader respectively. Thus, it would appear that the trommel screen reduced system utilization. Of course, productive rates are operationally linked to load times.

For instance, the lowest grinder utilization rates were found with the large grinder processing clean chipped material – 36.9%. These figures are a product of the load times associated with each system. The large grinder processing clean chipped material exhibited the shortest load times, consistently less than 20 minutes. Thus, production suffered as trucking struggled to keep up – trucking delays soared to 30.1% with that treatment.

It should be noted that mechanical repairs and other activities such as piling often occurred while trucks were not present, underestimating the size of trucking delays.

Table 2.6. Machine utilization analysis for four residue harvest treatment systems.

| | -----Unscreened----- | | ---Screened--- | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Large Grinder Roundwood | | Large Grinder Roundwood | | Large Grinder Clean Chipped | | Small Grinder Clean Chipped | |
| | Grinder | Loader | Grinder | Loader | Grinder | Loader | Grinder | Loader |
| Productive | | | | | | | | |
| Grinding | 58.4% | - | 47.3% | - | 36.9% | - | 54.3% | - |
| Loading | - | 58.0% | - | 40.7% | - | 36.1% | - | 51.4% |
| Piling | - | 6.2% | - | 0.4% | - | 3.3% | - | 0.0% |
| Mechanical Delays | 7.1% | 2.2% | 7.5% | 8.5% | 3.4% | 0.6% | 1.7% | 5.1% |
| Non-Mechanical Delays | | | | | | | | |
| Wait on Truck | 14.2% | 10.7% | 10.7% | 6.9% | 30.1% | 26.2% | 7.8% | 5.9% |
| Wait on Loader | 0.2% | - | 0.3% | - | 0.4% | - | 0.3% | - |
| Wait on Material | 5.4% | - | 6.5% | - | 0.8% | - | 0.3% | - |
| Wait on Grinder | - | 5.5% | - | 14.4% | - | 1.1% | - | 15.2% |
| Wait - Off | 4.1% | 3.4% | 10.3% | 11.1% | 11.4% | 15.4% | 14.4% | 4.1% |
| Idle | 0.1% | 0.1% | 1.4% | 1.1% | 0.1% | 0.1% | 0.6% | 0.3% |
| Misc. Delay | 10.5% | 13.9% | 16.1% | 17.0% | 16.9% | 17.2% | 20.3% | 18.1% |
| Total | 34.5% | 33.6% | 45.2% | 50.4% | 59.7% | 60.0% | 43.9% | 43.6% |
| | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

### 3.3 Cost Estimation

Base case production costs were estimated using data observed during field trials with the modified Auburn Harvesting Analyzer for four treatment systems on a field ton, dry ton, and mmBTU basis (Table 2.7). Transportation costs are included in cut & haul costs.

Table 2.7. Estimated costs of harvesting residue materials for four harvest treatment systems.

| | Unscreened | Screened | Screened Clean Chipped | |
|---|---|---|---|---|
| | Roundwood | Roundwood | Small Grinder | Large Grinder |
| Cut & Haul Cost per Field Ton = | $20.49 | $36.22 | $19.83 | $18.33 |
| Cut & Load Cost per Field Ton = | $13.99 | $29.72 | $13.33 | $11.83 |
| Cut & Haul Cost per ODT = | $29.25 | $51.74 | $33.05 | $30.55 |
| Cut & Load Cost per ODT = | $19.97 | $42.46 | $22.22 | $19.72 |
| Cut & Haul Cost per mmBTU = | $2.06 | $3.27 | $2.32 | $2.08 |
| Cut & Load Cost per mmBTU = | $1.41 | $2.68 | $1.56 | $1.34 |

Unscreened roundwood and both clean chipped systems were estimated to produce ground residues at very similar costs. The screened roundwood system, however demonstrated consistently higher costs, as a result of having the longest load times and lightest average payloads of any of the systems. Of course, screened roundwood also resulted in the lowest ash levels. On an energy basis, screening roundwood increased the delivered cost from $2.06 per mmBTU to $3.27. This corresponded with a reduction of ash levels from 4.0% to 1.4%.

Base case cost estimation comparisons in Table 2.7 were calculated using data recorded during field trials. As discussed previously, there were no field trials for unscreened, clean chipped systems. Therefore, to compare the cost effects of screening on clean chipped material, it was necessary to model the unscreened, clean chipped costs with estimated inputs. In this case, ash and energy contents were taken from lab data of pre-screened material streams. Productivity and payload measures were adjusted from data observed in the screened systems. These estimated costs to process unscreened, clean chipped residues were then compared with the costs for screened, clean chipped residues presented previously (Table 2.8).

Table 2.8. Estimated costs, with and without screening, of harvesting clean chipped materials.

| | ------------------------------Clean Chipped------------------------------ | | | |
|---|---|---|---|---|
| | Small Grinder | | Large Grinder | |
| | Unscreened | Screened | Unscreened | Screened |
| Cut & Haul Cost per Field Ton = | $15.05 | $19.83 | $16.20 | $18.33 |
| Cut & Load Cost per Field Ton = | $8.55 | $13.33 | $9.70 | $11.83 |
| | | | | |
| Cut & Haul Cost per ODT = | $25.09 | $33.05 | $27.01 | $30.55 |
| Cut & Load Cost per ODT = | $14.25 | $22.22 | $16.17 | $19.72 |
| | | | | |
| Cut & Haul Cost per mmBTU = | $1.94 | $2.32 | $2.09 | $2.08 |
| Cut & Load Cost per mmBTU = | $1.10 | $1.56 | $1.25 | $1.34 |

On a field weight basis, similar delivered cost patterns were seen with both grinder sizes. The addition of a screen increased costs of the small grinder system from $15.05 per field ton to $19.83, and from $16.20 to $18.33 with the large grinder. However, when considered on an energy basis, the delivered cost response to adding a screen differed. For the small grinder, costs increased from $1.94 per mmBTU to $2.32 by screening the material. The large grinder system actually decreased in cost from $2.09 to $2.08 when screening.

Sensitivity analyses were also performed to compare the effect of a number of variables on overall system costs. Treatment systems were: screened roundwood residues with large grinder (RW-S), unscreened roundwood residues with large grinder (RW-U), and screened clean chip debris with large and small grinders (LCC-S and SCC-S, respectively). In all cases, the screened roundwood system produced higher expected costs than the other systems. Estimated costs for the remaining three systems consistently produced similar cost results across all levels of sensitivity.

On an energy basis, higher residue moisture contents increase the total costs of the system (Figure 2.2). High moisture levels increase transportation costs without improving the energy content. Likewise, the presence of ash and contaminants reduces the energy content of the feedstock. Thus, lower ash levels decrease the cost per BTU to deliver to a purchaser (Figure 2.3).

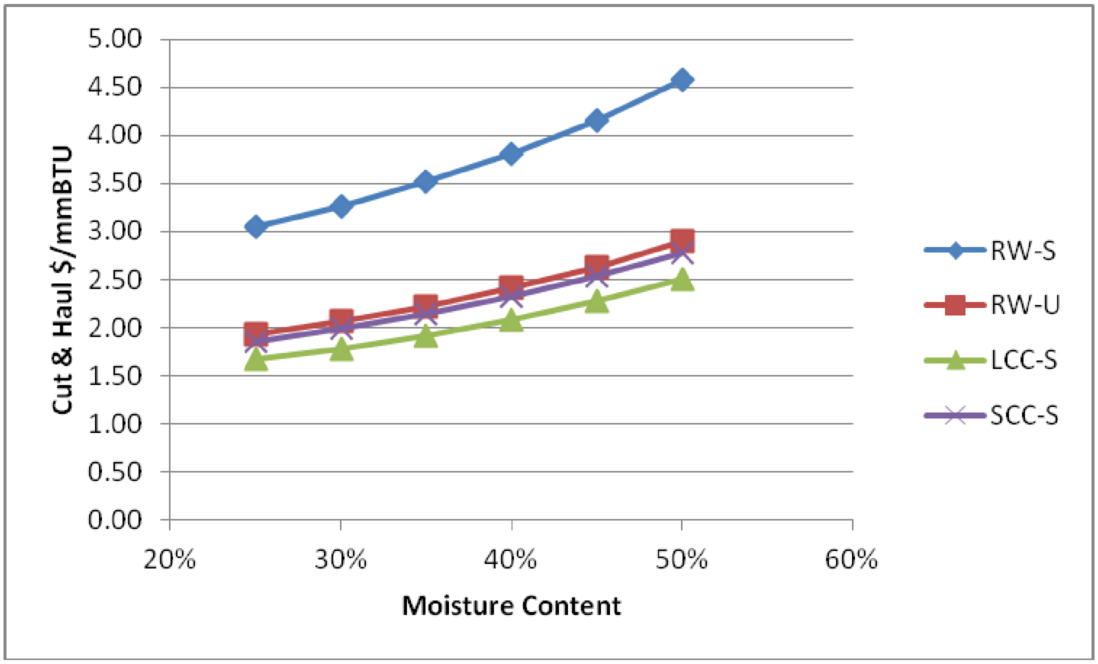


Figure 2.2. Delivered cost estimates on a mmBTU basis for increasing levels of moisture content.

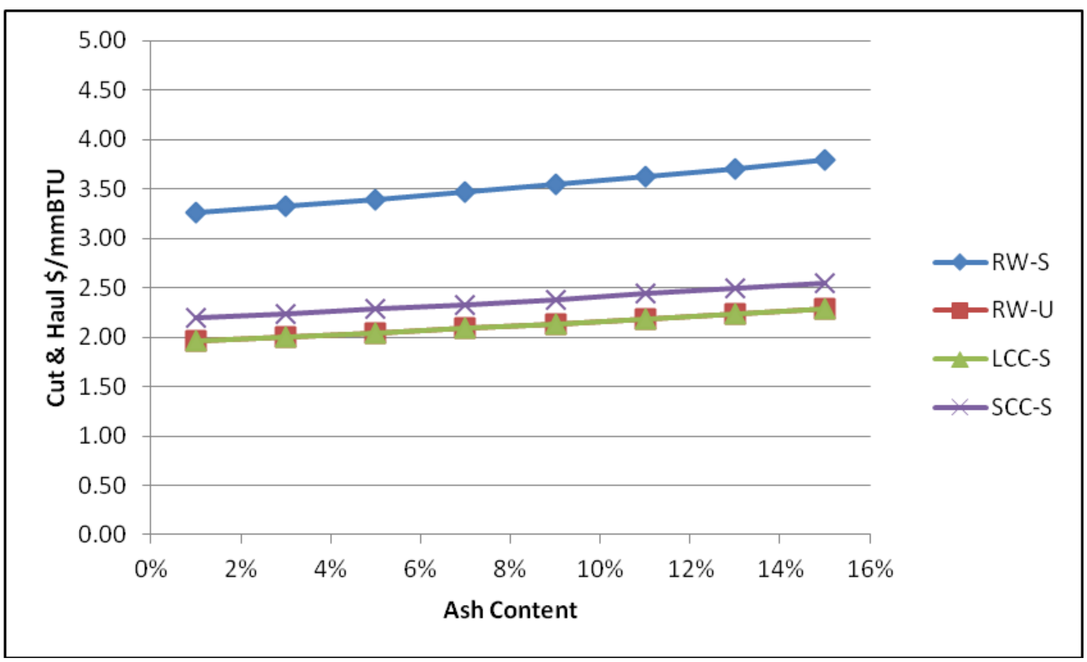


Figure 2.3. Delivered cost estimates on a mmBTU basis for increasing levels of ash content.

Fuel costs are a considerable component for most logging operations. The systems observed in this study are no exception, with a number of machines and support vehicles. The recent volatility of fuel prices demand consideration of this variable in studying economic viability. Estimated delivered costs for ground residue feedstocks on an energy basis were calculated for a wide range of fuel costs (Figure 2.4). Screened roundwood costs responded the most unfavorably to fuel price increases due to an unfortunate combination of poor fuel consumption and low hourly production. Costs for the other systems remained relatively stable across the extreme range of fuel costs – an encouraging trend for potential feedstock collection in the future.

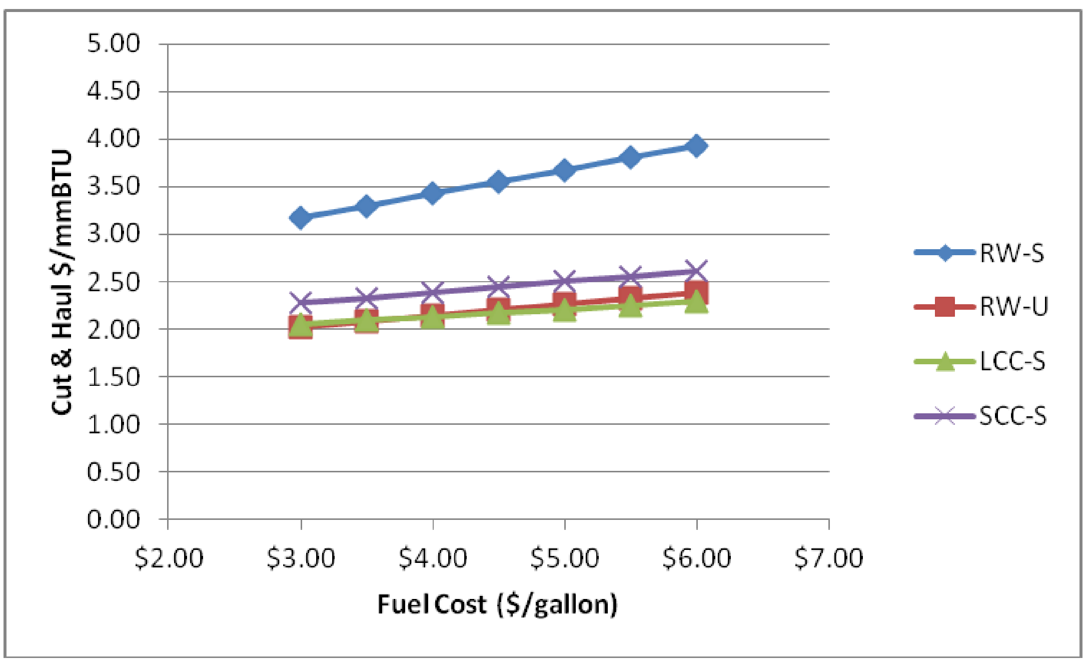


Figure 2.4. Delivered cost estimates on a mmBTU basis for increasing fuel costs.

The relationship between payloads and delivered cost was also calculated on an energy basis (Figure 2.5). Certainly, heavier payloads are desired to offset production costs. Observed field trials indicated payload limitations due to the physical properties of the ground residue feedstock. As discussed earlier, payload averages differed by residue type – indicating density differences. Low payloads can be mitigated by adapting transportation options. For instance, longer trailers, double trailers, or 'possum belly' trailers with lower floors can be used to maximize payload weight [29]. The marginal cost benefit with increasing payloads begins to decline at 20 tons.

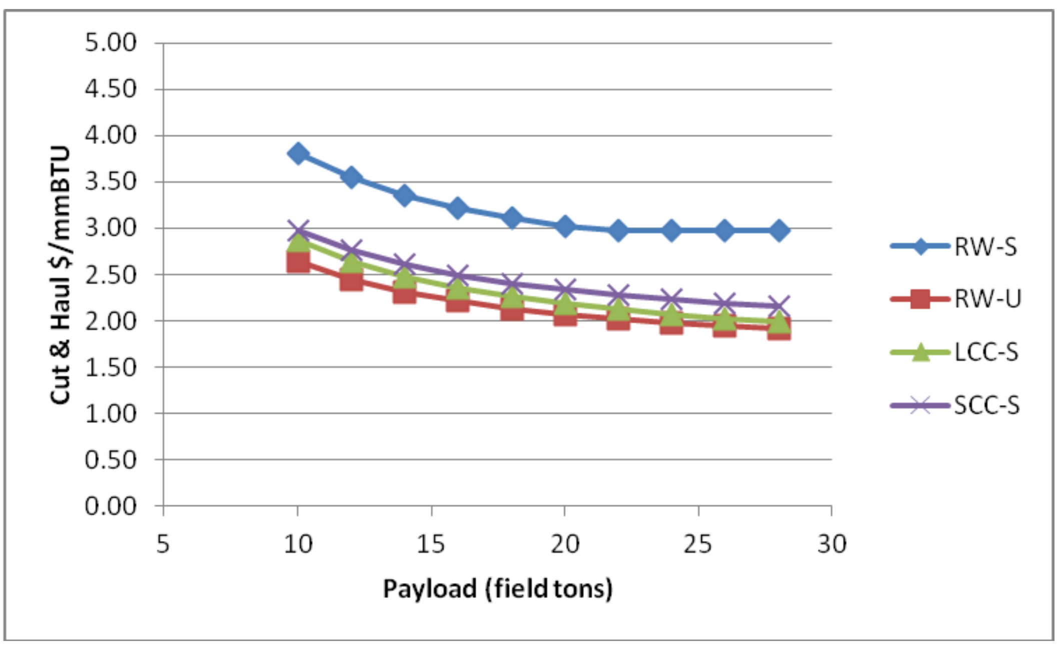


Figure 2.5. Delivered cost estimates on a mmBTU basis for increasing payloads.

Another influential variable of delivered cost is the haul distance, or distance to purchasing facility. Transportation costs are substantial for any forest product, and often influence procurement strategies. When considering low value, low density fuelwood products, trucking costs can account for up to 40% of the overall cost [29]. The effects of haul distance were examined on the estimated delivered costs (Figure 2.6).

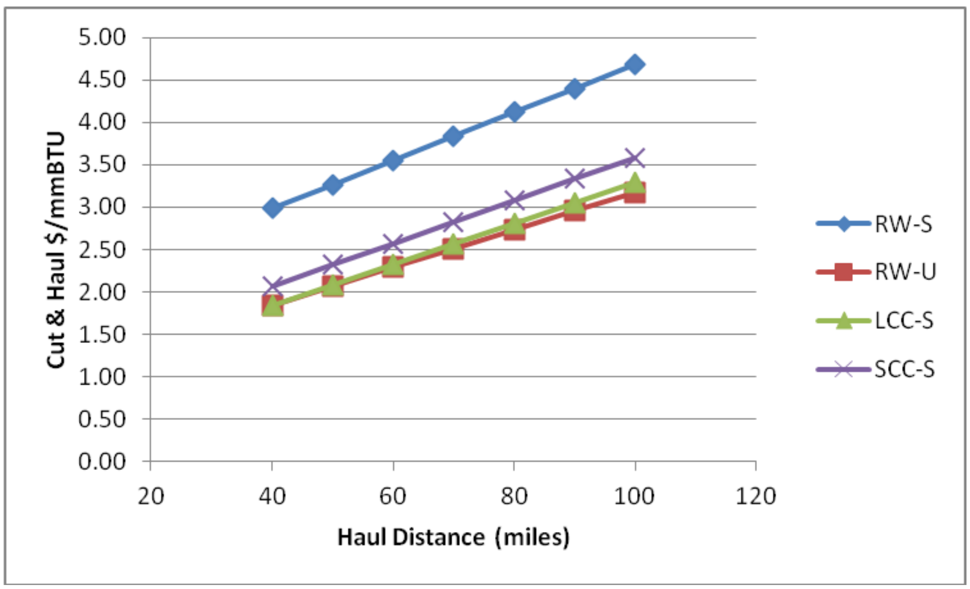


Figure 2.6. Delivered cost estimates on a mmBTU basis for increasing haul distances.

A final cost sensitivity analysis can be made across all treatment systems by modeling the effect of moisture content, ash content, fuel cost, payload, and haul distance increasing by ten percent and comparing with the estimated base case prices discussed earlier (Table 2.9). Of the inputs, moisture content and haul distance had the greatest effect on delivered costs.

Table 2.9. Cost response per mmBTU for 10% increase in inputs for four harvest treatment systems.

| | Unscreened Roundwood | Screened Roundwood | Screened Clean Chipped | |
|---|---|---|---|---|
| | | | Small Grinder | Large Grinder |
| Moisture Content | 4.6% | 4.9% | 6.9% | 7.2% |
| Ash Content | 0.0% | 1.0% | 0.9% | 1.0% |
| Fuel Cost | 2.8% | 2.4% | 1.7% | 1.4% |
| Payload | -2.8% | -1.5% | -2.6% | -2.4% |
| Distance | 4.3% | 5.8% | 5.6% | 5.8% |

## 4. DISCUSSION & CONCLUSIONS

Our results indicate that the addition of a trommel screen to a residue collection system can add significant value to ground residue feedstocks. Average ash contents were reduced for both debris types after screening, significantly so for chipped debris. Roundwood debris consistently demonstrated lower ash levels than clean chipped debris regardless of screening activity. Energy density trends corresponded favorably with the reduction of ash and were improved with screening. However, the ultimate concern for loggers and landowners is the marketability of the final product. Despite the improvements that were shown, ash levels may remain too high for some purchasers - even after screening, clean chipped debris contained 6% ash on average. Operationally, utilization was low – never exceeding 60% for the grinder and only once for the loader. As with many forest operations, trucking delays were often a substantial component. Improved mill turnaround and expanded market demand could improve productivity.

From a cost perspective, screened roundwood systems do not seem economically feasible, unless a purchaser is extremely sensitive to ash levels and is willing to pay for the increased cost. Screening increased roundwood costs by 77% on a field weight basis and 59% on an energy basis. Cost increases were much more modest with clean chipped residues. On an energy basis, screening clean chipped residues with the small grinder only increased costs by 20%, and actually decreased after screening for the large grinder. Financially, the screened clean chip systems and the unscreened roundwood material provide the most competitive residue on an energy basis. Opportunities for further study exist to compare alternate payment methods for delivered energy feedstocks. As discussed, payloads varied considerably between treatments due to differences in physical characteristics. In some cases, these payloads were quite low, an obvious concern if payments are based on weight measures. Energy based payments would provide obvious incentives for suppliers to seek and harvest more agreeable materials for purchasers.

CHAPTER 3

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