OPTIONS FOR REDUCING MOISTURE AND ASH CONTENT

IN FOREST BIOMASS HARVESTING SYSTEMS

by

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(Under the Direction of W. Dale Greene)

ABSTRACT

Renewable energy sources are increasingly important as part of a 21st century energy solution. Wood energy facilities prefer clean, dry raw material to maximize energy content and minimize ash remaining after combustion. This dissertation assessed properties and production costs of chipping and grinding systems processing whole trees and residues from roundwood and clean chipping operations. Moisture content was reduced from 53% for freshly felled trees to 43% and 39% for trees allowed to dry transpirationally for 4 and 8 weeks, respectively prior to a whole-tree chipping operation. Drying did not significantly change the ash content (<0.7%) associated with this feedstock. Truck payloads were 16% and 24% lower for material dried 4 and 8 weeks compared to green material, thus increasing hauling costs by $0.80 per ton (field condition) for each subsequent 4-week drying period. Transpirational drying increased the energy content of delivered chips by approximately 1,200 BTU/lb. While drying stems up to eight weeks increased on-board costs $0.68 on a field ton basis, it reduced those costs by $7.83 on a bone dry ton basis and by $0.47 on a million BTU basis. Data on production and the properties of chip and wood residue products were used to estimate costs per million BTU for forest biomass harvesting systems including conventional roundwood, clean chipping, whole-tree chipping, and screened and unscreened grinders processing logging and clean chip residue. Delivered costs for these systems were evaluated for a range of values for moisture content, ash content, tract size, tons of biomass removed per acre and at grinding decks, truck payload, haul distance, and diesel fuel price. Delivered cost per mmBTU decreased by over 50% for all systems as moisture content decreased from 55% to 30%. Whole tree chipping provided the lowest cost option ($4.39 per mmBTU) at ash content levels less than 1%, and unscreened grinding of clean chip residue produced the least expensive option at 5% ash ($2.87 per mmBTU). Tract size had minimal effects on any operation until the acreage declined below 40 acres. Clean chipping and roundwood systems were considerably more expensive than whole-tree chipping operations on all tract sizes. Costs declined significantly as truck payload increased and/or haul distance decreased. Optimizing truck payload to attain legal weight limits by lowering tare weight and/or increasing trailer volume capacity is an opportunity for forest biomass harvesting system managers to achieve lower costs especially when dealing with drier material or low-density screened roundwood grindings. Fuel price increases directly increase cut and haul costs and limit economical haul distances accordingly.

Index Words: forest biomass harvesting, chipping, grinding, moisture content, ash content

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Higher market prices for fossil fuels as well as proposed policy changes to support renewable energy use and to reduce carbon emissions have recently led to a large number of bioenergy projects being announced which will consume woody biomass. Projects recently announced for North America will substantially increase wood energy capacity and may consume more than 60 million green tons of woody biomass feedstock (RISI 2011). Woody biomass from forest residues has long been underutilized due to limited access and high costs associated with collection and transportation (Evans 2008). A survey of top state forestry officials identified the highly capital intensive nature of harvesting and transportation of woody biomass from forests as the top constraint to expanding this new industry (Aguilar and Garrett 2009).

Harvesting systems utilizing whole-tree chippers and grinders are used to convert woody biomass into a suitable feedstock for wood energy facilities. A system harvesting roundwood products typically piles logging residue (slash) for later collection by a biomass harvesting system using a grinder or chipper. This dissertation compares a range of likely forest biomass harvesting systems, including whole-tree chipping, clean chipping, conventional roundwood, and residue grinding to determine how each system may affect woody biomass energy facilities, biomass harvesting firms, and forest landowners.

1.2 Wood Energy Facilities

The forest products industry today purchases most raw materials on a green ton basis for convenience and to encourage the delivery of freshly cut wood. Wood energy facilities are likely to prefer drier raw material to maximize energy content. They also often prefer feedstock with a minimum of dirt or grit so that the ash remaining after combustion is reduced. Moisture content and ash content are especially important issues where logging residues such as limbs, tops, and understory stems are collected because moisture and ash affect energy value. Wood energy facilities are also concerned with the elemental or nutrient content of woody biomass feedstocks due to its effect on emissions affecting air quality (Obernberger et al. 1997).

When woody biomass feedstocks will be combusted to provide energy it is advantageous to have low moisture content to increase their energy value (BTU). The heating value of any fuel is the energy released per unit mass or per unit volume of the fuel when the fuel is completely burned (ANSI/ASABE S593.1 2011). Woody biomass has one of the highest energy contents of all biomass sources with over 25 million BTUs per oven-dry ton (Boundy et al. 2011). The moisture content of solid biomass influences the net calorific value and the combustion efficiency (Kristensen and Kofman 2000). Woody biomass products with particle sizes too small or too large negatively influence handling, combustion characteristics, and emissions. (Paulrud and Nilsson 2004).

A higher energy value results in greater burning efficiency. Wood energy markets (biorefineries, pellet manufacturers, wood-fired electric plants, and wood to liquid fuel processes) are often interested in procuring raw material that has lower moisture content than green wood to obtain a higher energy value. The transportation of bioenergy feedstocks has been found to be inherently more costly than fossil fuels because per unit energy density of fossil fuels is two to three times that of biomass (Young 1980). Each 10% reduction in moisture content can increase the net energy content of the wood by approximately 850 BTU (Ince 1979). Freshly felled trees have a moisture content of approximately 50% (wet basis) – this varies somewhat by species and region – but if allowed to dry for at least four weeks before delimbing and processing, moisture content can be reduced to as little as 30-35% (Stokes et al. 1993). This delayed delimbing and bucking is known by several names but we will refer to it as transpirational drying. Loblolly pine (*Pinus taeda*) stems dry at a greater rate with limbs intact than as delimbed stems, they dry more during summer months, and most moisture reduction occurs during the first 30 days of drying (Klepac et al. 2008).

While reducing moisture content is important, keeping ash content low in combustible woody fuels is also vital. Ash is formed from mineral matter during combustion and can cause slagging, which is the coating of internal surfaces in boilers from deposition of ash particles. Ash is a crucial aspect of the concept of sustainable, carbon neutral thermal biomass utilization and may be recycled where appropriate in forests and on agricultural land or put in a landfill (Narodoslawsky and Obernberger 1996).

Woody biomass with higher ash content is considered of poorer quality because it results in poorer combustion performance and increases maintenance and disposal costs caused by glass or slag deposits formed within some burning mechanisms (Sarenbo 2009). The biomass harvesting system employed, the type of woody biomass material, and the manner and duration of how woody biomass is stored and/or piled on-site can all affect moisture and ash content (Obernberger et al. 1997, Pettersson and Nordfjell 2007). Öhman et al. (2004)

observed ash content for different types of woody biomass used to make pellets and found that while ash deposits were affected both by burner and feedstock types, stem wood based material produced less ash than bark and logging residues. The wood pelletizing process is less forgiving of ash, as is the burning of woody biomass in stoker grate boilers where slag deposits are prone to form. More technologically advanced circulating fluidized bed boilers tolerate a greater amount of ash than stoker grate boilers (van den Broek et al. 1996).

Wu et al. (2011) measured moisture content from three different sizes of chips oven drying them for 24 hours at 105 degrees C and determined size distribution by screening chips in a horizontal classifier. The smallest and largest size chips (0-20mm and 40-100mm, respectively) had moisture contents higher than what is considered acceptable chips (20-40mm).

Spinelli et al. (2011) determined particle-size distribution, fiber and bark content, and heating value of a wide sample of wood chips collected from 60 operating commercial biomass terminals in northern Italy. High quality (clean, dry) and low cost biomass feedstock from sawmill residues were the preferred feedstock for bioenergy facilities. This study found that logging residues such as tops and branches could be obtained at a low cost, but did not match the same quality specifications. Small conifer and broadleaf trees from thinning operations and broadleaf trees from traditional coppice stands provide good product quality, but were costly to harvest.

Ragland et al. (1991) found that thermal property values such as specific heat, thermal conductivity, and emissivity vary with moisture content, temperature, and degree of thermal degradation by up to one order of magnitude. The carbon content of dry wood varies from about 47 to 53 percent due to varying lignin and extractives content. Mineral content of wood is less than 1%, but it can be over 10 times that value in bark. The composition of mineral matter can vary between and within each tree.

Lehtikangas (2001) tested nine pellet assortments, made of fresh and stored sawdust, bark and logging residues for moisture content, heating value and contents of ash, sulfur, chlorine, and Klason lignin. The heating value was highest in logging residue pellets. Ash content was highest in the bark and logging residue pellets, implying higher sintering risk compared with sawdust pellets. The results indicated that bark pellets had the highest durability, whereas sawdust pellets had the lowest. The study concluded that bark and logging residues are suitable raw materials for pellet production, especially if the ash content is controlled.

Filbakk et al. (2011) conducted a study on how bark content affected the quality of pellets. Pellets from pinewood containing zero, five, 10, 30 and 100 percent bark were produced and their quality parameters were evaluated. Pellets made from pure bark had the best mechanical properties compared with pellets made of wood containing various concentrations of bark.

Nurmia and Hillebrand (2007) studied fuel properties of small-sized whole-tree fuel stocks in roadside and in-stand storages. The significance of pile cover, season, and storage site on moisture content and heating value of Scots pine (*P. sylvestris*) and pubescent birch (*Betula pubescence*) fuel stocks were observed. When the fuel stocks were placed in a well-ventilated location moisture content could be lowered below the 40% mark during one summer period. Covered the piles had 6% lower moisture content than non-covered piles. Multi-tree harvested stemwood with no limbs seasoned equally well as the whole trees both in roadside and in-stand trials because the processing of multi-tree bunches caused some debarking to take place. As a result, the transpirational drying capability of whole trees was equalized by the evaporation of moisture via the open wood surface. Both assortments reached moisture contents below 30% in in-stand conditions during one summer's seasoning.

Suadicani and Gamborg (1999) found that when freshly felled trees were chipped, the loss of plant essential nutrients (calcium, magnesium, potassium and nitrogen) was significantly greater compared to the removal of nutrients when summer dried trees were chipped. The size distribution of the chips was significantly improved when the trees were left for summer drying. The moisture content dropped significantly from an average in the two trials of 57% of total weight to 42% of total weight after summer drying. The net caloric value per unit of weight increased significantly in the chips of summer dried wood. Net caloric value based on dry weight was slightly reduced during the drying period due to the loss of energy rich extractives. Summer drying ensures reduction in the loss of plant essential nutrients caused by the removal of biomass from the stand.

Roser et al. (2011 a) investigated methods to promote the natural drying of wood for bioenergy purposes. The effects on the drying process through covering the wood piles and partial debarking of stems were tested to identify methods to reduce the moisture content of the woody material in storage. Drying trials were established in Finland, Italy, and Scotland utilizing alder, beech, pine, and spruce. The study indicated that natural drying was a practical and effective method to enhance the energy efficiency of wood based fuel products in all the regions studied.

1.3 Harvesting Operations

A number of different biomass harvesting and transportation system configurations that can supply renewable energy facilities already exist, but each operates with a different incoming feedstock (residues, understory, standing trees, etc.), produces a product that differs in its characteristics (moisture content, particle size and uniformity, ash content, etc.), and differs in productivity and costs (Hartsough and Yomogida 1996). Few studies have examined methods that could improve woody biomass characteristics in the field to add value to the feedstock required by bioenergy facilities.

The timber harvesting and wood supply chain in the United States is globally competitive and well positioned to add woody biomass to the list of products it delivers. However, there are some significant issues to be addressed to support these new wood-using industries. Most traditional forest industries (paper and building products) purchase their raw material today on a green ton basis. Unlike some wood consuming mill in the Pacific Northwest that base payments on bone dry tons, most wood consuming mills in the US South exclusively use green tons. There are several advantages to this method, including automated weighing of trucks and the incentive a green ton basis provides to logging contractors to deliver fresh wood to markets. Fresh wood provides higher pulp and tall oil yields in most pulp processes as well as limiting checking and blue stain issues with sawtimber. Under existing green ton payment systems at biomass receiving facilities in the U.S. South, dried material results in lower truck payloads, thus higher trucking costs when evaluated on a green ton basis.

Different approaches for harvesting woody biomass for energy have been studied for decades. Koch (1980) described numerous methods for harvesting biomass, including chipping whole trees at the stump, extracting sawlogs at the landing and processing limbs and tops, chipping residues at a wood consuming mill, and transporting complete boles to a mill for merchandizing. Arola and Miyata (1981) reported on cost and productivity data for five different harvesting methods from conventional logging operations to a land clearing operation for site conversion.

A one-pass harvesting system harvests all products concurrently. Harvesting and recovering roundwood and woody biomass are performed in separate passes in a two-pass harvesting system. Watson et al. (1986 a) compared a conventional harvesting system with one and two pass biomass harvesting systems with the one-pass system having the best utilization and lowest costs.

Cubbage and Greene (1989) compared estimated costs for seven conventional logging systems for a variety of conventional and biomass harvests. Highly mechanized systems using feller-bunchers and grapple skidders were the least costly. Tract size did not greatly influence costs but the study design did not evaluate small harvest blocks.

Goulding and Twaddle (1990) studied approaches to improve conventional harvesting methods that lead to increased production of energy wood as a by-product of integrated systems. Economically successful systems were ones where the biomass component was kept attached to conventional products for as long as possible and increased biomass recovery was a consequence of improvements to one or more of the conventional harvesting tasks, i.e. delimbing and bucking.

Puttock (1995) examined two different approaches for estimating costs of producing conventional products and fuel wood with integrated harvesting systems. A marginal cost approach completely allocates the cost of common harvesting activities such as felling, forwarding and processing to conventional products, whereas a joint product approach distributes production costs among conventional products and fuel wood. Production costs are highly variable depending on the type of harvesting employed and the ratio of conventional products to fuel wood.

Roser et al. (2011 b) estimated the feasibility and cost level of selected supply chains for chips. While results showed that supply chains have to be tailored to local conditions, distance from receiving facilities, and product quality, overall, chipping at the landing seems was the best option. Angus-Hankin et al. (1995) studied various forms of fuel wood transportation systems, comparing their costs and payloads. The inherent low bulk density of woody biomass was a substantial drawback to reaching the maximum legal weight before exceeding legal truck and/or trailer dimensions. Moreover, a desire to minimize moisture content to increase product quality of the material prior to transport placed further constraints on achieving optimal truck payloads.

A GIS-based model for energy wood supply chains simulated costs for several supply chains in a study area in eastern Finland and found that more simple supply chains such as transporting loose residues by truck and chipping at the plant offered the lowest total costs at haul distances less than 60 kilometers. The amount of packing density and the ability to use full load capacity were more important for haul distances over 60 kilometers (Tahvanainen and Anttila 2011).

Yoshioka et al. (2006) developed and monitored a harvesting and transporting system for logging residues to determine the feasibility of the system based on cost, energy, and CO2.

Their results suggested that a chipper should be incorporated into the system as early as possible and that high capacity trailers and highly-maintained forest roads were effective measures to reduce the total cost.

Patterson et al. (2011) examined five forest biomass collection systems. Two of the systems utilized a chipper, one with thinning material and one with thinning residues. The other three systems utilized horizontal grinders to process roundwood logging residues. The chipping systems produced material with a higher energy content (8,168 vs. 7,785 BTU/lb) and lower ash content (1.2% vs. 4.5%) than the material produced by grinding systems processing roundwood residues.

1.4 Forest Landowners

Ninety percent of responding family and institutional forest landowners and public forestland managers in the U.S. South reported a willingness to sell to energy facilities if desirable prices were offered and all owners who previously sold timber to an energy facility were satisfied with the experience. Only 3.5% of respondents were unwilling to sell timber to an energy company, with only one of these respondents listing timber production as a primary objective (Conrad et al. 2011).

An Alabama survey indicated that most family forest landowners were willing to supply both timber and harvest residues for energy production with their willingness positively correlated with owned acreage, valuable markets, and the opportunity to contribute to local economic development and global climate change. Three-quarters of the Alabama respondents indicated willingness to manage their land for biomass production, compared with 43% of respondents who actively managed their land (Paula et al. 2011).

A study to assess factors affecting Arkansas, Florida, and Virginia nonindustrial private forest landowners' willingness to supply woody biomass for bioenergy showed that the majority of the landowners in the study area regarded energy security as critical for both national security and a healthy economy. A significant number of landowners were either uncertain or not familiar with the idea of producing alternative energy from cellulosic biomass. Older forest landowners were skeptical about wood-based energy, but the study's "willingness to supply" model indicated that younger landowners with large timber holdings were more likely to supply woody biomass. Landowners with wildlife management objectives were likely to supply woody biomass (Joshi and Mehmood 2011).

Forest landowners in Sweden reported that the price paid for forest biomass did not determine whether or not they would sell their forest biomass material. Potential losses in soil productivity negatively influenced their decision to sell the material and Swedish forest landowners who do sell reported that clearing the forest floor from residues was the primary reason (Bohlin and Roos 2002).

Recovering biomass presents forest landowners with an opportunity to utilize this material instead of piling and/or burning it prior to replanting. Furthermore, this practice tends to increase the plantable area and studies have shown that recovering harvesting residues and unmerchantable stems may reduce site preparation cost (Miller et al. 1987, Watson et al. 1986 (b), Ragan et al. 1987, Watson and Stokes 1989, and Westbrook 2008). Watson and Stokes (1989) reported a 25% reduction in site preparation cost due to the removal of residues and unmerchantable stems. Westbrook (2008) found up to 38% reduction in site preparation costs when understory material was removed from the site during harvesting.

Some concerns for forest landowners regarding energy wood harvesting were the removal of excessive amounts of logging residue because of perceived negative effects to wildlife habitat, nutrient cycling, and water quality. A study conducted in Maine by Briedis et al. (2011) found that an average of 45% of the logging residue was left on sites harvested for traditional forest products and energy wood and between 16 and 50% was left on skid trails.

Shorter rotations and an increase in utilization could lower site nutrient availability. Management of site nutrients via fertilization increases in importance as the proportion of nutrients removed increases unless nutrients are not a limiting factor on particular sites. The potential loss of nutrients from a site largely depends upon the distribution of biomass component such as stems, bark, branches, and foliage. The increase in loss of nutrients in harvested materials accompanying a change in utilization standards depends upon the distribution of biomass between the various components of the forest: stemwood, stembark, the stump (unharvested portion of the bole), branches of various dimensions, roots of various dimensions, and foliage (Kimmins 1977).

Some southern U.S. pine forests that are relatively unproductive prior to harvesting may be at risk of further productivity losses due to intensive harvesting treatments with slash removal and fertilization is often required to improve site productivity (Scott and Dean 2006).

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CHAPTER 2

TRANSPIRATIONAL DRYING EFFECTS ON ENERGY AND ASH CONTENT FROM WHOLE-TREE SOUTHERN PINE PLANTATION CHIPPING OPERATIONS[1]

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TRANSPIRATIONAL DRYING EFFECTS ON ENERGY AND ASH CONTENT FROM WHOLE-TREE SOUTHERN PINE PLANTATION CHIPPING OPERATIONS

2.1 ABSTRACT

Wood energy facilities prefer clean, dry raw material to maximize energy content and minimize the ash remaining after combustion. We allowed felled loblolly pine trees to transpirationally dry in-field for 4 and 8 weeks during late summer in central Georgia. We then compared costs of whole-tree chipping and transportation as well as the energy, ash, bark, and nutrient contents of the chips produced. Moisture content was reduced from 53% for freshly felled trees to 43% and 39% for trees allowed to dry for 4 and 8 weeks, respectively. Transpirational drying did not significantly change the ash content (<0.7%). Truck payloads were 16% and 24% lower for material dried 4 and 8 weeks compared to green material, thus increasing hauling costs by $0.80 per ton (field condition) for each subsequent 4-week drying period. Drying increased the energy content of delivered chips by approximately 1,200 BTU/lb. While drying stems up to eight weeks increased on-board costs $0.68 on a field ton basis, it reduced those costs by $7.83 on a bone dry ton basis and by $0.47 on a million BTU basis. Transpirational drying for 4 weeks or more appears to be a promising method for increasing the energy content without increasing the ash content of woody feedstocks.

Keywords: biomass, harvesting, cost, transpirational drying, energy content

2.2 INTRODUCTION

Higher market prices for fossil fuels, as well as proposed policy changes to support renewable energy use and reduce carbon emissions, have recently led to a large number of bioenergy projects that will consume woody biomass. Projects recently announced for North America will substantially increase wood energy capacity and will potentially consume more than 60 million green tons of wood biomass feedstock (RISI 2011). A survey of top state forestry officials identified the highly capital intensive nature of harvesting and transportation of woody biomass from forests as the top constraint to expanding this new industry (Aguilar and Garrett 2009).

Harvesting systems that could supply renewable energy facilities already exist, but each operates with a different incoming feedstock (residues, understory, standing trees, etc.) and produces a product that differs in its characteristics (moisture content, particle size and uniformity, ash content, etc.). Few studies have examined methods that could improve woody biomass characteristics in the field to add value to the feedstock required by bioenergy facilities (Stokes et al. 1993, Pettersson and Nordfjell 2007, Klepac et al. 2008, Patterson et al. 2010, Patterson et al. 2011).

The timber harvesting and wood supply chain in the United States is globally competitive and well positioned to add woody biomass to the list of products it delivers. However, there are some significant issues to be addressed to support these new wood-using industries. Most traditional forest industries (paper and building products) purchase their raw material today on a green ton basis. Unlike some wood-consuming mills in the Pacific

Northwest that base payments on bone dry tons, most wood-consuming mills in the US South exclusively use green tons.

There are several advantages to this method, including automated weighing of trucks and the incentive a green ton basis provides to logging contractors to deliver fresh wood to markets. Fresh wood provides higher pulp and tall oil yields in most pulp processes as well as limiting checking and blue stain issues with sawtimber. Under existing green ton payment systems at biomass receiving facilities in the U.S. South, dried material results in lower truck payloads, thus higher trucking costs.

Where woody biomass feedstocks will be combusted to provide energy it is generally advantageous to have low moisture content to increase their potential energy value (BTU). A higher energy value more often than not results in greater burning efficiency. Wood energy markets (biorefineries, pellet manufacturers, wood-fired electric plants, and wood to liquid fuel processes) are often interested in procuring raw material that has lower moisture content than green wood in order to obtain a higher energy value or to reduce drying costs during manufacture. The transportation of bioenergy feedstocks is inherently more costly than fossil fuels because per unit energy density of fossil fuels is two to three times that of biomass (Young 1980). Each 10% reduction in moisture content can increase the energy content of the wood by approximately 850 BTU (Ince 1979). Freshly felled trees have a moisture content of approximately 50% (wet basis) – this varies somewhat by species and region – but if allowed to dry for at least four weeks before delimbing and processing, moisture content can be reduced to as little as 30-35% (Stokes et al. 1993). This delayed delimbing and bucking is known by several names but we will refer to it as transpirational drying. Loblolly pine (*Pinus taeda L.*)

stems dry at a greater rate with limbs intact than as delimbed stems, they dry more during summer months, and most moisture reduction occurs during the first 30 days drying (Klepac et al. 2008).

Wider use of transpirational drying could have several significant benefits for wood energy markets. For example, it lowers moisture content without consuming any wood or fossil energy. It also eliminates the need to transport the water contained in green material, thus increasing the net energy content of each truck payload. This could lead to fewer truck trips needed to move the same energy content to markets, thus saving fuel and further improving net energy ratios. On the other hand, drier material will weigh less and unless trucking equipment is modified to compensate this can lead to truck payloads that are less than the legally allowed maximum. In addition, logging contractors commonly report a much shorter operating life for chipper knives between sharpening when processing dried material, which increases maintenance costs and reduces knife life. This can also reduce chipper productivity due to reduced mechanical availability. Finally, chipping drier material could negatively impact fuel consumption per green ton if the chipper increases the amount of work to produce the same volume.

While reducing moisture content is important, keeping ash content low in combustible woody fuels is also vital. Woody biomass with higher ash content is considered to have poorer quality because it results in poorer combustion performance, and increases maintenance and disposal costs caused by glass or slag (heavy) deposits formed within some burning mechanisms (Sarenbo 2009). The biomass harvesting system employed, the type of woody biomass material, and the manner and duration of how woody biomass is stored and/or piled on-site are all factors that can affect moisture and ash content (Obernberger et al. 1997, Pettersson and Nordfjell 2007). Öhman et al. (2004) observed ash content for different types of woody biomass used to make pellets and found that while ash deposits were affected both by burner and feedstock types, stem wood based material produced less ash than bark and logging residues. The wood pelletizing process is less forgiving of ash, as is the burning of woody biomass in stoker grate boilers where slag deposits are prone to form. More technologically advanced circulating fluidized bed boilers tolerate a greater amount of ash than stoker grate boilers (van den Broek et al. 1996).

This study assessed if increased drying times for loblolly pine were correlated with reduced moisture content while not increasing ash content, in addition to the effect of in-field drying on chip properties such as particle size, bark content, and nutrient content. The study also assessed how transpirational drying of trees up to 8 weeks impacts harvesting production and costs per ton and per unit of energy content.

2.3 METHODS

The study was conducted from August through October 2010 on a 113-acre, 14 year-old loblolly pine stand in Jones County, Georgia that was scheduled for a first commercial thinning using a row plus selection method. The harvesting system consisted of a Tigercat 718 rubber-tired feller-buncher, a Caterpillar 525 grapple skidder, a Tigercat 230B knuckleboom loader, and a 600-horsepower Morbark 40/36 drum-style chipper. The stand was divided into three roughly 37 acre harvest units that were randomly assigned to one of three harvest treatments. Trees from rows (or corridors) on two 37-acre units were felled and bunched in the harvested row and allowed to transpirationally dry for four and eight weeks, respectively, prior to chipping. After drying, trees were skidded to the landing by the grapple skidder and chipped during a commercial first thinning of the entire stand. The feller-buncher thinned a third unit (approximately 37 acres) of green material concurrently with the chipping operation to provide a comparison of freshly felled trees to the transpirationally dried material. The whole-tree chips produced from the study were delivered to a local pulp mill for use as boiler fuel.

We obtained climate data, including daily temperature, precipitation, and relative humidity, from the National Weather Service (www.nws.gov) for Macon, GA for each day during the drying periods. The study site was approximately 15 miles from Macon. We also located a rain gauge on the study site to monitor weekly rainfall during the drying periods. Weather radar was monitored to identify rain events on our site that might not be measured at the Macon station.

To track changes in moisture content during the two drying periods, we removed six 1-inch thick disks from the middle of felled trees in each treatment unit on a weekly to semiweekly basis. Moisture content samples collected from the middle of a tree best represent whole-tree moisture content (Antony et al. 2012). Different trees were sampled on each visit. The disks were weighed immediately in the field, then transferred to a 105ºC oven for a minimum of 24 hours, and reweighed to determine the field moisture content. We use the term “field” to reference the moisture content of any material at the time of chipping and use “green” wood to refer to freshly felled wood with the highest moisture content observed in the field which served as our control.

To quantify production impacts, we used work sampling and time study methods similar to those reported by Baker et al. (2010) to record data on the harvesting system. Continuous activity data were recorded separately for each drying treatment. Machine activity codes were recorded for the chipper on-site every two minutes for the duration of the field study to establish mechanical availability, utilization, and sources of delay. These machine activity codes included chipping, which represented productive time, and various delays such as mechanical delays, waiting on trucks, waiting on the knuckleboom loader, waiting on trees, waiting with chipper turned off, and miscellaneous delays. We used a stopwatch to record the time to load each truck in the field and obtained load weights from weight scale tickets as each load was delivered. The chipping contractor used chip trailers of various lengths. We measured trailer dimensions and calculated net pounds per cubic foot instead of total net tons (gross vehicle weight minus truck and trailer tare weight) to compare truck load weights. We measured the chipper's daily fuel consumption with a fuel meter attached to the contractor's fuel pump.

We collected and prepared all chip samples for laboratory analysis following the Technical Association of the Pulp and Paper Industry (TAPPI) standard for sampling and preparing wood for analysis (TAPPI 1985). During the loading of each truck, we used a 6-inch diameter PVC pipe with an elbow to collect samples from the chip stream. Samples were collected several times during the loading of a van and mixed to obtain a composite sample. From this composite sample we collected one 4-5 lb grab sample of chips which was placed in a kraft paper bag. The bag was immediately weighed to determine the field (or wet) weight of chips. The bags were later transferred to a 105ºC oven for a minimum of 24 hours and reweighed to determine the field moisture content.

Five dried bags were randomly selected from each harvesting treatment for further analysis. These bags were fractioned, with roughly one-eighth of the sample processed through a 1 mm screen Wiley mill and transferred to the University of Georgia Plant, Soil, and Water Lab for determination of energy, ash, and nutrient concentrations. The remaining contents of the bag were transferred to a William's chip size classifier following the TAPPI standard for chip classification (TAPPI 1999). The sample was oscillated in one dimension for ten minutes to separate the chips based on their length. Four classification screens with round holes were used to determine the size distribution: 45 mm, 15 mm, 7 mm, and 3 mm. Foliage was removed from the sample by hand and weighed separately. Bark was separated by hand and weighed separately from wood for chips collected on the 45 mm, 15 mm, and 7 mm trays.

We compared production data using analysis of variance with Tukey's range test used for means comparison (Oehlert 2000). Production data consisted of field pounds per cubic foot of trailer, loading time, chipper utilization, and tons per productive machine hour. Wood chip data were limited to five samples per treatment, necessitating use of Kruskal-Wallis exact test for comparison ($\alpha < 0.05$) (Hollander and Wolfe 1999). Work sampling data were analyzed using chi-square test to look for differences in the distribution of work amongst categories ($\alpha < 0.05$).

Hourly operating costs were calculated using the machine rate approach with 85% availability assumed for all machinery in each of the three drying periods (Miyata 1980). Additional assumptions for all machines included: labor rate of $16.00/SMH, labor fringe expenses of 40% of the base rate of pay, combined interest, insurance, and taxes of 10% of average annual investment, lubrication costs 37% of fuel expense, and off-road diesel costs of $3.40 per gallon. Individual machine assumptions are listed in Table 2.1. We modified a version of the Auburn Harvesting Analyzer (Tufts et al. 1985) to determine cut-and-load costs for each of the three treatments. Adjustments were made to the program to allow for differences in lab-derived moisture content, ash content, and BTU (oven dry, o.d.) among treatments. We considered a “field ton” to be a ton of wood with the observed moisture content for a specific treatment (green, 4-week, or 8-week). A bone dry ton (BDT) is a ton of wood with zero moisture content. We also evaluated costs on an energy content (million BTU) basis.

We compared haul costs per field ton-mile and per field ton for delivering chips to a facility 50 miles away in trailers 42 feet long. Cost per ton-mile is the unit of freight transportation equivalent to a ton of freight moved one mile. Recent analysis of the long-haul trucking industry found average cost per mile of $1.49 (Fender and Pierce 2011). We assumed this base cost and added an additional 15 percent for costs associated with low speed and off-road travel.

2.4 RESULTS AND DISCUSSION

Daily temperature averaged 76°F during the 8-week drying period. The average high temperature was 89°F and the average low temperature was 63°F. The highest reported temperature during the 8-week drying period was 98°F and the lowest was 41°F. During the first 30 days of the 8-week drying period, the average high and low temperatures were 93°F and 68°F, respectively. The average daily temperature was 71°F during the 4-week drying period (second 30 days of the 8-week period) with average high and low temperatures of 85°F and 56°F, respectively. The highest reported temperature during the 4-week drying period was 97°F and the lowest was 40°F.

Daily relative humidity averaged 66% during the 8-week drying period, with a high of 98% and low of 41%. Relative humidity averaged 67% during the 4-week drying period with a high of 97% and low of 36%.

Rainfall measured by the National Weather Service and verified by the on-site rain gauge was 7.1 inches for the 8-week drying period and 5.2 inches for the 4-week drying period (Table 2.2). We observed approximately three inches of rainfall during the first 37 days of the 8-week drying period. Over three inches of rain fell on day 38 of the 8-week drying period which was day 10 of the 4-week drying period. Another inch of rain fell over the next three days which was two weeks prior to the start of the chipping operation.

The tree-disk samples collected to monitor moisture content while felled trees were drying showed a high rate of moisture loss during the first 30 days (Table 2.2). This result agrees with previous findings for transpirational drying in loblolly pine (Stokes et al. 1993, Klepac et al. 2008). A number of factors could have contributed to the increase (from 31% to 41%) in moisture content for the eight-week disk samples during the last three weeks of the study. One disk sample collected on October 11 had a moisture content of 56%, higher than any other disk sample taken for all treatments. This could have resulted from human error. Removing this outlier from the data lowered moisture content from 41% to 38%, which more closely aligned with chips that dried 8 weeks (39%). The position of a thinned row in relation to sunlight availability, position of sampled stems within the felled piles, daily temperature, and recent rainfall may have influenced moisture content. Lower average daily temperatures of approximately 10°F combined with over four inches of rainfall during the final three weeks of the drying period may have caused an increase in moisture content. Stems dried four weeks maintained a steady reduction in moisture content, unlike the 8-week-old disk samples which showed consistently lower moisture content through the first six weeks before increasing over the final two weeks. Inferences associated with these different patterns cannot clearly be explained because we collected a relatively small number of disks (n=6) at each sampling interval.

Moisture content of the chips varied significantly based on the length of time that transpirational drying took place (Figure 2.1). Each subsequent four-week drying period significantly decreased the moisture content of chips produced ($p < 0.05$), with the largest reduction from 53 percent to 43 percent occurring during the first four-week period. During the second four-week period, the moisture content fell another four percent to 39 percent which was still found to be a statistically significant reduction. Chip sample results differed slightly from the disk samples (Table 2.2). However, as the chip samples represent larger, aggregate samples of multiple trees taken throughout the chipping process, we consider them a better representation of the true average moisture content.

Drying time of the material had a significant impact on the productivity of the chipper as measured by field tons produced per productive hour (Table 2.3). Chipper productivity measured in terms of field tons was significantly lower with feedstock dried eight weeks than with either four-week-old or green material ($p < 0.05$). After converting the material produced to a dry ton basis the productivity from the green treatment is significantly lower (34 dry tons/PMH) than from either of the dried treatments (38 dry tons/PMH). This result should be viewed with caution, because a different loader operator fed the chipper for two of the five days during the green treatment chipping period. The less experienced replacement loader operator averaged 5 dry tons/PMH lower production than the normal operator ($p < 0.05$). Average loading time was 20 minutes for the eight and four week material but was 22 minutes for the green material.

Utilization data showed that the chipper spent a significantly higher percentage of its time chipping when in the oldest and driest treatment (eight weeks) compared to either the four-week old or green material ($p < 0.05$). Most of the difference came from mechanical delays in the green and four-weeks-old treatment and handling by a less-experienced replacement operator during some of the green treatment. The mechanical delays were not attributed to the type of material being processed. Given the short timeframe of this study, it is uncertain that this result would be repeated over a longer time period.

The field weight of chips in pounds per cubic foot (lbs/cu.ft.) of trailer decreased significantly, from 15.56 field lbs/cu.ft. to 14.50 field lbs/cu.ft. (Table 3), as drying time was extended from 4 to 8 weeks ($p < 0.05$). For example, the weight of a 40 foot trailer with a capacity of 2720 cubic feet would weigh 25.0 tons when loaded with green chips and 19.7 tons with material allowed to dry for 8 weeks. When examining the weight of materials in the trailer on a dry-ton basis, there was no significant difference in the dry pounds per cubic foot among treatments (8.56, 8.85, and 8.80 lbs/cu.ft.). Thus the volume of material in the trailer did not differ across the treatments, although the weight was lowered due to the reduced moisture content.

Insufficient fuel measurements were available to allow for a statistical test of fuel consumption between the treatments. Observed fuel consumption based on field tons produced varied little (0.37 gallons per field ton for green material, 0.34 for 4-week-old material, and 0.36 for 8-week-old material). When based on oven dry tons, fuel consumption was 0.80 gallons per oven dry ton for green material and 0.60 for both 4 and 8-week old material. These consumption differences between the field ton and oven dry ton bases are explained by the differing moisture contents of each treatment. Furthermore, we observed that, unlike the regular loader operator, for some of the green treatment, the different operator did not turn off the chipper while waiting for extended periods of time.

We intended to monitor knife wear, but the duration of the study did not require a sufficient number of knife changes in any treatment to allow for statistical analysis. Knife changes were dictated by the crew foreman/chipper operator who changed knives at his discretion. Both the eight and four week treatments saw knife changes once during the duration of the study, after ten and fifteen loads respectively, while the knives were not changed during chipping of the green treatment (28 truck loads). Future studies could be strengthened to more adequately determine knife wear and its effects on chip quality by implementing more focused study designs for this particular chipping variable and covering longer operating periods (Nati et al. 2010).

There were no significant differences in chip size distribution among treatments (Table 2.4), but bark content for the 8-week drying period (9.0%) was significantly lower than that for the green and four week material (13.4% and 11.6%, respectively). This was likely due to the fact that bark tends to loosen and fall off as pine stems get drier. Bark has lower energy content than “white wood,” so these bark losses may actually improve energy content per oven dry pound. Foliage, ash content, and nutrient content did not vary by drying time.

BTU per field lb was significantly lower (3,737) for material loaded green (freshly chipped) than that of material dried for the four and eight weeks (4,947 and 4,979, respectively). However, once water was removed there were no significant differences between either energy content per o.d. lb or ash content per o.d. lb for chips in the three treatments. Energy content for chips was consistent with previous tests on pine feedstocks (Baker et al. 2010). Ash contents of less than one percent are also in-line with previous studies on field-run whole-tree chips (Baker, et al. 2011). Previous studies did not measure ash content with transpirationally dried stems, but given its importance, we wanted to determine if it changed with drying time.

The total costs per scheduled machine hour for the feller-buncher and skidder were assumed to be consistent across all three treatments (Table 2.5). Total cost/SMH for the chipper and knuckleboom loader were lower for processing green material than for material dried four or eight weeks due to slightly lower utilization necessary to handle green material. Total cost/SMH for the operation increased 3% when handling 4-week-old material and 4.5% when handling 8-week-old material, compared against chipping green material.

The cost per loaded field ton for harvesting material dried four and eight weeks was higher at $18.77 (2.3%) and $18.98 (3.7%), respectively, than for harvesting green material ($18.30). These costs include $4.31 per ton in overhead and profit. Average truck payloads (for a 42-foot trailer) were 26.46 field tons for green material, 22.26 for 4-week material, and 20.16 for 8-week material (Table 2.6). Transport costs per field ton-mile were highest for 8-week-old material at $0.17, followed by 4-week-old and green material at $0.15 and $0.13, respectively.

Costs per field ton for a 50-mile haul had similar results. Transporting 8-week material cost the most at $8.48, followed by $7.68 for 4-week material, and $6.46 for green material.

Conversely, the cost per loaded bone dry ton (BDT) for harvesting green material was about 25% higher ($38.94) than for harvesting material dried eight weeks ($31.11). Cost per loaded BDT was $32.93 for harvesting material dried four weeks. Truck payloads did not differ between the three treatments on a BDT basis (Table 2.3), thus transport costs per BDT are the same at about $0.28 per BDT-mile or between $13.57 and $14.04 per BDT for a 50-mile haul distance.

Delivered costs on a field ton basis for eight-week-old material were 10.8% higher ($27.48) than for green material ($24.80), with $2.00 of the cost difference resulting from hauling cost differences. On a dry ton basis, however, there were no transport cost differences between treatments, and green material delivered cost was 17.4% higher ($52.94) than material dried 8 weeks ($45.11). Hourly production efficiency driven by moisture content contributed less to cost differences than truck payload differences. Opting for higher volume capacity truck and trailer combinations to maximize legal truck payloads offers an opportunity to offset some of the costs associated with delivering dried woody biomass. If full legal payloads could be hauled from each of the three treatments, much of the cost disparity derived from a field ton comparison would disappear, while the cost advantages of drier material would increase based on a BDT comparison.

Whereas cost per loaded field ton was higher for dried material compared with green material, the cost per loaded mmBTU was highest for green material at $2.39, followed by $1.99 for 4-week material, and $1.92 for 8-week material. Truck payloads per mmBTU did not differ between treatments with each treatment averaging roughly 200 mmBTU per load. Hauling costs were $0.86 per mmBTU in each treatment. Allowing stems to transpirationally dry for up to 8 weeks significantly reduced moisture content and increased energy value, thus a lower cost per loaded mmBTU should be expected.

2.5 SUMMARY

Transpirational drying in late summer for periods of at least four weeks resulted in significant reductions in moisture content with no increase in ash content of the feedstock produced. The first four weeks of drying resulted in the greatest reduction in moisture content (from 53% to 43%) with the additional four weeks producing a smaller, but still significant reduction to 39%.

Chipping productivity as measured in field tons per hour was greatest for green material, but when compared in bone dry tons, the drying treatments produced slightly more than the green treatment (38 BDT/hr vs 34 BDT/hr). This result translated to widely different costs for material depending upon the unit of measure. The current convention in southern timber operations pays for material on a green ton basis, in which case significant savings are possible by harvesting and chipping green material. Much of this savings is due to transport cost, which is higher in dried material due to an inability to obtain full legal payloads. Examining material on a dry ton or mmBTU basis, however, changes the cost implications substantially. Dried material represented a reduction in cost on a BDT or energy content basis of roughly 15%. Improvements in trucking infrastructure could allow for full utilization of legal payloads for dried chips and further increase these cost savings.

Chip size distribution, ash content, nutrient content, and amount of foliage did not significantly differ among treatments. Bark content was significantly lower only for material dried for 8 weeks as compared to 4 weeks or freshly felled. This was likely due to bark slippage occurring during skidding and loading activities. While oven dry energy values for chips did not differ significantly between treatments, energy content on a field condition basis were over 30% higher for chips produced from material dried at least 4 weeks compared to green material.

Using transpirational drying in woody biomass harvesting operations may improve product quality by increasing energy values without increasing ash content. Trees that have been dried in the field to reduce moisture content cost more to harvest and transport than fresh material when based on a wet or field condition ton basis, but will cost less when based on energy content. Harvesting firms that deploy this strategy in a wood supply system that utilizes an energy content payment system, as opposed to a wet weight-based payment system, could take advantage of potential economic advantages of transpirationally drying stems in the field before processing and transportation.

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Table 2.1. Machine rate assumptions and cost inputs by machine.

Machine	Purchase Price	Salvage Value	Economic Life (yrs)	Availability (%SMH)	Fuel (gal/PMH)	Maintenance & Repair (% Depreciation)
Chipper	$460,000	30%	5	85%	29.60	90%
Feller-buncher	$200,000	20%	4	85%	8.14	100%
Skidder	$180,000	25%	4	85%	7.77	90%
Loader	$150,000	30%	5	85%	7.40	90%

Table 2.2. Observed rainfall and comparison of moisture content for tree disk samples collected periodically during four and eight week drying periods and wood chips harvested fresh and allowed to field dry four and eight weeks.

				Disk Samples[2]			Chip Samples		
Date	Rain (in.)	Avg. Temp.	Avg. Rel. Hum.	8 wk disk	4 wk disk	Green disk	8 wk chip	4 wk chip	Green chip
19-Aug	0	86°[1]	73%[1]	46%±2.9	-	-	-	-	-
14-Sep	2	81°	70%	36%±3.9	47%±2.7	-	-	-	-
24-Sep	0	79°	64%	31%±6.6	41%±3.5	-	-	-	-
1-Oct	5	72°	74%	40%±5.5	35%±7.3	-	-	-	-
11-Oct	0	64°	64%	41%±7.7	32%±5.3	48%±2.5	39%	-	-
14-Oct	0	67°	66%	-	-	-	-	43%	-
19-Oct	0	58°	62%	-	-	-	-	-	53%

[1]*Average daily temperature and relative humidity for August, 19. Each subsequent value is the average daily measure for the period between sample collection dates.*

[2]*Disk sample moisture content plus standard error at 95% confidence.*

Table 2.3. Truck payloads, chipper productivity, chipper utilization, and chipper fuel consumption of a whole-tree chipping operation processing fresh, four and eight week dried material.

	Green	**4 Weeks**	**8 Weeks**
Trailer load (lbs/cu.ft.)			
Field	18.36[a]	15.56[b]	14.50[c]
Oven dry	8.56[a]	8.85[a]	8.80[a]
Chipper productivity (tons/PMH)			
Field	73[a]	67[a]	63[b]
Oven dry	34[a]	38[b]	38[b]
Chipper utilization (%)	31%[a]	33%[a]	39%[b]
Chipper fuel consumption (gal/ton)			
Field	0.37	0.34	0.36
Oven dry	0.80	0.60	0.60

PMH = productive machine hour

Table 2.4. Chip size distribution, bark, foliage, ash, nutrient, and energy content of whole-tree chips fresh and that transpirationally dried in the field for four and eight weeks.

	Green	**4 Weeks**	**8 Weeks**
Chip size distribution (%)			
<3mm	4.0^{a}	3.3^{a}	5.1^{a}
7-3mm	12.8^{a}	10.8^{a}	11.8^{a}
15-7mm	33.8^{a}	29.3^{a}	29.8^{a}
45-15mm	32.6^{a}	41.6^{a}	41.3^{a}
>45mm	0.8^{a}	1.3^{a}	1.5^{a}
Bark (%)	13.4^{a}	11.6^{a}	9.0^{b}
Foliage (%)	2.8^{a}	2.0^{a}	1.6^{a}
Ash content (%)	0.67^{a}	0.54^{a}	0.69^{a}
Nutrient content			
C (%)	48^{a}	48^{a}	48^{a}
N (ppm)	1700^{a}	1300^{a}	1600^{a}
S (ppm)	90^{a}	80^{a}	70^{a}
K (ppm)	32^{a}	24^{a}	31^{a}
P (ppm)	5.3^{a}	11^{a}	5.0^{a}
Energy content			
BTU/o.d. lb.	8203^{a}	8329^{a}	8161^{a}
BTU/field lb.	3737^{a}	4947^{b}	4979^{b}

Note: Entries within a row with a different letter are statistically different at the alpha = 0.05 level.

Table 2.5. Estimates of hourly costs, costs per loaded field ton and bone dry ton, and costs per loaded mmBTU, of a whole-tree chipping operation processing fresh and four and eight week dried material.

	Green	**4 Weeks**	**8 Weeks**
Feller-buncher	$59.21	$59.21	$59.21
Skidder	$70.28	$70.28	$70.28
Loader	$39.74	$41.10	$41.71
Chipper	$86.07	$92.58	$95.49
Total cost ($/SMH)	$255.30	$263.17	$266.69
Field tons/PMH	77	65	61
Utilization (%)	27	32	34
Field tons/SMH	21	21	21
Cost/loaded field ton[1]	$18.30	$18.77	$18.98
Cost/bone dry ton (BDT)	$38.94	$32.93	$31.11
Cost/loaded MMBTU	$2.39	$1.99	$1.92

[1] *Costs include $4.31 per ton in overhead and profit, SMH =scheduled machine hour, PMH = productive machine hour*

Table 2.6. Transportation costs for whole tree chips produced from stems chipped green, dried four weeks and dried eight weeks. Costs assume payloads in a 42 foot trailer, hauled 50 miles each way, with average haul costs of $1.71 per mile.

Treatment	Avg. Payload (Field tons)	Haul Cost ($/Field ton)	Avg. Payload (BDT)	Haul Cost ($/BDT)
Green	26.46	$6.46	12.2	$14.04
Four weeks	22.26	$7.68	12.6	$13.57
Eight weeks	20.16	$8.48	12.2	$14.04

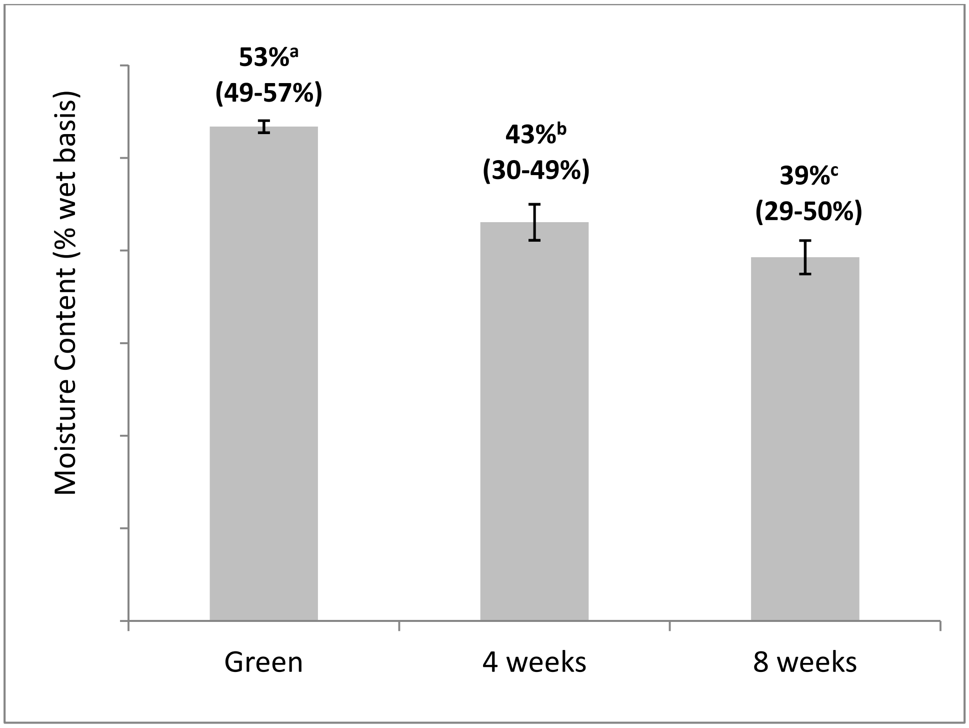

Figure 2.1. Average moisture content of wood chips harvested fresh and allowed to dry four and eight weeks. Values in parenthesis indicate minimum and maximum values. Different letters indicate significantly different values ($\alpha < 0.05$).

CHAPTER 3

FACTORS AFFECTING COSTS OF FOREST BIOMASS HARVESTING SYSTEMS AND THEIR IMPLICATIONS FOR STAKEHOLDERS[1]

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[1] Cutshall, J, D. Greene, S. Baker, M. Clutter, J. Siry, and S. Mani.
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FACTORS AFFECTING COSTS OF FOREST BIOMASS HARVESTING SYSTEMS AND THEIR IMPLICATIONS FOR STAKEHOLDERS

3.1 ABSTRACT

In this paper we compare a range of likely forest biomass harvesting systems including whole-tree chipping, clean chipping, conventional roundwood, and residue grinding to determine how each system affects woody biomass energy facilities, biomass harvesting firms, and forest landowners. Data on production and the properties of chip and wood residue products were used to estimate costs per million BTU for forest biomass harvesting systems including conventional roundwood, clean chipping, whole-tree chipping, and screened and unscreened grinders processing logging and clean chip residue. Delivered costs for these systems were evaluated for a range of values for moisture content, ash content, tract size, tons of biomass removed per acre and at grinding decks, truck payload, haul distance, and diesel fuel price. Delivered cost per mmBTU decreased by over 50% for all systems as moisture content decreased from 55% to 30%. Whole tree chipping provided the lowest cost option ($4.39 per mmBTU) at ash content levels less than 1%, and unscreened grinding of clean chip residue produced the least expensive option at 5% ash ($2.87 per mmBTU). Tract size had minimal effects on any operation until the acreage declined below 40 acres. Clean chipping and roundwood systems were considerably more expensive than whole-tree chipping operations on all tract sizes. Costs declined significantly as truck payload increased and/or haul distance decreased. Optimizing truck payload to attain legal weight limits by lowering tare weight

and/or increasing trailer volume capacity is an opportunity for forest biomass harvesting system managers to achieve lower costs especially when dealing with drier material or low-density screened roundwood grindings. Fuel price increases directly increase cut and haul costs and limit economical haul distances accordingly.

Index Words: forest biomass harvesting, chipping, grinding, moisture content, ash content

3.2 INTRODUCTION

Higher market prices for fossil fuels as well as proposed policy changes to support renewable energy use and to reduce carbon emissions have recently led to a large number of bioenergy projects being announced which will consume woody biomass. Projects recently announced for North America could substantially increase wood energy capacity and potentially consume more than 60 million green tons of woody biomass feedstock (RISI 2011). Woody biomass from forest residues has long been underutilized due to limited access and high costs associated with collection and transportation (Evans 2008). A survey of top state forestry officials recently identified high harvesting and transportation costs for woody biomass from forests as the top constraint to expanding this new industry (Aguilar and Garrett 2009).

Harvesting systems utilizing whole-tree chippers and grinders convert woody biomass into a suitable feedstock for wood energy facilities. A system harvesting roundwood products typically piles logging slash for later collection by a biomass harvesting system using a grinder or chipper. In this paper we compare a range of likely forest biomass harvesting systems, including whole-tree chipping, clean chipping, conventional roundwood, and residue grinding to determine how each system affects woody biomass energy facilities, biomass harvesting firms, and forest landowners.

3.2.1 Wood Energy Facilities

The forest products industry today purchases most raw materials on a green ton basis for convenience and to encourage the delivery of freshly cut wood. Wood energy facilities are likely to prefer drier raw material to maximize energy content. They also often prefer feedstock with a minimum of dirt or grit so that the ash remaining after combustion is reduced. Moisture content and ash content are especially important issues where logging residues such as limbs, tops, and understory stems are collected because moisture and ash affect energy value. Wood energy facilities are also concerned with the elemental or nutrient content of woody biomass feedstocks due to its effect on emissions affecting air quality (Obernberger et al. 1997).

When woody biomass feedstocks will be combusted to provide energy it is advantageous to have low moisture content to increase their energy value (BTU). The heating value of any fuel is the energy released per unit mass or per unit volume of the fuel when the fuel is completely burned (ANSI/ASABE S593.1 2011). Woody biomass has one of the highest energy contents of all biomass sources with over 25 million BTUs per oven-dry ton (Boundy et al. 2011). The moisture content of solid biomass influences the net calorific value and the combustion efficiency (Kristensen and Kofman 2000). Woody biomass products with particle sizes too small or too large negatively influence handling, combustion characteristics, and emissions (Paulrud and Nilsson 2004).

A higher energy value results in greater burning efficiency. Wood energy markets (biorefineries, pellet manufacturers, wood-fired electric plants, and wood to liquid fuel processes) are often interested in procuring raw material that has lower moisture content than green wood to obtain a higher energy value. The transportation of bioenergy feedstocks has been found to be inherently more costly than fossil fuels because per unit energy density of fossil fuels is two to three times that of biomass (Young 1980). Each 10% reduction in moisture content can increase the net energy content of the wood by approximately 850 BTU (Ince 1979). Freshly felled trees have a moisture content of approximately 50% (wet basis) – this varies somewhat by species and region – but if allowed to dry for at least four weeks before delimbing and processing, moisture content can be reduced to as little as 30-35% (Stokes et al. 1993). This delayed delimbing and bucking is known by several names but we will refer to it as transpirational drying. Loblolly pine (*Pinus taeda*) stems dry at a greater rate with limbs intact than as delimbed stems, they dry more during summer months, and most moisture reduction occurs during the first 30 days of drying (Klepac et al. 2008).

While reducing moisture content is important, keeping ash content low in combustible woody fuels is also vital. Ash is formed from mineral matter during combustion and can cause slagging, which is the coating of internal surfaces in boilers from deposition of ash particles. Ash is a crucial aspect of the concept of sustainable, carbon neutral thermal biomass utilization and may be recycled where appropriate in forests and on agricultural land or put in a landfill (Narodoslawsky and Obernberger 1996).

Woody biomass with higher ash content is considered of poorer quality because it results in poorer combustion performance and increases maintenance and disposal costs caused by glass or slag deposits formed within some burning mechanisms (Sarenbo 2009). The biomass harvesting system employed, the type of woody biomass material, and the manner and duration of how woody biomass is stored and/or piled on-site can all affect moisture and ash content (Obernberger et al. 1997, Pettersson and Nordfjell 2007). Öhman et al. (2004) observed ash content for different types of woody biomass used to make pellets and found that while ash deposits were affected both by burner and feedstock types, stem wood based material produced less ash than bark and logging residues. The wood pelletizing process is less forgiving of ash, as is the burning of woody biomass in stoker grate boilers where slag deposits are prone to form. More technologically advanced circulating fluidized bed boilers tolerate a greater amount of ash than stoker grate boilers (van den Broek et al. 1996).

Wu et al. (2011) measured moisture content from three different sizes of chips oven drying them for 24 hours at 105 degrees C and determined size distribution by screening chips in a horizontal classifier. The smallest and largest size chips (0-20mm and 40-100mm, respectively) had moisture contents higher than what is considered acceptable chips (20-40mm).

Spinelli et al. (2011) determined particle-size distribution, fiber and bark content, and heating value of a wide sample of wood chips collected from 60 operating commercial biomass terminals in northern Italy. High quality (clean, dry) and low cost biomass feedstock from sawmill residues were the preferred feedstock for bioenergy facilities. This study found that logging residues such as tops and branches could be obtained at a low cost, but did not match the same quality specifications. Small conifer and broadleaf trees from thinning operations and broadleaf trees from traditional coppice stands provide good product quality, but were costly to harvest.

Ragland et al. (1991) found that thermal property values such as specific heat, thermal conductivity, and emissivity vary with moisture content, temperature, and degree of thermal degradation by up to one order of magnitude. The carbon content of dry wood varies from about 47 to 53 percent due to varying lignin and extractives content. Mineral content of wood is less than 1%, but it can be over 10 times that value in bark. The composition of mineral matter can vary between and within each tree.

Lehtikangas (2001) tested nine pellet assortments, made of fresh and stored sawdust, bark and logging residues for moisture content, heating value and contents of ash, sulfur, chlorine, and Klason lignin. The heating value was highest in logging residue pellets. Ash content was highest in the bark and logging residue pellets, implying higher sintering risk compared with sawdust pellets. The results indicated that bark pellets had the highest durability, whereas sawdust pellets had the lowest. The study concluded that bark and logging residues are suitable raw materials for pellet production, especially if the ash content is controlled.

Filbakk et al. (2011) conducted a study on how bark content affected the quality of pellets. Pellets from pinewood containing zero, five, 10, 30 and 100 percent bark were produced and their quality parameters were evaluated. Pellets made from pure bark had the best mechanical properties compared with pellets made of wood containing various concentrations of bark.

Nurmia and Hillebrand (2007) studied fuel properties of small-sized whole-tree fuel stocks in roadside and in-stand storages. The significance of pile cover, season, and storage site on moisture content and heating value of Scots pine (*P. sylvestris*) and pubescent birch (*Betula* *pubescence*) fuel stocks were observed. When the fuel stocks were placed in a well-ventilated location moisture content could be lowered below the 40% mark during one summer period. Covered the piles had 6% lower moisture content than non-covered piles. Multi-tree harvested stemwood with no limbs seasoned equally well as the whole trees both in roadside and in-stand trials because the processing of multi-tree bunches caused some debarking to take place. As a result, the transpirational drying capability of whole trees was equalized by the evaporation of moisture via the open wood surface. Both assortments reached moisture contents below 30% in in-stand conditions during one summer's seasoning.

Suadicani and Gamborg (1999) found that when freshly felled trees were chipped, the loss of plant essential nutrients (calcium, magnesium, potassium and nitrogen) was significantly greater compared to the removal of nutrients when summer dried trees were chipped. The size distribution of the chips was significantly improved when the trees were left for summer drying. The moisture content dropped significantly from an average in the two trials of 57% of total weight to 42% of total weight after summer drying. The net caloric value per unit of weight increased significantly in the chips of summer dried wood. Net caloric value based on dry weight was slightly reduced during the drying period due to the loss of energy rich extractives. Summer drying ensures reduction in the loss of plant essential nutrients caused by the removal of biomass from the stand.

Roser et al. (2011 a) investigated methods to promote the natural drying of wood for bioenergy purposes. The effects on the drying process through covering the wood piles and partial debarking of stems were tested to identify methods to reduce the moisture content of the woody material in storage. Drying trials were established in Finland, Italy, and Scotland utilizing alder, beech, pine, and spruce. The study indicated that natural drying was a practical and effective method to enhance the energy efficiency of wood based fuel products in all the regions studied.

3.2.2 Harvesting Operations

A number of different biomass harvesting and transportation system configurations that can supply renewable energy facilities already exist, but each operates with a different incoming feedstock (residues, understory, standing trees, etc.), produces a product that differs in its characteristics (moisture content, particle size and uniformity, ash content, etc.), and differs in productivity and costs (Hartsough and Yomogida 1996). Few studies have examined methods that could improve woody biomass characteristics in the field to add value to the feedstock required by bioenergy facilities.

The timber harvesting and wood supply chain in the United States is globally competitive and well positioned to add woody biomass to the list of products it delivers. However, there are some significant issues to be addressed to support these new wood-using industries. Most traditional forest industries (paper and building products) purchase their raw material today on a green ton basis. Unlike some wood consuming mill in the Pacific Northwest that base payments on bone dry tons, most wood consuming mills in the US South exclusively use green tons. There are several advantages to this method, including automated weighing of trucks and the incentive a green ton basis provides to logging contractors to deliver fresh wood to markets. Fresh wood provides higher pulp and tall oil yields in most pulp processes as well as limiting checking and blue stain issues with sawtimber. Under existing green ton payment systems at biomass receiving facilities in the U.S. South, dried material results in lower truck payloads, thus higher trucking costs when evaluated on a green ton basis.

Different approaches for harvesting woody biomass for energy have been studied for decades. Koch (1980) described numerous methods for harvesting biomass, including chipping whole trees at the stump, extracting sawlogs at the landing and processing limbs and tops, chipping residues at a wood consuming mill, and transporting complete boles to a mill for merchandizing. Arola and Miyata (1981) reported on cost and productivity data for five different harvesting methods from conventional logging operations to a land clearing operation for site conversion.

A one-pass harvesting system harvests all products concurrently. Harvesting and recovering roundwood and woody biomass are performed in separate passes in a two-pass harvesting system. Watson et al. (1986 a) compared a conventional harvesting system with one and two pass biomass harvesting systems with the one-pass system having the best utilization and lowest costs.

Cubbage and Greene (1989) compared estimated costs for seven conventional logging systems for a variety of conventional and biomass harvests. Highly mechanized systems using feller-bunchers and grapple skidders were the least costly. Tract size did not greatly influence costs but the study design did not evaluate small harvest blocks.

Goulding and Twaddle (1990) studied approaches to improve conventional harvesting methods that lead to increased production of energy wood as a by-product of integrated systems. Economically successful systems were ones where the biomass component was kept attached to conventional products for as long as possible and increased biomass recovery was a consequence of improvements to one or more of the conventional harvesting tasks, i.e. delimbing and bucking.

Puttock (1995) examined two different approaches for estimating costs of producing conventional products and fuel wood with integrated harvesting systems. A marginal cost approach completely allocates the cost of common harvesting activities such as felling, forwarding and processing to conventional products, whereas a joint product approach distributes production costs among conventional products and fuel wood. Production costs are highly variable depending on the type of harvesting employed and the ratio of conventional products to fuel wood.

Roser et al. (2011 b) estimated the feasibility and cost level of selected supply chains for chips. While results showed that supply chains have to be tailored to local conditions, distance from receiving facilities, and product quality, overall, chipping at the landing seems was the best option. Angus-Hankin et al. (1995) studied various forms of fuel wood transportation systems, comparing their costs and payloads. The inherent low bulk density of woody biomass was a substantial drawback to reaching the maximum legal weight before exceeding legal truck and/or trailer dimensions. Moreover, a desire to minimize moisture content to increase product quality of the material prior to transport placed further constraints on achieving optimal truck payloads.

A GIS-based model for energy wood supply chains simulated costs for several supply chains in a study area in eastern Finland and found that more simple supply chains such as transporting loose residues by truck and chipping at the plant offered the lowest total costs at haul distances less than 60 kilometers. The amount of packing density and the ability to use full load capacity were more important for haul distances over 60 kilometers (Tahvanainen and Anttila 2011).

Yoshioka et al. (2006) developed and monitored a harvesting and transporting system for logging residues to determine the feasibility of the system based on cost, energy, and CO2. Their results suggested that a chipper should be incorporated into the system as early as possible and that high capacity trailers and highly-maintained forest roads were effective measures to reduce the total cost.

Patterson et al. (2011) examined five forest biomass collection systems. Two of the systems utilized a chipper, one with thinning material and one with thinning residues. The other three systems utilized horizontal grinders to process roundwood logging residues. The chipping systems produced material with a higher energy content (8,168 vs. 7,785 BTU/lb) and lower ash content (1.2% vs. 4.5%) than the material produced by grinding systems processing roundwood residues.

3.2.3 Forest Landowners

Ninety percent of responding family and institutional forest landowners and public forestland managers in the U.S. South reported a willingness to sell to energy facilities if desirable prices were offered and all owners who previously sold timber to an energy facility were satisfied with the experience. Only 3.5% of respondents were unwilling to sell timber to an energy company, with only one of these respondents listing timber production as a primary objective (Conrad et al. 2011).

An Alabama survey indicated that most family forest landowners were willing to supply both timber and harvest residues for energy production with their willingness positively correlated with owned acreage, valuable markets, and the opportunity to contribute to local economic development and global climate change. Three-quarters of the Alabama respondents indicated willingness to manage their land for biomass production, compared with 43% of respondents who actively managed their land (Paula et al. 2011).

A study to assess factors affecting Arkansas, Florida, and Virginia nonindustrial private forest landowners' willingness to supply woody biomass for bioenergy showed that the majority of the landowners in the study area regarded energy security as critical for both national security and a healthy economy. A significant number of landowners were either uncertain or not familiar with the idea of producing alternative energy from cellulosic biomass. Older forest landowners were skeptical about wood-based energy, but the study's "willingness to supply" model indicated that younger landowners with large timber holdings were more likely to supply woody biomass. Landowners with wildlife management objectives were likely to supply woody biomass (Joshi and Mehmood 2011).

Forest landowners in Sweden reported that the price paid for forest biomass did not determine whether or not they would sell their forest biomass material. Potential losses in soil productivity negatively influenced their decision to sell the material and Swedish forest landowners who do sell reported that clearing the forest floor from residues was the primary reason (Bohlin and Roos 2002).

Recovering biomass presents forest landowners with an opportunity to utilize this material instead of piling and/or burning it prior to replanting. Furthermore, this practice tends to increase the plantable area and studies have shown that recovering harvesting residues and unmerchantable stems may reduce site preparation cost (Miller et al. 1987, Watson et al. 1986 (b), Ragan et al. 1987, Watson and Stokes 1989, and Westbrook 2008). Watson and Stokes (1989) reported a 25% reduction in site preparation cost due to the removal of residues and unmerchantable stems. Westbrook (2008) found up to 38% reduction in site preparation costs when understory material was removed from the site during harvesting.

Some concerns for forest landowners regarding energy wood harvesting were the removal of excessive amounts of logging residue because of perceived negative effects to wildlife habitat, nutrient cycling, and water quality. A study conducted in Maine by Briedis et al. (2011) found that an average of 45% of the logging residue was left on sites harvested for traditional forest products and energy wood and between 16 and 50% was left on skid trails.

Shorter rotations and an increase in utilization could lower site nutrient availability. Management of site nutrients via fertilization increases in importance as the proportion of nutrients removed increases unless nutrients are not a limiting factor on particular sites. The potential loss of nutrients from a site largely depends upon the distribution of biomass component such as stems, bark, branches, and foliage. The increase in loss of nutrients in harvested materials accompanying a change in utilization standards depends upon the distribution of biomass between the various components of the forest: stemwood, stembark, the stump (unharvested portion of the bole), branches of various dimensions, roots of various dimensions, and foliage (Kimmins 1977).

Some southern U.S. pine forests that are relatively unproductive prior to harvesting may be at risk of further productivity losses due to intensive harvesting treatments with slash removal and fertilization is often required to improve site productivity (Scott and Dean 2006).

3.3 METHODS

3.3.1 Harvesting Systems

We calculated delivered costs per field ton and per million BTU (mmBTU) for seven harvesting systems. We use the term "field" to reference the moisture content of any material at the time of chipping or grinding and use "green" wood to refer to freshly felled wood with the highest moisture content observed in the field. The harvesting systems included: (1) a whole-tree chipping operation producing fuel chips, (2) a clean chipping operation producing pulp quality chips, (3) a horizontal grinding operation processing roundwood logging residues unscreened, (4) a horizontal grinding operation processing and screening roundwood logging residues, (5) a horizontal grinding operation processing clean chipping residues unscreened, (6) a horizontal grinding operation processing and screening clean chipping residues, and (7) a conventional roundwood logging operation.

3.3.2 Product Analysis

Physical properties including moisture content, ash content, energy content, and elemental analysis were obtained from Dukes (2012) for screened and unscreened grindings and from Cutshall et al. (in press) for whole-tree chips. Both of these studies collected samples and prepared them for laboratory analyses following the Technical Association of the Pulp and Paper Industry (TAPPI) standard for sampling and preparing wood for analysis (TAPPI 1985). A 6-inch diameter PVC pipe with an elbow was used to collect chip samples and a 5-gallon bucket was used to collect grinding material from each truck load. Small samples were collected several times during the loading of a van and mixed to obtain composite samples. Grab samples (1Kg) from the composite samples were transferred to a kraft paper bag and weighed immediately to determine the field (or wet) weight of the chips or grindings. Each bag was later transferred to a 105°C oven for a minimum of 24 hours and reweighed to determine moisture content. A subsample of bags from each harvesting system were fractioned, processed through a 1 mm screen Wiley mill and transferred to the University of Georgia Plant, Soil, and Water Lab to determine energy, ash, and nutrient content.

3.3.3 Production Analysis

Production rates and truck payloads were obtained from Cutshall et al. (in press) and Dukes (2012). These studies looked at production impacts by using work sampling and time study methods to record data on the whole-tree harvesting system and each grinding system. Production rates for the clean chipping system were assumed to mirror the whole-tree chipping system. Continuous activity data were recorded for each system, and machine activity codes were recorded for each processing machine on-site every two minutes for the duration of each field study to establish mechanical availability, utilization, and sources of delay. These machine activity codes included chipping or grinding, representing productive time, and assorted delays such as mechanical delays, waiting on trees or residue material, waiting on trucks, waiting on the loaders, waiting with processing machines turned off, and miscellaneous delays. A stopwatch was used in each study to record the time to load each truck in the field, and load weights were obtained from truck drivers from weight scale tickets upon return to the study site.

3.3.4 Cost Estimation

Hourly operating costs were calculated using the machine rate approach (Miyata 1980) assuming 85% mechanical availability for all machines in each of the seven harvesting systems.

Additional assumptions for all machines included: labor rate of $18.00/SMH; labor fringe/overhead expenses of 40% of the base rate of pay; combined interest, insurance, and taxes of 15% of average annual investment; lubrication costs at 37% of fuel expense; and 2,000 scheduled machine hours per year (Table 3.1). We evaluated diesel prices ranging from $3.00 to $6.00 per gallon.

We modified a version of the Auburn Harvesting Analyzer (Tufts et al. 1985) to determine delivered costs for each system. The model was adapted to evaluate a range of values in lab-derived moisture content, ash content, and energy content (BTU per oven dry pound) among whole-tree chipping and grinding systems based on results obtained from Cutshall et al. (in press) and Dukes (2012). For example, whole-tree chips ranged in moisture content from approximately 30% to 55% and ash content varied from approximately 0.5% to 1.0%. Truck payload data from the previous studies were used to obtain ranges in load weights. Trucks transporting whole-tree chips ranged in net weights from 20 to 30 tons, and trucks transporting screened roundwood residue grinding material ranged in net weights from 10 to 20 tons. We added 10% to total costs for a profit margin. Additional variables including tract size, tons removed per acre, tons per landing, truck payload (net tons), and miles of loaded haul distance to the receiving facility were adjusted to determine cost sensitivity (Table 3.2).

Delivered costs were calculated by adding a stumpage price of $8.00 per field ton for the RW system and $1.00 per field ton for each grinding system. We assumed the CC system to process 10% less material due to bark and chip sizing losses than the RW system resulting in a stumpage price of $8.89 per field ton and the WTC system to process 25% more material than the RW system resulting in a stumpage price of $6.40 per field ton. To further incorporate biomass costs for wood energy facilities, we added an additional $5.00 per field ton to the RW system to represent the cost of chipping roundwood at a facility. We compared delivered cost per mmBTU data at each variable level using analysis of variance with Tukey's range test used for means comparison (Oehlert 2000).

3.3.5 Nutrient Removals

To illustrate incremental nutrient removals, we compared estimated N, P, and K removals (pounds per acre) from chipping and grinding systems. We considered a pine stand with 100 field tons per acre of total biomass material 4 inches or greater in diameter containing 10% unmerchantable hardwood and calculated BDT per acre by assuming 50% moisture content. The 10% hardwood was assumed to be unavailable for recovery. A pine crown to stem weight ratio of 15% from Aman (2010) was used to determine the amount of merchantable biomass for RW and CC systems with an additional recovery rate of 85% for CC. Full available biomass recovery was assumed for the WTC system. Removals for each grinding system were determined by adding their respective first pass system (RW or CC) removals and applying an assumed grinding system-specific recovery rate. Recovery rates for the GRW, GRW/S, GCC, and GCC/S systems were 85%, 70%, 90%, and 80%, respectively. Pounds per acre of N, P, and K removals were calculated for each system by applying nutrient contents from Dukes (2012) and Cutshall (in press) (Table 3.5) and BDT per acre removals. Biomass material from the RW and CC systems were assumed to have the same elemental content as the WTC system.

3.4 RESULTS

3.4.1 Moisture Content

Estimated delivered costs on an energy basis (mmBTU) for whole-tree chipping and screened and unscreened grinding systems were compared by increasing moisture content (MC) from 30% to 55% (wet basis) (Figure 3.1). Delivered cost per mmBTU decreased by over 50% for all systems as moisture content decreased from 55% to 30%. The system grinding clean chipping residues without using a screen (GCC) had the lowest estimated delivered costs ranging from $2.68 per mmBTU at 30% MC to $4.17 at 55% MC. The grinding system processing and screening clean chipping residues (GCC/S) and the system grinding roundwood logging residues without using a screen (GRW) had marginally higher estimated cut and haul costs per mmBTU, respectively, than the GCC system. The whole-tree chipping system had the highest costs of the “economically feasible” systems. Estimated cut and haul costs for the system grinding and screening roundwood logging residues (GRW/S) were by far the highest. This system was not considered to be an economically feasible biomass harvesting option. Dukes (2012) reported that this system averaged 11.7 net tons of truck payload, a 47 minute loading time, and 15.3 tons per productive hour. By comparison, a 780 hp grinder processing and screening clean chip residues averaged 23.5 net tons of truck payload, a 16.9 minute loading time, and 84.7 tons per productive hour.

3.4.2 Ash Content

Ash content, along with moisture content, is a key characteristic affecting net energy content. The whole-tree chipping system produced the lowest estimated delivered cost per mmBTU at the lowest percent ash, $4.39 per mmBTU at 0.5% ash and $4.41 at 1% ash (Table

3.3). Cutshall et al. (in press) reported ash content of less 0.7% in whole-tree chips. The GCC system produced the lowest estimated delivered cost per mmBTU of $2.87 at 5% ash, but this system also produced loads with high ash content (up to 30%). If target ash content is less than 2%, the WTC system was the lowest delivered cost option followed by the GRW/S system (Table 3.3). No other system was observed to reduce ash below 2%. If 2% ash is acceptable, then the GCC/S system is the lowest delivered cost option at $3.33 per mmBTU. If ash content of up to 10% is acceptable, then the GRW, GCC, or GCC/S systems are options with the lowest costs observed for the GCC system. Delivered costs for the CC and GRW/S systems were not significantly different at α=.05.

3.4.3 Tract Size

Delivered costs per mmBTU for conventional roundwood logging (RW), whole-tree chipping (WTC), and clean chipping (CC) systems were compared by increasing tract size from 20 to 100 acres (Figure 3.2). Estimated delivered costs for the WTC system averaged almost $1.00 per mmBTU less than the CC system and $0.75 per mmBTU less than the RW system for all tract sizes. The CC and RW systems' costs were not significantly different for any tract size. Costs declined more (16%) as tract size increased from 20 to 60 acres, but fell only 3% when increased from 60 to 100 acres. Harvesting systems are capital-intensive, costly operations requiring high productivity to maintain profitability and are thus more affected by smaller tracts which require more frequent moving.

3.4.4 Tons per Acre and Tons per Landing

Delivered costs per mmBTU for conventional roundwood logging (RW), whole-tree chipping (WTC), and clean chipping (CC) systems were compared by increasing field tons removed per acre from 20 to 80 tons (Figure 3.3). Estimated delivered costs for the RW and CC systems averaged roughly $0.80 per mmBTU more than the WTC system when 60 tons per acre were removed. Costs declined sharply (35%) as tons per acre removed increased from 20 to 50 tons but declined only 12% as tons per acre increased from 50 to 80. Delivered costs were not significantly different between the CC and RW systems when 50 or more field tons per acre were removed.

Delivered costs per mmBTU for each grinding system were compared by increasing tons per landing or processing area (Figure 3.4). The unscreened system grinding clean chipping residues (GCC) had the lowest estimated delivered costs from $3.68 per mmBTU at 20 tons per landing to $3.17 at 250 field tons per landing. Costs for the system grinding and screening roundwood residues (GRW/S) were the highest by a considerable margin at $5.76 per mmBTU at 50 tons per landing and $5.13 at 250 tons. As field tons per landing increased from 50 to 250 costs for the GRW system dropped 10% followed by 11% for the GRW/S, 14% for the GCC, and 17% for the GCC/S systems. Costs for the GCC/S and GRW systems at 50 tons per landing and the GCC/S and GCC systems at 250 tons per landing did not significantly differ.

3.4.5 Truck Payload

Delivered costs per mmBTU for each harvesting system were also compared by increasing net tons of truck payload (Figure 3.5). The GRW, GCC, and GCC/S systems had the lowest costs for each load size. Costs declined approximately 11% for each system as load size increased except for the GRW/S system which declined 20%. Delivered costs for the GRW and GCC/S systems did not significantly differ at a trucks payload of 15 tons. The GCC and GCC/S systems did not differ at truck payloads of 20, 25 or 30 tons. The GRW and GCC systems and the CC and RW systems did not significantly differ at load sizes of 20 and 30 tons, respectively.

3.4.6 Distance to Market

Delivered costs per mmBTU for each harvesting system were compared by increasing distance to market from 40 to 100 miles (Figure 3.6). Each system's cost increased with increasing distance to market, however, the GCC, GCC/S, and GRW systems had among the greatest increases at 76%, 73% and 65%, respectively. Expanding distance to market from 40 to 100 miles increased estimated delivered costs by 50% for the GRW/S system and by 23% for the RW, CC, and WTC systems. Costs for the RW and GRW/S systems did not significantly differ at 60 miles, and the GRW/S and CC systems at 80 miles. The CC and RW system costs along with those for the GRW and GCC/S systems did not differ when distance to market was 100 miles.

3.4.7 Fuel Prices

Delivered costs per mmBTU for each harvesting system were compared by increasing diesel fuel prices from \$3.00 to \$6.00 per gallon (Figure 3.7). Together, the WTC, CC, and GRW/S systems were affected the most (20%, 18%, and 18% cost increase, respectively) by increasing fuel prices. Cost per mmBTU for the RW system increased 15%, and 14% for the GRW system. Likely due to their higher production and payload optimization capabilities, screened and unscreened clean chip residue grinding systems were least affected (7% cost increase) by rising fuel prices. The CC and GRW/S, CC and RW, GRW/S and RW, and GRW and GCC/S systems did not significantly differ in delivered costs per mmBTU at \$3.00 and \$4.00 diesel fuel prices. The CC and GRW/S systems differed at \$4.00 and \$5.00 diesel fuel prices as well.

3.4.8 Cost Summary by System

We compared delivered cost per field ton and per mmBTU for each system under likely conditions and with key assumptions outlined in Appendix G (Table 3.4). The GCC system had the lowest delivered cost per field ton and per mmBTU ($22.48 and $2.71, respectively) and the GRW/S system had highest costs at $46.49 and $4.20, respectively. When factoring in moisture and ash content to derive delivered costs on an energy content basis ($/mmBTU), costs per mmBTU for the GRW and WTC-40% (40% moisture content) systems were lowered relative to their cost per field ton equivalent measure. The RW and CC systems were among the costliest based on field tons and mmBTU.

Systems that collect residues behind clean chip or roundwood operations represent a second pass across the site or at minimum a second operation visiting the logging site. When examining these grinding systems from a holistic standpoint, they may not be as favorable due to costs of both passes. Residue collection systems are also limited by the availability of sites that have received a primary harvest first and by definition have less biomass available to collect since higher value products have already been removed in the first harvest pass. In this study the WTC systems produced a relatively costly product, but they had the advantages of requiring a single operation and handling large volumes per acre.

3.4.9 Nutrient Removals

We compared calculated nutrient (N, P, K) contents from Dukes (2012) and Cutshall et al. (in press) for a whole-tree chipping system processing material at 50% and 40% moisture content and from screened and unscreened residue grinding operations processing roundwood logging and clean chipped residues (Table 3.5). There were approximately 1,500 ppm of N in chips collected from whole-tree chipping operations compared with 2,000 ppm for roundwood logging residue grindings systems and roughly 2,800 ppm for clean chipped residue grinding material. Foliage contains high levels of N. Piles of clean chipped residue contain more foliage than roundwood logging residue and chipped whole trees contain more stemwood relative to foliage. Concentration of P in did not differ considerably among material removed from each system, and K content was somewhat lower in whole-tree chips.

The amount of biomass removed per acre was lowest for the CC system (33 BDT), followed by the RW system (38 BDT) (Table 3.6). The GRW and GCC systems removed the most biomass per acre at 48 BDT followed by the GCC/S, GRW/S, and WTC systems at 47, 46, and 45 BDT, respectively. Applying product nutrient contents from Table 3.5 to the amount of biomass removed indicated that estimated nutrient removals were lowest for the CC system (N=102 lbs/ac, P=8 lbs/ac, K=54 lbs/ac) followed by the RW system (N=120 lbs/ac, P=9 lbs/ac, K=64 lbs/ac). The GCC and GCC/S systems removed the highest estimated levels of N per acre at 195 and 180 lbs, respectively. Removals of P did not differ among grinding systems and K removals were highest in these systems. Each level of biomass removal intensity (from RW to GCC) resulted in an increase in overall nutrient removals.

3.5 SUMMARY

Delivered costs associated with harvesting forest biomass for energy production increased as moisture and ash content increased. A whole-tree chipping operation was a very suitable harvesting system if wood energy facilities require biomass material to meet an ash content specification of less than 2%. The only grinding system capable of producing material with less than 2% ash was one grinding roundwood logging residue using a screen, but its delivered cost was almost $1.00 per mmBTU higher than that for a whole-tree chipping system due to severely limited truck payloads. The least costly ($2.87 per mmBTU) option where 5% ash content was acceptable was a system grinding clean chipped residue without screening.

Tract size had minimal effects on any operation until the acreage declined below 40 acres. Clean chipping and conventional roundwood systems were considerably more expensive than whole-tree chipping operations on all tract sizes.

Costs for roundwood and chipping systems sharply declined as the amount of biomass available on site increased, especially as field tons per acre removed increased from 20 to 50. Truck payload and haul distance had considerable effects on delivered costs. Costs were reduced as truck payload increased and haul distance decreased. Optimizing truck payload to meet legal weight limits by lowering tare weight and increasing trailer volume capacity is an opportunity for forest biomass harvesting system managers to achieve lower costs especially when dealing with drier material or screened roundwood grindings. Fuel price increases directly increase delivered costs and limit economical haul distances accordingly.

In the U.S. South forest biomass in roundwood form, though wetter than dried chips or grindings, is typically more abundant, has an established harvesting and transportation infrastructure, and is perceived to be cheaper than processed biomass to cut and haul to the first delivery point. However, delivered pulpwood prices also include stumpage of approximately $8.00 per ton and forest residue prices generally include up to $2.00 per ton payable to forest landowners. There is also an additional cost to wood energy facilities to convert roundwood into chips. The combination of stumpage prices and additional processing costs for roundwood make in-woods chipping and grinding systems a more attractive option.

Nutrient removals increased as forest biomass removal intensity increased. While silvicultural applications are largely site-specific, fertilization of forest stands may be necessary to maintain site productivity following two-pass systems such as a clean chipping operation followed by its residue removal via a grinding operation. Fertilization may not be as necessary following conventional roundwood and whole-tree chipping operations. The effects of specific biomass harvesting systems on site productivity are an opportunity for future research.

3.6 ACKNOWLEDGEMENTS

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Table 3.1. Machine rate cost assumptions for machines in conventional roundwood, whole-tree chipping, clean chipping, screened grinding, and unscreened grinding systems.

Machine Rate Assumptions								
Assumption	**Feller-buncher**	**Skidder**	**Whole-tree chipper**	**Clean chipper**	**Knuckle boom loader**	**Screen**	**Grinder**	**Front-end Loader**
Purchase Price	$200,000	$180,000	$460,000	$600,000	$150,000	$265,000	$500,000	$185,000
Salvage (%)	20%	25%	30%	30%	30%	30%	30%	30%
Economic Life (years)	4	4	5	5	5	5	5	5
Maintenance & Repair (% of Depreciation)	100%	90%	90%	90%	90%	90%	90%	90%

Table 3.2. Ranges of variables by harvesting system used to determine cost sensitivity.

System	Moisture (%)	Ash (%)	Tract Size (acres)	Harvest Removal (tons/acre)	Residues (tons/pile)	Truck Payload (tons)
Whole-Tree Chipping (WTC)	30-55	0.5-1	20-100	20-80	na	20-30
Clean Chipping (CC)	50	0.5-1	20-100	20-80	na	20-30
Grinding Roundwood Residue (GRW)	30-55	2-10	na	na	50-250	15-30
Grinding Roundwood Residue with Screening (GRW/S)	30-55	0.5-3	na	na	50-250	10-20
Grinding Clean Chipping Residue (GCC)	30-55	5-30	na	na	50-250	15-30
Grinding Clean Chipping Residue (GCC) with Screening (GCC/S)	30-55	2-10	na	na	50-250	15-30
Roundwood (RW)	50	0.5-1	20-100	20-80	na	20-30

Table 3.3. Delivered cost estimates ($/mmBTU) by levels of ash content.

	Delivered Cost ($/mmBTU) by Harvesting System				
% Ash	**WTC**	**GRW**	**GRW/S**	**GCC**	**GCC/S**
0.5%	$4.39		$5.27		
1.0%	$4.41		$5.29		
1.5%			$5.32		
2.0%		$3.44	$5.35		$3.33
2.5%			$5.37		
3.0%			$5.40		
4.0%		$3.51			$3.40
5.0%				$2.87	
6.0%		$3.59			$3.47
8.0%		$3.66			$3.55
10.0%		$3.75		$3.03	$3.63
15.0%				$3.20	
20.0%				$3.40	
25.0%				$3.63	
30.0%				$3.89	

Table 3.4. Ranking (lowest=1) of delivered cost estimates ($/field ton and $/mmBTU) for biomass harvesting systems under likely conditions.

System	Delivered Cost ($/F-ton)	Rank	Delivered Cost ($/mmBTU)	Rank
GCC	$22.48	1	$2.71	1
GCC/S	$27.04	2	$3.05	3
GRW	$28.07	3	$2.77	2
WTC-50%	$28.94	4	$3.55	5
WTC-40%	$30.36	5	$3.10	4
RW	$31.07	6	$3.81	6
CC	$31.20	7	$3.82	7
GRW/S	$46.49	8	$4.20	8

Table 3.5. Nutrient content of materials produced by whole-tree chipping operations and screened and unscreened residue grinding operations processing roundwood and clean chipped residues.

Element	WTC-50%	WTC-40%	GRW	GRW/S	GCC	GCC/S
N (ppm)	1569	1517	2034	2180	2944	2796
P (ppm)	120	251	231	272	200	215
K (ppm)	832	795	951	1012	990	1042

Table 3.6. Estimated bone dry tons of biomass and pounds of N, P, and K removed per acre from forest biomass harvesting systems.

	RW	CC	WTC	GRW	GRW/S	GCC	GCC/S
BDT removed/ac	38	33	45	48	46	48	47
Element (lbs/ac)							
N	120	102	141	161	156	195	180
P	9	8	11	14	14	14	14
K	64	54	75	83	80	85	83

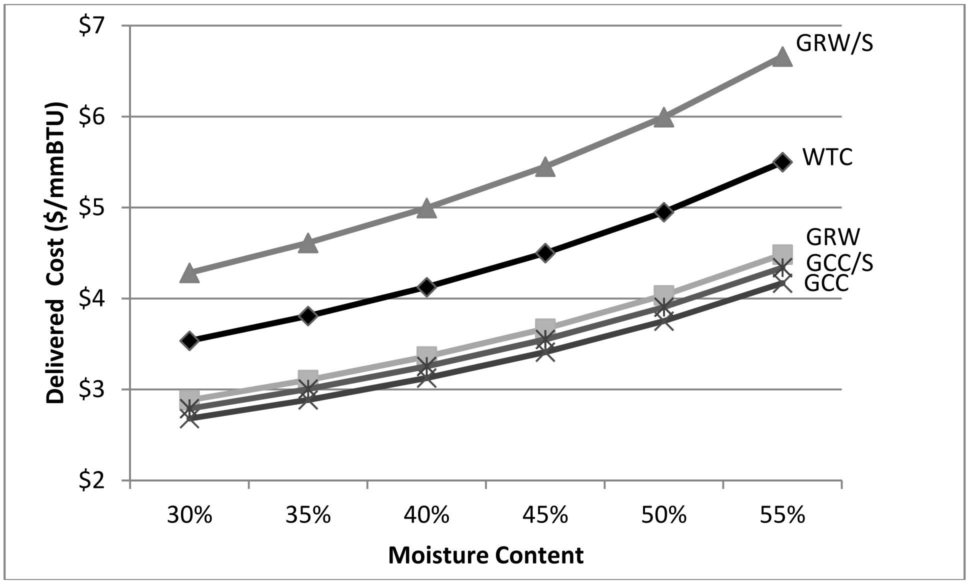

Figure 3.1. Delivered cost estimates ($/mmBTU) for increasing levels of moisture content.

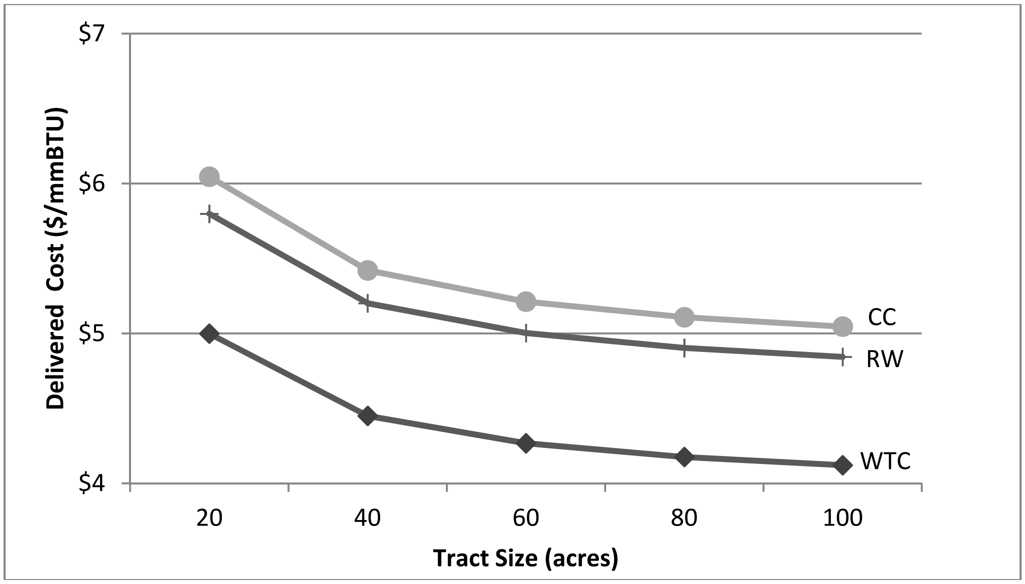

Figure 3.2. Delivered cost estimates ($/mmBTU) for increasing tract sizes.

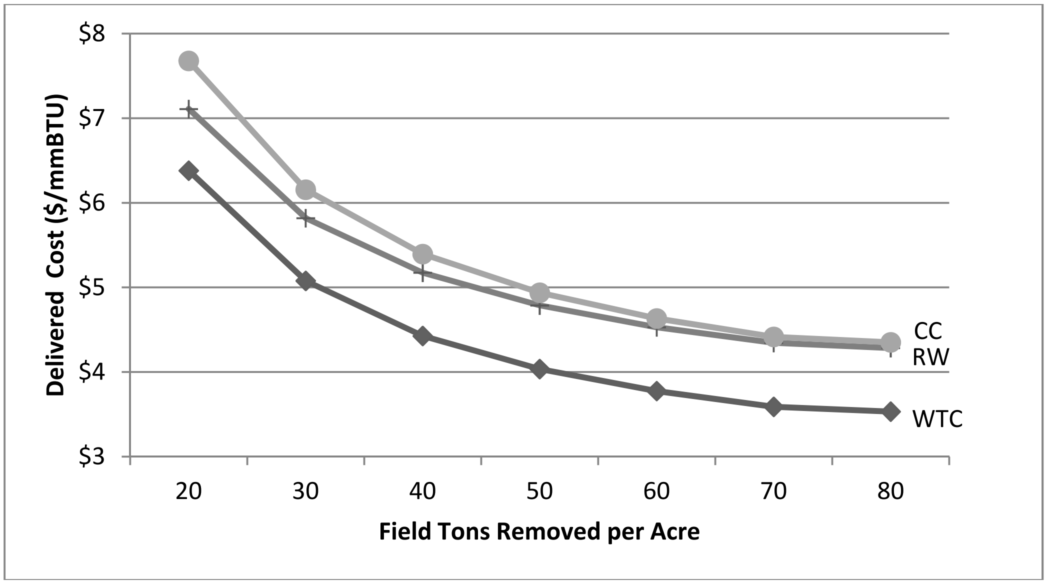

Figure 3.3. Delivered cost estimates ($/mmBTU) for increasing amounts of field tons removed per acre.

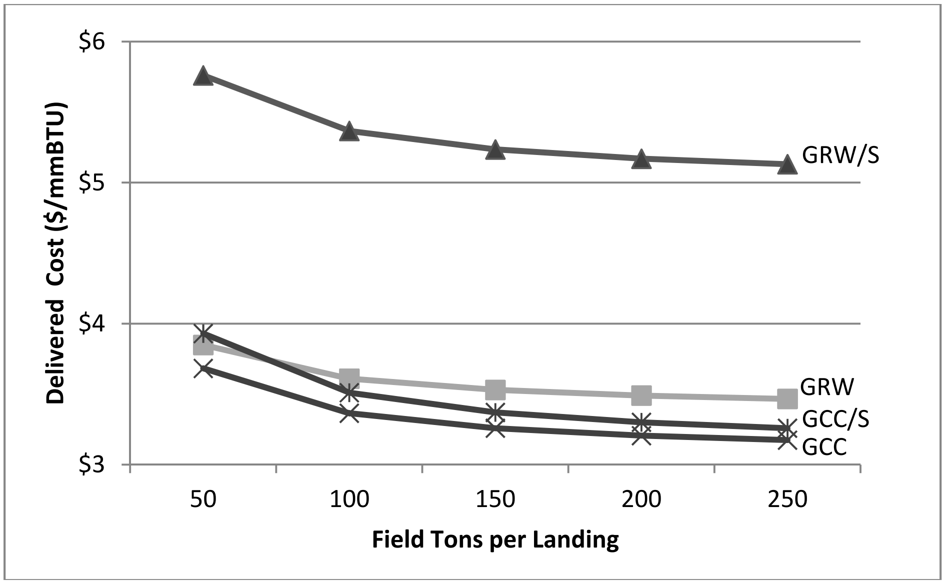

Figure 3.4. Delivered cost estimates ($/mmBTU) for increasing amounts of field tons per landing for grinding operations.

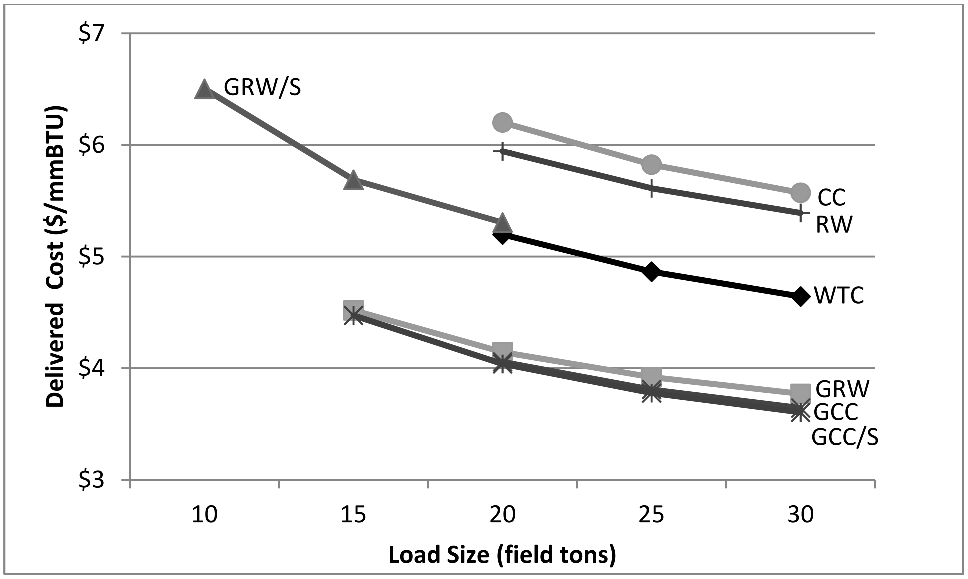

Figure 3.5. Delivered cost estimates ($/mmBTU) for increasing net tons of truck payload.

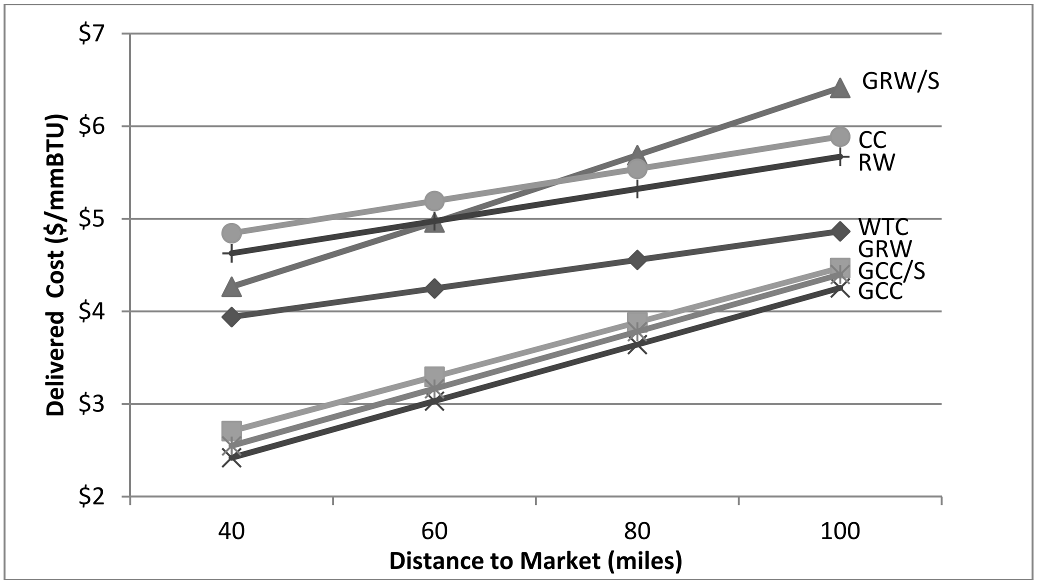

Figure 3.6. Delivered cost estimates ($/mmBTU) for increasing distance to market (miles).

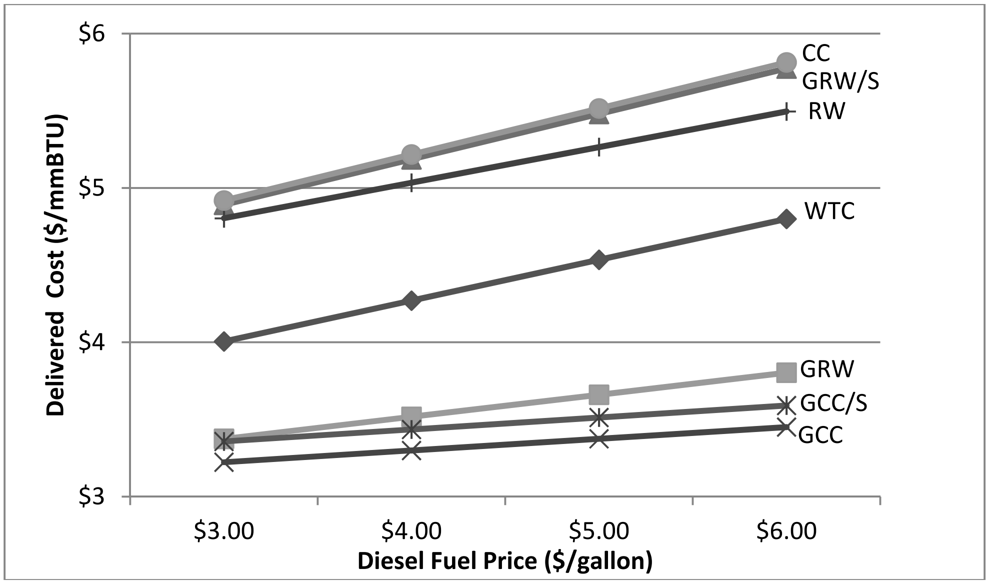

Figure 3.7. Delivered cost estimates ($/mmBTU) for increasing diesel fuel prices.

CHAPTER 4

SUMMARY

4.1 Transpirational Drying for Whole-Tree Chipping

Transpirational drying in late summer for periods of at least four weeks resulted in significant reductions in moisture content with no increase in ash content of the feedstock produced. The first four weeks of drying resulted in the greatest reduction in moisture content (from 53% to 43%) with the additional four weeks producing a smaller, but still significant reduction to 39%.

Chipping productivity as measured in field tons per hour was greatest for green material, but when compared in bone dry tons, the drying treatments produced slightly more than the green treatment (38 BDT/hr vs 34 BDT/hr). This result translated to widely different costs for material depending upon the unit of measure. The current convention in southern timber operations pays for material on a green ton basis, in which case significant savings are possible by harvesting and chipping green material. Much of this savings is due to transport cost, which is higher in dried material due to an inability to obtain full legal payloads. Examining material on a dry ton or mmBTU basis, however, changes the cost implications substantially. Dried material represented a reduction in cost on a BDT or energy content basis of roughly 15%. Improvements in trucking infrastructure could allow for full utilization of legal payloads for dried chips and further increase these cost savings.

Chip size distribution, ash content, nutrient content, and amount of foliage did not significantly differ among treatments. Bark content was significantly lower only for material dried for 8 weeks as compared to 4 weeks or freshly felled. This was likely due to bark slippage occurring during skidding and loading activities. While oven dry energy values for chips did not differ significantly between treatments, energy content on a field condition basis were over 30% higher for chips produced from material dried at least 4 weeks compared to green material.

Using transpirational drying in woody biomass harvesting operations may improve product quality by increasing energy values without increasing ash content. Trees that have been dried in the field to reduce moisture content cost more to harvest and transport than fresh material when based on a wet or field condition ton basis, but will cost less when based on energy content. Harvesting firms that deploy this strategy in a wood supply system that utilizes an energy content payment system, as opposed to a wet weight-based payment system, could take advantage of potential economic advantages of transpirationally drying stems in the field before processing and transportation.

4.2 Comparisons of Forest Biomass Harvesting Systems

Delivered costs associated with harvesting forest biomass for energy production increased as moisture and ash content increased. A whole-tree chipping operation was a very suitable harvesting system if wood energy facilities require biomass material to meet an ash content specification of less than 2%. The only grinding system capable of producing material with less than 2% ash was one grinding roundwood logging residue using a screen, but its delivered cost was almost $1.00 per mmBTU higher than that for a whole-tree chipping system due to severely limited truck payloads. The least costly ($2.87 per mmBTU) option where 5% ash content was acceptable was a system grinding clean chipped residue without screening.

Tract size had minimal effects on any operation until the acreage declined below 40 acres. Clean chipping and conventional roundwood systems were considerably more expensive than whole-tree chipping operations on all tract sizes.

Costs for roundwood and chipping systems sharply declined as the amount of biomass available on site increased, especially as field tons per acre removed increased from 20 to 50. Truck payload and haul distance had considerable effects on delivered costs. Costs were reduced as truck payload increased and haul distance decreased. Optimizing truck payload to meet legal weight limits by lowering tare weight and increasing trailer volume capacity is an opportunity for forest biomass harvesting system managers to achieve lower costs especially when dealing with drier material or screened roundwood grindings. Fuel price increases directly increase delivered costs and limit economical haul distances accordingly.

In the U.S. South forest biomass in roundwood form, though wetter than dried chips or grindings, is typically more abundant, has an established harvesting and transportation infrastructure, and is perceived to be cheaper than processed biomass to cut and haul to the first delivery point. However, delivered pulpwood prices also include stumpage of approximately $8.00 per ton and forest residue prices generally include up to $2.00 per ton payable to forest landowners. There is also an additional cost to wood energy facilities to convert roundwood into chips. The combination of stumpage prices and additional processing costs for roundwood make in-woods chipping and grinding systems a more attractive option.

Nutrient removals increased as forest biomass removal intensity increased. While silvicultural applications are largely site-specific, fertilization of forest stands may be necessary to maintain site productivity following two-pass systems such as a clean chipping operation followed by its residue removal via a grinding operation. Fertilization may not be as necessary following conventional roundwood and whole-tree chipping operations. The effects of specific biomass harvesting systems on site productivity are an opportunity for future research.

APPENDICES

Appendix A. Conventional Roundwood Logging Base Sensitivity Model

SYSTEM: ***Conventional Roundwood***

STAND & STOCK TABLE

DBH	Trees/Ac	Tons/Tree	Tons/Acre
6	64	0.094	5.99
8	46	0.219	10.09
10	30	0.417	12.52
12	20	0.524	10.49
14	10	0.910	9.10
16	4	1.204	4.82
18	2	1.605	3.21
20	2	2.408	4.82
22	0		0.00
24	0		0.00
TOTAL	178		80.00

GENERAL INFORMATION

Hours/Day =		8	
Days/Week =		5	
Weeks/Year =		50	
Scheduled Hrs/Year =		2000	
Support:			
Pkups	2	$1.00	per mile
Foreman		$5,000	per month
Overhead		$5,000	per month
Saws	1	$2,500	each
Pounds/cord =		5350	
Pounds/tree =		899	
Quad. Mean DBH =		9.35	

Tract Size =	60	Acres
Moving time =	5	Hours
Move Distance =	40	Miles
Distance home =	40	Miles

Roads to be Built:

Type	Miles/#	$/mi
Permanent	0	$10,000
Temporary	0.5	$3,000
Push-out	1	$1,500
Entrances	2	$2,000

Mill Quota (Tons per Week) = 9999

Machine Productivity

FELLING

BA/accum, sqft= 0.6

DBH	Min/T	Hr/Ac
6	0.29	0.31
8	0.34	0.26
10	0.38	0.19
12	0.43	0.14
14	0.47	0.08
16	0.52	0.03
18	2.51	0.08
20	2.88	0.10
22	3.27	0.00
24	3.67	0.00
TOTAL		1.20
Tons/PMH =		66.90
Oper Effy =		1.0

SKIDDING

Avg Skid Distance (feet) =	880
Avg Turn Volume (tons) =	2.75
Time per Turn (minutes) =	5.61
Tons/PMH	29.39
Oper Effy	1.0

LOADING

Prep. Time =	12.00
Trees/Load =	56
Cold (1=Yes) =	1
Loading Time =	20.00
Time per Load (minutes) =	32.00
Tons/PMH	75.00
Oper Effy	1.0

HAULING

Haul Distance (miles) =	60
Average Speed (mph) =	40
Load Size (tons) =	25.0
Unloading Time (minutes) =	30
Loading Time (minutes) =	30
Round Trip Time (hours) =	4.00
Tons/PMH	6.25
Oper Effy	1.0

Machine Cost

	Felling	Skidding	Loading		Hauling
D ($/SMH)=	20.00	16.88	10.50	Haul Rate	1
II&T ($/SMH)=	10.50	9.70	8.10	($/ton-mile) =	0.13
F&L ($/PMH)=	44.54	42.52	40.49	Minimum Haul	
M&R ($/PMH)=	23.53	17.87	11.12	(miles) =	40
Labor($/SMH)=	18.00	18.00	18.00		
Labor overhead (%)=	40%	40%	40%		
Avail.(%) =	85	85	85		90
Number =	1	2	1		6.0

Function	Tons /PMH	Avail%	Tons/SMH One	Tons/SMH All	Utiliz%	Cost per SMH Fixed	Cost per SMH Oper	Cost per SMH Labor	Cost per SMH Total	Cost $/Ton
Felling	66.90	85	56.86	56.86	75	30.50	50.85	18.07	99.42	1.99
Skidding	29.39	85	24.98	49.97	85	53.16	102.65	36.14	191.95	3.84
Loading	75.00	85	63.75	63.75	67	18.60	34.39	18.07	71.06	1.42
Hauling	6.25	90	5.63		133					8.20
Support	Pickups, Chainsaws, Foreman, and Overhead									1.63
Road Work										1.46
Moving	5.00 hours spent moving men & equipment to tract									0.19

System Rate (tons/SMH) =	49.97	
Weekly production (tons, truck loads) =	1999	80
Days required to cut tract =	13	

Onboard Cost/Ton:	10.52
Cut & haul Cost/Ton:	18.72
Cut & Haul Cost per mmBTU =	2.30

Minimum haul distance (miles)	40
Minimum haul rate ($/ton-mile)	$0.14
Incremental haul rate ($/ton-mile)	$0.13
Highway diesel price ($/gallon)	$4.00
Payload assumed in these rates	25

Assumed payload (tons)	25.0
Assumed fuel mileage (mpg)	5.5
Assumed diesel price ($/gallon)	$4.00

Base Case

Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
60	$8.20	$205.00	$87.27	43%	$0.00	$8.20

Appendix B. Clean Chipping Base Sensitivity Model

SYSTEM: ***Clean Chipping***

HARVESTED STAND INFORMATION	
Quad. Mean DBH =	8
Tons per acre removed =	80
Pred. Height =	***45.46***
Pred. Whole Tree Wt. =	***0.234***
Trees per acre =	***342.15***
% Moisture Content =	0.50
% Ash Content =	0.003
mmBTU/Dry Ton =	***16.4*** (8202)

GENERAL INFORMATION			
Hours/Day =	***8***		
Days/Week =	***5***		
Weeks/Year =	***50***		
Scheduled Hrs/Year =	2000		
Support:			
Pkups	***2***	***$1.00***	per mile
Foreman		***$5,000***	per month
Overhead		***$5,000***	per month
Saws	***1***	***$2,500***	each
Pounds/cord =		***5350***	
Pounds/tree =		468	

Tract Size =	60	Acres
Moving time =	***8***	Hours
Move Distance =	***40***	Miles
Distance home =	***40***	Miles
Roads to be Built:		
Tracts <= 40 acres	***$0.00***	per ton
Other tracts	***$0.00***	per ton
Profit	***$1.00***	per ton
Mill Quota (Tons per Week) =	***9999***	

Machine Productivity

FELLING		SKIDDING		LOADING		CHIPPING		HAULING	
BA/felled bunch (sqft) =	***0.6***	Avg Skid Distance (feet) =	***660***			Prep. Time, min. =	***5***	Load Size (tons) =	25.0
Felling time, PMH/acre	***1.56***	Avg Turn Volume (tons) =	***2.00***			Chipping time, min. =	***20***	Loading Time (minutes) =	25
		Time per Turn (minutes) =	4.89			Time per Load (minutes) =	25.00	Round Trip Time (hours) =	3.92
Tons/PMH =	51.24	Tons/PMH =	24.54	Tons/PMH =	75.00	Tons/PMH =	75.00	Tons/hour	6.38
Oper Effy =	***1.0***	Oper Effy =	***1.0***	Oper Effy =	***1.2***	Oper Effy =	***1.0***	Oper Effy =	***1.0***
								Haul Distance (miles) =	60
								Average Speed (mph) =	***40***
								Unloading Time (minutes) =	***30***

Machine Cost

	FELLING	SKIDDING	LOADING	CHIPPING	HAULING	
D ($/SMH)=	***20.00***	***16.88***	***10.50***	***42.00***	Haul Rate ($/ton-mile) =	***$0.13***
II&T ($/SMH)=	***10.50***	***9.70***	***8.10***	***32.40***		
F&L ($/PMH)=	***44.54***	***42.52***	***40.49***	***161.97***	Minimum Haul (miles) =	***40***
M&R ($/PMH)=	***23.53***	***17.87***	***11.12***	***44.47***		
Labor($/SMH)=	***18.00***	***18.00***	***18.00***	***0.00***		
Labor overhead (%)=	***40%***	***40%***	***40%***	***40%***		
Avail.(%) =	***85%***	***85%***	***85%***	***85%***	Avail.(%) =	***90%***
Number =	***1***	***2***	***1***	***1***	Number =	***4***

Function	Tons /PMH	Avail%	Tons/SMH One	Tons/SMH All	Utiliz%	Cost per SMH Fixed	Cost per SMH Oper	Cost per SMH Labor	Cost per SMH Total	Cost $/Ton
Felling	51.24	1	43.55	43.55	45%	30.50	30.53	25.20	86.23	3.75
Skidding	24.54	1	20.86	41.72	47%	53.16	56.55	50.40	160.10	6.97
Loading	90.00	1	76.50	76.50	26%	18.60	13.18	25.20	56.98	2.48
Chipping	75.00	1	63.75	63.75	31%	74.40	63.25	0.00	137.65	5.99
Hauling	6.38	1	5.74	22.98	90%					7.33
Support	Pickups, Chainsaws, Foreman, and Overhead									3.54
Road Work										0.00
Moving	8.00 hours spent moving men & equipment to tract									0.47
Profit										1.00

System Rate (tons/SMH) =	22.98					
Weekly production (tons, truck loads) =	919	37	Cut & Haul Cost per Field Ton =	31.52	$/BDT	63.04
Days required to cut tract =	27		Cut & Load Cost per Field Ton =	24.19	$/BDT	48.39
			Cut & Haul Cost per mmBTU =	3.85		
			Cut & Load Cost per mmBTU =	2.96		

Minimum haul distance (miles)	40	Assumed payload (tons)	25.0
Minimum haul rate ($/ton-mile)	$0.14	Assumed fuel mileage (mpg)	5.5
Incremental haul rate ($/ton-mile)	$0.13	Assumed diesel price ($/gallon)	$3.00
Highway diesel price ($/gallon)	$4.00		
Payload assumed in these rates	25		

Base Case

Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
60	$8.20	$205.00	$87.27	43%	-$21.82	$7.33

Appendix C. Whole-Tree Chipping (50% MC) Base Sensitivity Model

SYSTEM: ***Whole Tree Chipping 5(***

HARVESTED STAND INFORMATION		GENERAL INFORMATION				
		Hours/Day =	*8*		Tract Size =	60 Acres
Quad. Mean DBH =	8	Days/Week =	*5*		Moving time =	*8* Hours
		Weeks/Year =	*50*		Move Distance =	*40* Miles
Tons per acre removed =	80	Scheduled Hrs/Year =	2000		Distance home =	*40* Miles
		Support:			Roads to be Built:	
Pred. Height =	*45.46*	Pkups	*2*	*$1.00* per mile	Tracts <= 40 acres	*$0.00* per ton
Pred. Whole Tree Wt. =	*0.234*	Foreman		*$5,000* per month	Other tracts	*$0.00* per ton
		Overhead		*$5,000* per month		
Trees per acre =	*342.15*	Saws	*1*	*$2,500* each	Profit	*$1.00* per ton
		Pounds/cord =	*5350*			
% Moisture Content =	0.50	Pounds/tree =	468			
% Ash Content =	0.006					
mmBTU/Dry Ton =	*16.4*	8202				
					Mill Quota (Tons per Week) =	*9999*

Machine Productivity

FELLING		SKIDDING		LOADING		CHIPPING		HAULING	
BA/felled bunch (sqft) =	*0.6*	Avg Skid Distance (feet) =	*660*			Prep. Time, min. =	*5*	Load Size (tons) =	25.0
Felling time, PMH/acre	*1.56*	Avg Turn Volume (tons) =	*2.00*			Chipping time, min. =	*20*	Loading Time (minutes) =	25
		Time per Turn (minutes) =	4.89			Time per Load (minutes) =	25.00	Round Trip Time (hours) =	5.92
Tons/PMH =	51.24	Tons/PMH =	24.54	Tons/PMH =	75.00	Tons/PMH =	75.00	Tons/hour	4.23
Oper Effy =	*1.0*	Oper Effy =	*1.0*	Oper Effy =	*1.2*	Oper Effy =	*1.0*	Oper Effy =	*1.0*
								Haul Distance (miles) =	100
								Average Speed (mph) =	*40*
								Unloading Time (minutes) =	*30*

Machine Cost

FELLING		SKIDDING		LOADING		CHIPPING			
D ($/SMH)=	*20.00*	D ($/SMH)=	*16.88*	D ($/SMH)=	*10.50*	D ($/SMH)=	*32.20*	Haul Rate ($/ton-mile) =	*$0.13*
II&T ($/SMH)=	*10.50*	II&T ($/SMH)=	*9.70*	II&T ($/SMH)=	*8.10*	II&T ($/SMH)=	*24.84*		
F&L ($/PMH)=	*44.54*	F&L ($/PMH)=	*42.52*	F&L ($/PMH)=	*40.49*	F&L ($/PMH)=	*161.97*	Minimum Haul (miles) =	*40*
M&R ($/PMH)=	*23.53*	M&R ($/PMH)=	*17.87*	M&R ($/PMH)=	*11.12*	M&R ($/PMH)=	*34.09*		
Labor($/SMH)=	*18.00*	Labor($/SMH)=	*18.00*	Labor($/SMH)=	*18.00*	Labor($/SMH)=	*0.00*		
Labor overhead (%)=	*40%*	Labor overhead (%)=	*40%*	Labor overhead (%)=	*40%*	Labor overhead (%)=	*40%*		
Avail.(%) =	*85%*	Avail.(%) =	*85%*	Avail.(%) =	*85%*	Avail.(%) =	*85%*	Avail.(%) =	*90%*
Number =	*1*	Number =	*2*	Number =	*1*	Number =	*1*	Number =	*4*

Function	Tons /PMH	Avail%	Tons/SMH One	All	Utiliz%	Cost per SMH Fixed	Oper	Labor	Total	Cost $/Ton
Felling	51.24	1	43.55	43.55	30%	30.50	20.21	25.20	75.91	4.99
Skidding	24.54	1	20.86	41.72	31%	53.16	37.43	50.40	140.99	9.27
Loading	90.00	1	76.50	76.50	17%	18.60	8.72	25.20	52.52	3.45
Chipping	75.00	1	63.75	63.75	20%	57.04	39.77	0.00	96.81	6.36
Hauling	4.23	1	3.80	15.21	90%					13.40
Support	Pickups, Chainsaws, Foreman, and Overhead									5.34
Road Work										0.00
Moving	8.00 hours spent moving men & equipment to tract									0.44
Profit										1.00

System Rate (tons/SMH) =	15.21					
Weekly production (tons, truck loads) =	608	24	Cut & Haul Cost per Field Ton =	44.26	$/BDT	88.51
Days required to cut tract =	40		Cut & Load Cost per Field Ton =	30.86	$/BDT	61.71
			Cut & Haul Cost per mmBTU =	5.43		
			Cut & Load Cost per mmBTU =	3.78		

Minimum haul distance (miles)	40	Assumed payload (tons)	25.0
Minimum haul rate ($/ton-mile)	$0.14	Assumed fuel mileage (mpg)	5.5
Incremental haul rate ($/ton-mile)	$0.13	Assumed diesel price ($/gallon)	$4.00
Highway diesel price ($/gallon)	$4.00		
Payload assumed in these rates	25		

Base Case

Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
100	$13.40	$335.00	$145.45	43%	$0.00	$13.40

Appendix D. Whole-Tree Chipping (40% MC) Base Sensitivity Model

SYSTEM: ***Whole Tree Chipping 40%*** MC

HARVESTED STAND INFORMATION		GENERAL INFORMATION				Tract Size =	100	Acres
		Hours/Day =	*8*			Moving time =	*8*	Hours
Quad. Mean DBH =	8	Days/Week =	*5*			Move Distance =	*40*	Miles
		Weeks/Year =	*50*			Distance home =	*40*	Miles
Tons per acre removed =	80	Scheduled Hrs/Year =		2000				
		Support:				Roads to be Built:		
Pred. Height =	*45.46*	Pkups	*2*	*$1.00*	per mile	Tracts <= 40 acres	*$0.00*	per ton
Pred. Whole Tree Wt. =	*0.234*	Foreman		*$5,000*	per month	Other tracts	*$0.00*	per ton
		Overhead		*$5,000*	per month			
Trees per acre =	*342.15*	Saws	*1*	*$2,500*	each	Profit	*$1.00*	per ton
		Pounds/cord =		*5350*				
% Moisture Content =	0.55	Pounds/tree =		468				
% Ash Content =	0.01							
mmBTU/Dry Ton =	*16.4*	8202						
						Mill Quota (Tons per Week) =	*9999*	

Machine Productivity

FELLING		SKIDDING		LOADING		CHIPPING		HAULING	
BA/felled bunch		Avg Skid Distance				Prep. Time, min. =	*5*	Load Size	
(sqft) =	*0.6*	(feet) =	*660*			Chipping time, min. =	*22*	(tons) =	30.0
		Avg Turn Volume						Loading Time	
Felling time, PMH/acre	*1.56*	(tons) =	*2.00*					(minutes) =	27
		Time per Turn				Time per Load			
		(minutes) =	4.89			(minutes) =	27.00	Round Trip Time	
								(hours) =	5.95
Tons/PMH =	51.24	Tons/PMH =	24.54	Tons/PMH =	81.82	Tons/PMH =	81.82	Tons/hour	5.04
Oper Effy =	*1.0*	Oper Effy =	*1.0*	Oper Effy =	*1.2*	Oper Effy =	*1.0*	Oper Effy =	*1.0*
								Haul Distance	
								(miles) =	100
								Average Speed	
								(mph) =	*40*
								Unloading Time	
								(minutes) =	*30*

Machine Cost

FELLING		SKIDDING		LOADING		CHIPPING			
D ($/SMH)=	*20.00*	D ($/SMH)=	*16.88*	D ($/SMH)=	*10.50*	D ($/SMH)=	*32.20*	Haul Rate	
II&T ($/SMH)=	*10.50*	II&T ($/SMH)=	*9.70*	II&T ($/SMH)=	*8.10*	II&T ($/SMH)=	*24.84*	($/ton-mile) =	*$0.13*
F&L ($/PMH)=	*44.54*	F&L ($/PMH)=	*42.52*	F&L ($/PMH)=	*40.49*	F&L ($/PMH)=	*161.97*	Minimum Haul	
M&R ($/PMH)=	*23.53*	M&R ($/PMH)=	*17.87*	M&R ($/PMH)=	*11.12*	M&R ($/PMH)=	*34.09*	(miles) =	*40*
Labor($/SMH)=	*18.00*	Labor($/SMH)=	*18.00*	Labor($/SMH)=	*18.00*	Labor($/SMH)=	*0.00*		
Labor overhead (%)=	*40%*	Labor overhead (%)=	*40%*	Labor overhead (%)=	*40%*	Labor overhead (%)=	*40%*		
Avail.(%) =	*85%*	Avail.(%) =	*85%*	Avail.(%) =	*85%*	Avail.(%) =	*85%*	Avail.(%) =	*90%*
Number =	*1*	Number =	*2*	Number =	*1*	Number =	*1*	Number =	*4*

Function	Tons /PMH	Avail%	Tons/SMH One	All	Utiliz%	Cost per SMH Fixed	Oper	Labor	Total	Cost $/Ton
Felling	51.24	1	43.55	43.55	35%	30.50	24.11	25.20	79.81	4.40
Skidding	24.54	1	20.86	41.72	37%	53.16	44.67	50.40	148.22	8.17
Loading	98.18	1	83.45	83.45	18%	18.60	9.54	25.20	53.34	2.94
Chipping	81.82	1	69.55	69.55	22%	57.04	43.50	0.00	100.54	5.54
Hauling	5.04	1	4.54	18.15	90%					11.17
Support	Pickups, Chainsaws, Foreman, and Overhead									4.48
Road Work										0.00
Moving	8.00 hours spent moving men & equipment to tract									0.26
Profit										1.00

System Rate (tons/SMH) =	18.15		Cut & Haul Cost per Field Ton =	37.95	$/BDT	84.33
Weekly production (tons, truck loads) =	726	24	Cut & Load Cost per Field Ton =	26.78	$/BDT	59.51
Days required to cut tract =	56					
			Cut & Haul Cost per mmBTU =	5.19		
			Cut & Load Cost per mmBTU =	3.66		

Minimum haul distance (miles)	40	Assumed payload (tons)	30
Minimum haul rate ($/ton-mile)	$0.14	Assumed fuel mileage (mpg)	5.5
Incremental haul rate ($/ton-mile)	$0.13	Assumed diesel price ($/gallon)	$4.00
Highway diesel price ($/gallon)	$4.00		
Payload assumed in these rates	25		

	Base Case					
Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
100	$13.40	$335.00	$145.45	43%	$0.00	$11.17

Appendix E. Roundwood Residue Grinding Base Sensitivity Model

SYSTEM: Unscreened Large Grinder With 8 Week Roundwood Debris

HARVESTED STAND INFORMATION		GENERAL INFORMATION						
Tons per grinder setup =	150	Hours/Day =	10		Moving time =	8	Hours	
		Days/Week =	5		Move Distance =	40	Miles	
# Setups per site =	3	Weeks/Year =	50		Distance home =	40	Miles	
		Scheduled Hrs/Year =	2500					
Avg. Move Time		Support:			Roads to be Built:			
Between Setups (min.)	29	Pkups	1	$1.00 per mile	Tracts <= 40 acres	$0.00	per ton	
		Deckhand		$3,200 per month	Other tracts	$0.00	per ton	
% Moisture Content =	0.30	Overhead		$5,000 per month				
		Saws	0	$2,500 each	Profit	$1.00	per ton	
% Ash Content =	0.04							
mmBTU/Dry Ton =	15.1							
Residue Type	0							
(0=Roundwood 1= Clean Chip Residue)								
Grinder Size	Large							
Debris Age, weeks	8							
Screened	0							
(0=No, 1=Yes)					Mill Quota (Tons per Week) =	9999		

Machine Productivity

FRONT-END LOADER		GRINDER		SCREEN		HAULING	
Avg. Tons/Bite	0.63	Prep. Time, min. =	5			Load Size	
		Grinding time, min. =	34.9			(tons) =	25
Bites/Hour	65.4					Loading Time	
						(minutes) =	40
		Time per Load				Round Trip Time	
		(minutes) =	39.85			(hours) =	4.16
						Tons/hour =	6.00
Tons/PMH =	40.99	Tons/PMH =	43.04	Tons/PMH =	43.04		
Oper Effy =	1.1	Oper Effy =	1.1	Oper Effy =	1.0	Oper Effy =	1.0
						Haul Distance	
						(miles) =	60
						Average Speed	
						(mph) =	40
						Unloading Time	
Machine Cost						(minutes) =	30
D ($/SMH)=	12.95	D ($/SMH)=	35.00	D ($/SMH)=	18.55	Haul Rate	
II&T ($/SMH)=	9.99	II&T ($/SMH)=	27.00	II&T ($/SMH)=	14.31	($/ton-mile) =	$0.13
F&L ($/PMH)=	45.55	F&L ($/PMH)=	157.92	F&L ($/PMH)=	35.23	Minimum Haul	
M&R ($/PMH)=	13.71	M&R ($/PMH)=	37.06	M&R ($/PMH)=	19.64	(miles) =	40
Labor($/SMH)=	25.20	Labor($/SMH)=	0.00	Labor($/SMH)=	0.00		
Labor overhead (%)=	40%	Labor overhead (%)=	40%	Labor overhead (%)=	40%		
Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	90
Number =	1	Number =	1	Number =	1	Number =	4

	Tons		Tons/SMH			Cost per SMH				Cost
Function	/PMH	Avail%	One	All	Utiliz%	Fixed	Oper	Labor	Total	$/Ton
Front End	43.04	85	36.58	36.58	50	22.94	29.76	25.30	78.00	3.61
Grinding	45.19	85	38.41	38.41	48	62.00	93.25	0.00	155.25	7.18
Screen	43.04	0	0.00	0.00	50	0.00	0.00	0.00	0.00	0.00
Hauling	6.00	90	5.40	21.61	90					8.20
Support	Pickups, Chainsaws, Deckhand, and Overhead									2.19
Road Work										0.00
Moving Setup										0.13
Moving Tracts	8.00 hours spent moving men & equipment to tract									1.14
Profit										1.00

System Rate (tons/SMH) =	21.61		Cut & Haul Cost per Field Ton =	23.45
Weekly production (tons, truck loads) =	1081	43	Cut & Load Cost per Field Ton =	15.25
Days required to cut tract =	3			
			Cut & Haul Cost per ODT =	33.50
			Cut & Load Cost per ODT =	21.79
			Cut & Haul Cost per mmBTU =	2.31
			Cut & Load Cost per mmBTU =	1.51

Minimum haul distance (miles)	40	Assumed payload (tons)	25
Minimum haul rate ($/ton-mile)	$0.14	Assumed fuel mileage (mpg)	5.5
Incremental haul rate ($/ton-mile)	$0.13	Assumed diesel price ($/gallon)	$4.00
Highway diesel price ($/gallon)	$4.00		
Payload assumed in these rates	25		

Base Case

Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
60	$8.20	$205.00	$87.27	43%	$0.00	$8.20

Appendix F. Roundwood Residue Grinding (Screened) Base Sensitivity Model

SYSTEM: Screened Large Grinder With 8 Week Roundwood Debris

HARVESTED STAND INFORMATION		GENERAL INFORMATION					
Tons per grinder setup =	150	Hours/Day =	10		Moving time =	8	Hours
		Days/Week =	5		Move Distance =	40	Miles
# Setups per site =	3	Weeks/Year =	50		Distance home =	40	Miles
		Scheduled Hrs/Year =	2500				
Avg. Move Time		Support:			Roads to be Built:		
Between Setups (min.)	85	Pkups	1	$1.00 per mile	Tracts <= 40 acres	$0.00	per ton
		Deckhand		$3,200 per month	Other tracts	$0.00	per ton
% Moisture Content =	0.30	Overhead		$5,000 per month			
		Saws	0	$2,500 each	Profit	$1.00	per ton
% Ash Content =	0.014						
mmBTU/Dry Ton =	16.0						
Residue Type	0						
(0=Roundwood 1= Clean Chip Residue)							
Grinder Size	Large						
Debris Age, weeks	8						
Screened	1						
(0=No, 1=Yes)					Mill Quota (Tons per Week) =	9999	

Machine Productivity

FRONT-END LOADER		GRINDER		SCREEN		HAULING	
Avg. Tons/Bite	0.41	Prep. Time, min. =	5			Load Size (tons) =	25
		Grinding time, min. =	67.5				
Bites/Hour	51.4					Loading Time (minutes) =	72
		Time per Load (minutes) =	72.47			Round Trip Time (hours) =	4.71
						Tons/hour =	5.31
Tons/PMH =	21.17	Tons/PMH =	22.23	Tons/PMH =	22.23		
Oper Effy =	1.1	Oper Effy =	1.1	Oper Effy =	1.0	Oper Effy =	1.0
						Haul Distance (miles) =	60
						Average Speed (mph) =	40
Machine Cost						Unloading Time (minutes) =	30
D ($/SMH)=	12.95	D ($/SMH)=	35.00	D ($/SMH)=	18.55	Haul Rate ($/ton-mile) =	$0.13
II&T ($/SMH)=	9.99	II&T ($/SMH)=	27.00	II&T ($/SMH)=	14.31		
F&L ($/PMH)=	45.55	F&L ($/PMH)=	157.92	F&L ($/PMH)=	35.23	Minimum Haul (miles) =	40
M&R ($/PMH)=	13.71	M&R ($/PMH)=	37.06	M&R ($/PMH)=	19.64		
Labor($/SMH)=	25.20	Labor($/SMH)=	0.00	Labor($/SMH)=	0.00		
Labor overhead (%)=	40%	Labor overhead (%)=	40%	Labor overhead (%)=	40%		
Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	90
Number =	1	Number =	1	Number =	1	Number =	4

Function	Tons /PMH	Avail%	Tons/SMH One	Tons/SMH All	Utiliz%	Cost per SMH Fixed	Cost per SMH Oper	Cost per SMH Labor	Cost per SMH Total	Cost $/Ton
Front End	22.23	85	18.90	18.90	85	22.94	50.38	25.30	98.62	5.22
Grinding	23.34	85	19.84	19.84	81	62.00	157.84	0.00	219.84	11.63
Screen	22.23	85	18.90	18.90	85	32.86	46.64	0.00	79.50	4.21
Hauling	5.31	90	4.78	19.12	89					8.20
Support	Pickups, Chainsaws, Deckhand, and Overhead									2.51
Road Work										0.00
Moving Setup										0.60
Moving Tracts	8.00 hours spent moving men & equipment to tract									1.72
Profit										1.00

System Rate (tons/SMH) =	18.90				
Weekly production (tons, truck loads) =	945	38		Cut & Haul Cost per Field Ton =	35.08
Days required to cut tract =	3			Cut & Load Cost per Field Ton =	26.88
				Cut & Haul Cost per ODT =	50.12
				Cut & Load Cost per ODT =	38.40
				Cut & Haul Cost per mmBTU =	3.17
				Cut & Load Cost per mmBTU =	2.43

Minimum haul distance (miles)	40	Assumed payload (tons)	25
Minimum haul rate ($/ton-mile)	$0.14	Assumed fuel mileage (mpg)	5.5
Incremental haul rate ($/ton-mile)	$0.13	Assumed diesel price ($/gallon)	$4.00
Highway diesel price ($/gallon)	$4.00		
Payload assumed in these rates	25		

Base Case

Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
60	$8.20	$205.00	$87.27	43%	$0.00	$8.20

Appendix G. Clean Chip Residue Grinding Base Sensitivity Model

SYSTEM: G1C8 Screened Large Grinder With 8 Week Clean Chipped Debris

HARVESTED STAND INFORMATION		GENERAL INFORMATION							
Tons per grinder setup =	150	Hours/Day =	10			Moving time =	8	Hours	
		Days/Week =	5			Move Distance =	40	Miles	
# Setups per site =	3	Weeks/Year =	50			Distance home =	40	Miles	
		Scheduled Hrs/Year =	2500						
Avg. Move Time		Support:				Roads to be Built:			
Between Setups (min.)	85	Pkups	1	$1.00	per mile	Tracts <= 40 acres	$0.00	per ton	
		Deckhand		$3,200	per month	Other tracts	$0.00	per ton	
% Moisture Content =	0.40	Overhead		$5,000	per month				
		Saws	0	$2,500	each	Profit	$1.00	per ton	
% Ash Content =	0.12								
mmBTU/Dry Ton =	15.7								
Residue Type (0=Roundwood 1= Clean Chip Residue)	1								
Grinder Size	Large								
Debris Age, weeks	8								
Screened (0=No, 1=Yes)	1					Mill Quota (Tons per Week) =	9999		

Machine Productivity

FRONT-END LOADER		GRINDER		SCREEN		HAULING	
Avg. Tons/Bite	1.02	Prep. Time, min. =	5			Load Size (tons) =	25
		Grinding time, min. =	16.7				
Bites/Hour	83.3					Loading Time (minutes) =	22
		Time per Load (minutes) =	21.73			Round Trip Time (hours) =	3.86
						Tons/hour =	6.47
Tons/PMH =	85.41	Tons/PMH =	89.68	Tons/PMH =	89.68		
Oper Effy =	1.1	Oper Effy =	1.1	Oper Effy =	1.0	Oper Effy =	1.0
						Haul Distance (miles) =	60
						Average Speed (mph) =	40
Machine Cost						Unloading Time (minutes) =	30
D ($/SMH)=	12.95	D ($/SMH)=	35.00	D ($/SMH)=	0.00	Haul Rate ($/ton-mile) =	$0.13
II&T ($/SMH)=	9.99	II&T ($/SMH)=	27.00	II&T ($/SMH)=	0.00		
F&L ($/PMH)=	45.55	F&L ($/PMH)=	157.92	F&L ($/PMH)=	0.00	Minimum Haul (miles) =	40
M&R ($/PMH)=	13.71	M&R ($/PMH)=	37.06	M&R ($/PMH)=	0.00		
Labor($/SMH)=	25.20	Labor($/SMH)=	0.00	Labor($/SMH)=	0.00		
Labor overhead (%)=	40%	Labor overhead (%)=	40%	Labor overhead (%)=	40%		
Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	90
Number =	1	Number =	1	Number =	1	Number =	4

Function	Tons /PMH	Avail%	Tons/SMH One	Tons/SMH All	Utiliz%	Cost per SMH Fixed	Cost per SMH Oper	Cost per SMH Labor	Cost per SMH Total	Cost $/Ton
Front End	89.68	85	76.23	76.23	26	22.94	15.40	25.30	63.64	2.73
Grinding	94.16	85	80.04	80.04	25	62.00	48.25	0.00	110.25	4.73
Screen	89.68	85	76.23	76.23	26	0.00	0.00	0.00	0.00	0.00
Hauling	6.47	90	5.83	23.30	90					8.20
Support	Pickups, Chainsaws, Deckhand, and Overhead									2.03
Road Work										0.00
Moving Setup										0.39
Moving Tracts	8.00 hours spent moving men & equipment to tract									1.14
Profit										1.00

System Rate (tons/SMH) =	23.30		Cut & Haul Cost per Field Ton =	20.22
Weekly production (tons, truck loads) =	1165	47	Cut & Load Cost per Field Ton =	12.02
Days required to cut tract =	3		Cut & Haul Cost per ODT =	33.70
			Cut & Load Cost per ODT =	20.04
			Cut & Haul Cost per mmBTU =	2.43
			Cut & Load Cost per mmBTU =	1.45

Minimum haul distance (miles)	40		Assumed payload (tons)	25
Minimum haul rate ($/ton-mile)	$0.14		Assumed fuel mileage (mpg)	5.5
Incremental haul rate ($/ton-mile)	$0.13		Assumed diesel price ($/gallon)	$4.00
Highway diesel price ($/gallon)	$4.00			
Payload assumed in these rates	25			

Base Case

Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
60	$8.20	$205.00	$87.27	43%	$0.00	$8.20

Appendix H. Clean Chip Residue Grinding (Screened) Base Sensitivity Model

SYSTEM: Screened Large Grinder With 8 Week Clean Chipped Debris

HARVESTED STAND INFORMATION		GENERAL INFORMATION					
Tons per grinder setup =	150	Hours/Day =	10		Moving time =	8	Hours
		Days/Week =	5		Move Distance =	40	Miles
# Setups per site =	3	Weeks/Year =	50		Distance home =	40	Miles
		Scheduled Hrs/Year =	2500				
Avg. Move Time		Support:			Roads to be Built:		
Between Setups (min.)	85	Pkups	1	$1.00 per mile	Tracts <= 40 acres	$0.00	per ton
		Deckhand		$3,200 per month	Other tracts	$0.00	per ton
% Moisture Content =	0.40	Overhead		$5,000 per month			
		Saws	0	$2,500 each	Profit	$1.00	per ton
% Ash Content =	0.06						
mmBTU/Dry Ton =	15.7						
Residue Type	1						
(0=Roundwood 1= Clean Chip Residue)							
Grinder Size	Large						
Debris Age, weeks	8						
Screened	1						
(0=No, 1=Yes)					Mill Quota (Tons per Week) =	9999	

Machine Productivity

FRONT-END LOADER		GRINDER		SCREEN		HAULING	
Avg. Tons/Bite	1.02	Prep. Time, min. =	5			Load Size (tons) =	25
		Grinding time, min. =	16.7				
Bites/Hour	83.3					Loading Time (minutes) =	22
		Time per Load (minutes) =	21.73			Round Trip Time (hours) =	3.86
						Tons/hour =	6.47
Tons/PMH =	85.41	Tons/PMH =	89.68	Tons/PMH =	89.68		
Oper Effy =	1.1	Oper Effy =	1.1	Oper Effy =	1.0	Oper Effy =	1.0
						Haul Distance (miles) =	60
						Average Speed (mph) =	40
						Unloading Time (minutes) =	30

Machine Cost

D ($/SMH)=	12.95	D ($/SMH)=	35.00	D ($/SMH)=	18.55	Haul Rate ($/ton-mile) =	$0.13
II&T ($/SMH)=	9.99	II&T ($/SMH)=	27.00	II&T ($/SMH)=	14.31		
F&L ($/PMH)=	45.55	F&L ($/PMH)=	157.92	F&L ($/PMH)=	35.23	Minimum Haul (miles) =	40
M&R ($/PMH)=	13.71	M&R ($/PMH)=	37.06	M&R ($/PMH)=	19.64		
Labor($/SMH)=	25.20	Labor($/SMH)=	0.00	Labor($/SMH)=	0.00		
Labor overhead (%)=	40%	Labor overhead (%)=	40%	Labor overhead (%)=	40%		
Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	85	Avail.(%) =	90
Number =	1	Number =	1	Number =	1	Number =	4

Function	Tons /PMH	Avail%	Tons/SMH One	Tons/SMH All	Utiliz%	Cost per SMH Fixed	Cost per SMH Oper	Cost per SMH Labor	Cost per SMH Total	Cost $/Ton
Front End	89.68	85	76.23	76.23	26	22.94	15.40	25.30	63.64	2.73
Grinding	94.16	85	80.04	80.04	25	62.00	48.25	0.00	110.25	4.73
Screen	89.68	85	76.23	76.23	26	32.86	14.26	0.00	47.12	2.02
Hauling	6.47	90	5.83	23.30	90					8.20
Support	Pickups, Chainsaws, Deckhand, and Overhead									2.03
Road Work										0.00
Moving Setup										0.60
Moving Tracts	8.00 hours spent moving men & equipment to tract									1.72
Profit										1.00

System Rate (tons/SMH) =	23.30			
Weekly production (tons, truck loads) =	1165	47	Cut & Haul Cost per Field Ton =	23.03
Days required to cut tract =	3		Cut & Load Cost per Field Ton =	14.83
			Cut & Haul Cost per ODT =	38.39
			Cut & Load Cost per ODT =	24.72
			Cut & Haul Cost per mmBTU =	2.60
			Cut & Load Cost per mmBTU =	1.67

Minimum haul distance (miles)	40	Assumed payload (tons)	25
Minimum haul rate ($/ton-mile)	$0.14	Assumed fuel mileage (mpg)	5.5
Incremental haul rate ($/ton-mile)	$0.13	Assumed diesel price ($/gallon)	$4.00
Highway diesel price ($/gallon)	$4.00		
Payload assumed in these rates	25		

Base Case

Miles	$/ton	$/trip	Fuel Cost	Fuel %	Fuel Adjust	$/ton
60	$8.20	$205.00	$87.27	43%	$0.00	$8.20

Appendix I. Assumptions and Likely Conditions for Table 3.4 Delivered Cost Rankings

Variable	RW	CC	WTC-50%	WTC-40%	GRW	GRW/S	GCC	GCC/S
Additional Cost ($/F-ton)	$13.00	$8.89	$6.40	$6.40	$1.00	$1.00	$1.00	$1.00
Moisture Content (%)	50	50	50	40	30	30	40	40
Ash Content (%)	1	0.5	0.6	0.6	4	1.4	12	6
Load Size	27	27	25	22	20	15	23	21
Tract Size	60	60	60	60				
Field Tons/Ac	80	80	80	80				
Field Tons/Landing					150	150	150	150
Haul Distance	60	60	60	60	60	60	60	60
Fuel $	$4.00	$4.00	$4.00	$4.00	$4.00	$4.00	$4.00	$4.00