# Productivity and Product Quality Measures for Chippers and Grinders on Operational Southern US Timber Harvests

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## Abstract

Growth in bioenergy interests in the southeastern United States has created a need for cost-effective woody biomass harvesting systems. We evaluated three operational systems for their potential production and cost: horizontal grinders fed with residue from roundwood harvests, horizontal grinders fed with residue from clean chipping harvests, and whole tree chippers fed with entire stems. We evaluated three contractors operating each of the three system types over the course of approximately one working week each. Utilization rates for chippers and grinders were 44% and 38% respectively. Hourly production ranged between 22 – 30 metric green tonnes (gt)/SMH and 64 – 70 gt/PMH and did not differ significantly between the three systems. Delivered costs per gt of material were also very similar for the three systems and ranged between $22.68 and $23.81.

*Keywords:* wood biomass, chips, harvesting, logging costs.

## Introduction

Renewable energy sources are receiving increased attention due to increased and volatile fossil fuel prices, the threat of climate change associated with rising $CO_2$ levels, and energy security issues (Turner 1999). Renewable energy sources can play a vital role in shaping the economy of the future as fossil fuel prices rise. Biomass is one source of renewable energy that is being closely examined nationwide and particularly in the southeastern US. The southeastern region, with over 12 million hectares of land dedicated to managed pine plantations, is the largest producer of forest products in the country. These forests have the potential to play a major role in producing biomass feedstocks for various industries. Such feedstocks would typically come from logging residues (i.e., tree tops and branches), unmerchantable stems, and trees that are currently used as feedstock by traditional wood-using industries.

Southeastern timber harvesting systems typically use feller-buncher/grapple skidder systems that process harvested stems at roadside (Baker and Greene 2008). Grinders or chippers can be added to process residues or tree length material for biomass feedstocks, depending on the desired product. Grinding systems, which use hammerhogs to bluntly force the biomass material through screens, produce what is known as "hog fuel" (Naimi et al. 2006). This feedstock is typically burnt in boilers at mills or cogeneration electricity plants where it does not need to meet the size or bark specifications required of pulp chips. Chipping systems, which use knives attached to either rotating drums or discs, produce a feedstock with more uniform particle size (Naimi et al. 2006). Chippers can either produce high quality chips for pulp and paper applications or lower quality chips that utilize the entire tree and are better suited for energy production.

The timing of forest residue recovery operations can impact the cost and productivity of the residue harvesting system. Post-harvest residue recovery is difficult to perform due to breakage, disorientation, and entanglement of stems left on site. Also, standing trees left on site are often too large or small to be easily harvested with conventional logging equipment. Recovering residues post-harvest does have the advantage of reducing site preparation costs but has been shown to be less cost effective than integrated or pre-harvest recovery methods (Stokes and Sirois 1989). Pre-harvest recovery methods use feller-bunchers to remove small pine stems and unmerchantable hardwoods from the stand before the primary

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products are targeted. This method has the advantage of increasing the efficiency of the primary harvest, utilizing unmerchantable stems in the stand, and leaving a clean site which can reduce site preparation costs. The biggest disadvantage to this method is that limbs and tops from the primary harvest are unable to be utilized (Stokes and Sirois 1989).

Watson et al. (1986a) found that integrated harvesting methods were the most economically attractive option. These systems use a conventional logging system with the addition of a whole tree chipper located at the landing. The felled stand components can be separated into traditional and biomass categories by the feller-buncher operator in the woods or after skidding by the loader operator. Westbrook et al. (2007) demonstrated that an integrated system can maintain roundwood production levels while recovering residues at an acceptable cost. Baker et al. (2010) found that integrated systems with a small chipper (< 300 kW) can succeed in southern pine stands within a narrow range of harvest conditions which are dependent on the volume of biomass produced relative to the roundwood volumes.

Watson et al. (1986b) showed that the productivity of whole tree chipping for biomass is highly dependent on tree size. Spinelli and Hartsough (2001) studied a large number of chipping operations processing logs, whole trees, and harvesting slash, and concluded that while piece size had a substantial impact on chipping productivity, chipper size was also influential. Mitchell and Gallagher (2007) determined a whole tree chipping operation in southern pine stands of the US could produce forest biomass materials economically with a 340 kW chipper if operational delays could be eliminated. Spinelli and Visser (2009) examined utilization and causes of delay from a number of chipping operations. They determined that whole tree chipping suffered greater delays than did slash chipping, implying that the higher productivity of whole tree chipping may be somewhat offset by increased delays.

Grinders are an option for either post-harvest residue recovery or for integrated systems on high production harvesting crews. Previous research on grinders processing woody materials has highlighted the substantial increases in production rates that result from both increasing the size of the holes in screens used and processing lower moisture content materials (Arthur et al. 1982). Asikainen and Pulkkinen (1998) commented that a tub grinder was capable of increasing its potential productivity by processing clean chipping residue rather than roundwood logging residue because of the challenges in feeding roundwood residue into the tub. We were unable to find similar studies on horizontal grinders. Operational studies of horizontal grinders have shown relatively few factors that significantly impact the productive potential of the machines (Pan et al. 2008). The limited mobility of trailer-mounted knuckleboom loaders has been cited as a hindrance when handling large piles of residues with grinders (Arthur et al. 1982).

The goal of this study was to compare common harvesting systems for producing biomass feedstock to assess their efficiency and economy. We examined systems that grind logging residues left behind after roundwood timber harvests (GRW) and after in-woods chipping systems that produce “clean chips” for pulp and paper (GCC), as well as whole tree chipping systems that produce “dirty” chips (WTC).

## Methods

Local contacts provided information on GRW, GCC, and WTC crews operating in the southeastern US. After contacting contractors, nine crews (three of each system type) were identified for observation. Two of the WTC harvests were first thinnings while the third was a clearcut of a low-quality pine stand. Five of the grinder operations were following first thinnings, with the sixth (a GCC crew) following a clearcut. Each crew visited in this study was operating in either Alabama or Georgia on loblolly pine (*Pinus taeda*) stands. Pre-harvest inventories of stands to determine tree/ha and metric tonne/ha estimates were not performed due to time and budget constraints. Similar first thinnings in this area of the country reduce stands from roughly 1000 – 1200 stems/ha and 200 – 250 metric green tonnes/ha to roughly 500 stems/ha and 115 – 175 gt/ha.

Chipping and grinding operations involved different harvesting systems, and crew size varied by operation type (Table 1). Materials were left in piles by the previous harvesting operation, with one pile located per landing. Each landing

**Table 1.** Characteristics of forest biomass grinding and chipping systems in Georgia and Alabama studied during 2009-2010.

| Crew Type | State | Crew Size | No. of Trucks | Chipper/Grinder | Power (Kw) | Additional Equipment* |
|---|---|---|---|---|---|---|
| WTC | AL | 4 | 5 | Morbark 50/48 | 570 | KB, FB, SK(2) |
| WTC | AL | 5 | 4-5 | Precision Husky WTC 2366 | 520 | KB, FB, SK(2) |
| WTC | GA | 4 | 4 | Morbark 30/36 | 370 | KB, FB, SK(2) |
| GRW | AL | 1 | 4 | Peterson 4710B | 470 | FE |
| GRW | GA | 1 | 5 | Vermeer HG 6000 | 470 | FE, KB |
| GRW | GA | 2 | 3 | Morbark 4600 XL | 570 | FE, KB |
| GCC | AL | 4 | 4 | Peterson 4700C | 470 | FE, KB, FB, SK |
| GCC | GA | 2 | 4-5 | Peterson 4700B | 470 | FE, KB |
| GCC | GA | 1 | 2 | Morbark 3800 | 450 | FE, KB |

* Codes for additional equipment correspond to: KB – knuckleboom loader, FB – feller-buncher, SK – grapple skidder, FE – wheeled front-end loader. Unless otherwise noted, only one of each each machine was present on site.

varied widely in size, but they were typically less than 0.5 ha. Grinding crews used one or two employees with a knuckleboom loader and/or a wheeled front-end loader to move piled materials to the grinder. The grinders were almost always stationary on a given landing. Trucks were positioned under the outfeed conveyor and loaded directly. Waiting times for trucks were usually negligible unless they arrived during a breakdown or during loading of another truck. Available trucking capacity varied between two and five trucks (Table 1). All trucks in the study had maximum legal payloads between 23-27 metric green tonnes (gt).

Whole tree chipping operations employed larger crews as felling and skidding functions were also involved. The landing was organized similarly to grinding operations, with trucks loaded directly by the chipper. Skidders brought whole trees directly from the woods to the stationary knuckleboom loader that was used to feed the chipper. One GCC crew used four employees during the study period to fell residual hardwood stems and feed them to the grinder, but this was not a typical operation for that crew.

Work sampling studies were performed at each of the sites. The studies observed and recorded approximately 30 truckloads, typically lasting three to four days. The activity of each piece of equipment was recorded every two minutes throughout each workday into work categories based on previous studies (Westbrook et al. 2007). Delays were combined into the following categories for chippers/grinders, knuckleboom loaders, and front-end loaders: mechanical delays, waiting on trucks, and other delays. Delays for "waiting on trucks" were recorded when the system was unable to chip or grind material because no truck was available for loading at the harvest site. Other sources of delay were inconsistent and sporadic amongst the various harvesting systems and crews because of the relatively short time period of the study. As a result, all other causes of delay were grouped into a single category for comparison between systems. Work sampling categories for feller-bunchers and skidders included felling/skidding, operational delay, and idle/off. These data were combined by harvest system type (GRW, GCC, WTC) to calculate utilization rates. Work sampling categories were reported as a percentage of total scheduled machine hours.

The time required to load each truck was recorded along with the length of any delays that prolonged the loading process. Total number of grapple bites or swings of wood required to feed the chipper or grinder were also recorded. Data from mill scale tickets were used to obtain the weight of each load. The productivity of each grinder/chipper was calculated on both a scheduled machine hour (SMH) and productive machine hour (PMH) basis. Tonnes per scheduled machine hour included all delays encountered during harvest operations and was calculated for each observed day as the total tonnage hauled from the tract divided by the number of hours that the crew was on site and scheduled to work. Tonnes per productive machine hour was calculated by dividing the total tonnage hauled from the tract by the delay-free time required to load trucks. A sample of chipped or ground material was also collected from six of the nine operations observed to be tested for energy and ash content according to ASTM E 870. This information allowed us to make comparisons on both a green tonne (gt) and gigajoule (GJ) basis.

We created two modified versions of the Auburn Harvest Analyzer (Tufts et al. 1985) to estimate costs for grinder and whole tree chipping systems. Sensitivity analyses were performed for a variety of model inputs to determine their effect on the delivered cost per green tonne and cost per GJ of material that each system produced. Base case values and the range of values for each variable tested during sensitivity analysis are shown in Table 2.

**Table 2.** Base case and the range of values for the variables tested during sensitivity analysis.

| Variable | Low | Base | High |
|---|---|---|---|
| GRW - Tonnes/ha | 7 | 7 | 34 |
| GCC - Tonnes/ha | 7 | 11 | 34 |
| WTC - Tonnes/ha | 45 | 45 | 224 |
| Tract Hectares | 10 | 10 | 40 |
| GRW & GCC - Number of Piles | 1 | 5 | 10 |
| WTC - Quadratic Mean DBH (cm) | 13 | 13 | 20 |
| Truck Load Weight (tonnes) | 16 | 24 | 33 |
| Haul Distance (km) | 80 | 80 | 193 |
| Mill Turnaround Time (min.) | 20 | 30 | 60 |

## Results

### Machine Utilization Analysis

Chipper/grinder utilization was the highest for WTC systems with a utilization rate of 44% (Table 3). Both grinder systems had a slightly lower utilization rate of 38%. During the study period, all operations were working under production quotas that limited the volume of material they were able to deliver. Most crews employed relatively few trucks to haul material from the woods to ensure the allotted quota lasted throughout the week. The utilization of the chippers or grinders could have been greatly increased if the percentage of time waiting on trucks was reduced. These delays were the highest for the GRW and GCC systems with a rate of 49%.

Knuckleboom loaders were used to feed material to the chipper/grinder by each observed system except for one GRW crew that relied entirely on a front-end loader. The utilization rates of these machines closely mirror those of the chipper/grinder they were feeding. For this reason, trucking related delays were a big part of their delays (Table 3). No mechanical delays were observed during the study period for knuckleboom loaders.

Front-end loaders were used by the GRW and GCC crews to both load the grinder as well as pile material for a stationary knuckleboom loader if present. Without the front-end loader, knuckleboom loader productivity would have

**Table 3.** Utilization rates as a percentage of total scheduled hours for machinery in biomass harvesting systems utilizing whole-tree chipping (WTC), grinders processing roundwood harvest residue (GRW) and grinders processing clean chipping residue (GCC).

| Machine | Work Category | WTC | GRW | GCC |
|---|---|---|---|---|
| Chipper/ Grinder | Productive Time | 44% | 39% | 38% |
| | Waiting on Trucks | 31% | 50% | 49% |
| | Mechanical Delay | 11% | 4% | 9% |
| | Other Delay | 14% | 7% | 3% |
| Knuckle-boom Loader | Productive - Loading | 43% | 32% | 33% |
| | Productive - Piling | 3% | 4% | 3% |
| | Waiting on Trucks | 29% | 51% | 43% |
| | Mechanical Delay | 6% | 2% | 0% |
| | Other Delay | 20% | 11% | 21% |
| Front-end Loader | Productive - Loading | | 20% | 20% |
| | Productive - Piling | | 18% | 31% |
| | Waiting on Trucks | | 49% | 39% |
| | Mechanical Delay | | 1% | 1% |
| | Other Delay | | 12% | 10% |
| Feller-Buncher | Productive Time | 76% | | |
| | Mechanical Delay | 1% | | |
| | Other Delay | 24% | | |
| Skidder | Productive Time | 57% | | |
| | Other Work | 8% | | |
| | Mechanical Delay | 4% | | |
| | Other Delay | 32% | | |

decreased because residues were often not piled within easy reach of the grinder. Combined loading and piling utilization rates for front-end loaders on the GRW and GCC crews were 38% and 51%, respectively (Table 3). Front-end loaders spent significantly more work time on piling with GCC crews compared to GRW ($p < 0.001$). This may have been a function of the small size of residues handled on GCC operations. Although front-end loaders were able to pile material while the grinder was waiting for trucks, trucking related delays still hampered the utilization of these machines.

Feller-bunchers and skidders were used by the WTC systems because harvests occurred concurrently with the chipping operation. Feller-buncher utilization was 76% for the systems observed (Table 3). Skidder utilization was a bit lower than the felling machine with a rate of 57%. The other delays category is higher for skidders because they were used to perform other tasks on the harvest site such as helping push trucks or maintaining the loading deck and haul roads. Had the time spent performing other tasks been included, skidder utilization would have increased to 63%.

**Production Rate Analysis**

Observed production means (gt/SMH) for the three systems were not statistically different ($p = 0.178$). We also examined production rates per scheduled hour excluding trucking -related delays, because they were caused by sources external to the production study. While production rates were higher, they still were not statistically different, due to high levels of variability ($p = 0.413$). Each grinder or chipper could produce 65-71 gt/PMH (Table 4). Despite the operational differences in the three system types, the maximum potential production of the chipper/grinder did not differ significantly ($p = 0.190$).

A comparison between the production rate of the grinder when fed by front-end loaders and by knuckleboom loaders revealed few differences. When comparing loads loaded entirely with front-end loaders, entirely with knuckleboom loaders, and with a mix of each, no significant differences were found in production rates between the three ($p = 0.053$). The average weight of material gathered in a single turn differed between machines and between operation types. Front-end

**Table 4.** Productivity in metric green tonnes per scheduled machine hour (SMH), per SMH without delays related to trucking and per productive machine hour (PMH) of grinders or chippers and energy and ash content of wood samples from three biomass harvesting systems: whole-tree chipping (WTC), grinders processing roundwood harvest residue (GRW) and grinders processing clean chipping residue (GCC).

| | Tonnes/SMH | | Tonnes/SMH (No truck delays) | | Tonnes/PMH | | | Energy Content (MJ/kg) | Ash Content (%) |
|---|---|---|---|---|---|---|---|---|---|
| System | N | Mean (Std. Dev.) | N | Mean (Std. Dev.) | N | Mean (Std. Dev.) | N | Mean (Std. Dev.) | Mean (Std. Dev.) |
| GRW | 10 | 27.9 (8.3)[a] | 10 | 47.7 (13.1)[a] | 80 | 70.7 (25.2)[a] | 21 | 20.2 (1.3)[a] | 2.2 (2.1)[a] |
| GCC | 11 | 22.3 (5.8)[a] | 11 | 38.1 (12.7)[a] | 86 | 66.0 (17.9)[a] | 15 | 19.6 (0.6)[ab] | 5.2 (0.9)[b] |
| WTC | 9 | 29.9 (13.2)[a] | 9 | 44.5 (21.5)[a] | 73 | 65.2 (16.9)[a] | 12 | 19.2 (0.4)[b] | 0.6 (0.1)[c] |

[a,b,c] Different letters within a column indicate significant differences between values ($p < 0.05$)

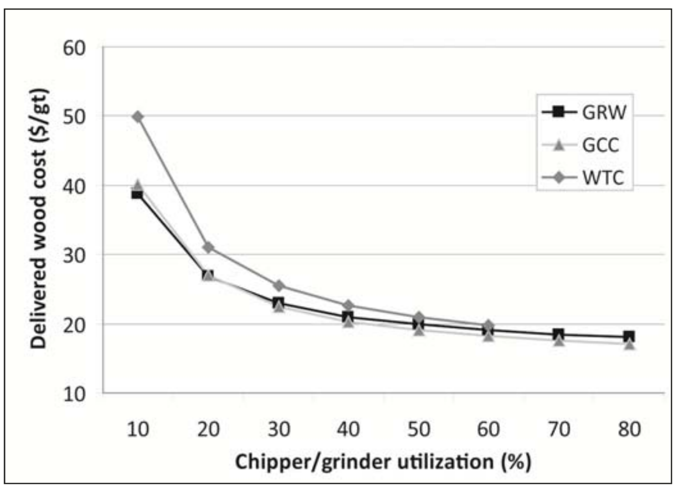
loaders were gathering 1.0 gt per bucket load from both clean chipping and roundwood residue. Knuckleboom loaders were gathering 0.39 gt from roundwood residue, but only 0.29 gt from clean chipping residue ($p$ = 0.02). While there were no differences in production rates, loads fed entirely from knuckleboom loaders were still reliant on the piling function of front-end loaders to maintain production.

**System Cost Analysis**

Whole tree chipping systems had an estimated delivered cost of material of $23.80/gt. Grinder systems had delivered costs of $23.70/gt for GRW operations and $22.70/gt for GCC operations. When the delivered cost was calculated on a GJ basis, delivered costs were $2.00, $2.00 and $1.90 for WTC, GRW and GCC systems respectively.

Increased utilization of the chipping or grinding machine can lower the delivered material cost substantially (Figure 1). Observed utilization rates averaged 40% for these machines but by reducing delays the utilization rate could be increased. If a utilization rate of 70% could be achieved the delivered cost for each system type would fall by nearly $3.00/gt.

**Figure 1.** Impact of chipper or grinder utilization rate on delivered wood cost of three biomass harvesting systems: whole-tree chipping (WTC), grinders processing roundwood harvest residue (GRW) and grinders processing clean chipping residue (GCC).




Per hectare removals were examined for grinding and whole tree chipping systems separately because they differ drastically from one another. Removals between 7 to 34 gt/ha of residual material represent a typical range for the grinder operations that were observed. The estimated delivered price fell by $2.80/gt, from an average cost of $23.90 to $21.10, as the removals increase to 34 gt/ha (Figure 2). The same trend occurred for WTC systems over a typical removal range of 45 to 224 gt/ha. The delivered price decreased $1.90/gt as the removals increased to the maximum of 224 tonnes/ha (Figure 3). Grinder systems appeared to be much more sensitive than WTC systems to changes in per hectare removals, probably because by nature they deal with residues that are available in lower amounts per hectare.

**Figure 2.** Delivered material cost estimates for increasing tonne/ha removals for grinders processing roundwood harvest residue (GRW) and grinders processing clean chipping residue (GCC).

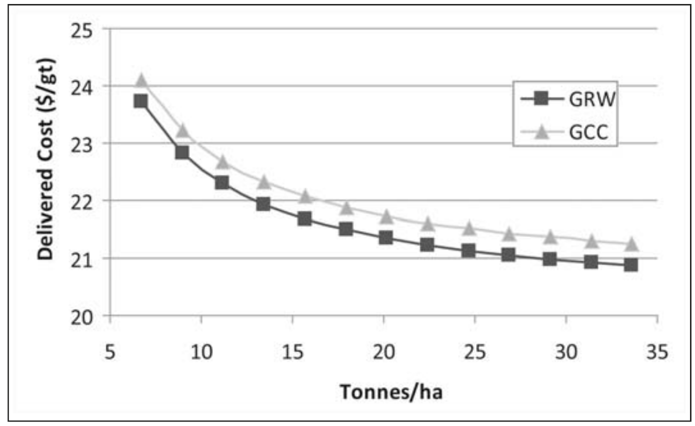
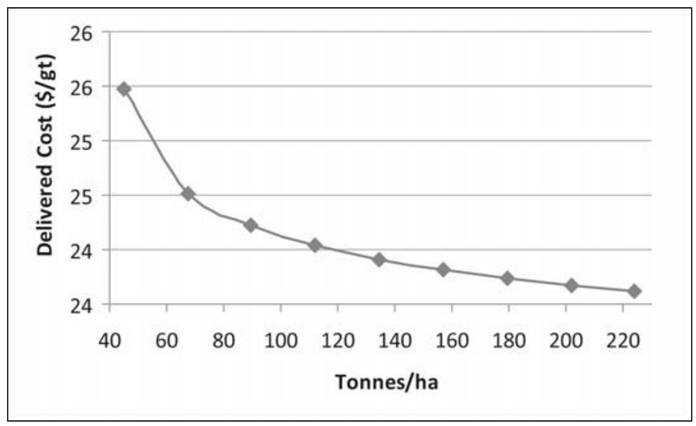


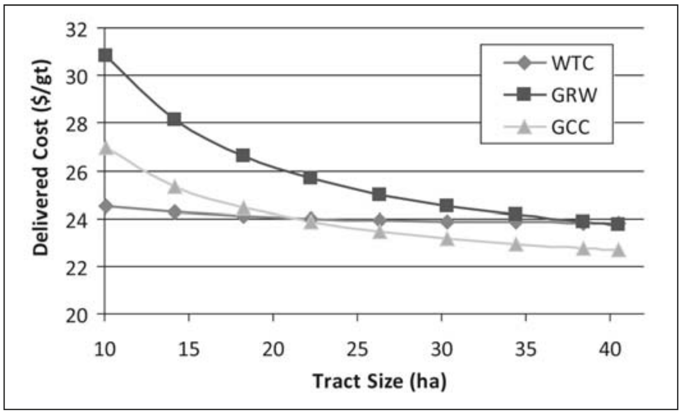

**Figure 3.** Delivered material cost estimates for increasing tonne/ha removals for whole tree chipping systems.




The tract size of harvests also plays an important role in the cost of delivered material for each system type. As tract size increased from 10 to 40 ha the delivered price falls by an average of $7.10/gt for GRW systems, $4.30/gt for GCC systems, and $0.70/gt for WTC systems (Figure 4). Grinder systems were more sensitive to changes in tract size because the per hectare amount of material they were processing is much lower than that for WTC systems. Therefore small tracts mean that the total amount of material harvested by grinder systems is small when compared to a WTC system. When total tract removals are small it increases costs associated with moving between tracts which can significantly decrease the logger's profit.

Costs associated with grinding systems are partially driven by the number of piles of residue that are present at the harvest site. A residue pile is generally present at each landing of the harvest site. The cost model calculated the number

**Figure 4.** Delivered material cost for increasing tract sizes (hectares) for three biomass harvesting systems: whole-tree chipping (WTC), grinders processing roundwood harvest residue (GRW) and grinders processing clean chipping residue (GCC).




of piles by dividing total tract acreage by the number of hectares per landing. As the number of piles increased from 1 to 10 the delivered material cost rose by $2.20/gt for GRW systems and $1.30/gt for GCC systems (Figure 5). Costs increased as the number of piles grew because it took time and money to move from pile to pile across the tract. Costs associated with trucking also played a significant part in the delivered cost of material. A range of load weights from 16 to 33 gt was tested to determine the effects of truck payload on delivered cost (Figure 6). When trucks hauled just 16 gt (legally underloaded in most states) the delivered cost was $29.80/gt for WTC systems, $27.60/gt for GRW systems, and $26.60/gt for GCC systems. If a truck hauled 33 gt the delivered costs fell by $9.20/gt for WTC systems and $6.00/gt for grinder systems. This means that a 10% increase in payload over the base case value of 24 gt reduces delivered costs by approximately 2% for grinder systems and 3% for WTC systems.

**Figure 5.** Delivered material cost for increasing number of piles at the harvest site for three biomass harvesting systems: whole-tree chipping (WTC), grinders processing roundwood harvest residue (GRW) and grinders processing clean chipping residue (GCC).

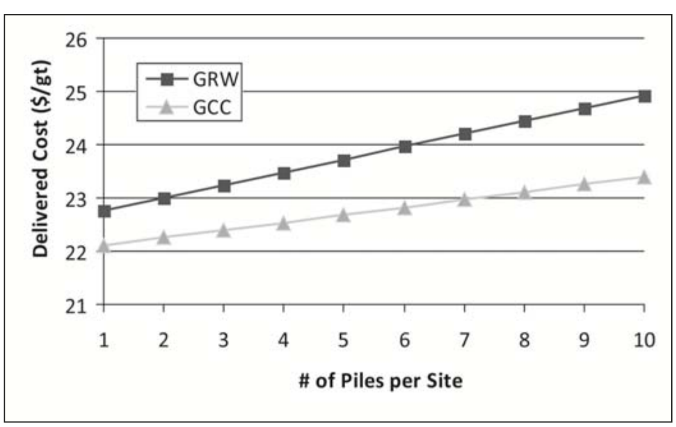
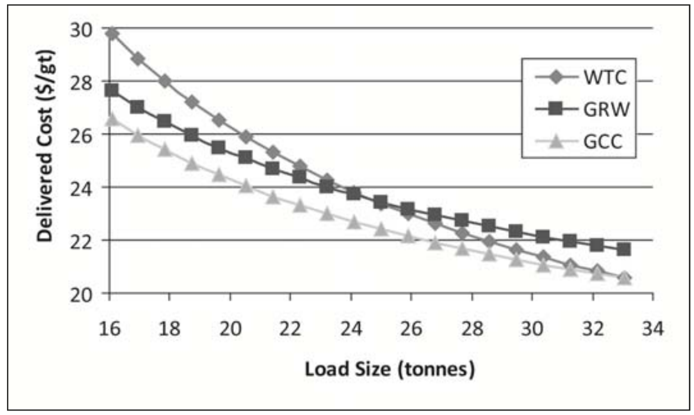



**Figure 6.** Delivered material cost for increasing truck load weights (tonnes) for three biomass harvesting systems: whole-tree chipping (WTC), grinders processing roundwood harvest residue (GRW) and grinders processing clean chipping residue (GCC).




Increases in haul distance also increased the delivered cost of material for each system type. As haul distance increased from a base case 80 km, the delivered cost of material rose by $1.80/gt for each additional 10 km for WTC systems and by $1.70/gt for both grinder systems. The time spent unloading a truck at the mill also affected the delivered cost of material. This time typically ranges from 20 to 60 minutes or more and directly affects the number of loads that a contractor can deliver in a given day. Sensitivity analysis showed that for each additional ten minutes spent unloading at the mill, the delivered cost increased by $0.48/gt for WTC systems and $0.42/gt for grinder systems.

**Chip Sample Analysis**

The number of chip samples varied by system type because samples were unable to be collected at some harvest sites and improper lab analyses forced us to discard some samples. Ash content (% dry weight) of the three systems each differed significantly ($p < 0.05$). GCC systems had the highest average percent ash content with 5.2%, followed by GRW systems at 2.2% and WTC systems at 0.58% (Table 4). Feedstocks from grinder systems likely have higher percentages of ash due to how the residue material is handled before grinding. Both roundwood and clean chip residues are often piled by knuckleboom loaders and/or grapple skidders. Clean chipping residue has to be pushed into piles as it lacks the piece lengths of roundwood residues which can be more readily handled by grapples. Most operators use skidders equipped with solid blades to push materials which increases the likelihood of soil contamination. Whole tree chipping systems have no need to pile the material since trees are skidded to the landing then fed directly into the chipper by a knuckleboom loader. This reduces the number of times the material is handled which likely explains the lower observed ash content.

Higher heating values (MJ/kg) were obtained for each sample submitted to the lab (Table 4). The two grinder feedstocks had average values of 20.2 MJ/kg for GRW systems and 19.6 MJ/kg for GCC systems. Whole tree chipping systems had an average value of 19.2 MJ/kg, significantly less than GRW systems ($p < 0.05$). These values are within the reported range for other forms of woody biomass (McKendry 2002).

## Discussion and Conclusions

The work sampling data that were collected showed that of the three systems studied, WTC operations had the highest utilization of the chipping machine at 44%. This is substantially lower than rates reported by Spinelli and Visser (2009) from numerous operational studies of whole-tree chipping operations in Europe, but is very similar to the findings of Mitchell and Gallagher (2007) from a short-term study of whole-tree chipping in the southern United States. While the elimination of trucking-related delays could greatly increase production for the chipper, felling capacity is fully utilized in the system configurations studied here. Given the tree sizes targeted for whole-tree chipping, greater felling capacity will likely be needed to increase production substantially. While trucking related delays are high, they are similar to those reported by Spinelli and Visser (2009) as outliers in a larger dataset of chipping related studies in Europe.

The grinder systems had a slightly lower utilization of the grinding machine with only 38%. Trucking related delays were the primary cause of low utilization of the chippers and grinders with a rate of 49% for the GRW and GCC systems and 31% for WTC systems. While WTC systems had fewer trucking related delays, the chipping machine suffered more mechanical problems than grinders from the GRW or GCC systems. If trucking related delays could be substantially reduced the utilization rates for the chipper/grinder could be 75% for WTC systems and 87% for grinder systems, which could potentially lead to a large increase in the crews' overall production. In order to achieve these production rates, however, nine haul trucks would be needed for each system, and WTC systems would require an additional feller-buncher and skidder.

Knuckleboom and front-end loader production is directly tied with the production of the chipper/grinder because loaders cannot feed a machine that is not running. Grinding systems in particular appear to require the use of a wheeled front-end loader due to the size of material piles that are processed. The front-end loader was capable of quickly moving material within reach of the knuckleboom loader. While mobile models of both grinders and knuckleboom loaders are available, they are not commonplace in the southern United States.

Based on our analysis, WTC had a delivered material cost of $23.80/gt or $2.00/GJ. These costs are significantly higher than previously reported by Mitchell and Gallagher (2007) for WTC systems in the southern US. While estimated hourly machine rate costs are similar between the two studies, the difference arises from our use of observed utilization rates to calculate costs rather than a theoretical maximum production rate as used by Mitchell and Gallagher (2007). Grinder systems had delivered costs of $23.70/gt for GRW systems and $22.70/gt for GCC systems. On a GJ basis, GRW and GCC systems had delivered costs of $2.00 and $1.90 respectively. Whole tree chipping systems are charged with the costs of additional equipment and crew to fell and skid trees to the landing. By nature WTC systems handle more tonnes/ha (which reduces costs) than grinder systems, which process residual material that is left after the primary harvest is completed. Therefore, the costs associated with felling and skidding equipment are not charged to grinder systems, but low tonne/ha amounts increase their costs. These differences in equipment and tonne/ha removals explain why all three systems have similar delivered material costs. Trucking related variables had the most significant impact on the delivered price per green tonne of material.

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