The Economic Feasibility of an Integrated Woody Biomass Harvest In the Missouri Ozark Highlands

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by

RYAN LEONARD SIMS

Dr. John P. Dwyer, Thesis Supervisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

The Economic Feasibility of an Integrated Woody Biomass Harvest in the Missouri Ozark Highlands

presented by Ryan Leonard Sims

candidate for the degree of Master of Science and hereby certify that in their opinion it is worthy of acceptance.

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Associate Professor John P. Dwyer

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Associate Professor Tom Gallagher

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Assistant Professor John M. Kabrick

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Associate Professor Keith W. Goyne

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Abstract

Questions have risen in recent years regarding the impacts of biomass harvesting for renewable energy production and on the cost and efficiency of biomass harvesting using different harvest equipment configurations. Missouri has a set of Best Management Practices (BMPs) to guide woody biomass harvesting. This study will address the different results (mainly cost and production data) that come with incorporating various BMPs and how costs and revenues can vary when implementing these different management practices. This study applied two silvicultural treatments and a control to 72 acres of oak-hickory stands comprising poles and small sawtimber-sized stems of primarily white oak (*Quercus alba*) and low quality black oaks (*Quercus velutina*) in the Missouri Ozark highlands. Treatments were: 1) clearcut to establish a new cohort of trees and 2) intermediate thin in an attempt to improve residual stand quality, in which both small diameter trees and merchantable sawlogs were removed. Both treatments used a mechanized, integrated harvest approach. Each treatment had 3 sub-treatments (clearcut had 4 sub-treatments) that called for leaving varying levels and types of residues on the ground to maintain soil nutrient pools. Trees were merchandized for the highest value possible, with biomass chips produced from limbs and tops or stems that were otherwise unmerchantable. A system feasibility analysis was implemented to determine productivity, costs, and prices needed for economic feasibility. An average of 49.4 tons of SHWP and 10.9 tons of fuel chips were removed per acre at an average cost per ton of $27.70 and $48.62 in the clearcut treatments, respectively. An average of 19.1 tons of SHWP and 3.7 tons of fuel chips were removed per acre at an average cost per ton of $32.87 and $64.84 in the intermediate thinning treatments, respectively.

1. INTRODUCTION

Higher energy prices and incentives to produce renewable energy have increased interest in sources of bioenergy (WDNR, 2008). The U.S. Government has centered research and development and policy initiatives to address the growing dependence on foreign oil and reliance on finite fossil energy supplies (Klepac et al. 2011). As these fossil fuel prices rise, opportunities to provide alternative fuel sources at competitive cost have become increasingly attractive (Baker et al. 2010). Woody biomass has long been a useful but underutilized byproduct of forest management activities (Evans, 2008). The U.S. Department of Energy (DOE) has set a goal to increase domestic biofuels use from approximately 2.1 to 51 billion gallons by 2030, and to increase biopower use from about 2.1 to 3.8 quadrillion BTU (DOE, 2006). It is believed that U.S. forests currently yield 129 million dry tons of biomass per year, and could potentially increase yield to 226 million dry tons per year by 2030. (Downing et al., 2011). Wood is an alternative source of energy that will not displace fossil, nuclear, or other renewable sources, but forestlands in the U.S. have the potential to sustainably produce enough biomass to supply energy and products equivalent to 10% of the nation's current level of petroleum consumption by year 2030 (Janowiak and Webster, 2010).

Concerns about greenhouse gas emissions associated with fossil fuel combustion have resulted in legislation that requires Missouri to increase current renewable energy production to 15 percent by 2021. Utilization of woody biomass for renewable energy production has the potential to reduce net greenhouse gas emissions, support renewable energy mandates, and increase energy dependence while meeting other forest resource management goals. In order for that to happen, woody biomass must be produced in a way that is socially, economically, and ecologically sustainable.

1.1 Previous Biomass Harvesting Studies

Since the 1970's many new methods for harvesting, collecting and processing woody biomass have been developed and tested (Howard 1979, Stokes et al. 1989). These vary from dedicated energy crop plantations that treat wood as a perennial crop to mechanized fuels reductions that remove small diameter material from a mature forest to reduce risk of wildfire (Evans, 1974). An economic analysis of these strategies is critical to forest land managers and private forest landowners for making informed decisions and creating a sustainable supply of renewable energy. Many different studies with a wide range of objectives and local conditions were conducted and continue to be implemented to assess the economic feasibility of harvesting woody biomass (Arola and Miyata 1981, Sturos et al. 1983, Berti 1984, Stokes 1986, Puttock 1995, Bolding 2002, Kellogg and Spong 2004, Becker et al. 2006, Bolding et al. 2006, Yoshioka et al. 2006, Mitchell and Gallagher 2007, O'Neal 2007, Bolding et al. 2009).

Biomass is generally defined as any organic material that can be converted into energy (PDCNR, 2008). Woody biomass is often described as the lowest-value material removed from the forest, typically logging slash, small-diameter trees, tops, limbs, or trees that cannot be otherwise sold as timber (Evans, 2008). As the demand for forest biomass increases, there is greater focus on utilizing small diameter, unmerchantable trees as well as residuals left after harvesting (Stokes et al. 1986). A major challenge in utilizing woody biomass for energy production is harvesting, processing, and transporting feedstock at reasonable costs (Rummer, 2009). In the southern United States, tree-length systems that fell and remove the entire tree to roadside for processing remain the predominant harvesting method (Baker et al. 2008). With this system, integrating roundwood and biomass in a one-pass operation is most cost effective and reduces site degradation (Hudson, 1995). Markets determine which trees are considered sawtimber and which are delegated to the low-value biomass category (Evans, 2008).

Operational costs must be kept at a minimum and the value of harvested products must be increased to make woody biomass harvesting profitable (Becker et al. 2006). In most scenarios, harvesting and transporting woody biomass is relatively costly because the smaller trees have low value relative to their volume and handling costs, and most harvesting systems were originally designed for removing larger-diameter timber (Evans, 2008). Logging equipment that will not significantly harm the residual stand, directly or otherwise, must be used (Becker et al. 2006).

Although the opportunity exists for forests to play a considerable role in the development and use of bioenergy technologies, justifiable concerns regarding the long-term sustainability of using forest-based energy feedstocks have arose (Janowiak and Webster, 2010). Biomass harvest removes more woody material from a site than would be removed under typical roundwood harvest (MFRC, 2007). A general premise of forestry that considers wildlife and biodiversity is that silvicultural prescriptions resemble relevant natural disturbance regimes and natural stand development. Furthermore, there is a greater opportunity for sustaining biodiversity when the disparity between managed stands and their natural analogs is reduced (MFRC, 2007). Creating and leaving biological legacies maintains vital structural elements of managed stands, which in turn sustains many organisms and ecological processes dependent upon these structures (Franklin et al. 2002).

1.2 Project Justification

Missouri has developed a set of Best Management Practices (BMP's) to guide woody biomass harvesting (MDC, 2009). The Woody Biomass Best Management Practices Guide is still a work in progress, with this study being the first in the state of Missouri to address the implementation of the current harvest intensity for harvesting woody biomass versus an alternative harvest regime in order to determine the most cost efficient and sustainable method for harvesting woody biomass. Questions have risen about the efficacy of this guide and the impacts of biomass harvesting on soil nutrients, on the cost and efficiency of biomass harvesting using different harvest equipment configurations, on biomass yield for stands managed under alternative silvicultural prescriptions, and on the condition of the residual stand following alternative harvest practices (Stokes and Sirois, 1986, Becker et al. 2006, Rummer, 2009, Baker et al. 2010).

There is little data on biomass harvesting costs in Missouri's forests. A recent study (Aguilar et al., 2010) showed that biomass logging costs ($36.20/ton) exceeded products revenues ($26.00/ton) for small diameter trees when chipped and delivered as fuel wood to a pulp mill in Kentucky. Loggers have little guidance when evaluating the profitability of entering the biomass harvesting market. Knowledge of production rates in different harvesting regimes allows both the logger and forester to match the proper silvicultural prescription with the right harvesting equipment. The purpose of this study was to evaluate the economic feasibility of a fully mechanized integrated harvesting system in the Missouri Ozark highlands that collects SHWP and converts low quality hardwood trees, tops, and residues into fuel chips for biomass energy needs.

1.3 Study Objectives

The specific objectives of the study were to:

- Implement biomass harvesting under realistic scenarios.
- Estimate harvesting efficiency for equipment configurations provided for the study.
- Determine costs and productivity associated with each component of the harvest to estimate the cost of production and revenues for the two wood products.
- Evaluate profitability of an integrated harvest under differing harvest intensities.
- Conduct a sensitivity analysis to determine effects of changes in fuel costs, equipment costs, hauling distances, and stumpage prices.
- Conduct a benefit:cost analysis to evaluate the economic merit of the project treatments.

2. METHODS

2.1 Study Site Characteristics

The study site was located in Township 34N, Range 4W, Sections 2, 3, and 4. The timber sale was implemented on approximately 72 acres of upland central hardwood forest (Pijut, 2005) in the Meramec River Hills subsection of Dent County, Missouri between Salem and Steelville, MO (Figure 1). The three harvest sites were all located in the Indian Trail Conservation Area, formerly used by the Sligo Iron Company in the early 1900’s to fuel their smelters with the vast supply of cordwood in the area (MDC, 2010). Slopes of the study site ranged from 7 to 32 percent and dependent upon replication, had north- and northeast-facing aspects. Site index was estimated to be 55 to 60-feet on a base age of 50 years and was average for this typical Ozarks site.

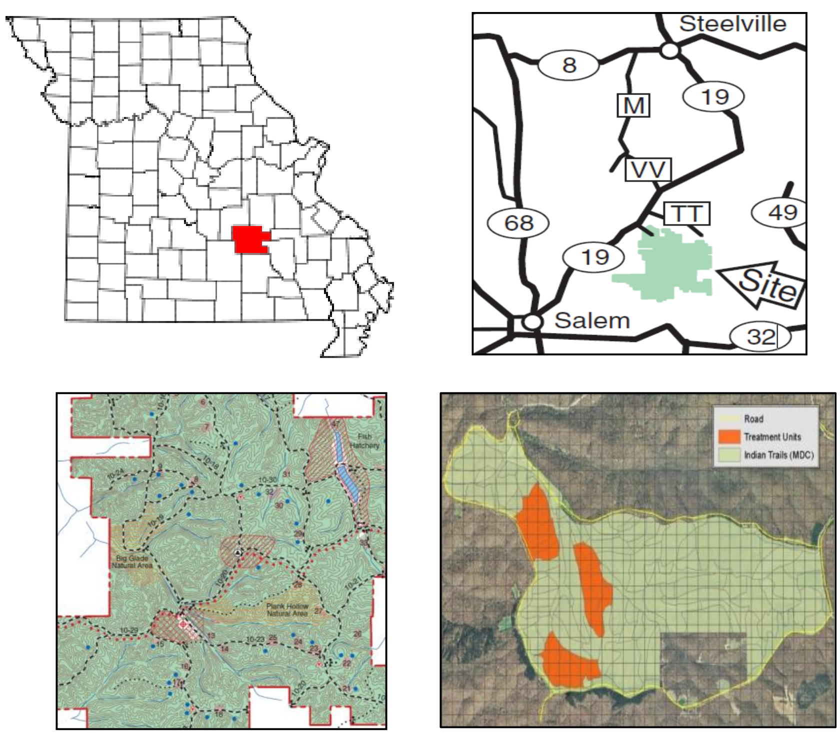

Figure 1. Maps (general and detailed location) of study site in Dent County, Missouri.

The over story species across the site ranged from 55 to 90 years old with smaller areas of 40-year-old shortleaf pine which overlapped the harvest boundary. The species most commonly found on site were white oak (*Quercus alba*), black oak (*Quercus velutina*), post oak (*Quercus stellata*), northern red oak (*Quercus rubra*), and hickory (*Carya spp*.) (Figure 2). Other minor species found on site include but are not limited to elm (*Ulmus spp*.), shortleaf pine (*Pinus echinata*), black walnut (*Juglans nigra*), downy serviceberry (*Amelanchier arborea*), red maple (*Acer rubrum*), shumard oak (*Quercus shumardii*) blackjack oak (*Quercus marilandica*), blackgum (*Nyssa sylvatica*), white ash (*Fraxinus americana*), flowering dogwood (*Cornus florida*), and sassafras (*Sassafras albidum*). A pre-treatment inventory of trees greater than 4 inches diameter at breast height (4.5 feet above ground) was implemented during the summer of 2011. The diameter distribution of pre-treatment stand conditions are presented in Figure 3. The pre-treatment basal area density for the entire site averaged 111 square feet (Figure 4) and ranged from 101 to 146 square feet (see appendix table 29 for pre-treatment inventory summary).

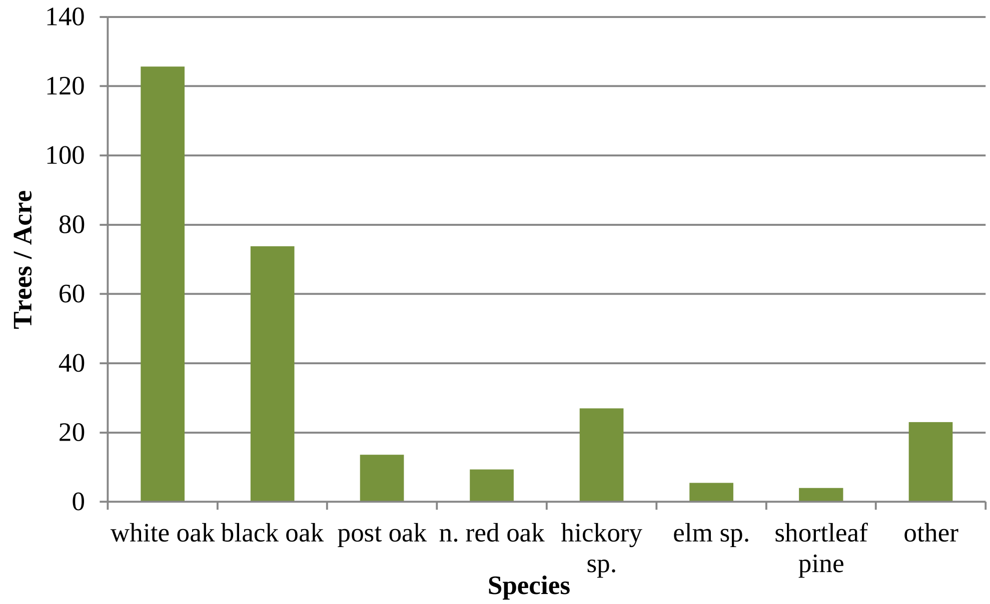

Figure 2. Pre-treatment inventory of most common tree species per acre and combined trees for the least common species.

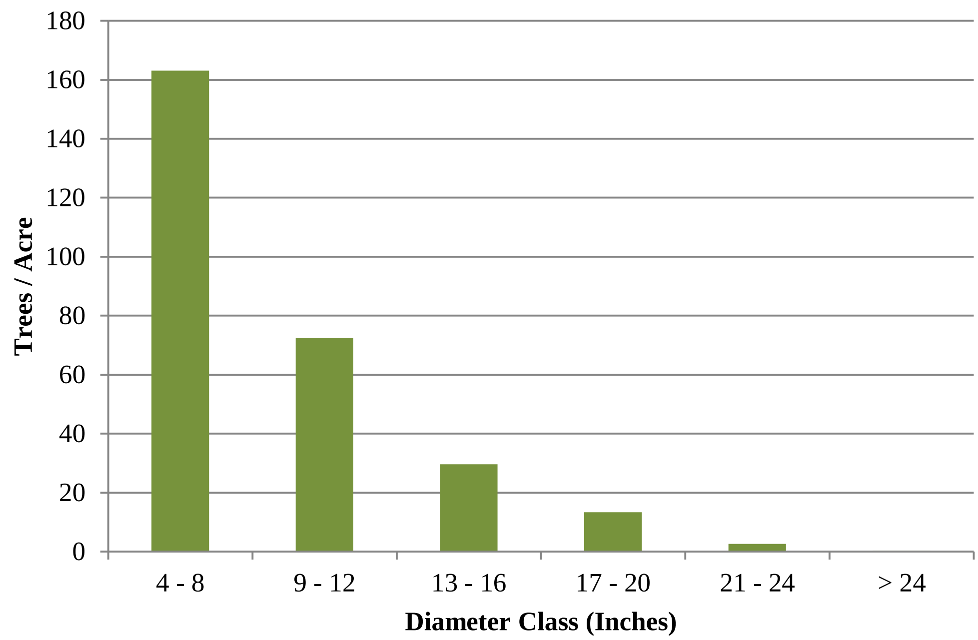

Figure 3. Pre-treatment inventory of diameter distribution.

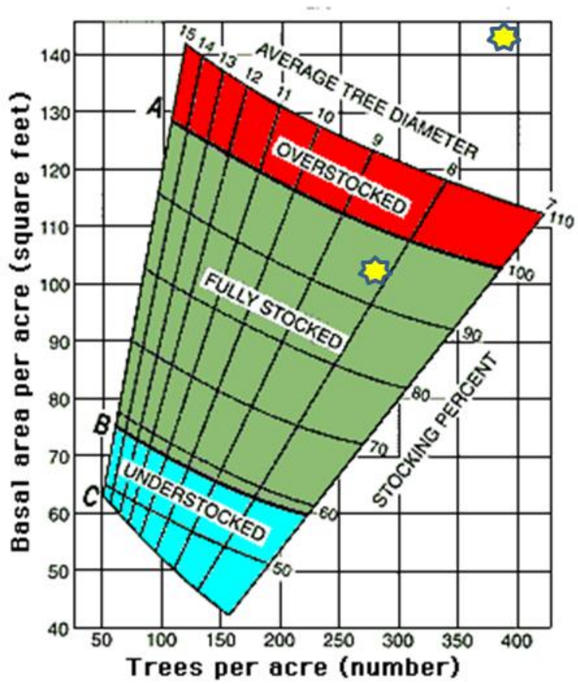

Figure 4. Stocking chart representative of stands harvested at Indian Trail. Represent the lowest and highest stocking averages from harvest treatments.

2.2 Soils of the Ozark Highlands

Questions have risen about the efficacy of Missouri's Woody Biomass Best Management Practice's guide and the impacts of biomass harvesting on soil nutrients and the condition of the residual stand following alternative harvest practices. A subsequent study investigating changes in nutrient flux and soil solid phase nutrient concentrations under conditions representative of various types of woody biomass harvesting is currently being conducted at Indian Trail Conservation Area. Due to the conjunction of these projects and the interest of harvest impacts on soils within the treatments at Indian Trial, a brief soil description is provided to give a background for developments in future research at this site.

Many variations in forest composition and forest site productivity can be explained by soil differences attributable to different parent rock materials (Read, 1952). Because the Missouri Ozark Highlands are such a small region of relatively uniform climate, it provides ample opportunities for determining the influence of geology upon soil formation, and the influence of rocks and soils upon types of vegetation. Since most of the forest soils in this region are mature and are usually derived from a single rock formation, the nature of the parent material may be more important than is usually realized. Given the geologic formation, topographic position, aspect, and slope, it may be possible to predict species occurrence on these soils, and perhaps give an idea of which species should perhaps be favored depending upon management objectives.

This eastern part of the Ozarks is believed to be the origin of an ancient mountain system that was exposed following a long period of erosion during the pre-Cambrian and then buried by the deposits of the Cambrian and Ordivician seas (Fletcher & McDermott, 1957). Geologically the Meramac River Hills Subsection is underlain by thick, cherty dolomites and sandstones of the Roubidoux formation. Soils derived from parent materials of the Roubidoux formation comprise highly weathered and very gravelly pedisediments and are typically classified as Ultisols with some Alfisols as geographically associated soils (Allen et al, 1983).

The warm, moist, humid climates under which these soils are formed help to accelerate the weathering and leaching processes, and thus enhance low base status and Ultisol development which are relatively stable, but unfertile soils. Ultisols may occupy hillslopes, stream or marine terraces, or level upland areas (Allen et al, 1983). In general, Ultisols tend to occupy the older, most stable and highly weathered positions on the landscape. They are quite acid in nature and this acidity can often be observed to great depths. The distinct morphology of Ultisols is dominated by horizons of eluviation and illuviation. Weathering and solution has removed much of the original basic minerals which results in soils that are very acidic. Due to their dense clay content, soils of this region have a limited moisture retention capacity (Allen et al, 1983).

Overall, genesis of Ultisols takes a long time because of the slow pace of the clay accumulation process, but for classification purposes the expression of the argillic horizon is required (Soil Survey Staff, 1975). Clay formation in deeper horizons and clay destruction in upper horizons are the dominating processes in these soils, this does not preclude the operation of other processes. Clay is translocated downward into the zone of accumulation where silicate clays and weatherable forms of iron and aluminum begin the formation of the argillic horizon (Ranney and Beatty, 1969). Base saturation is less than 35% in the argillic horizon or base saturation decreases with depth, and there is little presence of identifiable amounts of weatherable minerals in the soil. Because of increased leaching and weathering of Ultisols, a greater hydrogen ion activity results, thus decreasing the soil pH.

In general, despite low base saturation, Ultisol soils provide for good tree growth and extensive timber production (Buol et al. 2003). Deciduous and coniferous forests are managed, fertilized, and replanted to make forestry operations more profitable. Surface horizon fertility is dependent on nutrient cycling by deep-rooted plants. Harvesting of these forests can often lead to degradation in soil fertility, and it is believed that large areas of savanna in the Tropics have been formed by the deforestation of Ultisols. Since Ultisols generally have larger contents of quartz sand and 1:1 clay they are generally good for providing stable, workable ground for forest harvest operations (placement of log landings and skid trails).

2.2.1 The Clarksville Series

In general, Ozark soils are similar in some characteristics, but there are wide variations in other characteristics. The entire Ozark highlands area is characterized by a hilly to deeply dissected surface and the soils of this area are among the most productive in the interior Ozark Highlands region (Stambaugh, 2001). Common Ozark soils include the Clarksville, Baxter, Nixa, and Talbott (Miller, 1965). The Clarksville soil series is the only soil mapped within the boundaries of the timber harvest at Indian Trail Conservation Area. These soils are composed of a granular structure, and contain large amounts of chert at the surface with a region of cherty silty clay loam at depths of 60-80 cm (Gilbert, 1971). The Clarksville soils of the Ozarks are considered to be extensions of Red-Yellow Podzolic soils into a region of Gray-Brown Podzolic soils. They are classified as loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults with primarily pedisediment parent materials (Kabrick et al., 2008).

The Clarksville soil is an Ultisol, based largely upon the less than 35% base saturation in the profile and the continued decrease in base saturation with increase in depth. In general, the Clarksville is a well-drained very cherty soil that often has a pale brown silt loam A horizon, the B horizon is typically thicker and has textures ranging from silt loam in the upper Bt to clay in the lower Bt. The B horizon is often yellowish-red in color and can have around the same chert content as the A horizon. The material immediately below the B can have chert contents slightly less than does the B horizon itself. This reduction in chert often continues with depth, and can contain approximately 50% chert in the lower B horizon to around 15% near the unweathered carbonates (Miller, 1965).

2.3 Silvicultural Treatments

Two different silvicultural treatments were implemented to the forest stands at Indian Trail Conservation Area: intermediate thinning, and clearcut. Thinning treatments were applied with the intention of improving residual stand quality, increasing residual stock growth, and increasing cumulative stand yield relative to untreated stands, while the clearcut treatments were applied to remove the entire over story and begin a new cohort of trees. White oak species were favored as crop trees throughout the thinned areas. Red and black oaks were favored for removal because of the risk of mortality due to oak decline. Snags and cull trees were favored as leave trees in both treatments for the wildlife benefits they provide (Samuelsson et al. 1994) and to comply with Woody Biomass Best Management Practices (WBMP's) required by the harvest sale contract (MDC 2011).

2.3.1 Clearcut Treatments

The clearcut treatment removed the entire overstory down to trees with a 3" dbh (appendix table 29). The total area of plots with clearcut prescriptions was 35.4 acres. This is an even-aged regeneration harvest designed to initiate a new cohort of trees. As described in Table 1, each clearcut treatment called for leaving varying amounts and types of harvest residue per treatment. The Missouri Woody Biomass Harvesting – Best Management Practices Manual currently recommends that in thinning and commercial harvest using a feller buncher, 1/3 of treetops from sawtimber harvest and 1/3 of the typical size small trees cut on site be left and evenly distributed throughout the harvest area. However, limited knowledge is available about nutrient recycling as it is related to woody biomass harvesting on Ultisol soils in Missouri, so this BMP is subject to change as further research is developed (MDC, 2011).

Harvesting slash and other woody debris for biomass as part of a timber harvest decreases the amount of decaying wood on the forest landscapes and changes the chemical and physical environment in clear-cuts (Astrom et al. 2005). In clear-cuts, leaving amounts of slash and fine woody debris:

- Retains nutrients and minimizes erosion
- Provides shelter, reducing wind velocity and fluctuations in ground surface temperature (Proe et al. 1994).
- Provides habitat for small mammals (Ecke et al. 2002) and ground-active beetles (Gunnarsson et al. 2004).
- May shelter plants sensitive to desiccation, immediately following clear-cuts (Brakenhielm and Liu 1998).

Table 1. Silvicultural treatment lists with assigned harvest regime and acres harvested.

Treatment	Harvest Regime	Number of Plots	Area (Acres)
Clearcut Ca	1/3 of tops of sawlog-size trees and 1/3 of small diameter trees left on ground to provide wildlife habitat and nutrients for future cycling.	2	8.6
Clearcut Cb	Remove all biomass from harvested trees.	2	9.42
Clearcut Cc	Retain tops of all cut trees ≥ 8" dbh; remove boles, tops and limbs of all cut trees < 8" dbh.	2	8.26
Clearcut Cd	Traditional harvest of only sawtimber, no biomass removed	2	9.12
Intermediate Ia	1/3 of tops of sawlog-size trees and 1/3 of small diameter trees left on ground to provide wildlife habitat and nutrients for future cycling.	2	8.55
Intermediate Ib	Remove all biomass from harvested trees.	2	9.97
Intermediate Ic	Retain tops of all cut trees ≥ 8" dbh; remove boles, tops and limbs of all cut trees < 8" dbh.	2	9.22
Control X	No harvest or removal of woody residues.	2	8.87
Total study harvest		16	72.01

2.3.2 Intermediate Thinning Treatments

The intermediate thinning method aimed to reduce the basal area to 60 square feet per acre on average (appendix table 29). The total area of plots with intermediate thinning prescriptions was 27.74 acres. The overstory residual tree alignment was designed to leave trees evenly distributed across the site. However, small gaps were created in the harvest operation that were large enough to initiate a new cohort of trees with enough light to grow up into the overstory. This intermediate thinning was a crown thinning or "thinning from above" which favors dominant and co-dominant trees by releasing dominant and co-dominant trees that are competing for resources. This is an uneven-aged thinning harvest designed to improve the quality of residual trees by redistributing growth potential to crop trees, maintaining a vigorous, healthy stand, capturing mortality, and by shortening the rotation age of the stand.

2.4 Best Management Practices

When timber harvest rights are sold to a private logger from the Missouri Department of Conservation, compliance with recommended BMPs are included in the terms of agreement. These practices are voluntary in privately-owned forestlands across the state of Missouri, but are mandatory on all sales that take place on public land. Prior to and during harvest operations at Indian Trail CA, discussions regarding the implementation of these BMPs were held between the logger, logging crew, MDC officials, and researchers to ensure that compliance with the BMPs was maintained.

2.5 Experimental Design

Two replications of each treatment were harvested during the project. Each treatment was assigned per replication using a complete randomized block design method. Replications were installed across three blocks (Figure 5). Each treatment was designed to address different best management practices (BMPs) and the impacts of biomass harvesting on soil nutrients, cost and efficiency of biomass harvesting using different harvest equipment configurations, and biomass yield for stands managed under alternative silvicultural prescriptions. Each replicated block contained three intermediate thinning plots, four clearcut treatment plots, and one control plot approximately 4.5 acres each (Table 1).

As mentioned earlier in the report, this harvest began Jan. 2, 2012 and was not completed until May 1, 2012. Christoperson et al. (1989) reports that in stands other than southern forests, biomass harvesting is often performed in the wintertime. Several reasons reported for winter harvesting are listed below:

- Lower moisture content in wood (less weight and less subsequent drying necessary)
- Leaves remain in the field for recycling nutrients and reduce possible noxious emissions into the air during combustion
- Fewer insect/disease problems and less residual tree mortality
- Frozen ground protects against compaction and root damage by harvesting equipment and reduces erosion.

This project however, was originally scheduled for a start date in June of 2011. Due to the steep terrain in the Ozarks, the need to put in a new logging road to reach the east unit (Figure 5), and the combination of poor weather conditions (mostly rain), parts of the harvest took much longer than expected. A total of 18 days were lost due to unsuitable ground conditions caused by inclement weather. The original design of the harvest called for all three replications to be completed, however due to time constraints, inclement weather, availability of funding, and loss of field personnel, data was only collected from two complete replications. Data from the north unit (Figure 6) replications were collected in entirety, with data collection for the second replication being split between the east and south units (see Appendix Figures 1 and 2 for completed treatments).

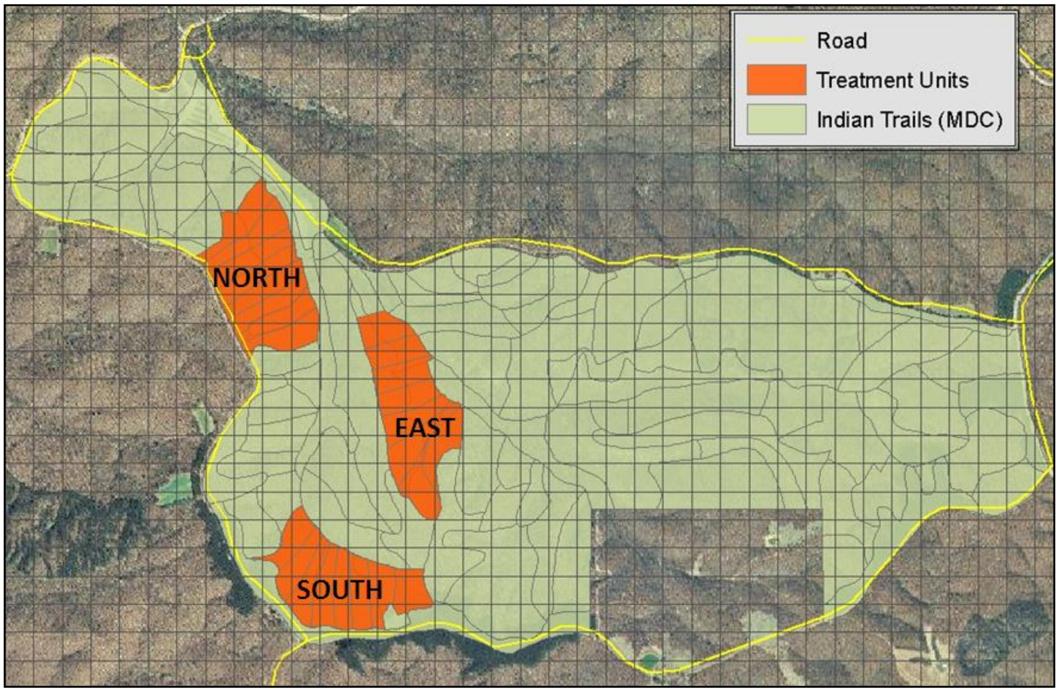

Figure 5. Schematic map of harvest block layout at Indian Trail Conservation Area.

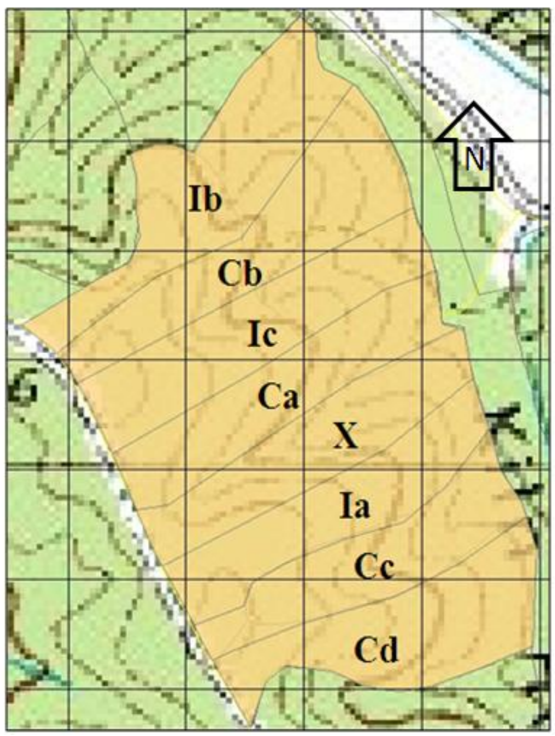

Figure 6. Schematic map of sample plot layout for the north harvest unit. First digit corresponds to the silvicultural treatment and second digit reflects residual biomass treatment replication (see Table 1).

2.6 Harvest System

2.6.1 Harvest Equipment

An integrated, fully mechanized harvest system was used to conduct the clearcut and intermediate thinning harvests. The equipment utilized in the harvest system include a rubber-tired, Hydro-Ax 511E feller-buncher with a hot saw; a rubber-tired, John Deere 548-G grapple skidder; a Prentice 280 loader with bucking saws, a de-limber, and a log bucking table; an additional Prentice 210E loader to stack biomass and feed the chipper; and a stationary Vermeer BC 2100xl chipper. The feller-buncher cut and bundled trees which were skidded to the landing by a grapple skidder. The skidder typically carried the bundles directly to the loader for processing, however there were times when bundles were decked on the skid trail due to the loader being inactive or in the rare situation that the deck was too full and did not have room for additional trees. The loader de-limbed and topped trees and sorted the logs by product class. Product classes consisted of stave logs, sawlogs, tie logs, pine posts, blocking, pulpwood, and biomass. For the purposes of this study, pine posts were placed in the SHWP category despite technically being a softwood species. The loader loaded the log truck which then transported the material to various buyers depending on the product class.

2.6.2 Data Collection: Yields and Revenues

Prior to harvest, trees selected for removal in the intermediate thinning treatments were marked by the Missouri Department of Conservation. All trees > 3” dbh were to be removed in clearcut treatments. As logs were felled, a color specific to each treatment was painted on the bottom of each tree to differentiate which plot they originated from. This enabled researchers to know which trees were from specific plots when the products were loaded onto the truck. These colors were re-sprayed on the logs if the ends were bucked off at the landing. Each truck load that left the site was tallied to determine the total number of logs leaving the site and from which plots they were harvested. Load weights reported by the mill were used to estimate how much material was removed from each treatment. Each buyer supplied scale tickets which reported purchase prices per unit for each load.

Determining exactly which plots biomass material originated from was more difficult. Due to the constant addition of biomass material to be chipped, spraying the bases of such material was not always possible. Field researchers and logging crew estimated the materials origin and when possible, the biomass pile was sprayed to indicate when products were being added from a new plot onto the material from the previously harvested plot. The plot numbers and percentages harvested from each were estimated for each biomass truckload.

2.6.3 Data Collection: Time-In-Motion

In order to determine productivity of each individual machine and the overall harvest system, each function of the operation was studied as harvesting occurred (time-in-motion study). Up to four researchers were used during a work day to gather data on the equipment. Two personnel were necessary to collect data on the skidder, one stationed at the landing entry where the skidder dropped log bundles in order to collect the time of entry, bundle release, departure for each skid turn, and any delays, and another in the woods following the skidder to take count of logs per bundle, the approximate DBH of each log per bundle, any delays in the woods, and the time of departure back to the landing. A skidder cycle began when the skidder left the landing to go pick up a bundle. This gave the total skid cycle time and any delays spent at the landing and in the woods. This data was also used to determine the percentage of the time that the skidder spent handling small diameter trees. The time spent delivering both SHWP and biomass-sized material was proportioned between the two products based on the percentage of the trees per bundle that consisted of either SHWP or biomass-sized material. This is based on the assumption that it takes an equal amount of time to fell and skid biomass and SHWP sized material to the landing (Saunders et al. 2012). Skid cycle distance was estimated using the *MultiDAT* GPS tracking system (GENEQ, 2011). Only one person was necessary to collect data on the feller-buncher and loader. Data collected by researchers were recorded on data sheets that were created specifically for each piece of equipment to be used on site. See (Appendix Tables 24-28) to view examples of each machines data sheet.

In each machine except the logging truck, a Yellow Activity Monitoring System or “Yellow Box” data recorder was placed inside to record the amount of time that each piece of equipment was in operation (Figure 7). The yellow box records the time that a piece of equipment is in operation by detecting equipment vibrations while it is running (KED 2011). This time is known as the equipment’s total productive machine hours (PMH). Yellow boxes are manufactured by Kinetic Electronic Designs and can yield time spent in operation with resolution down to the minute (see Appendix figure 3).

Figure 7. Yellow Activity Monitoring System "Yellow Box" placed inside chipper.

A *MultiDAT* collection hardware system was connected to the ignitions of both the feller-buncher and skidder throughout the entire harvest (figure 8). When each piece of equipment is turned on, the MultiDAT also turns on, and records PMH's as well as locations. *MultiDAT* tracks the total distance traveled by the equipment by taking GPS waypoints during operation. This allows for constant monitoring of the feller-buncher and skidder during the harvest instead of relying solely on data collected during activity sampling. For this project the MultiDAT was programmed to take waypoints every 3 seconds to display locations where the equipment moved and if there were any prolonged periods of inactivity.

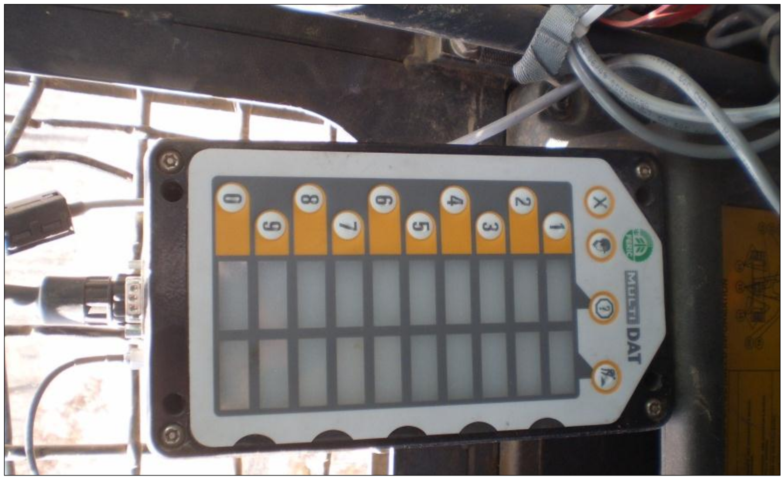

Figure 8. *MultiDAT* Data Collector placed inside skidder.

2.6.4 Activity Sampling

Activity sampling was used to collect data on the feller-buncher and loaders. Recording activity samples allows the percentage of time spent performing various tasks by each machine to be estimated for the duration of each work day (Olsen and Kellogg, 1983). Continuous activity sampling was recorded at 30-second intervals for the loaders and 20-second intervals for the feller-buncher to monitor delays and differences in equipment performance throughout the day (Saunders et al. 2012). At each interval the researcher recorded the activity being performed by tallying the specific task the machine was carrying out at that time. The number of observations for each activity was summed together and divided by the total number of samples taken over each hour period and for the whole workday. This gave the percent of time spent performing different tasks throughout the work day. This sampling method was utilized in previous Missouri biomass harvesting studies by Saunders et al. (2012) and Botard et al. (2012).

Loader activities were categorized as processing the trees into logs, stacking the logs, loading (all including product class), and delay time and reason. Feller-buncher activities were categorized as sawing the tree, dropping the tree (both by product class), moving to cut another tree, and delay time and reason. Delay types for both machines were most commonly categorized as mechanical difficulty and operator delay, i.e. talking on cell phone.

2.7 Data Analysis

2.7.1 Data Analysis Software

The "General Ground-based Harvesting System Analysis" model (USFS, year not available) produced by the U.S. Forest Service was used to estimate fixed cost per SMH and variable cost per PMH for all harvest equipment. PMH data for the skidder and feller-buncher was collected by the *MultiDAT* and was analyzed using the *MultiDAT* version 5.1.3 software. ArcGIS version 9.3.1 was used to estimate skidder turn distances and time spent on delay for equipment within each replication. Yellow box data was analyzed using the Yellow Activity Monitoring System software version 2.7.11.4 to determine the PMHs of both loaders, the chipper, and to supplement the PMH times collected by the *MultiDAT* for the feller-buncher and skidder. All data was entered into Microsoft Excel for analysis and estimation of production rates, to determine cost per ton, work day activity proportions, and to estimate breakeven prices in conducting a sensitivity analysis. The SAS version 9.3 statistical software (SAS Institute, 2008) was used to conduct an ANOVA to detect statistical differences between treatments for harvest yields of wood products.

2.7.2 Fixed Costs

Fixed costs (FC), also referred to as ownership or overhead costs, are those that remain constant with any level of output during the operation (Klemperer, 1996). The components necessary to determine ownership costs traditionally involve depreciation, interest, insurance, and taxes (Brinker, 1989). In order to calculate these costs, the purchase price, salvage value, and economic life are needed for all equipment involved in the operation (Miyata, 1980). These costs do not rely on operating conditions or operator technique. These costs instead occur irregardless of production, even if the machines are stored away for an entire work season (Brinker, 1989). All cost values were attained from the logger or estimated by field observations (Table 2). These costs were distributed over the total scheduled machine hours (SMH), assumed to be 1800 hours for the season (logger personal communication, March 2012). Values were placed into the General Ground-based Harvesting System Analysis model to yield cost per scheduled machine hour (SMH) for harvesting equipment (Equation 1). For the purposes of this study, a salvage value of approximately 75% was used for all equipment besides the chipper due to the fact that the equipment was used and would not depreciate in value as quickly as newer equipment, the feller-buncher and chipper were newer than other equipment resulting in a slightly lower salvage percentage. After ten years of use the depreciation rate decreases (USFS, 2007), and all equipment other than the chipper was beyond that threshold. An interest rate of 6% was provided by the logger to reflect the capital costs observed during the time of the harvest. Insurance and purchase prices for each machine were provided by the logger. An example of equation 1 being used for Loader 1 is presented in Appendix equation 1 (page 104).

Equation 1:

$$FC/SMH = \frac{\left(\left(\mathrm{PurchasePrice} * (1 - \mathrm{Salvage\%})\right) * CapitalRecoveryFactor + (Salvage\% * PurchasePrice * InterestRate\%) + Insurance + Taxes\right)}{SMH/year}$$

Where:

FC = Fixed costs

SMH = scheduled machine hours (yearly)

salvage % = Salvage Price/Purchase Price

Interest Rate = 6% and

Equation 2:

$$\text{Capital Recovery Factor} = \frac{InterestRate \times (1 + InterestRate)^{n}}{((1 + Interest\ Rate)^{n-1})}$$

n = the equipment lifespan in years.

Table 2. General Ground-Based Harvesting System Analysis model SMH fixed costs

	Feller/Buncher Hydro-Ax 511E	Skidder John Deere 548G-III	Loader 1 Prentice 280	Loader 2 Prentice 210 E	Chipper Vermeer BC 2100xl	Truck & Trailor Kenworth (T9)
Purchase Price (w/o tires)	$32,000	$41,500	$24,000	$22,500	$102,500	$45,400
SMH/yr	1800	1800	1800	1800	1800	1800
Life (yrs)	5	3	5	5	5	5
Salvage (% of new)	0.75	0.75	0.75	0.75	0.20	0.75
Insurance ($/yr)	$549	$718	$423	$380	$1,732	$5,550
Taxes/tags	0.00	0.00	0.00	0.00	0.00	412.50
Depreciation ($/yr)	$1,600	$200	$200	$200	$13,000	$4,960
Capital Recovery Factor	0.2358	0.2358	0.2374	0.2358	0.2358	0.2374
Owning Costs $/SMH	**$2.38**	**$2.75**	**$1.63**	**$1.49**	**$12.36**	**$5.94**

2.7.3 Variable Costs

Variable costs (VC), also known as operating costs, ensue entirely due to operation of a machine (Brinker, 1989). These costs vary in proportion to hours of operation or use and are subject to more management control than ownership costs (Miyata, 1980). Factors that affect the variable cost of operation include fuel use and price, oil use and price, maintenance and repair, tire life and price, and other miscellaneous operating costs. Variable costs were either obtained from the logger or estimated by field observations for each machine (Table 3). Values were placed into the General Ground-based Harvesting System Analysis model to yield cost per productive machine hour (PMH) for harvesting equipment (Equation 2). Fuel prices during this operation averaged \$3.33 per gallon for off-road diesel fuel, and \$3.78 per gallon for on-road diesel fuel, and \$8.00 per gallon for oil (hydraulic and motor). An example of this equation being used for the skidder is presented in Appendix equation 2 (page 105).

Equation 3:

$$\mathrm{VC/PMH} = FuelUse * HorsePower * FuelPrice + OilUse * OilPrice + \frac{AnnualR\&M}{SMH * Utilization\%} + \frac{TireCost}{TireLife} + \frac{MonthlyMisc.OperatingCosts}{\frac{Hours}{Month} \times Utilization}$$

Where fuel use is measured in gallons per horsepower per hour, oil use is measured in gallons per hour, tire life is measured in hours, and hours/month assumes 9-hour workdays, 5 days/week.

Table 3. General Ground-Based Harvesting System Analysis model PMH variable costs

	Feller/Buncher Hydro-Ax 511E	Skidder John Deere 548G-III	Loader 1 Prentice 280	Loader 2 Prentice 210 E	Chipper Vermeer BC 2100xl	Truck & Trailor Kenworth (T9)
Horsepower	135	129	160	155	275	500
Fuel Cons (g/hp-hr)	0.050	0.040	0.039	0.031	0.029	4.2
Daily Fuel Use (gal)	19	31	38	14	8.1	85.11
Oil use (gal/hr)	0.05	0.05	0.05	0.04	0.04	0.04
Monthly Oil Use (gal)	4	7	9	7	3	10
R&M (% of dep.)	100	90	90	90	100	90
Annual Repair & Maint ($)	$9,000	$4,500	$4,500	$4,250	$2,750	$4,500
Tire Cost ($)	$160.00	$2,400.00	$290.00	$290.00	$290.00	$495.00
Tire Life (hrs)	1800.00	7200	8400.00	8400.00	8400	1800
Misc. oper. ($/month)	$200	$200.00	$108	$45.00	$208.00	$1,200.00
Base Utilization	0.362	0.821	0.887	0.236	0.07	0.813
Variable costs ($/PMH)	**$39.43**	**$22.38**	**$24.80**	**$27.27**	**$64.09**	**$27.66**

2.7.4 Breakeven Prices

For the purposes of this study a breakeven analysis was conducted for the SHWP and woody biomass for all treatment types. In order to "break-even", the production costs per unit of product cannot exceed the revenue received per unit of product (LeDoux, 1984). To generate a total cost per ton for a given product type the fixed equipment cost per ton, variable equipment cost per ton, stumpage cost per ton, labor cost per ton, and hauling cost per ton were summed for each product class. Because there were two product types harvested in this project the %biomass estimate was needed to allocate the observed equipment costs between the two products. Equations 4 and 5 show the process used to determine fixed equipment costs (FC) per ton of SHWP for a single piece of equipment. Equations 6 and 7 were used to estimate the fixed equipment cost per ton of biomass chips.

Equation 4:

$$Tons\ SHWP/SMH = \left(\frac{(Tons\ SHWP)}{SHWP\ SMH * (1 - \%biomass)}\right)$$

Where % biomass is the proportion of biomass products removed from each plot (sections 3.4.1 – 3.4.7).

Equation 5:

$$FC/Ton\ SHWP = \frac{\frac{Cost}{SMH} * SHWP\ SMH}{Tons\ SHWP}$$

Equation 6:

$$Tons\ Biomass/SMH = \frac{Tons\ Biomass}{Biomass\ SMH * \%biomass}$$

Equation 7:

$$\frac{FC}{Ton\ Biomass} = \frac{\frac{Cost}{SMH} * biomass\ SMH}{Tons\ Biomass}$$

Equations 8 through 11 were used to estimate the variable cost (VC) per ton of material harvested during the study. Similar to equations 4 through 6 these equations were applied to each piece of equipment and the VC per ton was summed to get the total VC per ton of SHWP and total VC per ton for biomass chips for all equipment used for the study.

Equation 8:

$$Tons\ SHWP/PMH = \left(\frac{(Tons\ SHWP\ )}{SHWP\ PMH * (1 - \%biomass)}\right)$$

Equation 9:

$$\frac{VC}{Ton\ SHWP} = \frac{\frac{Cost}{PMH} * SHWP\ PMH}{Tons\ SHWP}$$

Equation 10:

$$Tons\ Biomass/PMH = \frac{Tons\ biomass}{biomass\ PMH * (1 - \%biomass)}$$

Equation 11:

$$\frac{VC}{Ton\ Biomass} = \frac{\frac{Cost}{PMH} * biomass\ PMH}{Tons\ biomass}$$

The labor costs were provided by the logger for each member of the crew. The labor costs for the crew averaged $454 per day and were distributed across hours spent in each treatment unit. The stumpage costs paid by the logger specified his rights to harvest all material in the clearcut treatments down to 3” dbh and all previously marked material in the intermediate thinning treatments. The actual stumpage price received for the material was much lower than normal stumpage prices for the region due to the equipment requirements required for the harvest contract and the long distance traveled by the crew to and from the job site every day. However for the purposes of this study, the original stumpage price that would have been used had this not been for a research project was used in this analysis. These costs will be further discussed in the next section

2.7.5 Benefit:Cost Analysis

A benefit-cost analysis (BCA) is a technique for evaluating a project or investment by comparing the economic benefits with the economic costs of the activity (Shively, 2008). A project’s benefit:cost ratio (B:C) is the present value of benefits (revenues) divided by the present value of costs (Klemperer, 1996). A BCA can be used to evaluate the economic merit of a project (Shively, 2008) and by using equation 12, the project can be evaluated and considered either “acceptable or unacceptable” based on the outcomes. When using this equation, present value revenues that equal present value costs yield a B:C ratio of 1. If present value revenues exceed present value costs, B:C must be greater than 1, and if present value costs exceed present value revenues, B:C < 1.

According to the B:C ratio criterion, projects are acceptable when the B:C ratio is 1 or greater, and unacceptable if the B:C is < 1.

Equation 12:

$$B{:}C\ ratio = \frac{PV\ Revenues}{PV\ Costs}$$

3. RESULTS

3.1 Treatment differences

The key parameter of interest in this case study was to test the efficacy of two treatment designs with various best management practices applied to each design type: clearcut, and intermediate thinning. The observed mean difference between treatments in the tons of SHWP and biomass removed per acre is presented in Tables 4 and 5. Observed differences in the tonnage removed between silvicultural treatments are presented in Figures 9 and 10. Tables 4 and 5 report the results of an ANOVA performed using SAS 9.3 (Cary, North Carolina, USA). The results of the analysis show that among the observed clearcut treatments, SHWP yield from clearcut treatment A was only significantly different from the yields from clearcut treatment B (Table 4). All other SHWP yields from clearcut treatments were not significantly different ($\alpha = 0.05$). All SHWP yields in the intermediate thinning treatments were significantly different than yields in clearcut treatments but were not significantly different from one another.

Table 5 reports the results of an ANOVA comparing mean differences between tons of biomass removed from each treatment type. Among observed treatments, mean biomass yields from treatment Cb were not significantly different from treatment Ca, however yields from treatment Cb were significantly greater than all other treatments. The analysis in Table 5 also shows that mean biomass yields from treatment Ca were not significantly different from yields from Cb or Ib, however yields from treatment Ca were significantly greater than all other treatments. Mean biomass yields from treatment Ib were not significantly different from Ca, Cc, or Ia, but yields were significantly greater than Ic and Cd, while yields from treatment Ib were significantly less than mean yields from treatment Cb. Mean biomass yields from treatments Cc and Ia were not significantly different from yields in treatments Ib, Ic, or Cd, however means were significantly less than yields from treatments Ca and Cb. Mean biomass yields from treatments Cd and Ic were not significantly different than yields from Ia and Cc but yields were significantly less than mean yields from all other treatments.

Table 4. Treatment mean comparisons of SHWP tons per acre removed. Sample means in column followed by the same letter(s) are not significantly different at $\alpha = 0.05$.

Grouping		Mean	Treatment
	A	56.30	Ca
B	A	52.19	Cd
B	A	48.49	Cc
B		41.70	Cb
	C	25.68	Ic
	C	16.66	Ib
	C	14.68	Ia

Table 5. Treatment mean comparisons of biomass tons per acre removed. Sample means in column followed by the same letter(s) are not significantly different at $\alpha = 0.05$.

Grouping		Mean	Treatment
	A	15.96	Cb
B	A	12.67	Ca
B	C	7.36	Ib
D	C	3.83	Cc
D	C	2.67	Ia
	D	1.45	Ic
	D	0.00	Cd

3.2 Volumes Harvested

Harvest volumes removed from the study site were recorded at the mills using two metrics: board feet and tonnage. Using 166[1] board feet / ton as a conversion factor; 2,279 tons of SHWP and 391 tons of biomass were removed from the site, or 2,670 total tons (Figure 9). Green tons (2000 pounds/ton) were the metric for reporting volume for this study to enable comparisons between SHWP and biomass chips. It was observed that 85.3 percent of the volume removed was SHWP while 14.7 percent of the volume removed was biomass chips. Volume removal throughout the study site varied from as low as 8.7 tons per acre in the intermediate thinning treatments to as high as 70.7 tons per acre in the clearcut treatments (Table 6). There were 89 log truck loads and 17 chip van loads removed over the duration of the harvest (Table 7).

Table 6. Total tons per acre, biomass chip tons per acre, and SHWP tons per acre removed from each sample plot.

Treatment/sample	Plot #	Tons/acre removed	Tons/acre chips	Tons/acre SHWP
Clearcut A	4	67.3	10.6	56.6
Clearcut A	23	70.7	14.7	56.0
Clearcut B	2	51.3	13.8	37.5
Clearcut B	24	64.1	18.2	45.9
Clearcut C	7	54.0	1.4	52.6
Clearcut C	21	50.7	6.2	44.4
Clearcut D	8	52.5	0	52.5
Clearcut D	13	51.9	0	51.9
Intermediate A	6	26.0	4.2	21.9
Intermediate A	12	8.7	1.2	7.5
Intermediate B	1	21.9	4.2	17.8
Intermediate B	11	26.2	10.6	15.6
Intermediate C	3	23.3	0	23.3
Intermediate C	22	30.9	2.9	28.0
Average		**42.8**	**6.3**	**36.5**

[1] This conversion factor was used by local saw mills during the study harvest

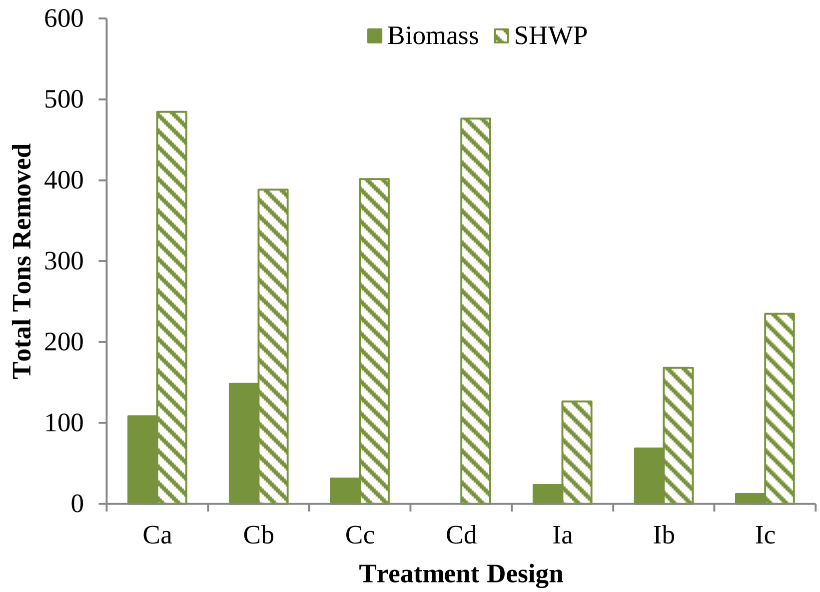

Figure 9. Total volume (tons) by product removed per treatment from study harvest

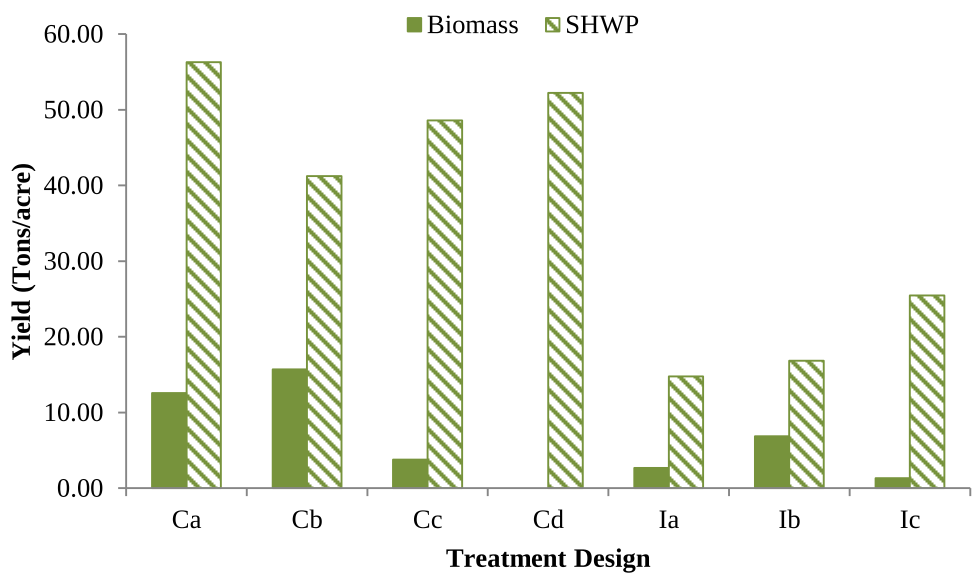

Figure 10. Average tons per acre by product removed per treatment from study harvest

3.3 Observed Prices for SHWP and Biomass Chips Products

The prices received for solid hardwood products (SHWP) and biomass chips varied throughout the duration of the harvest. SHWP products were hauled to 10 different sawmills, each mill paid different prices for various wood products. Only two biomass chip mills purchased products from this operation and hauling distance was a large contributing factor to the price paid for fuel chips. The observed average price for SHWP products was $36.98 per ton and ranged from $20.00 (blocking) to $183.65 (staves) per ton (Table 7). The observed average biomass chips price was $17.29 per ton and ranged from $15.00 to $28.00 per ton. Total revenues from this study harvest (72.01 acres) was $88,489.00 dollars. Of this total $6,508.77 (7%) was biomass fuel chips and $81,980.23 (93%) was from SHWP.

Table 7. Wood Product and biomass fuel chips price results for the twelve different product buyers observed in this study and the hauling distance to each buyer.

Product and buyer	# of loads delivered	Low Price ($ / Ton)	High Price ($ / Ton)	Average Price / Ton	Distance to Mill (one-way miles)
SHWP Mill 1	22	29.00	29.00	29.00	84
SHWP Mill 2	22	20.00	29.00	24.50	81
SHWP Mill 3	12	34.50	38.12	36.31	10
SHWP Mill 4	1	34.63	34.63	34.63	12
SHWP Mill 5	17	45.75	46.57	46.16	85
SHWP Mill 6	3	48.88	50.97	49.93	105
SHWP Mill 7	3	116.11	183.65	149.88	13
SHWP Mill 8	1	30.02	30.02	30.02	20
SHWP Mill 9	5	23.00	23.00	23.00	87
SHWP Mill 10	3	38.25	38.25	38.25	211
Biomass Mill 1	14	15.00	15.00	15.00	33
Biomass Mill 2	3	28.00	28.00	28.00	211

3.4 Equipment Productivity Observations

As described in section 2.6.3, the purpose of collecting time-in-motion data was to estimate how much time each piece of equipment spent handling biomass or SHWP for each treatment type. These results are presented before the cost estimates because the % biomass estimate is necessary to properly allocate the costs of harvesting between the two wood products. Harvest data from all treatments were analyzed as separate units. This section will describe in detail the productivity associated with each machine on each treatment utilized during the harvest. A complete activity percentage breakdown for each machine on each treatment can be found in Appendix Tables 1 – 5.

3.4.1 Clearcut Treatment A

The chipper and loader 2 both had % biomass values of 100% (1.0) due to their entire workload dedicated to feeding the chipper or chipping biomass. It should be noted that the chipper and loader 2 had % biomass values of 100% for every treatment during the harvest, thus productivity data in all other 3.4 sections will only report on the skidder, feller-buncher and loader 1 data.

A total of 157 skidder cycles (34.48 hours) were observed in clearcut treatment A with a total of 657 stems removed. Thus, stems per bundle averaged 4 pieces. Field observations estimated that 118 of the 657 stems brought to the landing were small diameter material. A total of 592.43 tons of material was removed from this treatment. From this total, 108.09 tons was biomass material, therefore 18.2% was used as the % biomass estimate for all components of this treatment.

A total of 398.4 minutes (1,195 observations) of feller-buncher activity and time-in-motion sampling was collected over the clearcut treatment A harvest duration.

Observed activities were classified into 6 categories: sawing SHWP, sawing block/pallet/pulp, dropping SHWP, dropping block/pallet/pulp, moving, and delay. The SHWP were segregated into two categories during the loader and feller-buncher activity sampling; SHWP and block/pallet/pulp were separate categories on the data sheet. This separation was likely unnecessary because both products were pooled into one SHWP category for cost and revenue analysis. However, for the sake of consistency, these categories were not modified during the harvest.

A total of 1,081.5 minutes (2,163 observations) of loader activity sampling was collected over the clearcut treatment A harvest duration. Observed activities were classified into 8 categories: processing SHWP; processing block/pallet/pulp; stacking SHWP; stacking block/pallet/pulp; stacking biomass; loading SHWP; loading block/pallet/pulp; and delay (Figure 11). Field observations through activity sampling estimated that loader 1 did handle some small diameter stems; it was not uncommon for loader 1 to sometimes stack smaller diameter trees in the biomass pile that was later handled entirely by loader 2.

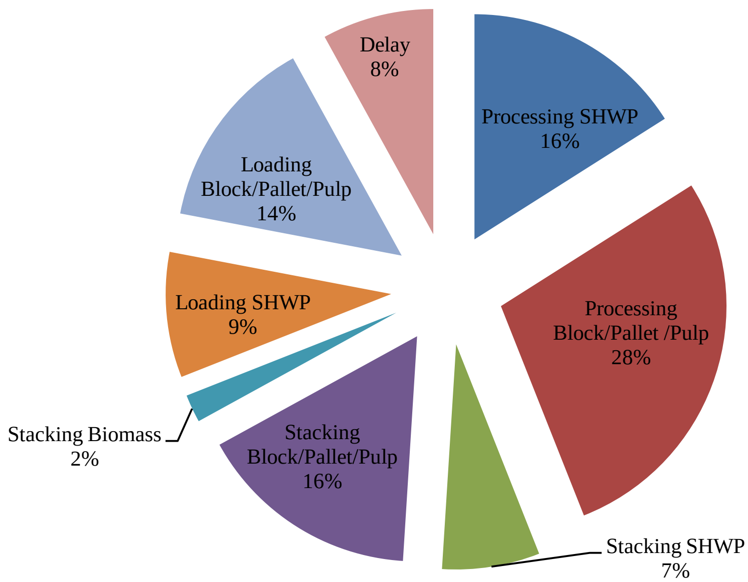

Figure 11. Loader 1 utilization time by harvest function for clearcut treatment A.

3.4.2 Clearcut Treatment B

A total of 114 skidder cycles (19.38 hours) were observed in clearcut treatment B with a total of 413 stems. Thus, stems per bundle averaged 4 pieces. Field observations estimated that 94 of the 413 stems brought to the landing were small diameter material. A total of 536.52 tons of material was removed from this treatment. From this total, 148.07 tons was biomass material, therefore 27.5% was used as the % biomass estimate for all components of this treatment.

A total of 301.1 minutes (904 observations) of feller-buncher activity and time-in-motion sampling was collected over the clearcut treatment B harvest duration. A total of 745 minutes (1,490 observations) of loader activity sampling was collected over the clearcut treatment B harvest duration.

3.4.3 Clearcut Treatment C

A total of 155 skidder cycles (22.5 hours) were observed in clearcut treatment C with a total of 625 stems. Thus, stems per bundle averaged 4 pieces. Field observations estimated that 183 of the 625 stems brought to the landing were small diameter material. A total of 432.53 tons of material was removed from this treatment. From this total, 31.24 tons was biomass material, therefore 7.2% was used as the % biomass estimate for all components of this treatment.

A total of 292.5 minutes (878 observations) of feller-buncher activity and time-in-motion sampling was collected over the clearcut treatment C harvest duration. A total of 876.5 minutes (1,753 observations) of loader activity sampling was collected over the clearcut treatment C harvest duration.

3.4.4 Clearcut Treatment D

A total of 118 skidder cycles (20.85 hours) were observed in clearcut treatment D with a total of 623 stems. Thus, stems per bundle averaged 4 pieces. Field observations estimated that 178 of the 623 stems brought to the landing were small diameter material. Due to the harvest regime associated with this treatment, small diameter stems were marketed as pulpwood products and were not processed on site as chip material.

A total of 266.8 minutes (801 observations) of feller-buncher activity and time-in-motion sampling was collected over the clearcut treatment D harvest duration. A total of 788.5 minutes (1,577 observations) of loader activity sampling was collected over the clearcut treatment D harvest duration. Because the associated harvest regime called for no biomass to be removed from treatment D, a value of 0.00 was used as the % of time utilized for biomass for all equipment during this treatment.

3.4.5 Intermediate Thinning Treatment A

A total of 62 skidder cycles (12.23 hours) were observed in intermediate thinning treatment A with a total of 210 stems. Thus, stems per bundle averaged 3 pieces. Field observations estimated that 3 of the 210 stems brought to the landing were small diameter material. A total of 149.39 tons of material was removed from this treatment. From this total, 23.07 tons was biomass material, therefore 15.4% was used as the % biomass estimate for all components of this treatment.

A total of 113.7 minutes (342 observations) of feller-buncher activity and time-in-motion sampling was collected over the intermediate thinning treatment A harvest duration. A total of 370 minutes (740 observations) of loader activity sampling was collected over the intermediate thinning treatment A harvest duration.

3.4.6 Intermediate Thinning Treatment B

A total of 60 skidder cycles (11.5 hours) were observed in intermediate thinning treatment B with a total of 219 stems. Thus, stems per bundle averaged 4 pieces. A total of 236.31 tons of material was removed from this treatment. From this total, 68.41 tons was biomass material, therefore 28.9% was used as the % biomass estimate for all components of this treatment.

A total of 168.1 minutes (505 observations) of feller-buncher activity and time-in-motion sampling was collected over the intermediate thinning treatment B harvest duration. A total of 464 minutes (928 observations) of loader activity sampling was collected over the intermediate thinning treatment B harvest duration.

3.4.7 Intermediate Thinning Treatment C

A total of 82 skidder cycles (13.65 hours) were observed in intermediate thinning treatment C with a total of 243 stems. Thus, stems per bundle averaged 3 pieces. A total of 246.85 tons of material was removed from this treatment. From this total, 12.15 tons was biomass material, therefore 28.9% was used as the % biomass estimate for all components of this treatment.

A total of 256.1 minutes (769 observations) of feller-buncher activity and time-in-motion sampling was collected over the intermediate thinning treatment C harvest duration. A total of 503.5 minutes (1,007 observations) of loader activity sampling was collected over the intermediate thinning treatment C harvest duration.

3.5 Observed System Costs

This section highlights all observed cost components of the harvest: fixed equipment costs, variable equipment costs, labor costs, hauling costs, stumpage costs, and a summary of the total observed costs.

3.5.1 Fixed Equipment Costs

The entire study harvest lasted a total of 72 working days. Assuming that no rain days or delays from hunting season occurred during the harvest, approximately 54 days would have been needed to complete the harvest and, thus, scheduled machine hours (SMH's) were modified to reflect only the days when the equipment was being utilized. Using the cost estimations in Tables 8 and 9, the total tons harvested (Figure 9), and the

% biomass estimates provided in sections 3.4.1 – 3.4.7, the fixed cost per ton of SHWP and biomass chips was calculated for each piece of harvest equipment. The cost-per-ton estimates for the log truck were calculated as a function of miles traveled, shown in section 3.5.3.

Table 8. Fixed equipment cost figures showing the cost per scheduled machine hour, observed scheduled machine hours, and fixed equipment costs for each piece of equipment and the entire equipment suite for all clearcut treatments. This table does not include stumpage costs.

Machine	Ca			Cb			Cc			Cd		
	SMH	Cost / SMH	Fixed Cost	SMH	Cost / SMH	Fixed Cost	SMH	Cost / SMH	Fixed Cost	SMH	Cost / SMH	Fixed Cost
Feller/Buncher	107	$2.38	$254.66	68.5	$2.38	$163.03	69.5	$2.38	$165.41	111.5	$2.38	$265.37
Skidder	107	$2.75	$294.25	68.5	$2.75	$188.38	69.5	$2.75	$191.13	111.5	$2.75	$306.63
Loader 1	107	$1.63	$174.41	68.5	$1.63	$111.66	69.5	$1.63	$113.29	111.5	$1.63	$181.75
Loader 2	107	$1.49	$159.43	68.5	$1.49	$102.07	69.5	$1.49	$103.56	0	$1.49	$0.00
Chipper	107	$12.36	$1,322.52	68.5	$12.36	$846.66	69.5	$12.36	$859.02	0	$12.36	$0.00
Truck & Trailer	107	$5.94	$635.58	68.5	$5.94	$406.89	69.5	$5.94	$412.83	111.5	$5.94	$662.31
Total			**$2,840.85**			**$1,818.68**			**$1,845.23**			**$1,416.05**

Table 9. Fixed equipment cost figures showing the cost per scheduled machine hour, observed scheduled machine hours, and fixed equipment costs for each piece of equipment and the entire equipment suite for all intermediate thinning treatments. This table does not include stumpage costs.

Machine	Ia			Ib			Ic		
	SMH	Cost / SMH	Fixed Cost	SMH	Cost / SMH	Fixed Cost	SMH	Cost / SMH	Fixed Cost
Feller/Buncher	26	$2.38	$61.88	59	$2.38	$140.42	36.5	$2.38	$86.87
Skidder	26	$2.75	$71.50	59	$2.75	$162.25	36.5	$2.75	$100.38
Loader 1	26	$1.63	$42.38	59	$1.63	$96.17	36.5	$1.63	$59.50
Loader 2	26	$1.49	$38.74	59	$1.49	$87.91	36.5	$1.49	$54.39
Chipper	26	$12.36	$321.36	59	$12.36	$729.24	36.5	$12.36	$451.14
Truck & Trailer	26	$5.94	$154.44	59	$5.94	$350.46	36.5	$5.94	$216.81
Total			**$690.30**			**$1,566.45**			**$969.08**

3.5.2 Variable Equipment Costs

Depending upon treatment, the equipment used in this study had observed PMH ranging from 1.25 to 80.51 hours (Tables 10-11). The equipment cost per PMH ranged from as low as $22.38 per hour (skidder) to as high as $64.09 per hour (chipper) (Table

10). The cost per hour was multiplied by the observed number of PMH for each piece of equipment to generate the variable equipment cost for each individual piece of equipment on site.

Table 10. Variable equipment cost figures showing the cost per productive machine hour, observed productive machine hours, and variable equipment costs for each piece of equipment and the entire equipment suite for all clearcut treatments. This table does not include labor costs.

Equipment	Ca			Cb			Cc			Cd		
	PMH	Cost/PMH	Variable Cost	PMH	Cost/PMH	Variable Cost	PMH	Cost/PMH	Variable Cost	PMH	Cost/PMH	Variable Cost
Feller/Buncher	13.06	$39.43	$514.96	12.6	$39.43	$496.82	9.51	$39.43	$374.98	17.58	$39.43	$693.18
Skidder	48.56	$22.38	$1,086.77	44.7	$22.38	$1,000.39	34.2	$22.38	$765.40	40.53	$22.38	$907.06
Loader 1	37.96	$24.80	$941.41	31.95	$24.80	$792.36	26.56	$24.80	$658.69	28.5	$24.80	$706.80
Loader 2	8.56	$27.27	$233.43	10.96	$27.27	$298.88	2.58	$27.27	$70.36	0	$27.27	$0.00
Chipper	7.11	$64.09	$455.68	8.26	$64.09	$529.38	1.55	$64.09	$99.34	0	$64.09	$0.00
Truck & Trailer	80.51	$27.66	$2,226.91	71.47	$27.66	$1,976.86	54.2	$27.66	$1,499.17	59.78	$27.66	$1,653.51
Total			**$5,459.15**			**$5,094.69**			**$3,467.93**			**$3,960.56**

Table 11. Variable equipment cost figures showing the cost per productive machine hour, observed productive machine hours, and variable equipment costs for each piece of equipment and the entire equipment suite for all intermediate thinning treatments. This table does not include labor costs.

Equipment	Ia			Ib			Ic		
	PMH	Cost/PMH	Variable Cost	PMH	Cost/PMH	Variable Cost	PMH	Cost/PMH	Variable Cost
Feller/Buncher	4.91	$39.43	$193.60	6.83	$39.43	$269.31	7.1	$39.43	$279.95
Skidder	14.45	$22.38	$323.39	18.63	$22.38	$416.94	23.03	$22.38	$515.41
Loader 1	9.46	$24.80	$234.61	24.86	$24.80	$616.53	13.46	$24.80	$333.81
Loader 2	2.03	$27.27	$55.36	6.96	$27.27	$189.80	1.63	$27.27	$44.45
Chipper	1.25	$64.09	$80.11	4.33	$64.09	$277.51	2.03	$64.09	$130.10
Truck & Trailer	15.81	$27.66	$437.30	30.76	$27.66	$850.82	32.43	$27.66	$897.01
Total			**$1,324.38**			**$2,620.90**			**$2,200.74**

Using the cost estimations in Table 10, the total tons harvested (Figure 9), and the % biomass estimates provided in section 3.4.1 – 3.4.7, the variable cost per ton of SHWP and biomass chips were calculated for each piece of harvest equipment (Table 11).

3.5.3 Hauling Costs

The total cost of hauling observed in this study was $12,380.91; this cost was obtained by the summation of all PMH and SMH data for the truck and trailer presented in Tables 8, 10, and in the appendices. This total cost was divided by the total observed distance traveled by the log truck (15,488 miles) to estimate the fuel cost per mile ($0.80). Estimated cost per mile was divided by the average load size (25.19 tons) to generate an estimated cost per ton per mile ($0.0317). This aforementioned fuel cost was believed to be too low (Tom Gallagher[2]) and a more commonly used estimate of $3.00/loaded mile was instead used as the fuel cost per mile. This modified fuel cost led to a new cost per ton per mile of $0.11.

3.5.4 Labor Costs

Labor costs used for the logging operation varied based upon productivity. Typically, the owner pays the crew daily flat wages, however, when this study began, the crew was in the training process for their new skidder operator, so the skidder operator was paid based on the volume that was harvested ($40 per load), while the rest of the crew were paid their daily flat wages (foreman-$160, cutter-$120, driver-$100 +$50 per load if over 10 loads per week). As mentioned in section 2.7.4 the labor costs for the entire crew averaged $454 per day and were distributed across hours spent in each treatment unit. Labor costs were then split between the two product types for each treatment using the % biomass figures from the harvesting equipment. The crew varied between 3 and 5 people throughout the duration of the study harvest. A total of 54 working days were observed for the crew over the time of the study. A total of $24,516 dollars was paid in wages. This methodology was applied because the crew had an unusually long travel time to the job site and was unaware of the expected yields due to the requirements of the research project.

[2] Personal communication May, 2013

3.5.5 Stumpage Costs

Only one bid was submitted due to the equipment specifications required in the bid contract. The stumpage for the 72 acre tract was $24,587.20. This stumpage cost was then distributed across individual plots according to the board footage estimates provided in the bid solicitation. The clearcut pre-treatment inventory estimated 307,551 board feet which sold for $17,210. The intermediate thinning pre-treatment inventory estimated 131,977 board feet which sold for $7,376.10. These costs were then distributed across treatments by the percentage of acreage in each treatment replicate. The actual stumpage paid by the logger was much lower than the sale contract specified. This lower price was attributed to additional costs associated with the data collection process and the fact that the crew had to travel a longer distance to the study site each day which added to the routine operational expenses. For the purposes of this study the stumpage price ($24,587.20) provided in the bid contract was used, as that is what this timber sale would have gone for under normal circumstances.

3.5.6 Cost Summary

This section is designed to arrange all the fixed and variable costs presented earlier in sections 3.5.1 and 3.5.2 and display them in figures and tables. The total observed costs of the harvest operation was $84,354.40. Labor and stumpage generally captured the greatest share of harvest costs among treatments, ranging between 20 and 50 percent, respectively (Figure 12 and Appendix figures 5 - 10).

Table 12. Observed variable, fixed and total costs for equipment, stumpage, and labor for all clearcut treatments.

	Clearcut Treatment A			Clearcut Treatment B			Clearcut Treatment C			Clearcut Treatment D		
Component	Variable Cost	Fixed Cost	Total Cost	Variable Cost	Fixed Cost	Total Cost	Variable Cost	Fixed Cost	Total Cost	Variable Cost	Fixed Cost	Total Cost
Feller/Buncher	$514.96	$254.66	$769.62	$496.82	$163.03	$659.85	$374.98	$165.41	$540.39	$693.18	$265.37	$958.55
Skidder	$1,086.77	$294.25	$1,381.02	$1,000.39	$188.38	$1,188.76	$765.40	$191.13	$956.52	$907.06	$306.63	$1,213.69
Loader 1	$941.41	$174.41	$1,115.82	$792.36	$111.66	$904.02	$658.69	$113.29	$771.97	$706.80	$181.75	$888.55
Loader 2	$233.43	$159.43	$392.86	$298.88	$102.07	$400.94	$70.36	$103.56	$173.91	$0.00	$0.00	$0.00
Chipper	$455.68	$1,322.52	$1,778.20	$529.38	$846.66	$1,376.04	$99.34	$859.02	$958.36	$0.00	$0.00	$0.00
Truck & Trailer	$2,226.91	$635.58	$2,862.49	$1,976.86	$406.89	$2,383.75	$1,499.17	$412.83	$1,912.00	$1,653.51	$662.31	$2,315.82
Labor	$5,448.00	na	$5,448.00	$3,632.00	na	$3,632.00	$3,178.00	na	$3,178.00	$5,902.00	na	$5,902.00
Stumpage	na	$4,180.52	$4,180.52	na	$4,579.82	$4,579.82	na	$4,015.09	$4,015.09	na	$4,433.29	$4,433.29
Total	$10,907.15	$7,021.37	**$17,928.52**	$8,726.69	$6,398.50	**$15,125.18**	$6,645.93	$5,860.32	**$12,506.25**	$9,862.56	$5,849.34	**$15,711.90**

Table 13. Observed variable, fixed and total costs for equipment, stumpage, and labor for all intermediate thinning treatments.

	Intermediate Thinning Treatment A			Intermediate Thinning Treatment B			Intermediate Thinning Treatment C		
Component	Variable Cost	Fixed Cost	Total Cost	Variable Cost	Fixed Cost	Total Cost	Variable Cost	Fixed Cost	Total Cost
Feller/Buncher	$193.60	$61.88	$255.48	$269.31	$140.42	$409.73	$279.95	$86.87	$366.82
Skidder	$323.39	$71.50	$394.89	$416.94	$162.25	$579.19	$515.41	$100.38	$615.79
Loader 1	$234.61	$42.38	$276.99	$616.53	$96.17	$712.70	$333.81	$59.50	$393.30
Loader 2	$55.36	$38.74	$94.10	$189.80	$87.91	$277.71	$44.45	$54.39	$98.84
Chipper	$80.11	$321.36	$401.47	$277.51	$729.24	$1,006.75	$130.10	$451.14	$581.24
Truck & Trailer	$437.30	$154.44	$591.74	$850.82	$350.46	$1,201.28	$897.01	$216.81	$1,113.82
Labor	$1,362.00	na	$1,362.00	$2,724.00	na	$2,724.00	$2,270.00	na	$2,270.00
Stumpage	na	$2,273.31	$2,273.31	na	$2,650.97	$2,650.97	na	$2,451.07	$2,451.07
Total	$2,686.38	$2,963.61	**$5,649.99**	$5,344.90	$4,217.42	**$9,562.32**	$4,470.74	$3,420.15	**$7,890.88**

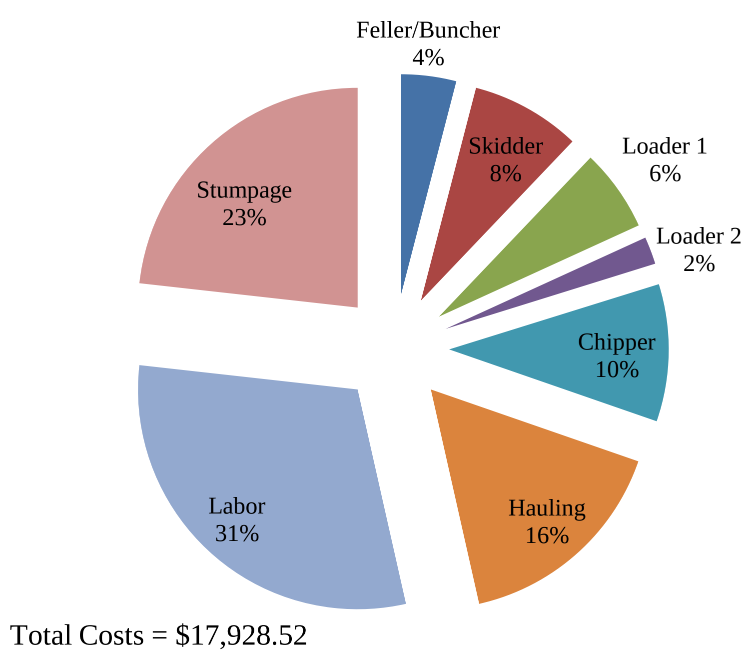

Figure 12. Total observed cost components for clearcut treatment A.

3.6 Harvesting System Productivity

This section presents the cost dynamics of the system used for the study harvest. The cost components of the integrated system consist of harvest, stumpage, and hauling. For analysis in section 3.6.1, all labor and machine costs were combined into the "harvest" category, where stumpage and hauling remained separate costs. Section 3.6.1 uses the revenue and cost estimates presented in section 3.2 through 3.5 to estimate the profit/loss of the integrated system in a balance sheet format.

3.6.1 Profit/loss of the Integrated System

The harvest component of the integrated system cost figures (Figures 13 & 14) are the pooling of all cost per ton data on machines used for the study in addition to labor. The hauling and stumpage costs remain separate as they were individual cost components not directly associated with the physical harvest operation. The cost per ton of SHWP and biomass chips in the clearcut treatments ranged from \$24.91 to \$32.99 and \$36.79 to \$62.46, respectively (Table 14). The cost per ton of SHWP and biomass chips in the intermediate thinning treatments ranged from \$29.22 to \$35.05 and \$53.75 to \$85.05, respectively (Table 15).

Table 14. Estimated cost per ton for each component of the study harvest for solid hardwood products and biomass chips on all clearcut treatments.

Equipment	Ca		Cb		Cc		Cd	
	Total Cost / Ton SHWP	Total Cost / Ton Biomass	Total Cost / Ton SHWP	Total Cost / Ton Biomass	Total Cost / Ton SHWP	Total Cost / Ton Biomass	Total Cost / Ton SHWP	Total Cost / Ton Biomass
Feller/Buncher	$1.30	$1.30	$1.23	$1.23	$1.25	$1.25	$2.01	$0.00
Skidder	$2.33	$2.33	$2.22	$2.21	$2.21	$2.20	$2.55	$0.00
Loader 1	$1.88	$1.88	$1.69	$1.68	$1.79	$1.78	$1.87	$0.00
Loader 2	$0.00	$3.63	$0.00	$2.71	$0.00	$5.57	$0.00	$0.00
Chipper	$0.00	$16.45	$0.00	$9.29	$0.00	$30.68	$0.00	$0.00
Truck & Trailer	$4.83	$4.82	$4.45	$4.43	$4.42	$4.41	$4.86	$0.00
Stumpage	$7.06	$7.04	$8.55	$8.51	$9.29	$9.25	$9.31	$0.00
Labor	$9.20	$9.17	$6.78	$6.75	$7.35	$7.32	$12.39	$0.00
Total Cost / Ton	**$26.61**	**$46.62**	**$24.91**	**$36.79**	**$26.30**	**$62.46**	**$32.99**	**$0.00**

Table 15. Estimated cost per ton for each component of the study harvest for solid hardwood products and biomass chips on all intermediate thinning treatments.

Equipment	Ia		Ib		Ic	
	Total Cost / Ton SHWP	Total Cost / Ton Biomass	Total Cost / Ton SHWP	Total Cost / Ton Biomass	Total Cost / Ton SHWP	Total Cost / Ton Biomass
Feller/Buncher	$1.71	$1.71	$1.74	$1.73	$1.49	$1.48
Skidder	$2.64	$2.64	$2.45	$2.45	$2.50	$2.48
Loader 1	$1.86	$1.85	$3.02	$3.01	$1.59	$1.59
Loader 2	$0.00	$4.08	$0.00	$4.06	$0.00	$8.13
Chipper	$0.00	$17.40	$0.00	$14.72	$0.00	$47.84
Truck & Trailer	$3.79	$3.78	$5.09	$5.07	$4.51	$4.49
Stumpage	$15.22	$15.18	$11.23	$11.20	$9.93	$9.88
Labor	$9.12	$9.09	$11.54	$11.51	$9.20	$9.15
Total Cost / Ton	**$34.35**	**$55.72**	**$35.05**	**$53.75**	**$29.22**	**$85.05**

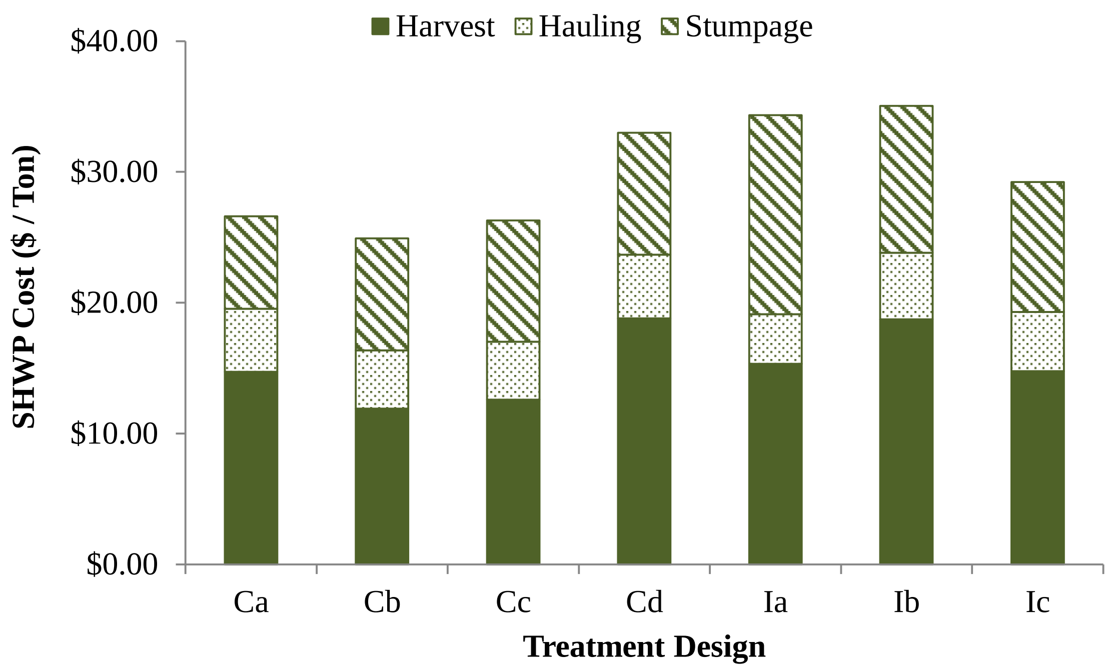

Figure 13. Integrated system cost per ton for SHWP products for each component of the harvest on all treatment types.

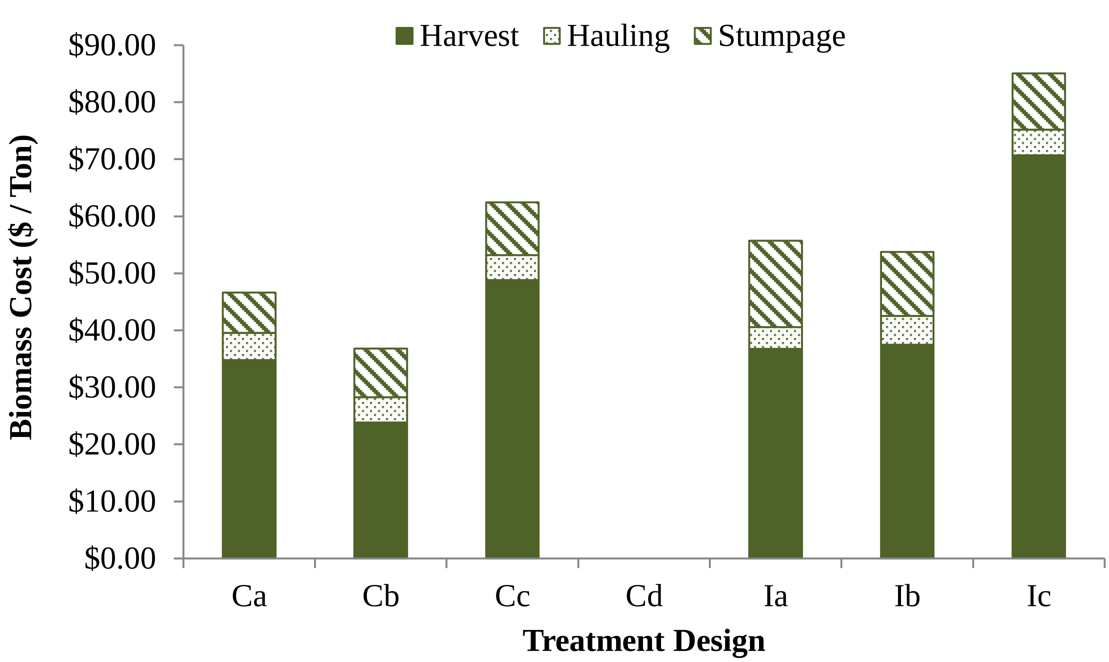

Figure 14. Integrated system cost per ton for biomass fuel chips for each component of the harvest on all treatment types.

The observed prices for the two products varied by treatment because products were hauled to different mills at different times throughout the duration of the harvest. In all clearcut treatments the SHWP sold for a greater price than its breakeven price and the fuel chips sold for lower than its breakeven price. Ultimately, the profits from the SHWP in each clearcut treatment were large enough to offset the losses endured from harvesting the biomass, leading to an overall net profit for each clearcut treatment (Table 16). In the intermediate treatments A and B, the SHWP did not sell for a greater price than its breakeven price, additionally, the fuel chips sold for lower than its breakeven price resulting in a net loss for the two treatments (Figure 15). The SHWP products in intermediate treatments were generally lower quality black oak taken to the "blocking" mills due to their form and size dimensions. Revenues from these products were generally not as high as some of the products removed from the clearcut treatments such as staves, ties, and logs (flooring), which in addition to lower yields, likely led to such low profit margins in the intermediate treatments when compared to the clearcuts. The SHWP products in intermediate treatment C were able to sell for more than the breakeven price, which ultimately offset the losses from the fuel chips in this treatment and resulted in a net profit of $935.72 for this treatment (Table 17).

Table 16. Balance sheet for integrated system harvest showing profit/loss per ton for each component of the harvest and the net revenue for all clearcut treatments

	Ca		Cb		Cc		Cd	
	SHWP	Biomass	SHWP	Biomass	SHWP	Biomass	SHWP	Biomass
Revenue / Ton	$34.48	$15.00	$36.34	$15.00	$35.14	$15.00	$38.91	$0.00
Harvest cost per ton	$15.57	$30.93	$13.61	$19.59	$11.36	$64.72	$18.82	$0.00
Hauling cost per ton	$4.83	$4.82	$4.45	$4.43	$4.42	$4.41	$4.86	$0.00
Stumpage cost per ton	$7.06	$7.04	$8.55	$8.51	$9.29	$9.25	$9.31	$0.00
Profit / ton	$7.88	-$31.62	$11.42	-$21.80	$8.76	-$46.42	$5.93	$0.00
Total tons	484.34	108.09	388.45	148.07	401.29	31.24	476.3	0
Profit	$3,814.46	-$3,417.69	$4,437.56	-$3,227.74	$3,513.73	-$1,450.16	$2,822.17	$0.00
Grand Total Profits	**$396.77**		**$1,209.82**		**$2,063.57**		**$2,822.17**	

Table 17. Balance sheet for integrated system harvest showing profit/loss per ton for each component of the harvest and the net revenue for all intermediate thinning treatments

	Ia		Ib		Ic	
	SHWP	Biomass	SHWP	Biomass	SHWP	Biomass
Revenue / Ton	$34.01	$17.86	$33.28	$23.44	$36.83	$15.00
Harvest cost per ton	$17.25	$26.25	$23.86	$24.91	$14.61	$73.88
Hauling cost per ton	$3.79	$3.78	$5.09	$5.07	$4.51	$4.49
Stumpage cost per ton	$15.22	$15.18	$11.23	$11.20	$9.93	$9.88
Profit / ton	-$0.33	-$37.86	-$1.79	-$22.19	$7.61	-$70.05
Total tons	126.32	23.07	167.9	68.41	234.7	12.15
Profit	-$41.95	-$873.51	-$299.73	-$1,517.80	$1,786.79	-$851.07
Grand Total Profits	**-$915.46**		**-$1,817.53**		**$935.72**	

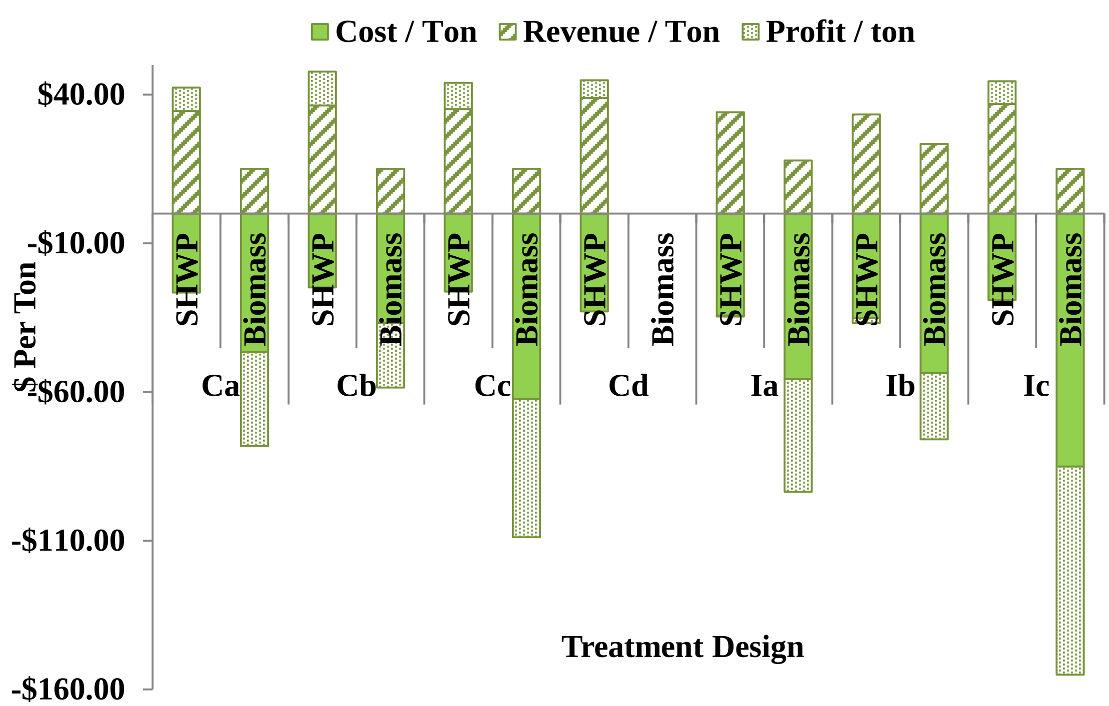

Figure 15. Integrated harvest system's cost, revenue, and profit/loss per ton for SHWP and biomass fuel chips products on all treatment types.

3.7 Benefit:Cost Ratios

As outlined in section 2.7.5 a benefit:cost analysis was performed to evaluate the economic merit of the treatments and BMP practices within the treatments. The outcome of the B:C analysis calculations for each harvest treatment are displayed in Table 18. All clearcut treatment types generated revenues that exceeded the cost of operation as well as intermediate treatment C which actually had a benefit:cost ratio greater than two of the clearcut treatments. Intermediate thinning treatments A and B had B:C ratios of less than one which indicate that the cost of preforming these treatments were greater than the revenues, thus making these treatments economically unacceptable.

Table 18. Benefit:Cost Ratios by treatment type. Treatments with a B:C ratio greater than 1 considered economically acceptable, treatments with a B:C ratio less than 1 are considered economically unacceptable.

Treatment	B:C Ratio
Cd	1.17
Cc	1.16
Ic	1.11
Cb	1.07
Ca	1.02
Ia	0.83
Ib	0.79

3.8 Sensitivity Analysis

Analysis in section 3.6.1 dealt with different scenarios and market conditions that could be faced by loggers in the Missouri Ozarks. The effects of changes in diesel fuel price (3.8.1), changes in equipment suite price (3.8.2), changes in stumpage prices (3.8.3), and changes in hauling distance (3.8.4) on the total production cost per ton for each product type for each treatment was determined through a sensitivity analysis. In the analysis all other costs per treatment were held constant while only the cost being examined was changed. For all treatment analyses the original cost being examined was decreased by a total of 50% and increased by a total of 100% in 10% increments.

3.8.1 Changes in Diesel Prices

Fuel costs are a critical factor that goes into determining the cost per PMH. An increase in fuel prices alters the harvesting and hauling costs, which ultimately increases the total cost per ton and the revenues required per ton in order to break even. This increase does not cause changes to stumpage or labor costs. For the duration of the harvest off-road diesel prices in the Ozarks were at an average of $3.33 (designated with an X in Figures 16 and 17) per gallon. This assumed fuel price was used to estimate the production costs per ton for each treatment. An increase in diesel fuel prices from $3.00 to $5.00 per gallon, a $2.00 (66%) change was used for the sensitivity for each treatment.

<u>Clearcut Treatment A</u>

The assumed fuel price of $3.33 per gallon resulted in production costs per ton of $26.61 and $46.62 for the SHWP and biomass chips, respectively (designated with an X in Figure 16). A $2.00 increase in diesel fuel prices from $3.00 to $5.00 per gallon resulted in a change in the total cost per ton from $26.04 to $29.46 for the SHWP, a $3.42 dollar increase (13.1 % change), and a change in the total cost per ton from $45.94 to $50.02 for the biomass chips, a $4.08 dollar increase (8.8% change).

<u>Clearcut Treatment B</u>

The assumed fuel price of $3.33 per gallon resulted in production costs per ton of $24.91 and $36.79 for the SHWP and biomass chips, respectively (designated with an X in Figure 16). A $2.00 increase in diesel fuel prices from $3.00 to $5.00 per gallon resulted in a change in the total cost per ton from $24.30 to $27.96 for the SHWP, a $3.66 dollar increase (15.1% change), and a change in the total cost per ton from $36.25 to $39.49 for the biomass chips, a $3.24 dollar increase (8.2% change).

Clearcut Treatment C

The assumed fuel price of $3.33 per gallon resulted in production costs per ton of $26.30 and $62.46 for the SHWP and biomass chips, respectively (designated with an X in Figure 16). A $2.00 increase in diesel fuel prices from $3.00 to $5.00 per gallon resulted in a change in the total cost per ton from $25.85 to $28.55 for the SHWP, a $2.70 dollar increase (10.4% change), and a change in the total cost per ton from $61.12 to $69.16 for the biomass chips, a $8.04 dollar increase (13.1% change).

Clearcut Treatment D

The assumed fuel price of $3.33 per gallon resulted in production costs per ton of $32.99 for the SHWP (designated with an X in Figure 16). A $2.00 increase in diesel fuel prices from $3.00 to $5.00 per gallon resulted in a change in the total cost per ton from $32.44 to $35.74 for the SHWP, a $3.30 dollar increase (10.1% change).

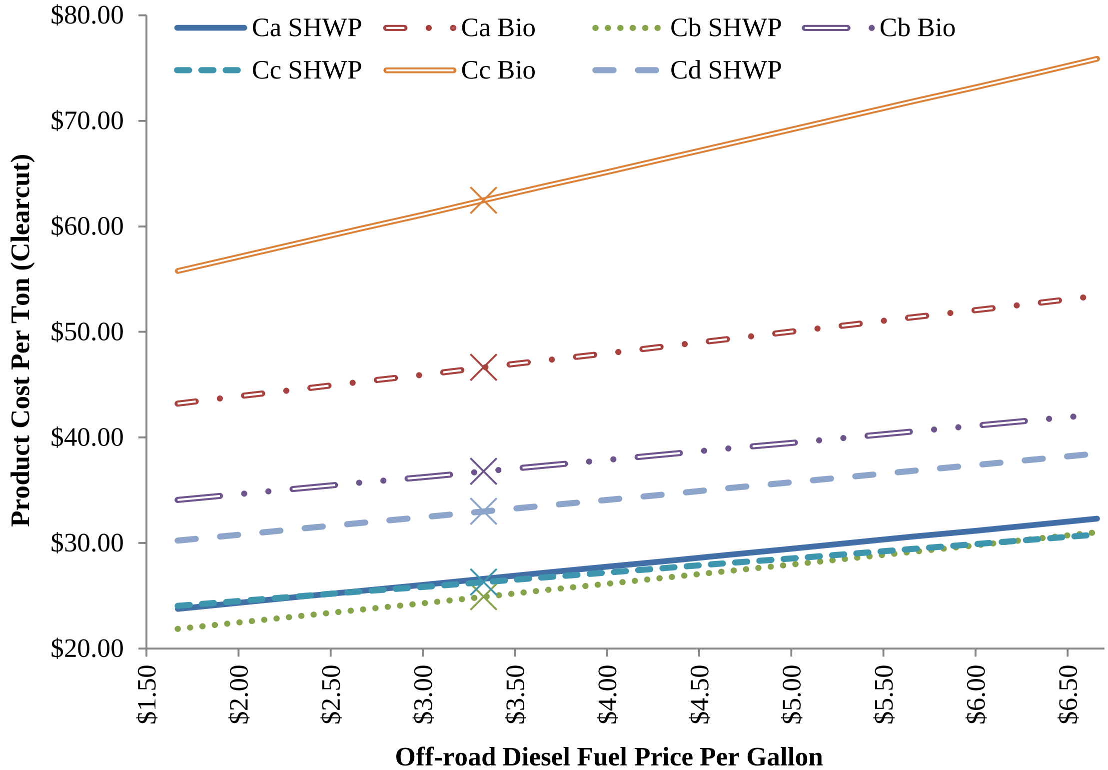

Figure 16. Sensitivity analysis of a 10% incremental increase in diesel fuel prices and its effect on the total production cost per ton. Cost components per ton include harvesting, hauling, and stumpage for the SHWP products and biomass chips respectively, for each clearcut treatment type.

Intermediate Thinning Treatment A

The assumed fuel price of $3.33 per gallon resulted in production costs per ton of $34.35 and $55.72 for the SHWP and biomass chips, respectively (designated with an X in Figure 17). A $2.00 increase in diesel fuel prices from $3.00 to $5.00 per gallon resulted in a change in the total cost per ton from $33.75 to $37.35 for the SHWP, a $3.60 dollar increase (10.6 % change), and a change in the total cost per ton from $55.26 to $58.02 for the biomass chips, a $2.76 dollar increase (4.7% change).

Intermediate Thinning Treatment B

The assumed fuel price of $3.33 per gallon resulted in production costs per ton of $35.05 and $53.75 for the SHWP and biomass chips, respectively (designated with an X in Figure 17). A $2.00 increase in diesel fuel prices from $3.00 to $5.00 per gallon resulted in a change in the total cost per ton from $34.23 to $39.15 for the SHWP, a $4.92 dollar increase (14.3% change), and a change in the total cost per ton from $53.28 to $56.10 for the biomass chips, a $2.82 dollar increase (5.2% change).

Intermediate Thinning Treatment C

The assumed fuel price of $3.33 per gallon resulted in production costs per ton of $29.22 and $85.05 for the SHWP and biomass chips, respectively (designated with an X in Figure 17). A $2.00 increase in diesel fuel prices from $3.00 to $5.00 per gallon resulted in a change in the total cost per ton from $28.69 to $31.87 for the SHWP, a $3.18 dollar increase (11% change), and a change in the total cost per ton from $83.50 to $92.80 for the biomass chips, a $9.30 dollar increase (11.1% change).

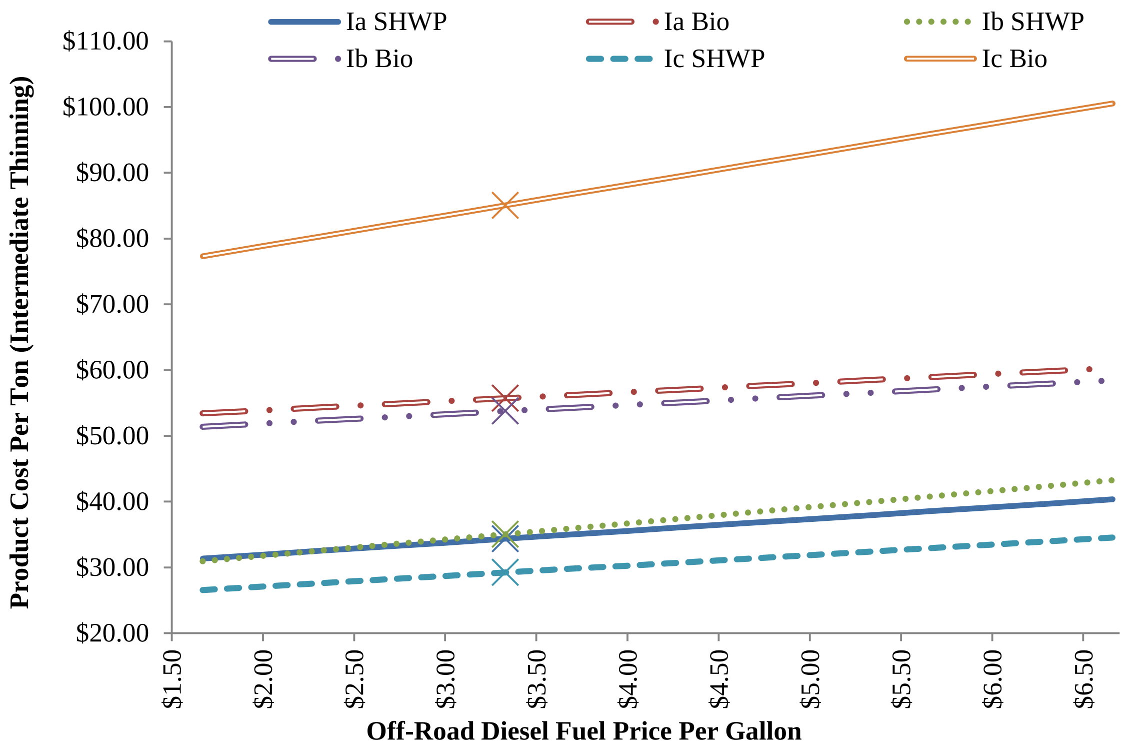

Figure 17. Sensitivity analysis of a 10% incremental increase in diesel fuel prices and its effect on the total production cost per ton. Cost components per ton include harvesting, hauling, and stumpage for the SHWP products and biomass chips respectively, for each intermediate thinning treatment type.

3.8.2 Changes in Equipment Costs

Purchase price of equipment plays the largest role in determining the ownership cost (SMH). Cost information on purchase price for each piece of equipment was supplied by the logger. All equipment besides the chipper utilized in this study harvest was purchased used at prices lower than those of brand new equipment. The effects of changes in equipment purchasing price were determined in a similar manner as changes in fuel price. This analysis examines how increasing the total equipment suite purchase prices can affect the cost of production and ultimately, gives the necessary breakeven price to account for such changes in equipment cost. The total equipment suite cost for the observed study harvest was $222,500 (designated with an X in Figures 18 and 19). An increase in entire suite equipment purchase price from $222,500 to $400,500 a $178,000 (80%) change was used for each treatment.

<u>Clearcut Treatment A</u>

The entire suite equipment purchase price of $222,500 resulted in production costs per ton of $26.61 and $46.62 for the SHWP and biomass chips, respectively (designated with an X in Figure 18). A $178,000 increase in equipment suite purchase price from $222,500 to $400,500 resulted in a change in the total cost per ton from $26.61 to $27.89 for the SHWP, a $1.28 increase (4.8 % change), and a change in the total cost per ton from $46.62 to $57.42 for the biomass chips, a $10.80 increase (23.1% change).

<u>Clearcut Treatment B</u>

The entire suite equipment purchase price of $222,500 resulted in production costs per ton of $24.91 and $36.79 for the SHWP and biomass chips, respectively (designated with an X in Figure 18). A $178,000 increase in equipment suite purchase price from $222,500 to $400,500 resulted in a change in the total cost per ton from $24.91 to $25.95 for the SHWP, a $1.04 increase (4.1% change), and a change in the total cost per ton from $36.79 to $41.99 for the biomass chips, a $5.20 increase (14.1% change).

<u>Clearcut Treatment C</u>

The entire suite equipment purchase price of $222,500 resulted in production costs per ton of $26.30 and $62.46 for the SHWP and biomass chips, respectively (designated with an X in Figure 18). A $178,000 increase in equipment suite purchase price from $222,500 to $400,500 resulted in a change in the total cost per ton from $26.30 to $27.18 for the SHWP, a $0.88 increase (3.3 % change), and a change in the total cost per ton from $62.46 to $87.90 for the biomass chips, a $25.44 increase (40.7% change).

Clearcut Treatment D

The entire suite equipment purchase price of $222,500 resulted in production costs per ton of $32.99 for the SHWP (designated with an X in Figure 18). A $178,000 increase in equipment suite purchase price from $222,500 to $400,500 resulted in a change in the total cost per ton from $32.99 to $34.51 for the SHWP, a $1.52 increase (4.6 % change).

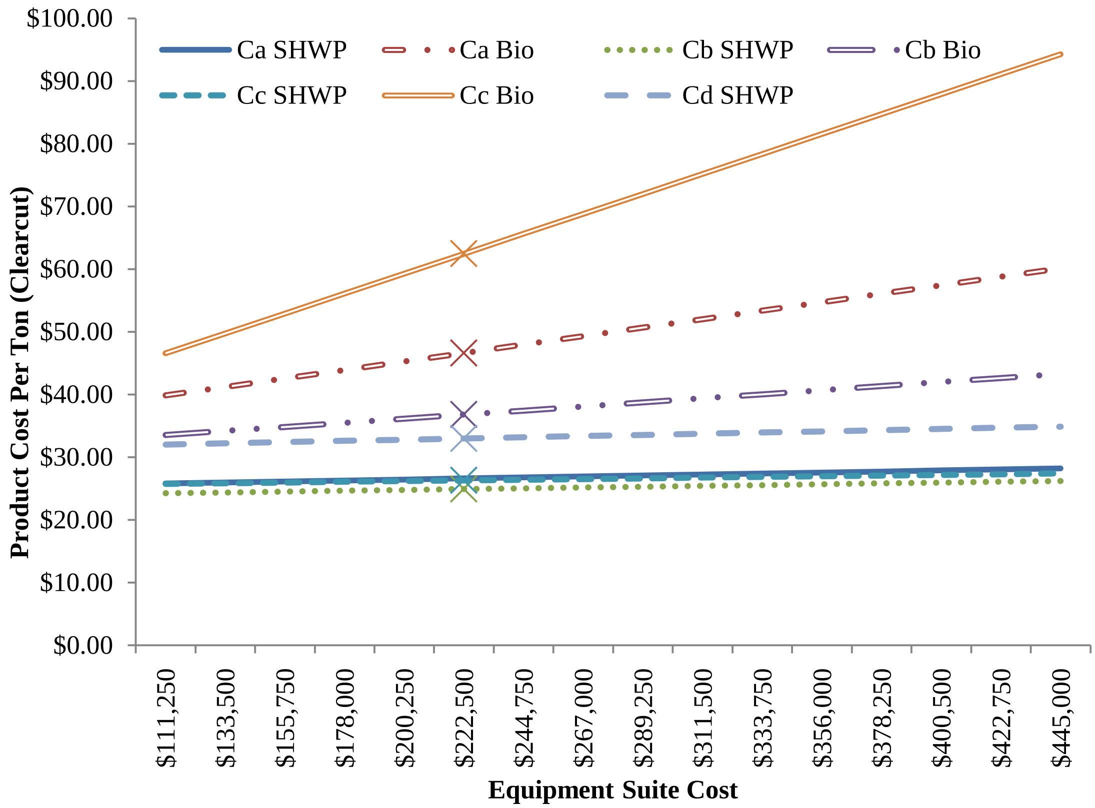

Figure 18. Sensitivity analysis of a 10% incremental increase in the total purchase price of the logging equipment on the total production cost per ton. Cost components per ton include harvesting, hauling, and stumpage for the SHWP products and biomass chips respectively, for each clearcut treatment type.

Intermediate Thinning Treatment A

The entire suite equipment purchase price of $222,500 resulted in production costs per ton of $34.35 and $55.22 for the SHWP and biomass chips, respectively (designated with an X in Figure 19). A $178,000 increase in equipment suite purchase price from $222,500 to $400,500 resulted in a change in the total cost per ton from $34.35 to $35.63 for the SHWP, a $1.28 dollar increase (3.7 % change), and a change in the total cost per ton from $55.72 to $67.64 for the biomass chips, a $11.92 dollar increase (21.4% change).

Intermediate Thinning Treatment B

The entire suite equipment purchase price of $222,500 resulted in production costs per ton of $35.05 and $53.75 for the SHWP and biomass chips, respectively (designated with an X in Figure 19). A $178,500 increase in equipment suite purchase price from $222,500 to $400,500 resulted in a change in the total cost per ton from $35.05 to $37.29 for the SHWP, a $2.24 increase (6.4 % change), and a change in the total cost per ton from $53.75 to $63.03 for the biomass chips, a $9.28 increase (17.3 % change).

Intermediate Thinning Treatment C

The entire suite equipment purchase price of $222,500 resulted in production costs per ton of $29.22 and $85.05 for the SHWP and biomass chips, respectively (designated with an X in Figure 19). A $178,000 increase in equipment suite purchase price from $222,500 to $400,500 resulted in a change in the total cost per ton from $29.22 to $30.34 for the SHWP, a $1.12 increase (3.8 % change), and a change in the total cost per ton from $85.05 to $117.05 for the biomass chips, a $32.00 increase (37.6 % change).

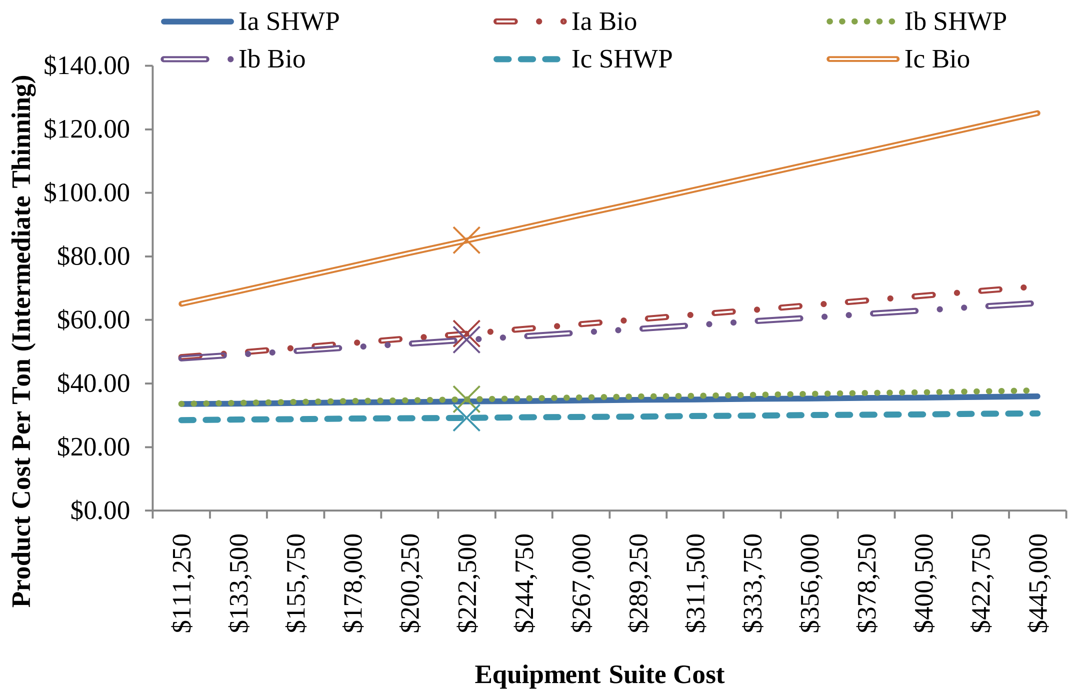

Figure 19. Sensitivity analysis of a 10% incremental increase in the total purchase price of the logging equipment on the total production cost per ton. Cost components per ton include harvesting, hauling, and stumpage for the SHWP products and biomass chips respectively, for each intermediate thinning treatment type.

3.8.3 Changes in stumpage prices

Stumpage prices often comprised the largest single item of the total cost per ton in this study harvest for both SHWP and biomass chips (tables 14 & 15) and caused the total cost per ton to increase as stumpage costs increased. Stumpage costs varied by treatment (designated with an X in figures 20 and 21) which explains the variation in the range of the possible stumpage costs per ton on the x-axis in both figures. A 10% increase in stumpage purchase price (varied by treatment) was used for each treatment analysis.

Previous biomass harvesting studies (Saunders et al 2012, Botard et al 2012) in Missouri have assumed SHWP and biomass stumpage prices based on harvest rights being sold much lower than market rates at that time. The stumpage rights in those studies were assumed in order to avoid reaching artificially low breakeven point for both products. For the purpose of this analysis the stumpage prices were based off the bid contract which had stumpage in clearcut treatments selling for $17,208.72 and stumpage in the intermediate thinning treatments selling for $7,375.35 at approximately $89/mbf. This cost was then split between the two product types by dividing the total cost per treatment by the tons removed in each product class for that treatment and multiplying cost per ton by the % biomass and % SHWP estimates from the feller-buncher and skidder on each treatment. This yielded a split cost between the two product types which may have resulted in stumpage costs per ton for the biomass that were somewhat higher than expected, but there was limited insight found in previous literature to accurately split the stumpage costs between these two product types.

Clearcut Treatment A

Because increases in stumpage costs are directly added to the cost of total production, a one dollar increase in stumpage cost per ton will result in a one dollar total cost per ton. Therefore, the slope of the sensitivity lines in these analyses tend to be close to 1.0 in every treatment, only falling short of 1.0 due to rounding differences from breaking the overall stumpage cost down between the two product types. In clearcut treatment A, an increase in stumpage price from $6.50 per ton to $7.06 per ton resulted in a change in the total cost per ton from $26.04 to $26.61, a 2.1 % change. The biomass purchase price of $7.04/ton resulted in a production cost per ton of $46.62 for the biomass products (designated with an X in Figure 20). A $0.56 increase in stumpage price from $6.48 to $7.04 resulted in a change in the total cost per ton from $46.05 to $46.62 for the biomass, a $0.57 dollar increase (1.2% change).

Clearcut Treatment B

The SHWP purchase price of $8.55/ton resulted in a production cost per ton of $24.91 for the SHWP products respectively (designated with an X in figure 20). A $0.67 increase in stumpage purchase price from $7.88 to $8.55 resulted in a change in the total cost per ton from $24.23 to $24.91 for the SHWP, a $0.68 increase (2.8% change). The biomass purchase price of $8.54/ton resulted in a production cost per ton of $36.79 for the biomass products (designated with an X in Figure 20). A $0.68 increase in stumpage price from $7.86 to $8.54 resulted in a change in the total cost per ton from $36.11 to $36.79 for the biomass, a $0.68 increase (1.8% change).

Clearcut Treatment C

The SHWP purchase price of $9.29/ton resulted in a production cost per ton of $26.30 for the SHWP products (designated with an X in Figure 20). A $0.71 increase in stumpage purchase price from $8.58 to $9.29 resulted in a change in the total cost per ton from $25.59 to $26.30 for the SHWP, a $0.71 increase (2.7% change). The biomass purchase price of $9.25/ton resulted in a production cost per ton of $62.46 for the biomass products respectively (designated with an X in Figure 20). A $0.71 increase in stumpage price from $8.54 to $9.25 resulted in a change in the total cost per ton from $61.76 to $62.46 for the biomass, a $0.70 increase (1.1% change).

Clearcut Treatment D

The SHWP purchase price of $9.31/ton resulted in a production cost per ton of $32.99 for the SHWP products (designated with an X in Figure 20). A $0.76 increase in stumpage purchase price from $8.55 to $9.31 resulted in a change in the total cost per ton from $32.23 to $32.99 for the SHWP, a $0.76 increase (2.3% change).

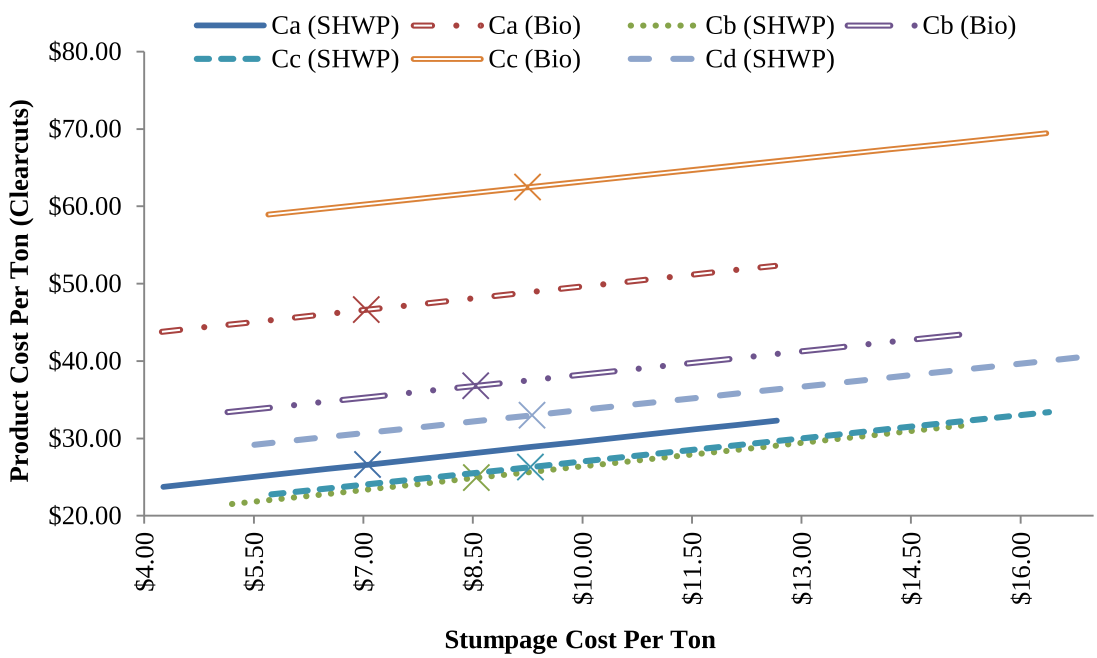

Figure 20. Sensitivity analysis of a 10% incremental increase in stumpage on the total production cost per ton. Other cost components held constant include harvesting, hauling, and labor for the SHWP products and biomass chips respectively, for each clearcut treatment type.

Intermediate Thinning Treatment A

The SHWP purchase price of $15.22/ton resulted in a production cost per ton of $34.35 for the SHWP products (designated with an X in Figure 21). A $2.24 increase in stumpage purchase price from $12.98 to $15.22 resulted in a change in the total cost per ton from $32.11 to $34.35 for the SHWP, a $2.24 increase (6.9% change). The biomass purchase price of $15.18/ton resulted in a production cost per ton of $55.72 for the biomass products respectively (designated with an X in Figure 21). A $2.24 increase in stumpage price from $12.94 to $15.18 resulted in a change in the total cost per ton from $53.48 to $55.72 for the biomass, a $2.24 increase (4.1% change).

Intermediate Thinning Treatment B

The SHWP purchase price of $11.23/ton resulted in a production cost per ton of $35.05 for the SHWP products (designated with an X in Figure 21). A $1.65 increase in stumpage purchase price from $9.58 to $11.23 resulted in a change in the total cost per ton from $33.40 to $35.05 for the SHWP, a $1.65 increase (4.9% change). The biomass purchase price of $11.20/ton resulted in a production cost per ton of $53.75 for the biomass products (designated with an X in Figure 21). A $1.65 increase in stumpage price from $9.55 to $11.20 resulted in a change in the total cost per ton from $52.09 to $53.75 for the biomass, a $1.66 dollar increase (3.1% change).

Intermediate Thinning Treatment C

The SHWP purchase price of $9.93/ton resulted in a production cost per ton of $29.22 for the SHWP products (designated with an X in Figure 21). A $1.47 increase in stumpage purchase price from $8.46 to $9.93 resulted in a change in the total cost per ton from $27.75 to $29.22 for the SHWP, a $1.47 increase (5.2% change). The biomass purchase price of $9.88/ton resulted in a production cost per ton of $85.05 for the biomass products (designated with an X in Figure 21). A $1.47 increase in stumpage price from $8.46 to $9.93 resulted in a change in the total cost per ton from $83.58 to $85.05 for the biomass, a $1.47 increase (1.7% change).

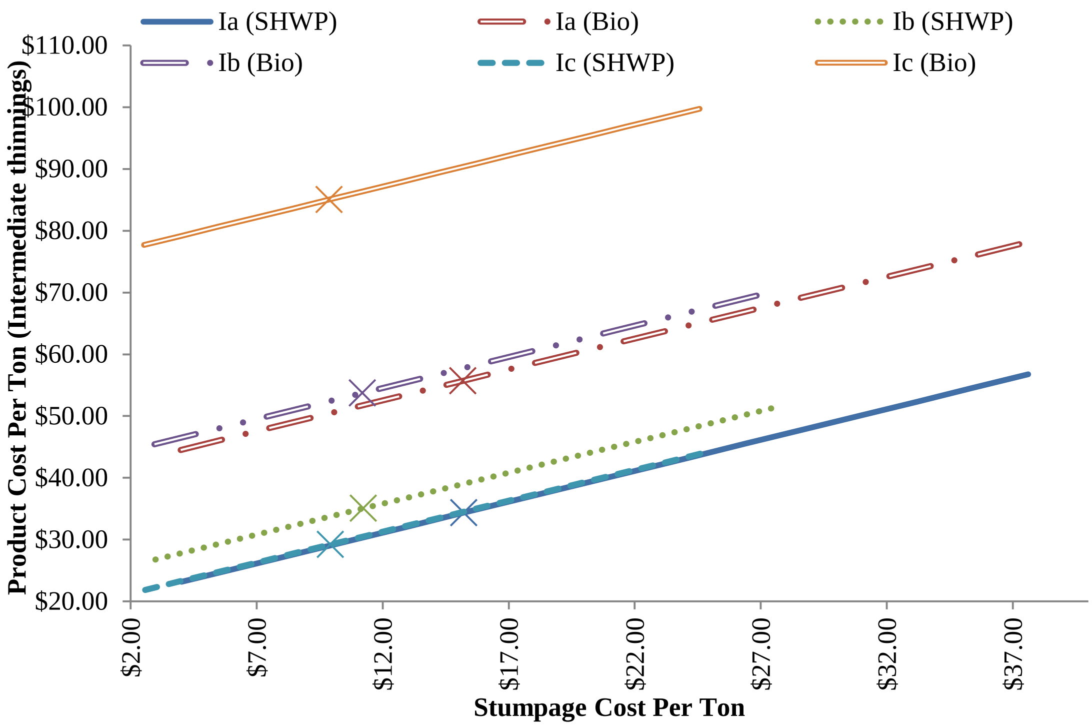

Figure 21. Sensitivity analysis of a 10% incremental increase in stumpage on the total production cost per ton. Cost components per ton include harvesting, hauling, and labor for the SHWP products and biomass chips respectively, for each intermediate thinning treatment type.

3.8.4 Changes in Hauling Distances

Hauling distance was a critical component that altered the total hauling costs. This scenario examines how changing an assumed round trip hauling distance affected the total production cost per ton. An assumed round trip distance of 100 miles was used for this analysis (designated with an X in Figures 22 and 23). As expected, increasing the round trip hauling distance also increased the total cost per ton. An increase in round trip travel distance from 50 to 100 miles, a 50% change was used for each treatment in this analysis.

Clearcut Treatment A

The assumed round trip hauling distance of 100 miles resulted in production costs per ton of $26.61 and $46.62 for the SHWP and biomass chips, respectively (designated with an X in Figure 22). A 50 mile increase in equipment suite purchase price from 50 to 100 miles resulted in a change in the total cost per ton from $24.06 to $26.61 for the SHWP, a $2.55 increase (10.5% change), and a change in the total cost per ton from $44.77 to $46.62 for the biomass chips, a $1.85 increase (4.1% change). The difference between the two products is a function of average payload capacity (25.61 and 23 tons) since it was assumed that hauling both products had the same cost per mile of $1.02. Since the slope of the SHWP is slightly greater than the biomass chips this analysis indicates that hauling this product is more sensitive to hauling distances because it generally carries a larger load.

Clearcut Treatment B

The assumed round trip hauling distance of 100 miles resulted in production costs per ton of $24.91 and $36.79 for the SHWP and biomass chips, respectively (designated with an X in Figure 22). A 50 mile increase in equipment suite purchase price from 50 to 100 miles resulted in a change in the total cost per ton from $22.26 to $24.91 for the SHWP, a $2.65 increase (11.9 % change), and a change in the total cost per ton from $35.64 to $36.79 for the biomass chips, a $1.15 increase (3.2% change). The difference between the two products is a function of average payload capacity (25.61 and 23 tons) since it was assumed that hauling both products had the same cost per mile of $0.86. Since the slope of the SHWP is slightly greater than the biomass chips this analysis indicates that hauling this product is more sensitive to hauling distances because it generally carries a larger load.

Clearcut Treatment C

The assumed round trip hauling distance of 100 miles resulted in production costs per ton of $26.30 and $62.46 for the SHWP and biomass chips, respectively (designated with an X in Figure 22). A 50 mile increase in equipment suite purchase price from 50 to 100 miles resulted in a change in the total cost per ton from $24.25 to $26.30 for the SHWP, a $2.05 dollar increase (8.4% change), and a change in the total cost per ton from $78.28 to $82.63 for the biomass chips, a $4.35 increase (7.4% change). The difference between the two products is a function of average payload capacity (25.61 and 23 tons) since it was assumed that hauling both products had the same cost per mile of $0.89. Since the slope of the SHWP is slightly greater than the biomass chips it indicates that hauling this product is more sensitive to hauling distances because it generally carries a larger load.

Clearcut Treatment D

The assumed round trip hauling distance of 100 miles resulted in a production cost per ton of $32.99 for the SHWP (designated with an X in Figure 22). A 50 mile increase in equipment suite purchase price from 50 to 100 miles resulted in a change in the total cost per ton from $30.54 to $32.99 for the SHWP, a $2.45 increase (8% change). Hauling SHWP products in this treatment had a cost per mile of $0.96.

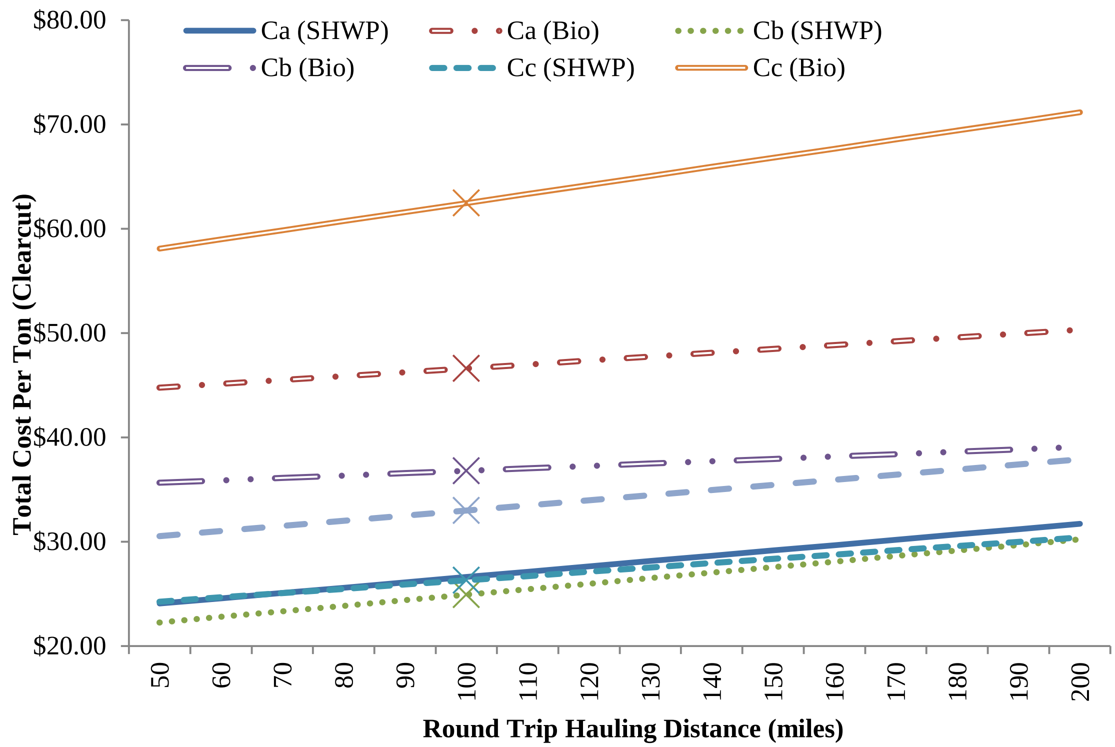

Figure 22. Sensitivity analysis of a 10% incremental increase in round trip hauling distance (assumed 100 miles) on the total production cost per ton. Cost components per ton include harvesting, hauling, and labor for the SHWP products and biomass chips respectively, for each clearcut treatment type.

<u>Intermediate Thinning Treatment A</u>

The assumed round trip hauling distance of 100 miles resulted in production costs per ton of $34.35 and $55.72 for the SHWP and biomass chips, respectively (designated with an X in Figure 23). A 50 mile increase in equipment suite purchase price from 50 to 100 miles resulted in a change in the total cost per ton from $32.35 to $34.35 for the SHWP, a $2.00 r increase (6.1 % change), and a change in the total cost per ton from $53.92 to $55.72 for the biomass chips, a $1.80 increase (3.3% change). The difference between the two products is a function of average payload capacity (25.61 and 23 tons) since it was assumed that hauling both products had the same cost per mile of $0.42. Since the slope of the SHWP is slightly greater than the biomass chips it indicates that hauling this product is more sensitive to hauling distances because it generally carries a larger load.

<u>Intermediate Thinning Treatment B</u>

The assumed round trip hauling distance of 100 miles resulted in production costs per ton of $35.05 and $53.75 for the SHWP and biomass chips, respectively (designated with an X in Figure 23). A 50 mile increase in equipment suite purchase price from 50 to 100 miles resulted in a change in the total cost per ton from $31.95 to $35.05 for the SHWP, a $3.10 increase (9.7% change), and a change in the total cost per ton from $52.50 to $53.75 for the biomass chips, a $1.25 increase (2.3% change). The difference between the two products is a function of average payload capacity (25.61 and 23 tons) since it was assumed that hauling both products had the same cost per mile of $0.64. Since the slope of the SHWP is slightly greater than the biomass chips it indicates that hauling this product is more sensitive to hauling distances because it generally carries a larger load.

<u>Intermediate Thinning Treatment C</u>

The assumed round trip hauling distance of 100 miles resulted in production costs per ton of $29.22 and $85.05 for the SHWP and biomass chips, respectively (designated with an X in Figure 23). A 50 mile increase in equipment suite purchase price from 50 to 100 miles resulted in a change in the total cost per ton from $27.17 to $29.22 for the SHWP, a $2.05 increase (7.5% change), and a change in the total cost per ton from $78.60 to $85.05 for the biomass chips, a $6.45 increase (8.2% change). The difference between the two products is a function of average payload capacity (25.61 and 23 tons) since it was assumed that hauling both products had the same cost per mile of $0.54.

Since the slope of the SHWP is slightly greater than the biomass chips it indicates that hauling this product is more sensitive to hauling distances because it generally carries a larger load.

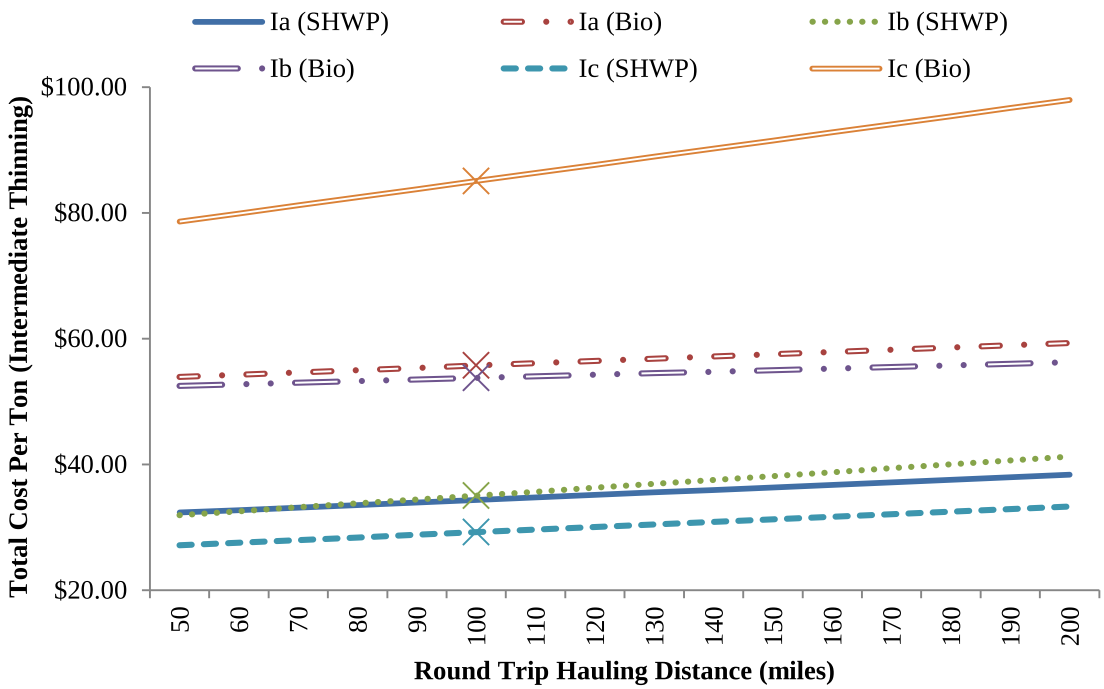

Figure 23. Sensitivity analysis of a 10% incremental increase in round trip hauling distance (assumed 100 miles) on the total production cost per ton. Cost components per ton include harvesting, hauling, and labor for the SHWP products and biomass chips respectively, for each intermediate thinning treatment type.

4. DISCUSSION

One of the main objectives of the study was to determine costs and productivity associated with each component of the harvest to estimate the total cost of production and revenues solid hardwood products and biomass from each treatment and BMP practice. Other main objectives were to; 1) evaluate the efficiency and profitability of the harvesting equipment used in this study, 2) determine harvest feasibility and methods to reduce harvesting costs, 3) conduct a sensitivity analysis to examine the effects of changes in different costs that have the potential to vary over time, and 4) to conduct a benefit:cost analysis to evaluate the economic merit of the project. This section will analyze the results of the harvest in order to satisfy these objectives and help develop the conclusions formed in section 5.

4.1 Equipment Productivity

Each piece of harvest equipment used for the study had varying utilization rates between the harvest treatments. In some cases the utilization rates were similar to rates observed in prior integrated woody biomass studies conducted by Saunders et al. (2012), and Botard et al. (2012), in the Missouri Ozarks. Feller–buncher utilization rates averaged 36.2% in this study compared to 32% in the Botard and 36% in Saunders harvests. The skidder utilization of rate of 82.1% was greater but comparable to Botards' rate of 72% and Saunders' rate of 71%. The loader 1 average utilization rate of 88.7% was much higher than that of Botard (54%) and Saunders (45%). This variance can likely be attributed to the fact that loader 1 dealt exclusively with SHWP and never experienced delays associated with feeding the chipper as did loader 2. Loader 2 had a low utilization rate of 22.6% likely associated with the considerable downtime associated with being idle while the loggers were running other equipment. No single person was assigned to loader 2 only. The chipper had the lowest utilization rate of 7.1% and this rate is similar to the second loader because the chipper was only used in short intervals once sufficient biomass was stacked from the treatments to fill the trailer.

Results from activity and time-in-motion sampling (Appendix Tables 1 and 3) suggest that all harvesting equipment spent the majority of the productive machine hours handling SHWP material. Results from these samplings were likely artificially high due to the sampling methods inability to separate time spent handling tree-length material into separate categories for time spent handling SHWP versus biomass. These sampling techniques assumed it took the same amount of time for harvesting equipment to harvest and skid a tree-length product as it did a merchantable length SHWP and biomass-sized product. As shown in (appendix table 1), data gathered through activity sampling indicates that the feller-buncher work activities on a time proportional basis were similar between the clearcut and intermediate thinning treatments. For all harvesting systems the feller-buncher spent approximately 45% of its productive hours moving throughout the plot in order to cut the next tree. It can be assumed that in all treatment types the percentage of time spent moving to cut SHWP versus biomass-sized trees was similar to that of the % biomass used in sections 3.4.1 – 3.4.7, which was the percentage of the total tons of biomass removed from each treatment. In all treatment types, the second greatest amount of time spent by the feller-buncher was allocated to dropping SHWP sized timber after it was cut. In all treatment types the next greatest proportion of work time was the active sawing of SHWP followed closely by time spent on delay. Dropping and cutting small diameter trees did not account for any proportion of time of the feller-buncher’s work activities likely due to the speed at which such small diameter trees are generally cut and the fact that sampling intervals were set for the feller-buncher at 20 seconds. This was consistent with results from Botard et al. (2012), which had a very small (3%) proportion of time allocated to cutting biomass-sized material. Saunders et al. (2012) had no activity sampling data for the feller-buncher presented in their study.

Handling SHWP was also the greatest proportion of work observed for loader 1 (Appendix Table 3). The majority of this time was spent de-limbing and topping SHWP trees, bucking SHWP logs at merchantable length, and stacking and loading these products. Because loader 2's primary workload was re-stacking and feeding the chipper with biomass, loader 1 rarely handled biomass-sized material other than in the event that it quickly dropped a small diameter piece or a cull log over into the biomass pile. Time allocated to handling SHWP for loader 1 was approximately 85% for work activities on all treatment types. Time spent handling SHWP was fairly consistent between treatments and processing time ranged from 36 to 54% of the time, stacking ranged from 16 to 31% of the time, and loading ranged from 18 to 34% of the time, with delay and stacking biomass making up the lesser percentages of time across treatments (Appendix Table 3). Productivity rates from loader 1 were also fairly consistent with results from a previous biomass harvesting study in Missouri conducted by Botard et al. (2012). The loader work activities on the Botard study spent 81% of its time handling SHWP compared to 85% in this study. The Saunders et al. (2012) study presented activity sampling data collected on the loader but a major difference between those observed loader activities was that a single loader handled all biomass and SHWP where this study had a separate loader allocated to each product type. In the Saunders study, handling biomass while feeding the chipper accounted for 33% of the observed loader work activity while 53% of the time was spent sorting and loading SHWP. So while the majority of time in all three studies was allocated to handling SHWP for the loader, the lower rate in Saunders' study can be attributed to the fact that there was only one loader for all work duties and it can be assumed that the rate would have been closer to results found in this study and Botard et al. (2012) had there been a second loader to assume biomass handling work activities.

In all harvest treatments the skidder's time was either allocated to skidding or delay. Delay percentages were generally higher in intermediate thinning treatments commonly due to time spent waiting on the feller-buncher to cut and create bundles. Because it was assumed that it took the same amount of time to skid a biomass-sized tree as a SHWP tree, and because often times both products were brought to the landing in the same bundle, these estimates allocate time spent handling each product class by the skidder. Due to this assumption, the feller-buncher and skidder have similar percentages of their time allocated to handling biomass. Time-in-motion data collected by Botard's study had the skidder allocating more time (11%) to handling biomass than any other piece of harvesting equipment. In this study, equipment on clearcut treatment C had the greatest amount of time harvesting and handling biomass at 29%. Harvesting equipment on intermediate thinning treatments never spent more than 5% of time handling biomass, this was likely attributed to the majority of biomass that originated from these plots coming from tops rather than small diameter trees marked for removal. Time-in-motion data collected in Saunders' study indicated that 46% of the skidder's time was allocated to handling small diameter biomass trees, a much greater percentage than this study or the study by Botard. This is possibly due to better operator utilization for the feller-buncher throughout the duration of Saunders' study.

It should be noted that there were ample opportunities for this logging operation to decrease overall harvesting cost by increasing productivity. This is not a reflection of the integrity of this crew; the owner of this operation is a Missouri Master Logger and was very dedicated to the completion of this harvest. However, at the time of this harvest the owner was trying to start up another trucking business, so it can be assumed at times there was a slight conflict of interest that may have had some effect on the productivity. It should also be noted that weather conditions for much of the duration of this harvest were highly unfavorable. Seventeen days were taken off during this study due to weather conditions far too severe to implement the harvest while maintaining compliance with Missouri's standard Best Management Practices. While these days were taken off and not directly associated with the actual productivity, the unfavorable conditions from precipitation in the form of rain and snow were clearly evident in the days when harvesting resumed in the form of deep ruts that prevented the skidder from using the same skid trail throughout the duration of several treatments. The skidder operator was also a relatively new employee with only a few months experience operating that machine. It can be assumed that a more experienced skidder operator would be quicker and more efficient with time spent on the machine. Yoshioka et al. (2006) specifically noted that operator skill has an impact on cost and productivity. A potential way the skidder operator could have increased productivity would be to build and carry larger bundles on skid turns. A higher average stems/turn would have increased turn volume which would have ultimately increased machine productivity and reduced the number of turns into the woods to gather log bundles. The loader operator was also scheduled to assume responsibility for managing the up-and-coming trucking business so there were times spent making phone calls and other important business tasks that arguably could have been spent operating the loader. However, compared to other studies, loader productivity on this study was quite high regardless of potential conflicting operator interests. Throughout the harvest there were three full-time employees working in the woods and five machines that each required a person to operate the mechanics of the equipment. In the event of chipping biomass, the feller-buncher operator assumed responsibility for running loader 2 and the skidder operator ran the chipper. This added significant downtime for the skidder and feller-buncher, but was largely unavoidable due to the equipment and personnel configurations available for the harvest.

At times the skidder and loader operator were not working at the same time. This scenario required the skidder operator to stage log bundles in the field and later go back and handle each bundle a second time in order to bring logs to the loader operator. This extra handling increased skidder costs and while was not a direct decrease of productivity, should likely be considered as delay or some separate category for future research in forest harvest operations. Time spent in steeper terrain also required additional downtime for the feller-buncher. Wet and steep topographical conditions provided a difficult scenario for the feller-buncher when a larger diameter tree or any tree on a steep slope was to be cut. Conversations with the logger and researchers lead to the agreement that the feller-buncher was under-powered for trees that exceeded approximately 14” DBH. When dealing with trees of this size, the feller-buncher operator would often have to reposition the machine two or three times to cut the tree down. When dealing with larger trees on steep terrain, these conditions usually required the operator to shut down and manually cut the tree with a chainsaw. Due to the USFS's "General ground harvest model" not accounting for the use of chainsaw in the cost structure, costs and productivity of chainsaw use were unaccounted for in this study. Chainsaws require the use of fuel and routine maintenance, thus the use of such equipment should be considered in future research. Previous biomass harvesting studies in the Ozarks by Botard (et al., 2012) and Saunders (et al. 2012) also did not account for any chainsaw use throughout the duration of their harvests. Increasing machine utilization rates would surely serve to reduce costs by decreasing the time spent on the harvest site. Increasing the efficiency of work scheduling and routine maintenance would also increase the productivity and utilization of the entire equipment suite.

A consistent and notable harvesting system bottleneck for this study was feller-buncher and skidder productivity. The feller-buncher and skidder operators depended on one another to keep operation flowing at a desirable pace. A typical scenario for this study involved the feller-buncher operator sitting idle, waiting for the skidder to remove bundles in order to proceed with felling. The operator on the feller-buncher preferred to work in a systematic manner that involved cutting and felling all trees in one area before moving on. This preference often involved considerable idle time waiting for bundle removal in order to avoid the log bundles becoming scattered and disorganized. When considering production across all intermediate thinnings, skidder production was on average, 5.2 tons / hour (rate of $2.55/ton), far too low to be considered a productive operation.[3] It is quite possible that with an increase in productivity to 10 tons / hour the

[3] Personal communication, Tom Gallagher 5/23/13

hourly rates would have decreased to \$1.30 / ton, which would have led to much better overall productivity and an increase in profits across treatments.

4.2 Yields, Revenues, Costs, and Profits

Economic feasibility evaluates the processes that identify whether total costs are less than or equal to the revenues of the operation. This harvest explored the scenario of whether harvesting SHWP and biomass chips in the Missouri Ozark highlands with a fully mechanized, integrated harvest system was a feasible endeavor when dealing with current market conditions. The following subsections summarize these findings.

4.2.1 Yields and Revenues

This study harvested two products: SHWP and biomass fuel chips. The SHWP accounted for the largest share of the revenues (93%) because a greater total volume (85%) was harvested and secondly, it was sold at a higher per unit price. A total of 2,279 tons of SHWP were harvested from the 63.14 treated acres at an average of 36.09 tons per acre. A total of 89 log trucks of SHWP were removed from the site (average weight: 25.61 tons) and sold to ten different sawmills according to product type. The average price received for SHWP was \$36.98 per ton but priced ranged from \$20.00 (blocking) to \$183.65 (staves) per ton. The revenues from SHWP totaled \$81,980.23, at a price of \$1,298.38 per treated acre. It should be noted that revenues from more than half the SHWP (sawlog) loads could have been higher had the local sawmills used for the study site been more cooperative with the loggers. On average, the local mills were paying \$9.85 less per ton for the same sawlog product than where the logger typically took this same product. This fluctuation in revenues was not well received by the logger and ultimately led to hauling these products an average of 75 miles (one-way) farther than the local mills. Using the average hauling cost of $3.00/ loaded mile, this extra hauling distance would cost approximately $450 per load. When subtracted from the extra revenues associated with taking the product to a mill that paid $9.85 higher per ton ($252.25/load average), this $197.75/load loss was a critical component to the low profitability associated with the SHWP from this harvest.

Biomass fuel chips comprised of 15 percent of the total tonnage harvested and only 7 percent of the total revenues received. A total of 391 tons were harvested from the 54.02 acres treated with biomass removal at an average of 7.23 tons per acre. A total of 17 truckloads of biomass fuel chips were removed from the site (average weight: 23 tons) and were sold to two different mills. The average price received for fuel chips was $17.29 but ranged from $15.00 to $28.00 per ton. Total revenue from biomass sales amounted to $6,508.77 at a revenue of $120.49 per acre. It should be noted that the logger had set up biomass chip quotas with local mills prior to the beginning of this harvest, but these agreements were broken before the first loads were to be delivered. These broken agreements ultimately led to taking the majority (14/17 loads) of biomass products to a storage yard for a contractor that supplied wood chips to the University of Missouri's new biomass boiler. After the storage yard filled its biomass quota, a second contract was signed to take fuel chips to a pulp mill in Kentucky. Only three loads of chips were taken to this mill during the harvest which was 178 miles (one-way) further than the original mill. Using the same average hauling cost of $3.00/ loaded mile, this additional hauling distance would cost approximately $1,068.00 extra per load. Revenues at the mill in Kentucky were larger than the local mills at $28.00/ton, but this increase in revenues was not enough to alleviate the large increase in haul distance. Other studies (Bowe and Bumgardner, 2006, Yoshioka et al. 2006, Arnosti et al. 2008, Saunders et al. 2012) recommend much shorter hauling distances in order to maximize profitability.

Table 19. Total volume (tons) removed from study harvest according to product class and treatment.

Product	Clearcut Treatments				Intermediate Thinning Treatments		
	Ca	Cb	Cc	Cd	Ia	Ib	Ic
SHWP	484.34	388.45	401.29	476.3	126.32	167.9	234.7
Biomass Chips	108.09	148.07	31.24	0	23.07	68.41	12.15
Total	592.43	536.52	432.53	476.3	149.39	236.31	246.85

Table 20. Total revenues from study harvest according to product class and treatment.

Product	Clearcut Treatments				Intermediate Thinning Treatments		
	Ca	Cb	Cc	Cd	Ia	Ib	Ic
SHWP	$16,701.91	$14,115.38	$14,102.55	$18,534.07	$4,296.19	$5,587.01	$8,643.12
Biomass Chips	$1,621.35	$2,221.05	$468.60	$0.00	$412.03	$1,603.49	$182.25
Total	$18,323.26	$16,336.43	$14,571.15	$18,534.07	$4,708.22	$7,190.50	$8,825.37

4.2.2 Treatment Costs

Clearcut Treatments

When comparing the break-even price, or total cost per ton of materials brought to the landing, processed, and delivered, the cost per ton of SHWP material in clearcut treatment B was less expensive than any other treatment at $24.91 per ton. Clearcut treatment C had lower overall costs than any other clearcut treatment at $12,506.25. This cost was $2,618.93 less than the second least expensive clearcut treatment (clearcut treatment B, Table 12). This is likely due to several factors: First, the variable costs for clearcut C were less expensive than any other clearcut due to the amount of PMH spent by each machine on this treatment being less than other clearcut treatments. The PMHs on clearcut treatment C were also low due to the fact that less biomass was harvested

(31.24 tons) on clearcut treatment C than treatments A and B (treatment D did not harvest biomass). This led to significantly less PMH for loader 2 and the chipper (Table 10) but ultimately resulted in the highest break-even price for biomass ($62.46 per ton) in clearcut treatments. If more biomass was removed from these treatments during the harvest, it can be expected that the break-even price for biomass would have decreased. However, due to the harvest intensity associated with this treatment, most of the biomass from trees marked to cut was left in the woods for future nutrient cycling. Second, Appendix Figure 1 shows log landing proximity relative to each treatment and these locations indicate that clearcut treatment C was located closer to the landing in both replication situations. The fact that these plots were closer to the landings likely played a determining factor in less PMH being necessary for the skidder to deliver products to the landings than the other treatments. It should also be noted that treatment C only had 401.29 total tons of SHWP removed, which was less than clearcut treatments A and D (484.34 and 476.30 tons). However, the products were removed more efficiently and it can be assumed that spending less PMH on a treatment can drive the breakeven price down, which means operator efficiency is a driving factor when attempting to maximize profit in a logging operation.

Higher break-even prices in all other clearcut treatments can be attributed to similar rationale. Clearcut treatment B had the lowest break-even price of all clearcut treatments at $24.91 per ton for SHWP and an overall cost of $15,125.18. Similarly to the situation in treatment C, the variable costs were lower than clearcuts A and D despite having less tonnage removed (388.45 tons) due to less PMH spent on those treatments. Treatment B did however have the lowest break-even price for biomass throughout the entire study at $36.79 per ton. This low price is entirely attributed to having the highest biomass yield at 148.07 tons (Table 19) due to the prescription calling for the removal of all biomass from the treated area.

Clearcut treatment D was the third most expensive treatment at an overall break-even price of $15,711.90 and $32.99 per ton for SHWP. Because no biomass was removed from this treatment, the biomass per ton cost was not a factor in the overall price, thus resulting in a lower overall break-even price than clearcut treatment A. The SMH costs on clearcut treatment D were the highest of any clearcut treatment; this was partially a result of the poor weather conditions while on the south harvest unit (Appendix Figure 2). A week was taken off due to inclement weather during this treatment and conditions were still highly unfavorable when the crew returned to work the following week, making for slower operation in the woods. Clearcut treatment D also called for the retention of all biomass harvested to be left in the woods for future nutrient cycling. This harvest regime required every SHWP to be bucked off at merchantable length in the woods and was a very time consuming operation for the feller-buncher operator. This typically required that the operator stop felling trees with the feller-buncher, and get out of the machine to manually cut the tops of trees with a chainsaw before continuing onto the next tree. This methodology was likely the driving factor in the higher SMH associated with this treatment.

Clearcut treatment A is the current biomass harvesting retention method being used in Missouri, so it is especially interesting that this treatment yields the highest break-even price compared to all other treatments in the clearcut treatments. This treatment had the highest overall break-even price at $17,928.52, $671.98 dollars higher than treatment D. Treatment A also had the third highest SHWP break-even price at $26.61 per ton and the second highest biomass break-even price at $46.62 (table 14). It should be noted that this project started on the east unit (Appendix Figure 1) on clearcut treatments B and A (plots 24 and 23). These plots had the steepest topographical conditions experienced throughout the harvest at an average of 34% and 28% slope, respectively. The combination of working out the logistics of starting the harvest, steep slope, and poor weather conditions gave the beginning of this harvest a much slower start than was expected. These conditions were a driving factor for the highest PMH experienced by the skidder throughout the harvest on clearcut treatment A (Table 10). Skidding tree length logs up a steep slope in inclement conditions with a new skidder operator should not be overlooked when considering possible rationale for the high PMH in these treatments. The steep conditions on the east block also called for the greatest number of water bars to be installed across both treatments B and A in an effort to prevent erosion following the harvest. Exact hours differentiating water bar construction from skidding trees was not recorded, but it should be noted that some of the high PMH values for the skidder on these treatments can be attributed to the construction of these features. Despite having higher SHWP yield than any other treatment (Table 19), this treatment had the highest overall break-even price in this study harvest.

Intermediate Thinning Treatments

When comparing the break-even price, or total cost per ton of materials brought to the landing, processed, and delivered, the cost of SHWP and biomass material from intermediate thinning treatment A was cheaper than any other thinning treatment at an overall cost of $5,649.99. SHWP and biomass break-even prices were $34.35 and $55.72

per ton, respectively (Table 15). These low costs were largely attributed to the low PMH and SMH spent on this treatment (Tables 9 and 10). This treatment is an ideal example of a treatment having low machine hours and all operations having high efficiency rates ultimately leading to all around low costs. Treatment A however, did not have the lowest cost per ton for either product class when compared to the other thinning treatments due to the relatively low amount of each product removed from the harvests.

Intermediate thinning treatment C had the second lowest overall break-even price at $7,890.88. Treatment C had the lowest SHWP cost-per-ton at $29.22 but the highest cost per ton of biomass harvesting at $85.05. Again, this relatively high cost to harvest biomass is a function of the low yield due to the prescription assigned to this treatment, rather than poor equipment efficiency during the harvest. The lowest SHWP cost per ton can be attributed to treatment C having the highest SHWP yield (Table 19) as well as relatively low PMH values. The relatively low variable costs for the chipper and loader 2 were a function of the prescription for this treatment.

Intermediate treatment B had the highest overall break-even price of $9,562.32; $1,671.44 more expensive than treatment C. Treatment B had the highest fixed and variable costs in the intermediate treatments, this was likely a function of the prescription calling for whole-tree biomass removal in an intermediate thinning scenario (Table 1). Skid turns generally took longer in this treatment due to the concern associated with causing residual damage to the crop trees. In addition, more tree-length trees being removed from these treatments resulted in loader 1 to have higher PMH because of the need to de-limb and process the entire tree at the landing. As a result of the increase in biomass removed due to the whole-tree processing, the biomass break-even price was lowest in thinning treatment B at $53.75 per ton.

4.2.3 Profits

The results of the benefit:cost analysis presented in section 3.7 show that the clearcut treatments were able to generate the highest overall profit from this harvest with all treatments having B:C ratios greater than 1. Monetary breakdowns including net profit for each treatment type were also presented in section 3.6.1 in tables 16 and 17. Treatment C was the only intermediate treatment able to generate profit according to results presented in the benefit:cost analysis (table 18). This result should be of significant interest to forest agencies and landowners in the state of Missouri due to the fact that this treatment was presented in this study as an alternative biomass harvesting intensity to contrast with the treatment currently in use. Both thinning treatments A and B are considered economically unacceptable due to their high fixed and variable costs associated with performing the harvest ultimately being greater than the revenues generated.

4.3 Sensitivity Analysis

<u>Fuel Price Sensitivity</u>

Four sensitivity analyses were examined to determine how changes in different input prices affect the cost per ton. It was observed that a $2.00 (66%) change in fuel prices had the greatest effect on treatment B in both the clearcut and intermediate thinning treatments for SHWP (Appendix Tables 16 and 17). In these treatments a $2.00 change in fuel prices changed the cost of SHWP production by $3.66 and $4.92 per ton, respectively. This same change in fuel prices affected the cost of biomass production similarly to the SHWP. It was observed that a 66% change in fuel prices had the greatest effect on biomass in clearcut treatment C. In these treatments the same $2.00 increase in fuel prices changes the cost of biomass production by $8.04 and $9.30 per ton, respectively. The production cost for biomass was less likely affected by these changes due to biomass production rarely using loader 1 and the fact that when producing biomass, the chipper and loader 2 generally had very low PMH values. The fact that the production cost for biomass was less affected by this change leads to the assumption that given this scenario, the cost per ton production of SHWP is more sensitive to a $2.00 increase in fuel prices than the cost per ton production of biomass.

An alternative change in diesel price scenario that averages cost per ton data for all harvest intensities, for each product on both silvicultural treatments is presented in Appendix Figure 11. This scenario is set up in order to generalize the overall sensitivities of cost per ton data on a $1.00 increase in fuel prices. The same pooling of cost per ton data is presented for sensitivity analysis on changes in equipment suite purchase price and change in round trip hauling distance which display the dollar and percent change amount in each figure for each “what-if” scenario (see Appendix Figures 12-13) An alternative scenario for changes in stumpage price is not included due to the fluctuation in stumpage prices for each treatment.

Equipment Price Sensitivity

Change in equipment purchasing costs had the least overall effect on the cost per ton of SHWP in these analyses. These findings were consistent with previous research conducted in Missouri by Saunders et al. (2012) and Botard et al. (2012). Changes in equipment purchasing price generally have a less pronounced effect on overall harvesting costs due to the ability of equipment to spread their purchasing costs over the course of the work year (Saunders et al. 2012). Changes in equipment suite purchase price did however have the greatest effect on the cost per ton to produce biomass. It was observed that an 80% change in equipment suite purchase price had the greatest effect on SHWP break-even prices in clearcut treatment A but the greatest effect on treatment B in the intermediate thinning. In those treatments a $178,000 (80%) change in equipment purchase price only changed the cost of SHWP production by $1.28 and $2.24 per ton, respectively. This same change in equipment purchase price had a much more dramatic effect on the cost of biomass production. It was observed that a 80% change in equipment purchase price had the greatest effect on treatment C in both the clearcut and intermediate thinning treatments for biomass (Appendix Tables 18 and 19). In these treatments a $178,000 (80%) change in purchase price changed the cost of biomass production by $25.44 and $32.00 per ton respectively. This was likely due to the fact that biomass production included the second loader and the chipper where the SHWP production did not have costs from those two pieces of machinery. In addition, with such an increase in equipment purchase price and such little overall biomass production across treatments, one would expect that a $178,000 change in equipment purchase price would not be beneficial to a logger unless he was able to generate more biomass production. This scenario demonstrates how sensitive the cost to produce biomass could potentially be with such an increase in equipment prices.

Stumpage Sensitivity

Changes in stumpage purchase price had the greatest overall effect on the break-even price per ton, especially in intermediate thinning treatments. It was observed that a 10% change in stumpage prices had the greatest effect on SHWP break-even prices in clearcut treatment B and the greatest effect in the intermediate thinnings on treatment A. Stumpage purchase prices varied by treatment (Appendix Tables 20 and 21) but a 10% in stumpage changed the cost of SHWP production by $0.68 and $2.24 per ton respectively. It was observed that a 10% change in stumpage prices had the greatest effect on biomass break-even prices in clearcut treatment B and the greatest effect on the intermediate thinnings on treatment A. On these treatments, a 10% change in stumpage purchase price changes the cost of biomass production by $0.68 and $2.24 per ton respectively. The larger impact on stumpage price in the thinning treatments is likely attributed to having a more minimal investment of equipment time handling biomass in the form of tops and small diameter trees. Since stumpage costs in the intermediate thinning treatments make up a greater portion of biomass harvesting costs compared to the clearcut treatments, changes in stumpage cost have a greater effect on biomass costs in the intermediate thinning treatments.

Hauling Distance Sensitivity

Changes in round trip hauling distance had the most pronounced effect on hauling SHWP. It was observed that a 50 mile increase in round trip hauling distance had the greatest effect on SHWP in clearcut and intermediate thinning treatment B. In those treatments a 50 mile increase in round trip hauling distance changed the cost of SHWP production by $2.65 and $3.10 per ton, respectively. This same change in round trip hauling distance did not affect the cost of biomass production as much as the SHWP in either silvicultural prescription. It was observed that a 50 mile increase in round trip hauling distance had the greatest effect on treatment C in the clearcut and intermediate thinning treatments for biomass (Appendix Tables 22 and 23). In those treatments a 50 mile increase in round trip hauling distance changed the cost of biomass production by $4.35 and $6.45 per ton, respectively.

4.4 Cost Comparison to Other Studies

Several other studies were reviewed to compare the cost of harvesting biomass in those studies with the costs generated in this study. Comparison was done in an effort to determine if cost estimates for harvesting woody biomass in this study are within reason when compared to previous studies. Table 21 lists six integrated biomass harvests that were examined to find similarities in biomass harvesting costs. It should be noted that costs in all studies were not adjusted for inflation. Of the six studies, two were conducted in the Western region of the United States, two were in the southeastern U.S., while Saunders et al. (2012) and Botard et al. (2012) were conducted in Missouri. Studies by Saunders and Botard were the only studies conducted in hardwood stands; all other studies were conducted in coniferous forest stands. All studies used a fully mechanized, integrated harvesting approach that consisted mainly of feller-bunchers with grapple skidders and a loader with a chipper or grinder. This study was unique in having two loaders, so additional costs were generated from this piece of equipment. All studies used similar data collection techniques in the form of time-in-motion and activity sampling, as well as using similar methods to sample the proportions of biomass harvested in efforts to accurately allocate the cost of biomass to the respective pieces of equipment used in the study.

As displayed in Table 21, the costs of harvesting biomass in this study were only within the range of the observed costs from the study conducted by Hartsough et al. (1994). These higher costs in Hartsough's study were conducted in a cut-to-length harvesting system that used a harvester and a forwarder in a California coniferous forest setting. The lowest cost in this study (clearcut treatment B) was only slightly greater than the cost range observed in Saunders and Bolding's studies. This is likely due to Bolding and Saunders' studies which harvest a greater volume of biomass compared to each treatment in this study. Of the six studies examined Saunders et al. (2012) and Botard et al. (2012) had the most similar site conditions and equipment suite when compared to this study. The main differences between this study and Saunders et al. (2012) were the integration of the different harvest intensities into this study and the lack of information provided by Saunders regarding the cost differences between treatments. Saunders' study did not report on SHWP and biomass harvesting costs and revenues between the shelterwood and single-tree selection treatments they implemented, rather the results were combined to give an overall cost analysis for the project as a whole. The main difference between this study and Botard et al. (2012) was that Botard only observed the cost structure of harvesting tops and small diameter trees. Botard did not report on revenues and did not factor hauling costs into the cost structure of the study.

Table 21. Comparison of biomass harvesting costs between studies

Study	Biomass cost/ton ($)
Watson et al. 1986	8.30 - 13.34
Miller et al. 1987	6.14 - 13.60
Hartsough et al. 1994	10.90 - 52.40
Bolding et al. 2009	27.78
Saunders et al. 2012	22.80
Botard et al. 2012	11.11 - 14.16
This study	36.79 - 85.05

5. SUMMARY

Harvesting Biomass in the Missouri Ozarks

The results of this study show that for an integrated harvest in the Missouri Ozarks, the break-even price needed to profit from harvesting woody biomass is far too high given the current market conditions and hauling distances required to be able to generate revenue from these products. In every treatment type, biomass was produced at a cost per ton that was higher than the observed revenues. These findings are consistent with previous biomass harvesting research done in Missouri by Saunders et al. (2012) and Botard et al. (2013) who found that small diameter woody biomass is unprofitable to harvest using an similar integrated approach. The cost of harvesting this material was significantly greater in this project due to logging inefficiencies that magnified the cost of harvesting these products.

Most Profitable Treatments

Implementing the harvest prescriptions associated with each treatment type carried significant impact on cost and productivity. Clearcut treatment D was able to generate the most profit ($2,822.17) and ended up having the highest benefit:cost ratio (1.17) of all treatments in the harvest. This was not surprising as the prescription for this treatment called for harvesting only solid hardwood products and had therefore required no extra time or effort dealing with biomass products. When integrating biomass with the SHWP, treatment C, which only extracted biomass from whole trees $\leq$ 8" DBH generated the next highest revenues among clearcut treatments and generated the overall highest revenues among intermediate thinnings ($2,063.57 and $935.72). These two treatments also had the next highest B:C ratios (1.16 and 1.11) which when compared to the highest

B:C ratio (1.17), were not far behind considering the extra costs associated when dealing with an additional product.

When comparing the break-even price, or total cost per ton of materials brought to the landing, processed, and delivered, the price of SHWP material in clearcut treatment B was less than any other treatment at $24.91 per ton. This was only $1.39 less expensive than the SHWP harvest cost per ton on clearcut treatment C. The PMH on clearcut treatment C were lower due to the fact that less biomass was harvested (31.24 tons) on clearcut treatment C than both treatments A and B (treatment D did not include harvest of biomass). This led to significantly less PMH for loader 2 and the chipper, but ultimately resulted in the highest break-even price for biomass ($62.46 per ton) in clearcut treatments. It should also be noted that treatment C only had 401.29 total tons of SHWP removed, which was less than clearcut treatments A and D (484.34 and 476.30 tons), but since the products were removed more efficiently the break-even price was lower.

Intermediate thinning treatment C had the lowest SHWP cost per ton at $29.22 but the highest break-even price for biomass at $85.05 per ton. This high cost was a function of the low yield due to the harvest prescription assigned to this treatment rather than poor equipment efficiency during the harvest. The lowest SHWP cost per ton can be attributed to treatment C having the highest SHWP yield in addition to relatively low PMH values for the equipment used to handle biomass. These low variable costs for the chipper and loader 2 were a function of the prescription for this treatment and would be expected to increase with additional biomass production. The results in this case study from both silvicultural prescriptions, show that from strictly an economic break-even standpoint, clearcut and intermediate treatment C show potential to be a viable alternative to the current woody biomass harvest regime standards implemented by MDC.

Markets

Revenues reported in this study validate the instability of the biomass market in the state of Missouri. Only one mill in the immediate area (33 miles from site) agreed to buy fuel chips and they only purchased the chips because the logger was willing to sell them at such a low price ($15/ton). The second mill was in Kentucky (211 miles from site), far beyond an ideal distance to haul and maximize revenues. These hauling distances and low prices result in large hauling costs and thus less profit for the logger. The development of more fuel chip buyers in the Ozarks is essential in establishing a market for these products. If a biomass market were to emerge in the Ozarks area, the financial means to perform treatments such as in this study would be justifiable and could also improve growing conditions for the residual stocking, which would improve the value of these forests in the future. Feasibility studies such as this help provide insight to land managers and owners with useful information when making decisions regarding woody biomass harvesting and the benefits associated with such operations.

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Appendices:

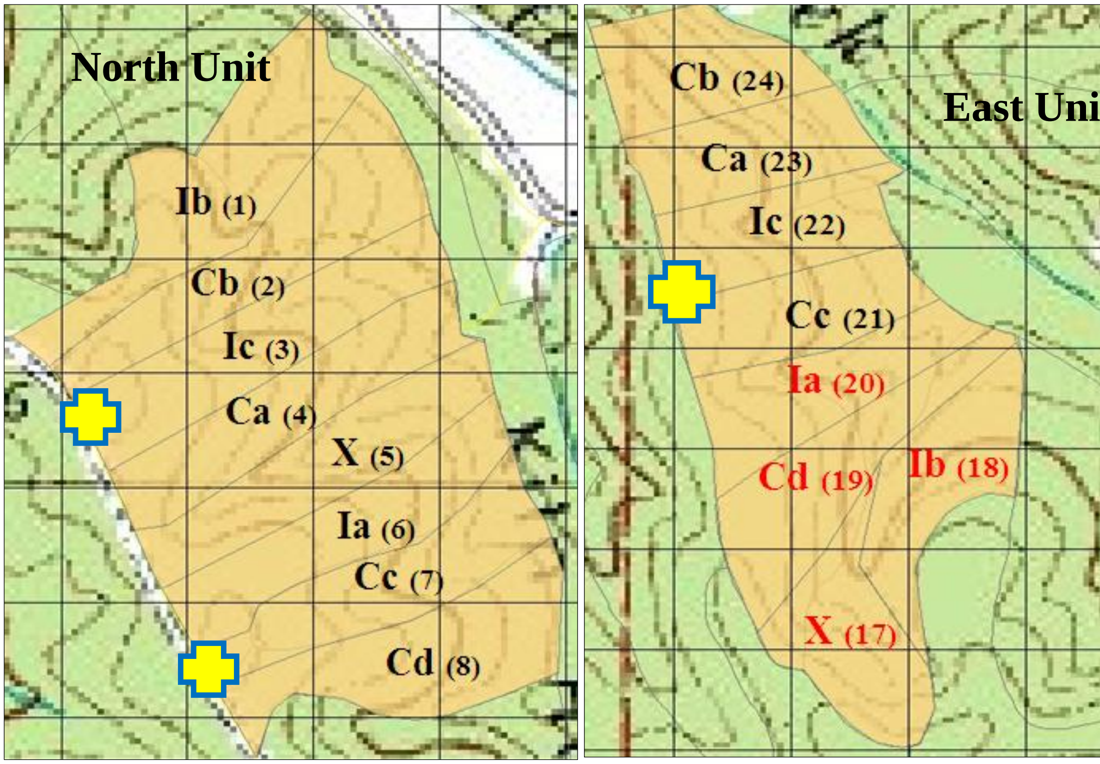

Figure 1. Schematic map of sample plot layout for the north and east harvest units. First digit corresponds to the silvicultural treatment and second digit reflects residual biomass treatment replication. Number in parenthesis reflects the plot number used for each unit. Plots colored in red were not used in this study. ✚ represents log landings.

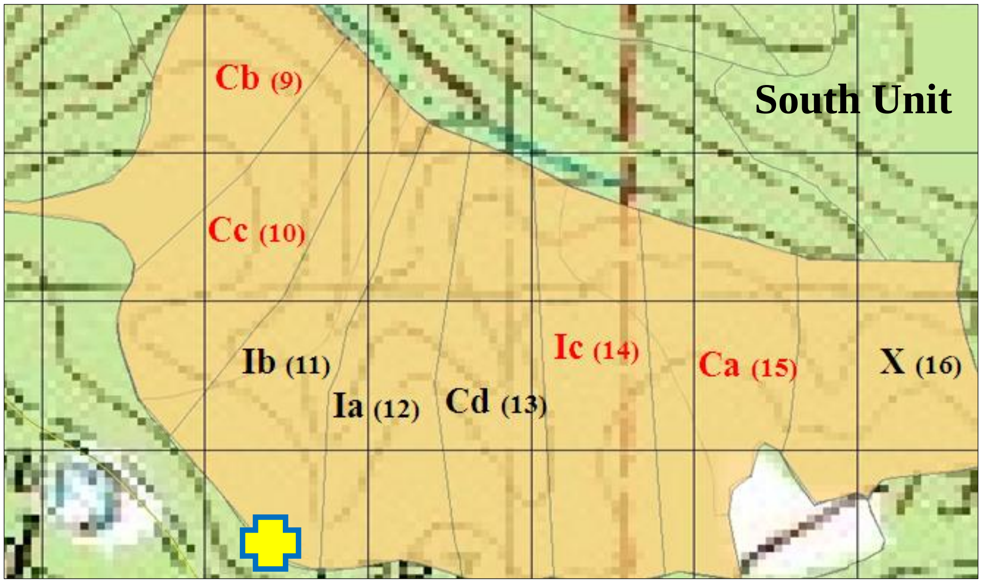

Figure 2. Schematic map of sample plot layout for the south harvest unit. First digit corresponds to the silvicultural treatment and second digit reflects residual biomass treatment replication. Number in parenthesis reflects the plot number used for each unit. Plots colored in red were not used in this study. represents log landing.

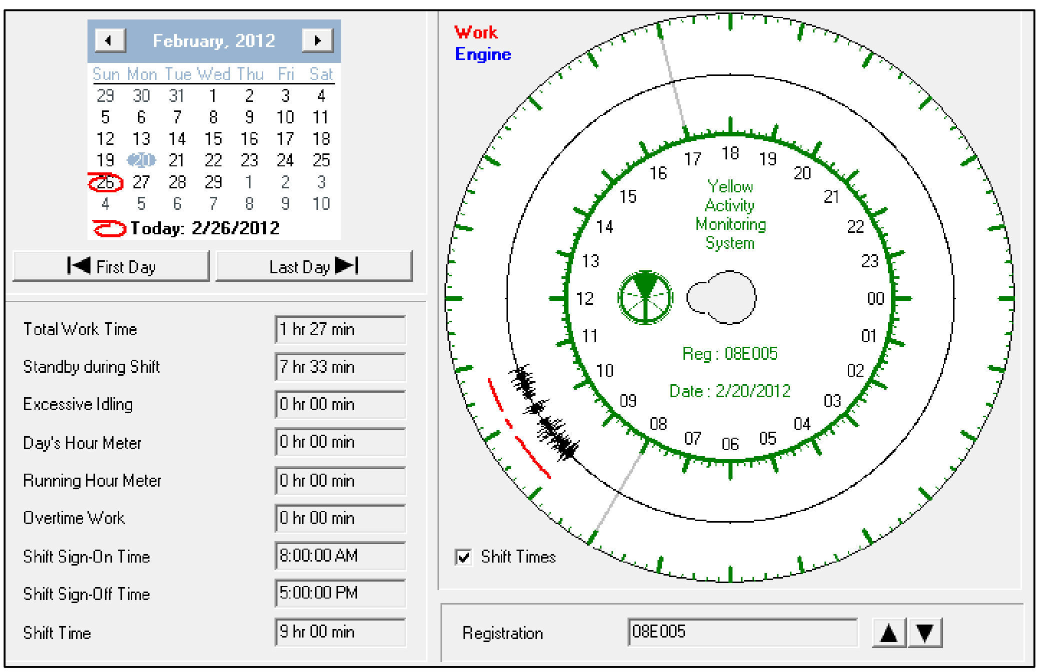

Figure 3. Sample Yellow Activity Monitoring System daily readout

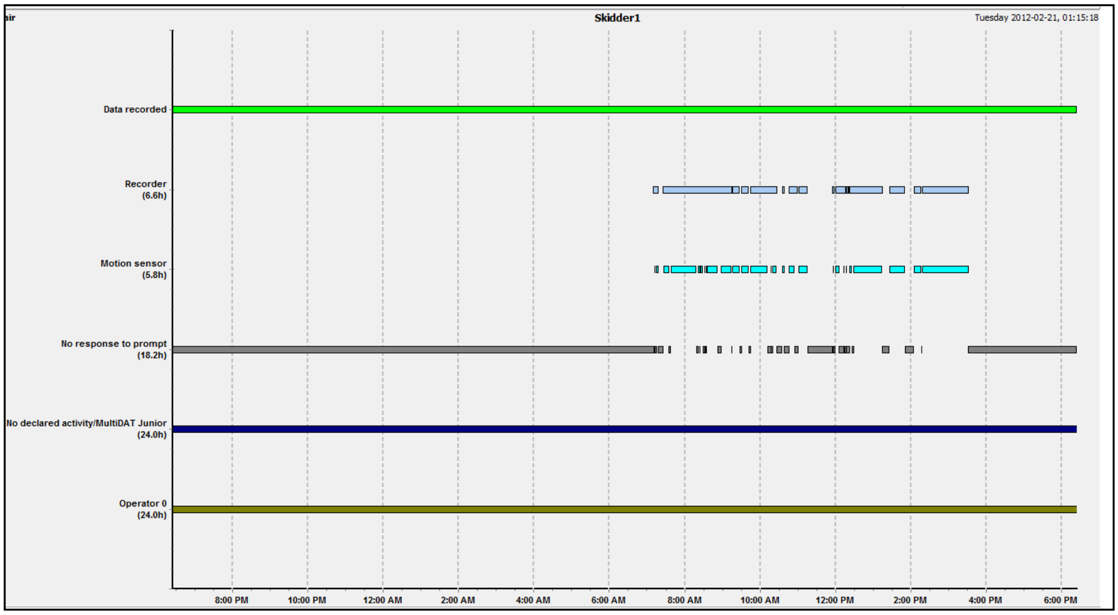

Figure 4. Sample Multi*DAT* System daily readout

Example 1: Loader 1 – Prentice 280 Ownership Cost ($/SMH)

Capital Cost = (((Purchase Price*(1-Salvage%))* CapitalRecoveryFactor)+(Salvage%*PurchasePrice*InterestRate)) / SMH/year)

= (((24,000 * (1 – 0.75)) * 0.2373) + (0.75 * 24,000 * 0.06)) / 1800 = $1.391/SMH

Capital Recovery Factor = (Interest Rate * (1 + Interest Rate)^n) / (((1+Interest Rate)^n)-1)

= (0.06 * (1 + 0.06)^5 / (((1 + 0.06)^5)-1) = 0.2373

Insurance Cost = Insurance / (SMH/year)

= $423 / 1800 = $0.235/SMH

Tax Cost = Taxes / (SMH/year)

=$0.00/1800 = $0.00 / SMH

Total Cost = Capital Cost + Insurance + Taxes

= $1.391/SMH + $0.235/SMH + $0.00/SMH = $1.63/SMH

Example 2: Skidder – John Deere 548 G-III Operating Cost ($/PMH)

Fuel Cost =Fuel Use * Horsepower * Fuel Price
=0.04041 * 129 * $3.33 = $17.36/PMH

Oil Cost =Oil Use * Oil Cost
=0.05 * $8.00 = $0.40/PMH

R&M Cost =Annual R&M/(SMH * Utilization%)
=$4,500/(1800 * 0.821) = $3.04/PMH

Tire Cost =Tire Cost/Tire Life
=$2,400/7,200 = $0.33/PMH

Misc. Cost =Monthly Misc. Operating Cost / ((Hours/Month) * Utilization%)
=$200 / ((9(hours/day) * 5 (days/week) *4.3 (week/month)) *0.821) = $1.25/PMH

Total Cost =Fuel Cost + Oil Cost + R&M + Tire Cost + Misc. Cost
=$22.38/PMH

Table 1. Activity breakdown percentages for feller-buncher on all treatments.

Observed Activity	Ca	Cb	Cc	Cd	Ia	Ib	Ic
% Sawing SHWP	5	10	8	7	5	12	12
% Sawing Block/Pallet /Pulp	13	10	17	8	6	6	12
% Dropping SHWP	3	5	2	7	8	7	5
% Dropping Block/Pallet/Pulp	21	15	23	22	17	13	15
% Moving	44	44	40	39	53	47	43
% Delay	14	16	10	17	11	15	13

Table 2. Activity breakdown percentages for skidder on all treatments.

Observed Activity	Ca	Cb	Cc	Cd	Ia	Ib	Ic
% Skidding	68	84	75	64	58	64	74
% Delay	32	16	25	36	42	36	26

Table 3. Activity breakdown percentages for Loader 1 on all treatments.

Observed Activity	Ca	Cb	Cc	Cd	Ia	Ib	Ic
% Processing SHWP	16	24	20	26	29	27	25
% Processing Block/Pallet /Pulp	28	30	16	18	19	24	22
% Stacking SHWP	7	6	9	10	9	7	9
% Stacking Block/Pallet/Pulp	16	10	12	21	14	11	14
% Stacking Biomass	2	3	3	1	1	0	3
% Loading SHWP	9	7	13	7	8	8	11
% Loading Block/Pallet/Pulp	14	12	21	11	13	13	9
% Delay	8	8	6	6	7	10	7

Table 4. Activity breakdown percentages for Loader 2 on all treatments.

Observed Activity	Ca	Cb	Cc	Cd	Ia	Ib	Ic
% Feeding Chipper	66	59	54	0	56	57	78
% Stacking Biomass	28	34	36	0	44	38	0
% Delay	6	7	10	0	0	5	22

Table 5. Activity breakdown percentages for chipper on all treatments.

Observed Activity	Ca	Cb	Cc	Cd	Ia	Ib	Ic
% Chipping	98	95	93	0	100	100	94
% Delay	2	5	7	0	0	0	6

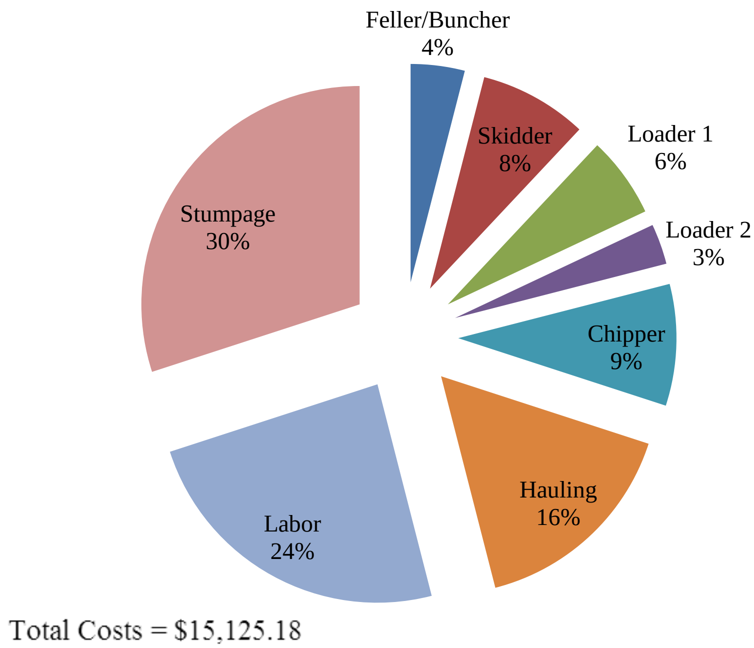

Figure 5. Total observed cost components for clearcut treatment B

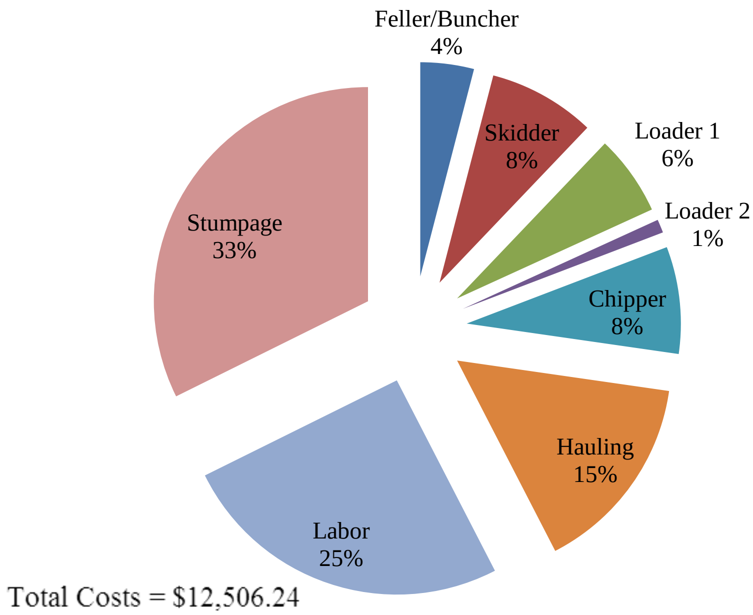

Figure 6. Total observed cost components for clearcut treatment C

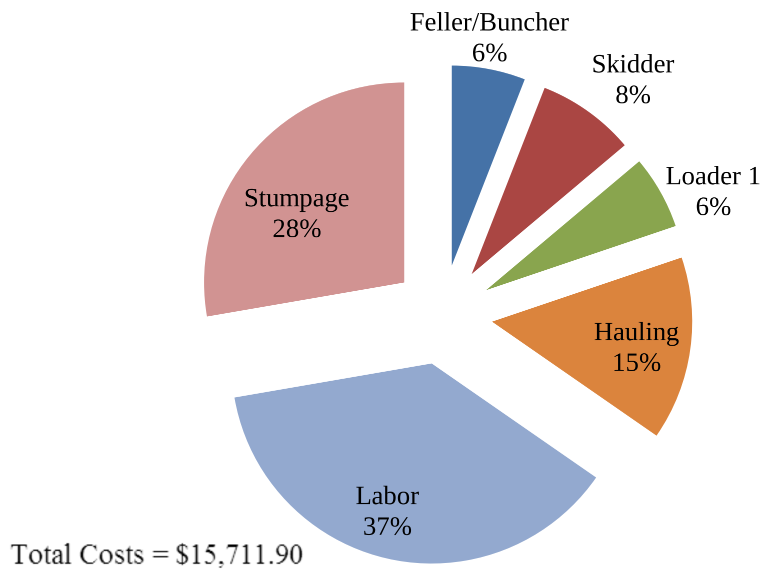

Figure 7. Total observed cost components for clearcut treatment D

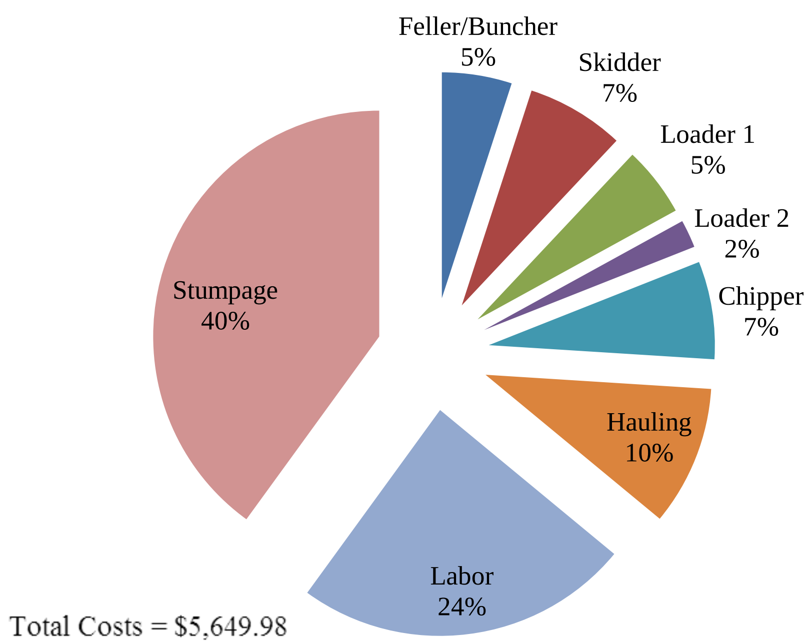

Figure 8. Total observed cost components for intermediate thinning treatment A

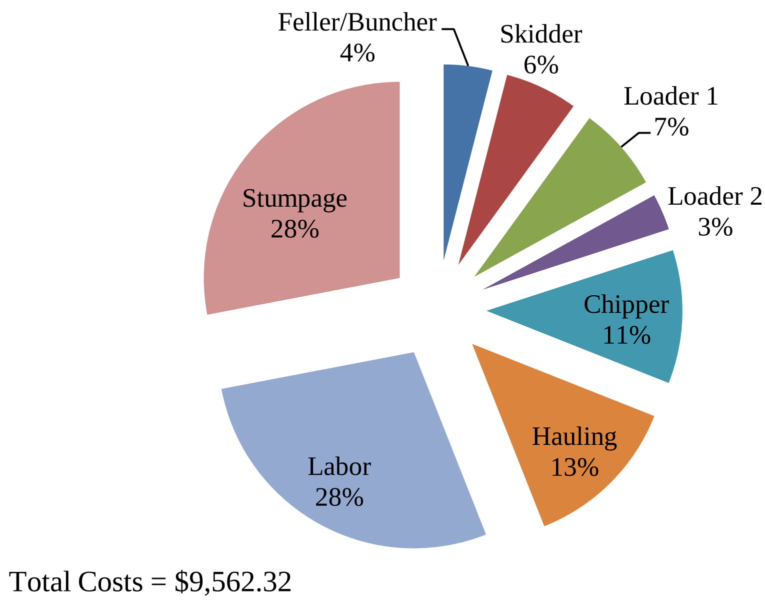

Figure 9. Total observed cost components for intermediate thinning treatment B

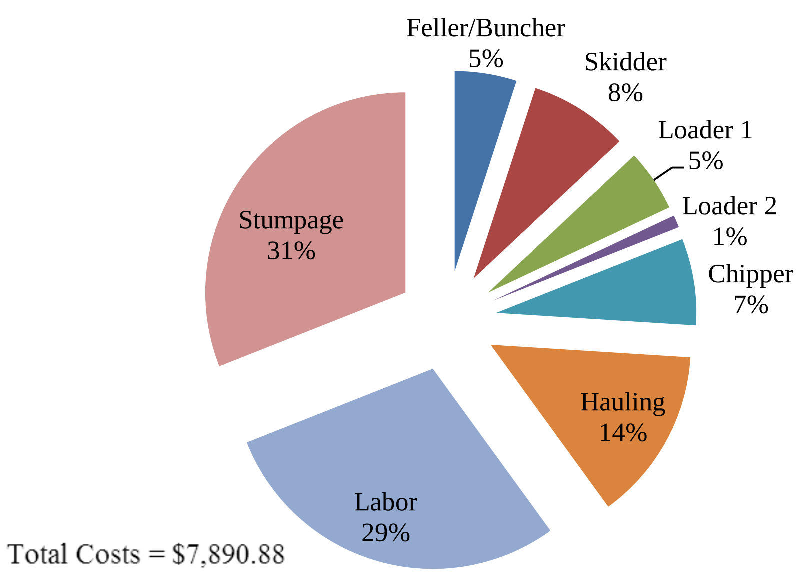

Figure 10. Total observed cost components for intermediate thinning treatment C

Table 12. Estimation of the fixed costs per ton for both SHWP and biomass chips for each clearcut treatment.

Equipment	Ca		Cb		Cc		Cd	
	Fixed Cost / Ton SHWP	Fixed Cost / Ton Biomass	Fixed Cost / Ton SHWP	Fixed Cost / Ton Biomass	Fixed Cost / Ton SHWP	Fixed Cost / Ton Biomass	Fixed Cost / Ton SHWP	Fixed Cost / Ton Biomass
Feller/Buncher	$0.43	$0.43	$0.30	$0.30	$0.38	$0.38	$0.56	$0.00
Skidder	$0.50	$0.50	$0.35	$0.35	$0.44	$0.44	$0.64	$0.00
Loader 1	$0.29	$0.29	$0.21	$0.21	$0.26	$0.26	$0.38	$0.00
Loader 2	$0.00	$1.47	$0.00	$0.69	$0.00	$3.31	$0.00	$0.00
Chipper	$0.00	$12.24	$0.00	$5.72	$0.00	$27.50	$0.00	$0.00
Truck & Trailer	$1.07	$1.07	$0.76	$0.76	$0.95	$0.95	$1.39	$0.00
Stumpage	$7.06	$7.04	$8.55	$8.51	$9.29	$9.25	$9.31	$0.00
Total	**$9.36**	**$23.04**	**$10.17**	**$16.53**	**$11.33**	**$42.10**	**$12.28**	**$0.00**

Table 13. Estimation of the fixed costs per ton for both SHWP and biomass chips for each intermediate thinning treatment.

Equipment	Ia		Ib		Ic	
	Fixed Cost / Ton SHWP	Fixed Cost / Ton Biomass	Fixed Cost / Ton SHWP	Fixed Cost / Ton Biomass	Fixed Cost / Ton SHWP	Fixed Cost / Ton Biomass
Feller/Buncher	$0.41	$0.41	$0.59	$0.59	$0.35	$0.35
Skidder	$0.48	$0.48	$0.69	$0.69	$0.41	$0.40
Loader 1	$0.28	$0.28	$0.41	$0.41	$0.24	$0.24
Loader 2	$0.00	$1.68	$0.00	$1.29	$0.00	$4.48
Chipper	$0.00	$13.93	$0.00	$10.66	$0.00	$37.13
Truck & Trailer	$1.03	$1.03	$1.48	$1.48	$0.88	$0.87
Stumpage	$15.22	$15.18	$11.23	$11.20	$9.93	$9.88
Total	**$17.44**	**$32.99**	**$14.40**	**$26.31**	**$11.81**	**$53.36**

Table 14. Estimation of the variable costs per ton for both SHWP and biomass chips for each clearcut treatment.

Equipment	Ca		Cb		Cc		Cd	
	Variable Cost / Ton SHWP	Variable Cost / Ton Biomass	Variable Cost / Ton SHWP	Variable Cost / Ton Biomass	Variable Cost / Ton SHWP	Variable Cost / Ton Biomass	Variable Cost / Ton SHWP	Variable Cost / Ton Biomass
Feller/Buncher	$0.87	$0.87	$0.93	$0.92	$0.87	$0.86	$1.46	$0.00
Skidder	$1.84	$1.83	$1.87	$1.86	$1.77	$1.76	$1.90	$0.00
Loader 1	$1.59	$1.59	$1.48	$1.47	$1.52	$1.52	$1.48	$0.00
Loader 2	$0.00	$2.16	$0.00	$2.02	$0.00	$2.25	$0.00	$0.00
Chipper	$0.00	$4.22	$0.00	$3.58	$0.00	$3.18	$0.00	$0.00
Truck & Trailer	$3.76	$3.75	$3.69	$3.67	$3.47	$3.46	$3.47	$0.00
Labor	$9.20	$9.17	$6.78	$6.75	$7.35	$7.32	$12.39	$0.00
Total	**$17.26**	**$23.58**	**$14.74**	**$20.26**	**$14.98**	**$20.36**	**$20.71**	**$0.00**

Table 15. Estimation of the variable costs per ton for both SHWP and biomass chips for each intermediate thinning treatment.

Equipment	Ia		Ib		Ic	
	Variable Cost / Ton SHWP	Variable Cost / Ton Biomass	Variable Cost / Ton SHWP	Variable Cost / Ton Biomass	Variable Cost / Ton SHWP	Variable Cost / Ton Biomass
Feller/Buncher	$1.30	$1.29	$1.14	$1.14	$1.13	$1.13
Skidder	$2.17	$2.16	$1.77	$1.76	$2.09	$2.08
Loader 1	$1.57	$1.57	$2.61	$2.60	$1.35	$1.35
Loader 2	$0.00	$2.40	$0.00	$2.77	$0.00	$3.66
Chipper	$0.00	$3.47	$0.00	$4.06	$0.00	$10.71
Truck & Trailer	$2.76	$2.75	$3.60	$3.59	$3.63	$3.62
Labor	$9.12	$9.09	$11.54	$11.51	$9.20	$9.15
Total	**$16.91**	**$22.73**	**$20.65**	**$27.44**	**$17.41**	**$31.69**

Table 16. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each clearcut treatment and product type at each 10% incremental change in diesel price.

Off Road Diesel Price ($/gal)	Cost Per Ton (Breakeven Price)						
	Ca SHWP	Ca Bio	Cb SHWP	Cb Bio	Cc SHWP	Cc Bio	Cd SHWP
$1.67	$23.76	$43.22	$21.86	$34.09	$24.05	$55.76	$30.24
$2.00	$24.33	$43.90	$22.47	$34.63	$24.50	$57.10	$30.79
$2.33	$24.90	$44.58	$23.08	$35.17	$24.95	$58.44	$31.34
$2.66	$25.47	$45.26	$23.69	$35.71	$25.40	$59.78	$31.89
$3.00	$26.04	$45.94	$24.30	$36.25	$25.85	$61.12	$32.44
$3.33	$26.61	$46.62	$24.91	$36.79	$26.30	$62.46	$32.99
$3.66	$27.18	$47.30	$25.52	$37.33	$26.75	$63.80	$33.54
$4.00	$27.75	$47.98	$26.13	$37.87	$27.20	$65.14	$34.09
$4.33	$28.32	$48.66	$26.74	$38.41	$27.65	$66.48	$34.64
$4.66	$28.89	$49.34	$27.35	$38.95	$28.10	$67.82	$35.19
$5.00	$29.46	$50.02	$27.96	$39.49	$28.55	$69.16	$35.74
$5.33	$30.03	$50.70	$28.57	$40.03	$29.00	$70.50	$36.29
$5.66	$30.60	$51.38	$29.18	$40.57	$29.45	$71.84	$36.84
$6.00	$31.17	$52.06	$29.79	$41.11	$29.90	$73.18	$37.39
$6.33	$31.74	$52.74	$30.40	$41.65	$30.35	$74.52	$37.94
$6.66	$32.31	$53.42	$31.01	$42.19	$30.80	$75.86	$38.49

Table 17. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each intermediate thinning treatment and product type at each 10% incremental change in diesel price.

Off Road Diesel Price ($/gal)	Cost Per Ton (Breakeven Price)					
	Ia SHWP	Ia Bio	Ib SHWP	Ib Bio	Ic SHWP	Ic Bio
$1.67	$31.35	$53.42	$30.95	$51.40	$26.57	$77.30
$2.00	$31.95	$53.88	$31.77	$51.87	$27.10	$78.85
$2.33	$32.55	$54.34	$32.59	$52.34	$27.63	$80.40
$2.66	$33.15	$54.80	$33.41	$52.81	$28.16	$81.95
$3.00	$33.75	$55.26	$34.23	$53.28	$28.69	$83.50
$3.33	$34.35	$55.72	$35.05	$53.75	$29.22	$85.05
$3.66	$34.95	$56.18	$35.87	$54.22	$29.75	$86.60
$4.00	$35.55	$56.64	$36.69	$54.69	$30.28	$88.15
$4.33	$36.15	$57.10	$37.51	$55.16	$30.81	$89.70
$4.66	$36.75	$57.56	$38.33	$55.63	$31.34	$91.25
$5.00	$37.35	$58.02	$39.15	$56.10	$31.87	$92.80
$5.33	$37.95	$58.48	$39.97	$56.57	$32.40	$94.35
$5.66	$38.55	$58.94	$40.79	$57.04	$32.93	$95.90
$6.00	$39.15	$59.40	$41.61	$57.51	$33.46	$97.45
$6.33	$39.75	$59.86	$42.43	$57.98	$33.99	$99.00
$6.66	$40.35	$60.32	$43.25	$58.45	$34.52	$100.55

Table 18. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each clearcut treatment and product type at each 10% incremental change in equipment suite purchase price.

Equipment Suite Purchase Price	Cost Per Ton (Breakeven Price)						
	Ca SHWP	Ca Bio	Cb SHWP	Cb Bio	Cc SHWP	Cc Bio	Cd SHWP
$111,250	$25.81	$39.87	$24.26	$33.54	$25.75	$46.56	$32.04
$133,500	$25.97	$41.22	$24.39	$34.19	$25.86	$49.74	$32.23
$155,750	$26.13	$42.57	$24.52	$34.84	$25.97	$52.92	$32.42
$178,000	$26.29	$43.92	$24.65	$35.49	$26.08	$56.10	$32.61
$200,250	$26.45	$45.27	$24.78	$36.14	$26.19	$59.28	$32.80
$222,500	$26.61	$46.62	$24.91	$36.79	$26.30	$62.46	$32.99
$244,750	$26.77	$47.97	$25.04	$37.44	$26.41	$65.64	$33.18
$267,000	$26.93	$49.32	$25.17	$38.09	$26.52	$68.82	$33.37
$289,250	$27.09	$50.67	$25.30	$38.74	$26.63	$72.00	$33.56
$311,500	$27.25	$52.02	$25.43	$39.39	$26.74	$75.18	$33.75
$333,750	$27.41	$53.37	$25.56	$40.04	$26.85	$78.36	$33.94
$356,000	$27.57	$54.72	$25.69	$40.69	$26.96	$81.54	$34.13
$378,250	$27.73	$56.07	$25.82	$41.34	$27.07	$84.72	$34.32
$400,500	$27.89	$57.42	$25.95	$41.99	$27.18	$87.90	$34.51
$422,750	$28.05	$58.77	$26.08	$42.64	$27.29	$91.08	$34.70
$445,000	$28.21	$60.12	$26.21	$43.29	$27.40	$94.26	$34.89

Table 19. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each intermediate thinning treatment and product type at each 10% incremental change in equipment suite purchase price.

Equipment Suite Purchase Price	Cost Per Ton (Breakeven Price)					
	Ia SHWP	Ia Bio	Ib SHWP	Ib Bio	Ic SHWP	Ic Bio
$111,250	$33.55	$48.27	$33.65	$47.95	$28.52	$65.05
$133,500	$33.71	$49.76	$33.93	$49.11	$28.66	$69.05
$155,750	$33.87	$51.25	$34.21	$50.27	$28.80	$73.05
$178,000	$34.03	$52.74	$34.49	$51.43	$28.94	$77.05
$200,250	$34.19	$54.23	$34.77	$52.59	$29.08	$81.05
$222,500	$34.35	$55.72	$35.05	$53.75	$29.22	$85.05
$244,750	$34.51	$57.21	$35.33	$54.91	$29.36	$89.05
$267,000	$34.67	$58.70	$35.61	$56.07	$29.50	$93.05
$289,250	$34.83	$60.19	$35.89	$57.23	$29.64	$97.05
$311,500	$34.99	$61.68	$36.17	$58.39	$29.78	$101.05
$333,750	$35.15	$63.17	$36.45	$59.55	$29.92	$105.05
$356,000	$35.31	$64.66	$36.73	$60.71	$30.06	$109.05
$378,250	$35.47	$66.15	$37.01	$61.87	$30.20	$113.05
$400,500	$35.63	$67.64	$37.29	$63.03	$30.34	$117.05
$422,750	$35.79	$69.13	$37.57	$64.19	$30.48	$121.05
$445,000	$35.95	$70.62	$37.85	$65.35	$30.62	$125.05

Table 20. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each clearcut treatment and product type at each 10% incremental change in stumpage purchase price.

Ca				Cb				Cc				Cd	
Stumpage Purchace Price	SHWP Cost / Ton	Stumpage Purchace Price	Bio Cost / Ton	Stumpage Purchace Price	SHWP Cost / Ton	Stumpage Purchace Price	Bio Cost / Ton	Stumpage Purchace Price	SHWP Cost / Ton	Stumpage Purchace Price	Bio Cost / Ton	Stumpage Purchace Price	SHWP Cost / Ton
$4.26	$23.76	$4.24	$43.77	$5.20	$21.51	$5.14	$33.39	$5.74	$22.75	$5.70	$58.96	$5.51	$29.19
$4.82	$24.33	$4.80	$44.34	$5.87	$22.19	$5.82	$34.07	$6.45	$23.46	$6.41	$59.66	$6.27	$29.95
$5.38	$24.90	$5.36	$44.91	$6.54	$22.87	$6.50	$34.75	$7.16	$24.17	$7.12	$60.36	$7.03	$30.71
$5.94	$25.47	$5.92	$45.48	$7.21	$23.55	$7.18	$35.43	$7.87	$24.88	$7.83	$61.06	$7.79	$31.47
$6.50	$26.04	$6.48	$46.05	$7.88	$24.23	$7.86	$36.11	$8.58	$25.59	$8.54	$61.76	$8.55	$32.23
$7.06	$26.61	$7.04	$46.62	$8.55	$24.91	$8.54	$36.79	$9.29	$26.30	$9.25	$62.46	$9.31	$32.99
$7.62	$27.18	$7.60	$47.19	$9.22	$25.59	$9.22	$37.47	$10.00	$27.01	$9.96	$63.16	$10.07	$33.75
$8.18	$27.75	$8.16	$47.76	$9.89	$26.27	$9.90	$38.15	$10.71	$27.72	$10.67	$63.86	$10.83	$34.51
$8.74	$28.32	$8.72	$48.33	$10.56	$26.95	$10.58	$38.83	$11.42	$28.43	$11.38	$64.56	$11.59	$35.27
$9.30	$28.89	$9.28	$48.90	$11.23	$27.63	$11.26	$39.51	$12.13	$29.14	$12.09	$65.26	$12.35	$36.03
$9.86	$29.46	$9.84	$49.47	$11.90	$28.31	$11.94	$40.19	$12.84	$29.85	$12.80	$65.96	$13.11	$36.79
$10.42	$30.03	$10.40	$50.04	$12.57	$28.99	$12.62	$40.87	$13.55	$30.56	$13.51	$66.66	$13.87	$37.55
$10.98	$30.60	$10.96	$50.61	$13.24	$29.67	$13.30	$41.55	$14.26	$31.27	$14.22	$67.36	$14.63	$38.31
$11.54	$31.17	$11.52	$51.18	$13.91	$30.35	$13.98	$42.23	$14.97	$31.98	$14.93	$68.06	$15.39	$39.07
$12.10	$31.74	$12.08	$51.75	$14.58	$31.03	$14.66	$42.91	$15.68	$32.69	$15.64	$68.76	$16.15	$39.83
$12.66	$32.31	$12.64	$52.32	$15.25	$31.71	$15.34	$43.59	$16.39	$33.40	$16.35	$69.46	$16.91	$40.59

Table 21. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each intermediate thinning treatment and product type at each 10% incremental change in stumpage purchase price.

Ia				Ib				Ic			
Stumpage Purchace Price	SHWP Cost / Ton	Stumpage Purchace Price	Bio Cost / Ton	Stumpage Purchace Price	SHWP Cost / Ton	Stumpage Purchace Price	Bio Cost / Ton	Stumpage Purchace Price	SHWP Cost / Ton	Stumpage Purchace Price	Bio Cost / Ton
$4.02	$23.15	$3.98	$44.52	$2.98	$26.80	$2.95	$45.45	$2.58	$21.87	$2.53	$77.70
$6.26	$25.39	$6.22	$46.76	$4.63	$28.45	$4.60	$47.11	$4.05	$23.34	$4.00	$79.17
$8.50	$27.63	$8.46	$49.00	$6.28	$30.10	$6.25	$48.77	$5.52	$24.81	$5.47	$80.64
$10.74	$29.87	$10.70	$51.24	$7.93	$31.75	$7.90	$50.43	$6.99	$26.28	$6.94	$82.11
$12.98	$32.11	$12.94	$53.48	$9.58	$33.40	$9.55	$52.09	$8.46	$27.75	$8.41	$83.58
$15.22	$34.35	$15.18	$55.72	$11.23	$35.05	$11.20	$53.75	$9.93	$29.22	$9.88	$85.05
$17.46	$36.59	$17.42	$57.96	$12.88	$36.70	$12.85	$55.41	$11.40	$30.69	$11.35	$86.52
$19.70	$38.83	$19.66	$60.20	$14.53	$38.35	$14.50	$57.07	$12.87	$32.16	$12.82	$87.99
$21.94	$41.07	$21.90	$62.44	$16.18	$40.00	$16.15	$58.73	$14.34	$33.63	$14.29	$89.46
$24.18	$43.31	$24.14	$64.68	$17.83	$41.65	$17.80	$60.39	$15.81	$35.10	$15.76	$90.93
$26.42	$45.55	$26.38	$66.92	$19.48	$43.30	$19.45	$62.05	$17.28	$36.57	$17.23	$92.40
$28.66	$47.79	$28.62	$69.16	$21.13	$44.95	$21.10	$63.71	$18.75	$38.04	$18.70	$93.87
$30.90	$50.03	$30.86	$71.40	$22.78	$46.60	$22.75	$65.37	$20.22	$39.51	$20.17	$95.34
$33.14	$52.27	$33.10	$73.64	$24.43	$48.25	$24.40	$67.03	$21.69	$40.98	$21.64	$96.81
$35.38	$54.51	$35.34	$75.88	$26.08	$49.90	$26.05	$68.69	$23.16	$42.45	$23.11	$98.28
$37.62	$56.75	$37.58	$78.12	$27.73	$51.55	$27.70	$70.35	$24.63	$43.92	$24.58	$99.75

Table 22. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each clearcut treatment and product type at each 10% incremental change in round trip hauling distance.

Round Trip Haul Distance (Miles)	Cost per ton (Breakeven Price)						
	Ca SHWP	Ca Bio	Cb SHWP	Cb Bio	Cc SHWP	Cc Bio	Cd SHWP
50	$24.06	$44.77	$22.26	$35.64	$24.25	$58.11	$30.54
60	$24.57	$45.14	$22.79	$35.87	$24.66	$58.98	$31.03
70	$25.08	$45.51	$23.32	$36.10	$25.07	$59.85	$31.52
80	$25.59	$45.88	$23.85	$36.33	$25.48	$60.72	$32.01
90	$26.10	$46.25	$24.38	$36.56	$25.89	$61.59	$32.50
100	$26.61	$46.62	$24.91	$36.79	$26.30	$62.46	$32.99
110	$27.12	$46.99	$25.44	$37.02	$26.71	$63.33	$33.48
120	$27.63	$47.36	$25.97	$37.25	$27.12	$64.20	$33.97
130	$28.14	$47.73	$26.50	$37.48	$27.53	$65.07	$34.46
140	$28.65	$48.10	$27.03	$37.71	$27.94	$65.94	$34.95
150	$29.16	$48.47	$27.56	$37.94	$28.35	$66.81	$35.44
160	$29.67	$48.84	$28.09	$38.17	$28.76	$67.68	$35.93
170	$30.18	$49.21	$28.62	$38.40	$29.17	$68.55	$36.42
180	$30.69	$49.58	$29.15	$38.63	$29.58	$69.42	$36.91
190	$31.20	$49.95	$29.68	$38.86	$29.99	$70.29	$37.40
200	$31.71	$50.32	$30.21	$39.09	$30.40	$71.16	$37.89

Table 23. Sensitivity analysis results displaying changes in the overall harvest cost per ton for each intermediate thinning treatment and product type at each 10% incremental change in round trip hauling distance.

Round Trip Haul Distance (Miles)	Cost per ton (Breakeven Price)					
	Ia SHWP	Ia Bio	Ib SHWP	Ib Bio	Ic SHWP	Ic Bio
50	$32.35	$53.92	$31.95	$52.50	$27.17	$78.60
60	$32.75	$54.28	$32.57	$52.75	$27.58	$79.89
70	$33.15	$54.64	$33.19	$53.00	$27.99	$81.18
80	$33.55	$55.00	$33.81	$53.25	$28.40	$82.47
90	$33.95	$55.36	$34.43	$53.50	$28.81	$83.76
100	$34.35	$55.72	$35.05	$53.75	$29.22	$85.05
110	$34.75	$56.08	$35.67	$54.00	$29.63	$86.34
120	$35.15	$56.44	$36.29	$54.25	$30.04	$87.63
130	$35.55	$56.80	$36.91	$54.50	$30.45	$88.92
140	$35.95	$57.16	$37.53	$54.75	$30.86	$90.21
150	$36.35	$57.52	$38.15	$55.00	$31.27	$91.50
160	$36.75	$57.88	$38.77	$55.25	$31.68	$92.79
170	$37.15	$58.24	$39.39	$55.50	$32.09	$94.08
180	$37.55	$58.60	$40.01	$55.75	$32.50	$95.37
190	$37.95	$58.96	$40.63	$56.00	$32.91	$96.66
200	$38.35	$59.32	$41.25	$56.25	$33.32	$97.95

Table 24. Feller-buncher data collection sample sheet

Feller / Buncher - Indian Trails Conservation Area							Activity Sampling		
Date:			Recorder:		Plot #				
Time	Sawing SHWP	Sawing Pallet	Dropping SHWP	Dropping Pallet	Moving	Delay	# of SHWP	# of pallet	Notes
0.20									
0.40									
1.00									
1.20									
1.40									
2.00									
2.20									
2.40									
3.00									
3.20									
3.40									
4.00									
4.20									
4.40									
5.00									
5.20									
5.40									
6.00									
6.20									
6.40									
7.00									
7.20									
7.40									
8.00									
8.20									
8.40									
9.00									
9.20									
9.40									
10.00									

Table 25. Skidder – At landing data collection sample sheet

Skidder - **At Landing** - Indian Trails Conservation Area							Delay Notes / etc
Date:		Recorder:					
Plot-Cycle #	Start Time	Re-Enter Time	Release Time	Delay Start	Delay End	Cylce End Time	

Table 26. Skidder – In Woods data collection sample sheet

Skidder - In woods bunches			Date:				Notes:
Time-In-Motion			Start Time:	Data Collector:			
			End Time:				
Logger -		Trees / Bunch		Delay Start Time	Delay End Time	Departure Time	
Plot - Cycle #	DBH						

Table 27. Loader data collection sample sheet

Loader - Activity Sampling			Operator:								
Recorder:	Start Time:										
	End Time:		Date:								
Sample Time	Processing SHWP	Processing Pallet	Stacking Sawlogs	Stacking Pallet	Stacking Biomass	Loading Sawlogs	Loading Pallet	Loading Biomass	Delay	# of Logs /truck	Notes
0.30											
1.00											
1.30											
2.00											
2.30											
3.00											
3.30											
4.00											
4.30											
5.00											
5.30											
6.00											
6.30											
7.00											
7.30											
8.00											
8.30											
9.00											
9.30											
10.00											
10.30											
11.00											
11.30											
12.00											

Table 28. Chipper data collection sample sheet

Chipper - Indian Trials CA					Delay Notes / Other Notes
Date:	Recorder:				
Plot	Start Time	End Time	Delay Start	Delay End	

Table 29. Pre-Treatment inventory summary

Treatment	Rep	Basal Area (ft²/ac) /	Basal Area (ft²/ac) / pallet	Tree Density	Sawtimber Volume (bf/ac)	Pallet / Block Volume
Ia	East	53	70	308	3,274	1,700
	South	46	56	282	2,910	1,364
	North	37	70	182	2,397	3,168
Average		**45**	**65**	**257**	**2860**	**2077**
Ib	East	50	77	408	1,966	2,507
	South	13	60	191	1,437	2,565
	North	33	77	195	2,484	3,510
Average		**32**	**71**	**265**	**1962**	**2861**
Ic	East	47	107	171	4,012	3,364
	South	13	53	260	650	2,180
	North	40	47	364	3,447	1,859
Average		**33**	**69**	**265**	**2703**	**2468**
Ca	East	67	97	138	5,644	2,432
	South	30	60	165	2,747	1,823
	North	17	63	248	1,361	3,004
Average		**38**	**73**	**184**	**3251**	**2420**
Cb	East	40	73	357	3,791	1,988
	South	17	57	272	1,415	2,245
	North	33	83	246	2,600	4,003
Average		**30**	**71**	**292**	**2602**	**2745**
Cc	East	37	93	512	2,988	2,624
	South	40	87	346	2,124	2,947
	North	63	120	335	4,715	4,401
Average		**47**	**100**	**398**	**3276**	**3324**
Cd	East	33	70	379	2,594	1,684
	South	47	70	148	3,517	1,772
	North	20	90	394	1,450	4,037
Average		**33**	**77**	**307**	**2520**	**2498**
X	East	30	67	297	2,919	1,789
	South	50	73	390	4,857	1,524
	North	27	67	320	2,307	3,055
Average		**36**	**69**	**336**	**3361**	**2123**

(bf/ac) – board feet, international ¼” log scale

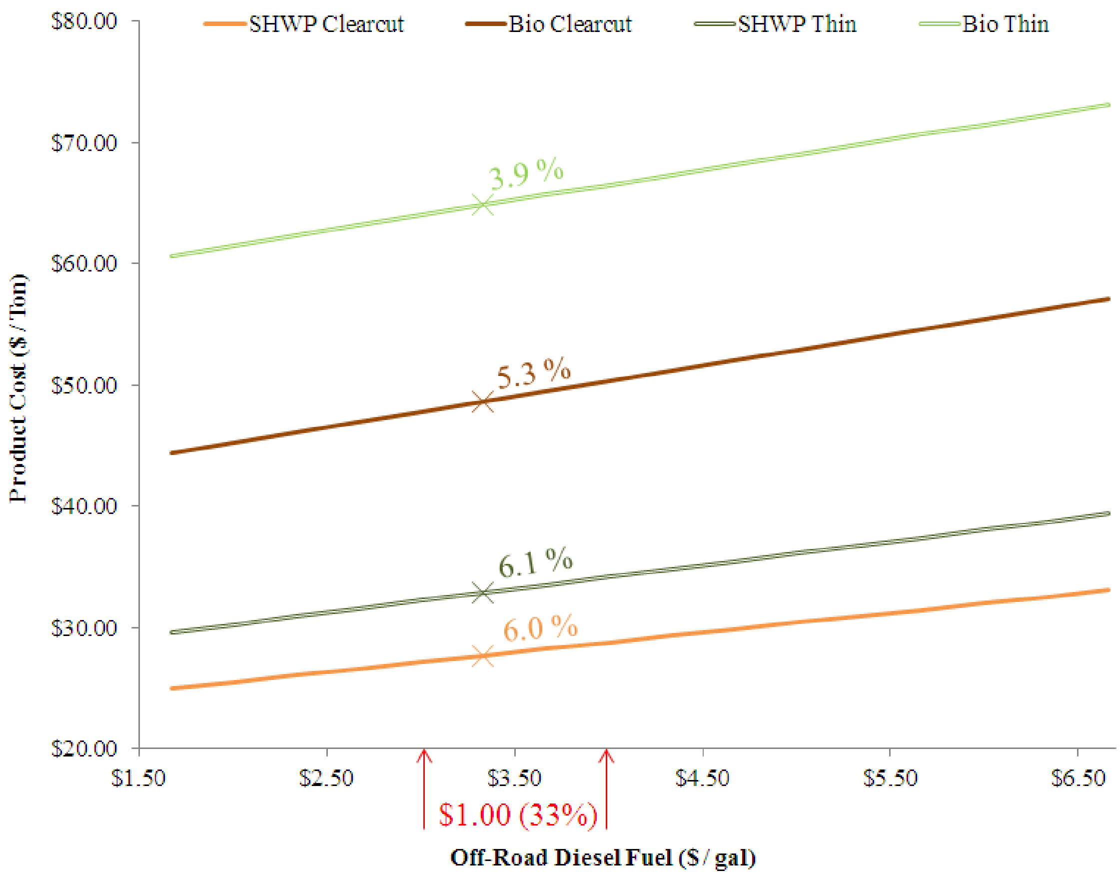

Figure 11. Alternative sensitivity analysis: scenario showing effect of $1.00 (increase from $3.00 to $4.00) change in off-road diesel cost on average production cost for SHWP and biomass products on each silvicultural treatment.

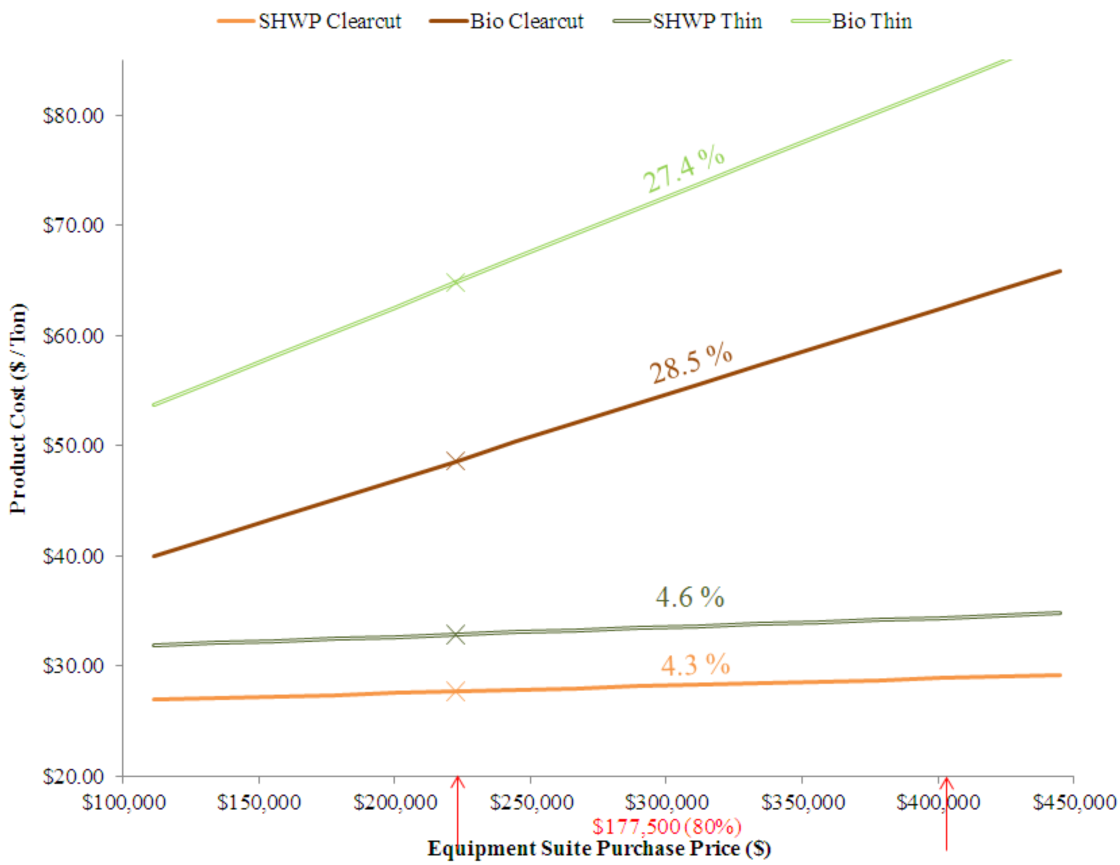

Figure 12. Alternative sensitivity analysis: scenario showing effect of $178,000 (increase from $222,500 to $400,500) change in equipment suite purchase price on average production cost for SHWP and biomass products on each silvicultural treatment.

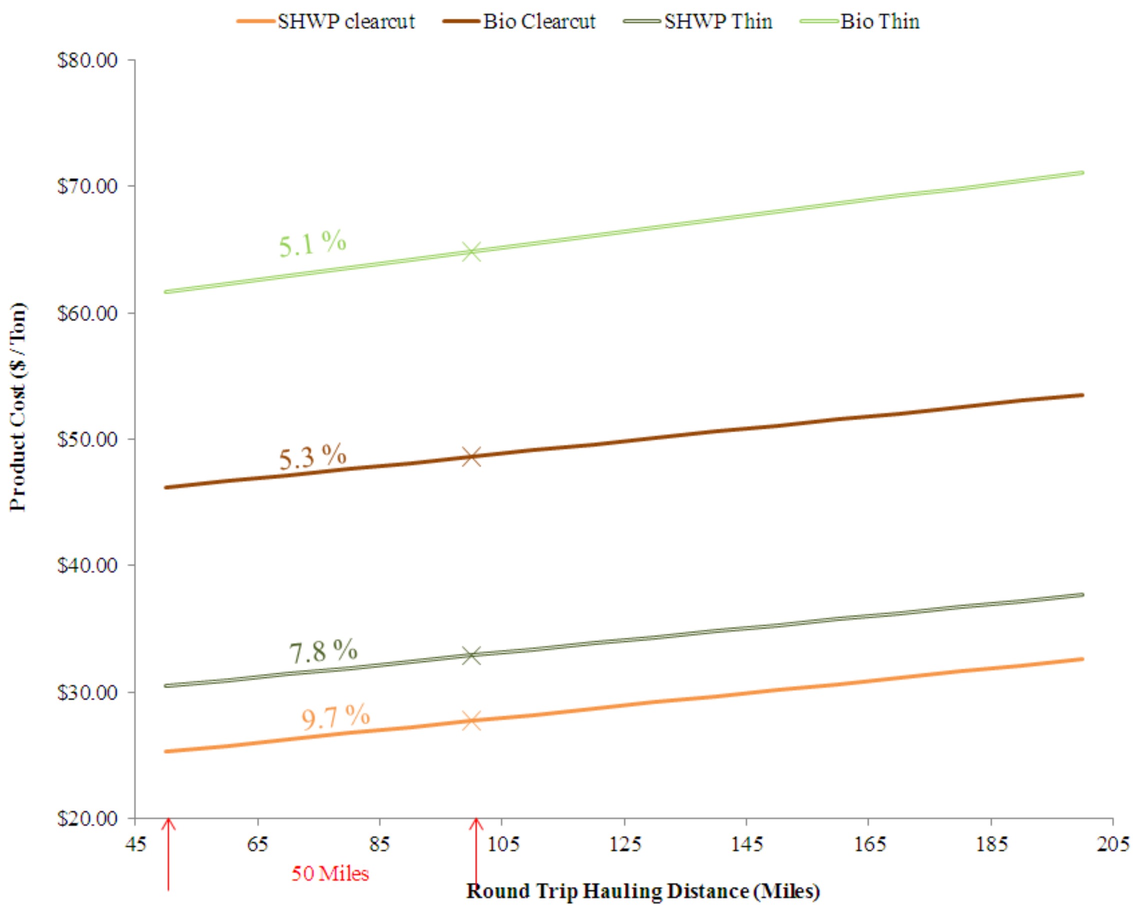

Figure 13. Alternative sensitivity analysis: scenario showing effect of 50 mile (increase from 50 to 100 miles) increase in round trip haul distance on average production cost for SHWP and biomass products on each silvicultural treatment.