EVALUATION OF SHORT ROTATION WOODY CROP HARVESTING SYSTEMS FOR BIOENERGY FEEDSTOCK PRODUCTION

By

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ABSTRACT

EVALUATION OF SHORT ROTATION WOODY CROP HARVESTING SYSTEMS FOR BIOENERGY FEEDSTOCK PRODUCTION

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As the utilization of woody biomass from short rotation woody crop (SRWC) plantations increases as a stationary fossil-fuel alternative, it is imperative that lesser-known harvesting avenues be explored. With specific focus on the ground-based whole-tree traditional harvesting system (traditional system) and the tractor-pulled cut-and-chip reconfigured forage harvesting system (reconfigured system), this study aimed to: (1) conduct system evaluations of both harvesting systems operating in SRWC stands, (2) conduct an economic analysis, and (3) conduct a life cycle assessment (LCA) to determine the total global warming (GWP) and eutrophication (Eutr.) potential of both systems. Results were produced from time-and-motions analysis, time trials, in-field data, and simulation. System evaluation results demonstrated a production rate, cost, and machine hourly rate of 9.7-39.1 oven dry tons/productive machine hour (ODT/PMH), $20.23/ODT, and $283.6/scheduled machine hour (SMH), respectively, for the traditional system, and 1.7 ODT/PMH, $81.17/ODT, and $141.10/SMH for the reconfigured system, respectively. The economic analysis demonstrated the traditional system could breakeven more practically than the reconfigured system through feasible labor optimization and stand initiation simulations. The LCA determined that either harvesting system could be utilized for feedstock production due to inconsequential Eutr. contributions, and net negative GWP contributions, due to carbon sequestration, throughout the entire supply chain.

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KEY TO ABBREVIATIONS

AC: Acre

ALCA: Attributional Life Cycle Assessment

BTU: British Thermal Unit

CLCA: Consequential Life Cycle Assessment

CNH: Case New Holland

DBH: diameter at breast height

FBIC: Forest Biomass Innovation Center

HHV: higher heating value

HL: heat loss

ISO: International Standards Organization

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

MC: moisture content

ODT: oven dry ton

PMH: productive machine hour

Reconfigured system: tractor-pulled cut-and-chip reconfigured forage harvesting system

RHV: recoverable heating value

SMH: scheduled machine hour

SRWC: short rotation woody crop

SUNY: State University of New York

TPA: trees per acre

Traditional system: traditional ground-based whole-tree harvesting system

U.S.: United States

TRC: Tree Research Center

Yr: year

1. INTRODUCTION

1.1. Woody Biomass Utilization in the United States

In order to combat the effects of climate change, there has been significant interest in utilizing alternative energy sources that produce less greenhouse gas emissions. The diversity of organic materials utilized as renewable energy sources can vary greatly, and include products such as: municipal wastes, forest and agricultural residues, agro-industrial by-products, and dedicated biomass crops (Djomo, Kasmioui et al. 2011). As the fourth largest energy source worldwide, with approximately 65% of the worlds primary energy consumption, woody biomass has the potential to play a significant roll in meeting increasing energy demands while reducing produced greenhouse gas emissions (Chang, Zhao et al. 2012, lauri, Havlik et al. 2014). Having a carbon neutral status, high abundance, and unique feedstock advantages allow woody biomass to be converted in to fuels and chemicals using thermo-chemical and biochemical processes.

In 2011 the United States Forest Service conducted The Billion Ton Study to determine if the U.S. would have the availability to produce at least one billion dry tons of sustainable biomass annually for industrial production of renewable energy. This was to be done without burdening the farm and forest industry that produce food, feed, and fiber crops. Estimates from this report indicate that the United States (U.S.) has sufficient resources to reach this goal. Baseline estimates suggest that forest resources will account for approximately 40% of all produced biomass energy, come 2017 (Perlack et al. 2005). As a result, much interest has been growing around the use of woody biomass for fuel. The lake states and northern regions of the U.S., in particular, were among the first to research the cultivation and utilization of woody biomass for fuel, starting in the late 1980's (Volk, Verwijst et al. 2004). Nearly 30 years later, these areas of the U.S. are still leading the country in woody biomass innovations.

Centralized around Michigan, the Lakes States region of the U.S. will play an increasingly important role in providing woody biomass for bioenergy for the entire county. With approximately 19.7 million acres of forestland, Michigan can currently provide about 4.5 million dry tons of woody biomass feedstock on an annual basis (Michigan DNRE 2009). With more than 1,400 forest products manufacturing facilities, Michigan has a rich history of wood product utilization that can provide the framework to develop, and subsequently lead, the development woody bioenergy production systems within the country.

1.2. Increasing the Competitiveness of Woody Biomass

When used for fuel, woody biomass is known as a bio-fuel, and will generally have an energy content (higher heating value) between 4,300-5,160 BTUs/lb. when utilized without any additional chemical upgrading procedures (Tumuluru, Sokhansanj et al. 2011). Bituminous coal, by comparison, can contain as much as 14,190 BTUs/lb. (Coe, 2005). As a result, chemical upgrading procedures are often utilized to increase the higher heating (HHV) value of woody biomass to better compete with the traditional fuel sources they were intended to supplement and replace. Some common chemical conversion techniques to increase the per-unit energy of woody biomass include torrefaction, pyrolysis, and gasification. These three conversion techniques are either anaerobic thermo-chemical processes, or utilize minimal amount of oxygen. These treatments are generally done within temperature ranges of 200-400°C, 400-700°C and >700°C for torrefaction, pyrolysis, and gasification, respectively (Mohan, Pittman et al. 2006, Saffron and Li 2011). Following chemical upgrading procedures, biofuels derived from woody biomass can attain energy densities ranging from 8600-12900 BTUs/lb. (van der Stelt, Gerhauser et al. 2008, Tumuluru, Wright et al. 2010, Tumuluru, Sokhansanj et al. 2011). Upgraded woody biomass biofuels are, therefore, considered to compare favorably with coal on a per-unit energy basis (Mohan, Pittman et al. 2006) At a produced and delivered cost between \$3.16-3.75MM BTU^{-1} for managed and natural timer forest residues, though, the utilization of chipped or ground woody biomass has been hindered due to the current cost to produce coal and other stationary fossil fuel products, which can be as low as \$1.37MM BTU^{-1} (Tharakan, Volk et al. 2005, Centofanti 2014). Because of this disproportionate difference, it was considered imperative to develop a more cost effective feedstock that could be produced in a manner that better competed with other stationary fossil fuel products.

1.2.1. Short Rotation Woody Biomass Crops

In the mid 1980's the State University of New York (SUNY) began to research and utilize woody biomass crops in the U.S. for bioenergy generation with a specific focus on increases in the per-unit volume of planted biomass species. By increasing the amount of biomass grown in a given area, and utilizing quickly accumulating woody species, product yields can theoretically increase. These efforts have been apportioned to what is known as short rotation woody crops (SRWC). These crops are often grown on open or fallow agriculture land in a dense double-row style to facilitate the use of agricultural style harvesting equipment (Volk, Verwijst et al. 2004). Within the Lake States and Northeastern U.S., poplar (*populus* species), willow (*salix* species), and their respective hybrids have, in particular, been deemed to be good woody crops due to several favorable characteristics, including: high yield after only a few years of cultivation, a short breeding cycle, a large genetic base, and the ability to coppice (Volk, Verwijst et al. 2004). These crops are also generally genetically modified to further increase yield per-unit acre.

Salix species are of an early successional type tree that grow vigorously following colonization, and are known to display rapid phenotypic changes in shoot morphology as a response to intensive management (Willebrand, Ledin et al. 1993). The most popular *Salix* subgenus has primarily been *Caprisalix* Vetrix. Willow stems are generally coppiced on a 3-4 year cycle (resulting in very small DBH stems), and can last upwards of 30 years if well managed. Coppicing has been shown to remove apical dominance and allows for rapid canopy development, thereby inhibiting competition related to primary succession and allowing for increased biomass yields (Koeleian and Volk 2005). Similar to willow, *populus* species demonstrate many phenotypic characteristics that make them terrific woody biomass crops. Having had its complete genome sequenced, new poplar clones have recently been introduced that are optimized for biofuel production. Poplars are among the fastest growing trees in North America, and display high levels of drought and pest resistance. The most popular poplar subgenus include: *Populus deltoides, Populus balsamifera,* and *Populus trichocarpa.*

1.2.2. Harvesting Systems Utilized to Produce Woody Biomass from SRWC Stands

In order to efficiently harvest SRWC, machinery known as reconfigured forage harvesting equipment has been recently designed and implemented by universities and companies throughout the U.S. and Europe coinciding with woody biomass crops research. This equipment is also commonly known as cut-and-chip harvesting equipment because they simultaneously sever tree stems and produce a chipped biomass product in one concurrent step. These harvesters can be self-propelled units, or can come in tractor-pulled variations. While some type of harvesting unit is always included, the complete reconfigured forage harvesting system does not consist of a specific set of machinery. Largely, though, this relatively new system employs at least two pieces of equipment for the self-propelled variety, and three pieces of equipment for the tractor-pulled variety. The tractor-pulled harvesting system will generally employ a tractor with an attached harvester, and a separate chip collector to collect biomass directly as it is produced in the field. This chip collector generally consists of a large mobile bin attached to a tractor with durable wheels. The self-propelled system, on the other hand, foregoes the need to attach a harvester because it is built-in.

Extensive work from SUNY and Case New Holland (CNH) has been allocated in to designing and testing the productivity of a recent CNH self-propelled forage harvester. This harvester (the FR-9000 series forage harvester with attached 130 FB Coppice Header) has been shown to be highly productive when utilized in SRWC plantations with long straight rows of trees typically less than 5 inches in diameter (Keefe, Anderson et al. 2014). This system is not yet widely used, though, because it is expensive to buy, and current demand for the woody feedstock it produces is fairly low to warrant the upfront capital cost of over $450,000 (Ehlert and Pecenka 2013; Hartsough and Stokes 1997). Tractor-pulled forage harvesters, on the other hand, are generally much cheaper to purchase (between approximately $50,000-$100,000), but suffer from a lack of sound productivity estimates produced by trustworthy scientific communities. These harvesters are also relatively unknown within the American market. Ny Vraa, a very popular tractor-pulled forage harvester manufacturer, for example, has units in the U.S. that number under 10 total. As a result, farming communities who have access to large tracts of reserve fallow land and readily available tractors for easy system implementation have, therefore, largely been excluded from SRWC harvesting.

In order to simultaneously gain confidence and demonstrate the ability of the tractor-pulled reconfigured forage harvesting system (reconfigured forage harvesting system), further investigations must be made in to their performance and productivity as a harvesting tool. If conclusive, the utilization of woody biomass produced in dedicated SRWC plantations by expensive highly specialized machinery could expand to encompass many more stakeholders. Adjoining these inquiries, investigations pertaining to the performance of other harvesting systems operating in SRWC plantations must be made to determine if the benefit sought from reconfigured systems, in general, are warranted. Machinery such as the “traditional whole-tree ground-based harvesting system”, common to the logging industry within the Lake States region, has been shown to effectively harvest SRWC as needed but has yet to be evaluated for productivity and cost.

Although generally reserved for larger sized boles, the dominant harvesting system utilized in the lake states region is the traditional whole-tree ground-based harvesting system (traditional harvesting system). While not necessarily designed to harvest woody biomass, this machinery has been employed to produce pulpwood in the lakes states region for many years. The traditional system utilizes a mechanized feller-buncher to sever and accumulate woody stems in to piles, a grapple skidder to collect and transport bunched biomass piles to a general landing location, a loader to manipulate biomass at the landing, a grinder or chipper to increase biomass bulk density, and a chip van to transport chipped/ground woody biomass to a conversion facility (Conway 1979; Nurminen et al. 2006).

Due to its pervasiveness throughout the Lakes States region, investigation in to the performance of the traditional system operating in SRWC stands must be conducted. Being the established and dominant system in the area means forgoing the upfront capital required to start producing woody biomass. While its productivity as a harvesting tool may not fair with that of the newer reconfigured forage harvesting systems, the traditional system will be considered a worthy biomass harvesting alternative if a profit can be generated.

Through analyses of production and cost for the tractor-pulled reconfigured forage harvesting system and the traditional system, a context of the true feasibility and necessity will be provided for self-propelled reconfigured forage harvesting equipment. Moreover, documentation of complete energy output ratios, resource requirements, and the environmental loading associated with their production of woody biomass are required to understand their impact on the environment and will, thus, further scrutinize their potential as harvesting tools. As interest in the utilization of woody biomass feedstock increases with concerns over the environmental impacts associated with atmospheric carbon dioxide, it is imperative to fully understand these system dynamics.

1.3. Problem Statement

As the utilization of woody biomass from SRWC plantations increases as a stationary fossil fuel alternative, it is imperative that lesser-known harvesting avenues be explored to increase stakeholder participation and simultaneously scrutinize the necessity of expensive established harvesting systems.

1.4. Project Objectives

Based upon the provided background and the suggested gaps in knowledge, the general goals of this research are to conduct system evaluations, economic analyses, and to investigate the environmental impacts associated with woody biomass production from SRWC plantations for the traditional ground-based and tractor-pulled cut-and-chip reconfigured forage harvesting systems.

Specific objectives of this project include: (1) conduct system evaluations on the traditional ground-based harvesting system and tractor-pulled cut-and-chip reconfigured forage harvesting system operating in SRWC stands to produce woody biomass feedstock, based on: machine productivity, cost, and fuel ratios, (2) conduct an economic analysis through: scenario-based breakeven estimation, benefit-cost analyses, and predictive hedonic regression for both harvesting systems and their encompassing supply chain from stand initiation through biomass combustion, and (3) conduct a life cycle assessment (LCA) to determine the total global warming and eutrophication potential of producing woody biomass from both the traditional harvesting system and reconfigured forage harvesting system, with a system boundary of stand initiation through biomass combustion.

The outcome of this research is to, therefore, provide the scientific community with greater understanding of how short rotation woody crop harvesting methods can be expanded from the utilization of large, expensive, and highly specific machinery to a system easily implementable by Lakes States logging and farming communities. Ultimately, the results developed in this study can be used by natural resource managers, loggers, farmers, and landowners to guide the decision making process in how to best produce woody biomass from bioenergy crop plantations. This research was designed to facilitate the promotion and utilization of woody biomass as an energy alternative source by exploring its accessibility to potential stakeholders who have much to gain from short rotation woody crop harvesting. Research findings were designed for utilization within the Lakes States and Northwestern regions of the U.S.

2. LITERATURE REVIEW

2.1. Overview

This literature review provides in-depth background information required to understand and scientifically assess the research objectives. Detailed gaps in literature will be presented throughout the review, which will simultaneously validate and provide justification for the identified research objectives. The first section of the literature review describes the steps that encompass an optimized woody biomass supply chain operating in a short rotation woody crop plantation for bioenergy generation. Although circumstantial, this section demonstrates the framework required of all the analyzed harvesting systems to produce woody biomass from short rotation woody crops. Chosen harvesting systems for review include: the traditional harvesting system, the tractor-pulled cut-and-chip forage harvesting system, and the self-propelled cut-and-chip forage harvesting system. Next, known inputs related to harvesting and cost efficiencies of both the traditional and reconfigured harvesting systems to produce woody biomass are discussed. Based upon the previously identified steps required for an optimized supply chain, gaps of understanding will be presented that need to be addressed in order for confidence in utilization of the traditional and tractor-pulled reconfigured forage harvesting systems to be gained by potential stakeholders. Finally, the net-energy requirements, resource requirements, and environmental stressors associated with the production of woody biomass through limited-scope life cycle analyses are discussed for both the traditional and reconfigured forage harvesting system. Likewise in previous sections, gaps in understanding will be addressed to further support the identified thesis objectives.

2.2. The Woody Biomass Supply Chain in Short Rotation Woody Crop Plantation

The term *woody biomass supply chain* has been derived from Mentzer's definition for *supply chain management*, which is:

> "A set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer" (Mentzer et al. 2001, *Defining Supply Chain Management*).

The woody biomass supply chain is concerned with optimizing all supply chain management logistics specifically for producing woody biomass for fuel. This term is, therefore, an applied extension of the definition provided by Mentzer. While applicable to any product that holds a distinct supply chain, the woody biomass supply chain is critically concerned with optimizing all involved logistics to the greatest degree possible because the combined logistics of producing woody biomass can exceed the delivered value by a substantial margin (Keefe, Anderson et al. 2014, Miller 2014).

In general, the woody biomass supply chain consists of four parts (Figure 1), including: timber collection, processing, storage, and transportation (Han, Lee et al. 2004). Timber collection can further be broken down into harvesting and extraction, processing includes either chipping or grinding, while storage and transportation are stand-alone components within the system. The system of machines required to harvest and extract timber are together known as the timber harvesting system. Depending on the specific machinery being utilized, two or more of the listed steps can be combined or reduced, thereby producing a more efficient harvesting system when compared to a system that has more distinct steps. An optimized woody biomass supply chain focuses on managing these components in the most logical way possible so that biomass can be supplied in a cost effective, efficient, environmentally sound, and socially acceptable manner.

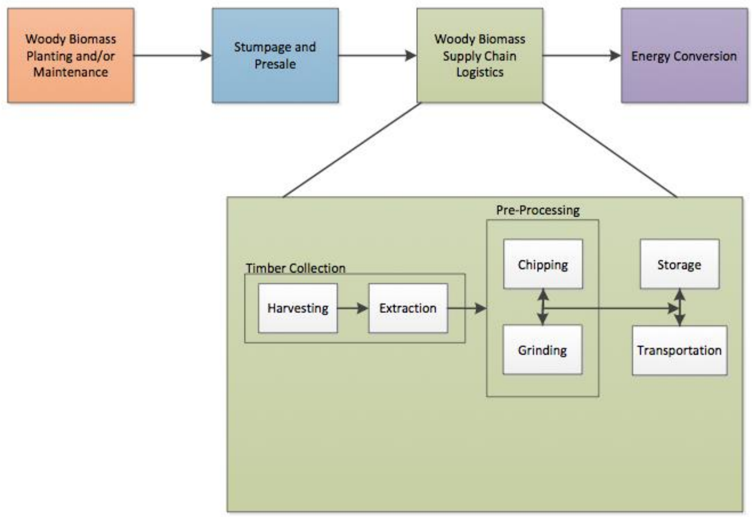

Figure 1: Systems flow diagram for the woody biomass supply chain.

Through the use of short rotation woody crops, the logistic steps involved with timber collection and processing becomes theoretically maximized when compared to that of a natural stand due to increased biomass yield per-unit acre. Genetic modification of biomass accumulation rates aside, SRWC plantations allow biomass to be produced with minimal harvesting and extraction movement, and the incredibly dense spacing between stems make processing easier than traditional forest stands. (Volk, Verwijst et al. 2004, Miller and Bender 2014).

2.2.1. The traditional harvesting system operating in a SRWC plantation

The traditional ground-based harvesting system to produce woody biomass from a SRWC plantation must involve the utilization of a feller-buncher, a grapple skidder, a log loader, a grinder or chipper, and at least one chip chip van. The feller-buncher is known as dual-function machine because it can fell trees and also “bunch” them in to piles. The machine’s cutting head is generally hydraulically powered and may have a few different types of blades equipped, including double action shears or a guillotine shear. Felling head types often include the double post, full wrist, or pocket size varieties. No matter what type of blade is equipped, though, it will be mounted on a knuckle boom to provide for length and mobility when cutting. Movement of the boom can occur both vertically and laterally. In a similar fashion, the grapple skidder will utilize a hydraulically powered grapple attached to a boom to pick-up and subsequently drag biomass stems to a landing location. The boom on a skidder is slightly different from a feller-buncher, though, in that it’s movement is fixed vertically, perpendicular to the ground.

The log loader functions in a manner similar to both the feller-buncher in that it utilizes a grapple to manipulate woody stems, which can swivel both vertically and laterally. The loader is generally much larger than a feller-buncher, though, and, thus, is more productive so that pace can be kept with an industrial grinder or chipper. Chippers are machines that utilize sharp knives mounted on a rotating disk or plate to cut and slice wood in to smaller pieces, while grinders are machines that utilize blunt hammers attached to a rapidly rotating drum to smash wood in to smaller pieces (Spinelli, Cavallo et al. 2011). Grinders are often used on woody material that has been contaminated during the harvesting or storage process with a high amount of dirt, stones, metal, or other inconsistent material, while chippers are often used on woody material that is relatively clean (Goldstein and Diaz 2010, Spinelli, Ivorra et al. 2011). In general, though, the chipper can be thought of as a more effective tool to produce biomass in a manner that utilizes less energy, is more productive, and provides a product that is more suitable for most energy conversion facilities (Strehler 2000, Spinelli, Cavallo et al. 2011). Although potentially limited in highly productive logistics, the optimized traditional harvesting system can undoubtedly produce woody biomass from short rotation woody crops. The steps required of the traditional harvesting system in its optimized form to collect and process woody biomass from a SRWC plantation is described below, in Figure 2**,** Figure 3**,** and Figure 4. Specifically, the step-by-step process of feller-buncher operation is described in Figure 2, while skidding steps are described in Figure 3, and biomass processing via loading and grinding/chipping is described in Figure 4. Detailed feller-buncher operations activities are described below:

- Step 1: The feller-buncher operator will approach a nearby stem within the biomass plantation by simultaneously driving the machine's tracks while extending its knuckle boom and attached cutting head (also known as a hot saw, in this case) in preparation to sever a live tree.
- Step 2: The feller-buncher operator will open the hot saw cutting shears, thereby prompting the saw to activate, where the targeted tree will be severed and retained within the saw. Two separate sets of shear arms ensure that the cut stem(s) remain in place by opening and closing individually. The operator will generally continue to cut stems until the saw's capacity has been met.
- Step 3: Following capacity of the hot saw, the feller-buncher will have made a full "bunch". The bunched trees will be placed on the ground to be subsequently skidded. Piles will generally be large enough to reach capacity of the skidders grapple, thereby

increasing system efficiency. Because SRWC stems are quite small, the feller-buncher may need to place numerous bunches in to a single pile.

- Step 4: The feller-buncher will repeat the process until the stand is clearcut. Because woody biomass boles are not merchantable and can be coppiced, there is largely no need to selectively harvest a SRWC stand to manage for increased stem diameter.

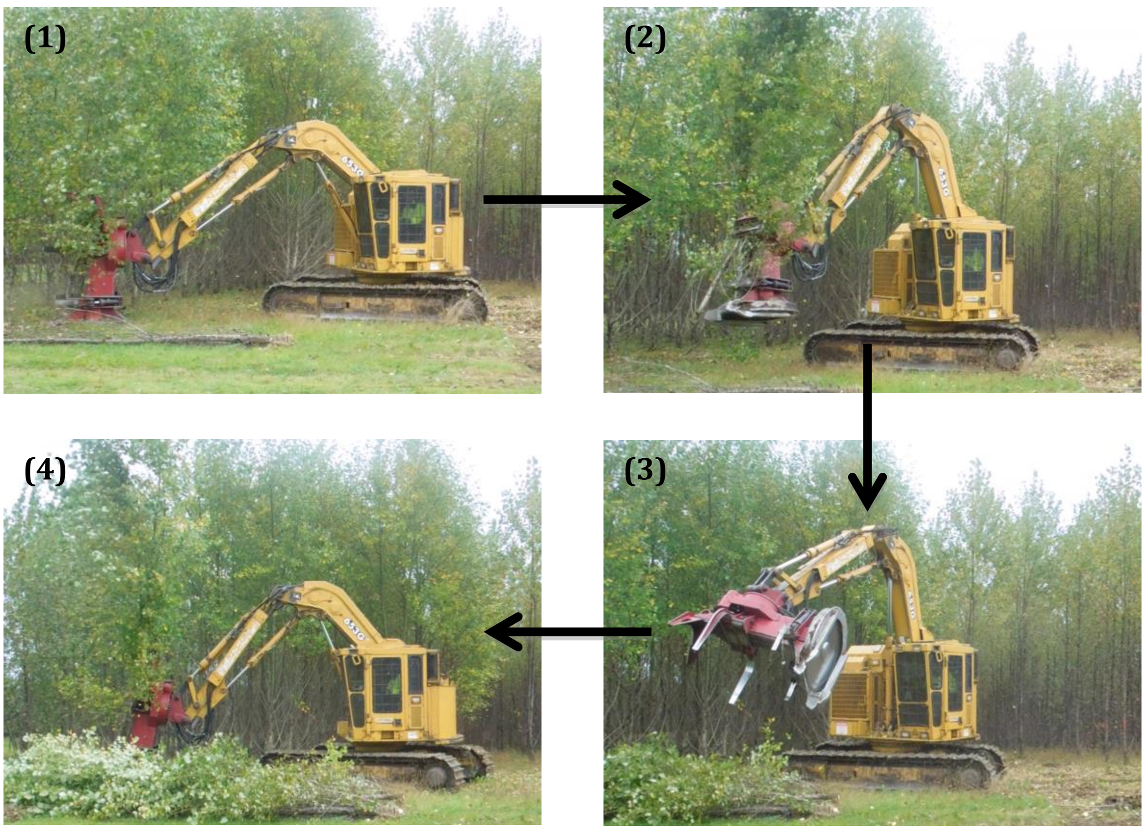

Figure 2: Feller-buncher operations activities for harvesting SRWC.

Coinciding with the availability of bunched stems, the skidder will commence operations. Skidding can occur simultaneously with the feller-buncher or after it has completed harvesting. Ultimately, the skidders objective is to extract piled biomass for subsequent processing by the mobility-limited loader and chipper/grinder:

- Step 1: Starting at the landing location, the grapple skidder will approach a bunched biomass pile accrued by the feller-buncher and situate nearby the severed end of the stems.
- Step 2: The skidder operator will employ the hydraulic grapple arm to grab the piled stems for subsequent transport. The piled biomass is easier to manipulate and drag along the ground when branches agree with the direction of skidder movement.
- Step 3: The skidder brings the grappled biomass to the landing location housing the log loader and chipper/grinder. The skidder operator will place the biomass near the loader for ease of manipulation and increased efficiency.
- Step 4: The skidder will repeat the process by approaching another pile of biomass and subsequently supplying the log loader until the site is completely clear.

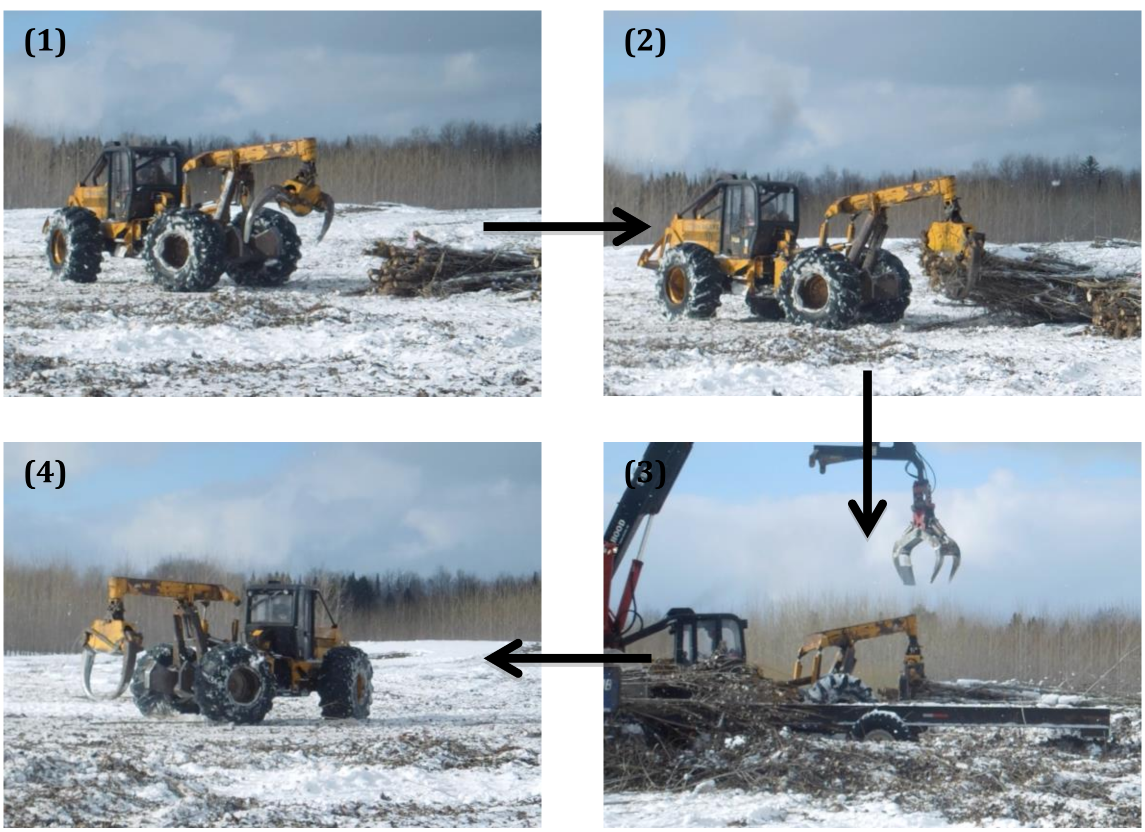

Figure 3: Grapple skidder operations activities for harvesting SRWC.

While extraction of woody stems is occurring with the skidder, subsequent loading and chipping/grinding will coincide simultaneously to further increase system efficiency. The sole purpose of the log loader is to supply the chipper or grinder with biomass for processing to ultimately increase bulk density for transportation and energy conversion. In the case presented below, a grinder was utilized (Figure 4). Alternatively, loading and grinding/chipping can occur after all the stems have been skidded. This method operation generally does not occur, though, due to often having a space-limited landing size, and the low level of maneuverability associated with the loader and grinder/chipper. The steps for the loader-grinder unit are as follows:

- Step 1: Following placement of biomass at the landing by the skidder, the log loader will utilize its boom arm to grapple woody biomass stems for processing
- Step 2: The log loader operator will maneuver the grappled biomass stems and situate them in the grinder/chippers feed conveyor to be processed. In this case, a grinder is being utilized.
- Step 3: The biomass will be processed by the grinder/chipper for increased bulk density. The biomass will subsequently be fed in to a chip van for transportation.
- Step 4: The loader continues to feed the chipper/grinder until the chip van is full. The chip van will subsequently travel to the energy conversion facility where payment for the biomass and services are received. Chip vans will continue to be supplied until all of the biomass has been processed.

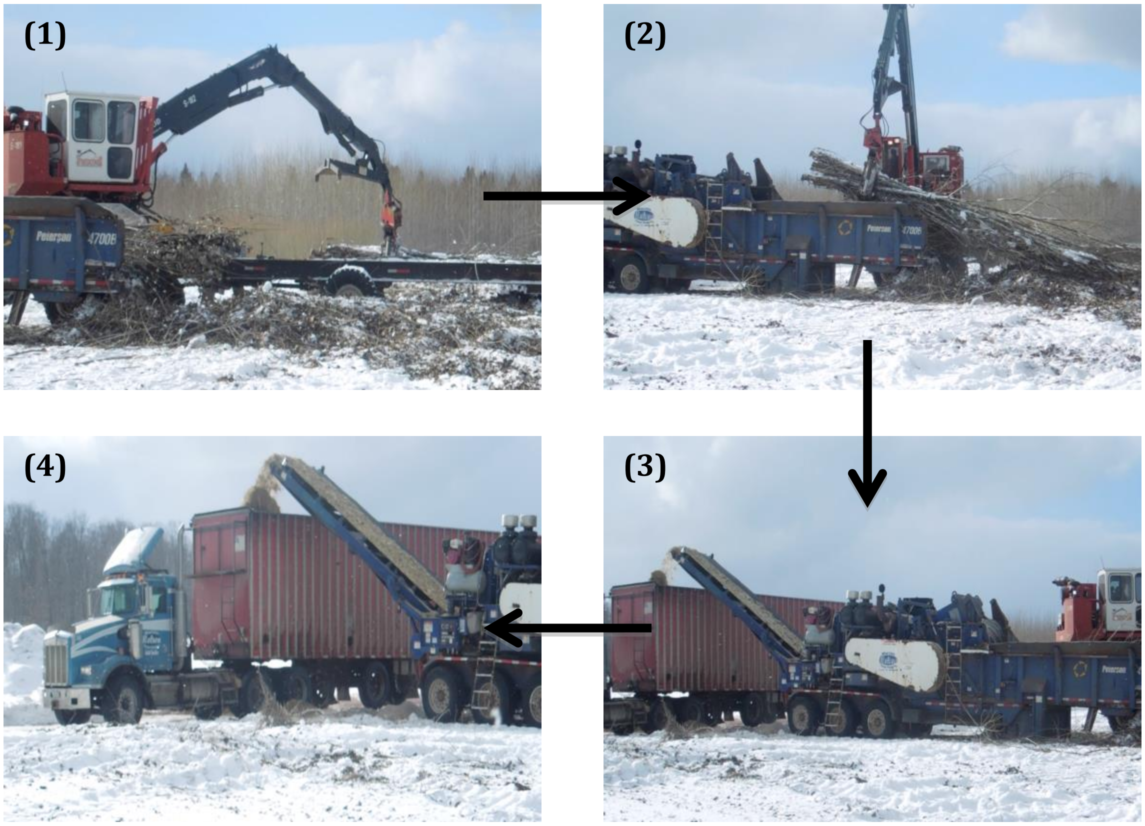

Figure 4: Loading and grinding operations activities for harvesting SRWC.

2.2.1.1. Literature Gaps of a Traditional System Operating in a SRWC Plantation

While it is evident that woody biomass from a SRWC plantation can be supplied by the traditional harvesting system, studies have yet to determine system efficiencies and resulting costs associated with this type of biomass production. Because the feller-buncher was not designed to manipulate woody stems at or around 4 inches DBH, logistic system bottlenecking may occur during the operation. Often times, to reduce the number of logistic steps involved with the harvest, a logging firm will operate in a “hot system”, where felling, skidding, and processing occur simultaneously in one concurrent step. With a relatively high production rate upwards of 500 yards^3 per hour that is unaffected by stem diameter, the grinding/chipping unit may be left idling while biomass is being brought to the landing location (Goldstein and Diaz 2010). In order to make up for any deficit in productivity, the logger would subsequently be forced to increase the number of employed operators working at the plantation. An increased workforce, as well as more simultaneously operating machines, will ultimately decrease the competitiveness of the traditional system in woody biomass feedstock production. As a result, it is imperative that productivity and cost estimates be provided through scientific literature so that stakeholders can better understand logistic management strategies required of the traditional harvesting system operating in SRWC plantations.

2.2.2. The reconfigured forage harvesting system operating in a SRWC plantation

The following two sections (sections 2.2.2.1 and 2.2.2.2) provide in-depth information pertaining to the tractor-pulled and self-propelled forage harvesting systems. Both systems are of the “cut-and-chip” variety, meaning they harvest woody biomass stems and subsequently chip them in one logistical step, with one machine. Because of this, the reconfigured forage harvesting system utilizes fewer steps than the traditional system to produce a chipped biomass product. The difference between both reconfigured system varieties, though, lies in how the harvester cutting-unit is powered: either through an attachment to a tractor drive shaft for the tractor-pulled system, or through hydraulically driven saw blades for the self-propelled system. Most companies who design and produce reconfigured forage harvesters (Ny Vraa, CNH, Claas) do so in a way where the harvester saw blades cut biomass grown in a double-row configuration, like other the traditional row crop harvesting systems these machines were designed around, such as corn and sugarcane.

2.2.2.1. The tractor-pulled reconfigured forage-harvesting system

The tractor-pulled reconfigured forage harvesting system utilizes a tractor, an attached harvesting unit, a chip collection unit, and at least one chip van to produce woody biomass. Depending on the productivity of the attached harvester and size of the SRWC plantation, the amount of active chip collection units and vans will be adjusted accordingly to keep pace with the harvester, lest a drop in productivity will occur. Figure 5shows a tractor-pulled cut-and-chip harvesting unit produced by Ny Vraa (JF 192 model) in detail. This particular unit was originally built to harvest sugarcane, but was subsequently modified to harvest small-diameter woody stems. As such, this particular unit was manufactured in Brazil by JF Maquinas for sugarcane production, and was subsequently modified in Denmark by Ny Vraa to handle SRWC stems (JF Máquinas 2016, Ny Vraa 2016). Modifications to the JF 192 included the addition of an extension side-arm to sit offset of the attached tractor (Figure 5, Savoie et al. 2013). This allows the operator to drive directly beside the woody stems being harvested without running in to them. A hydraulic rotor was also amended to the JF 192 to improve the flow of stems during cutting and chipping (Savoie et al. 2013). As the harvester passes over stems, the front push bar will bend stems over, exposing the bole area to be subsequently severed. Attached to the tractor's drive shaft, the harvesting unit's saw blades sever woody biomass stems approximately 10 inches above their base as the tractor is moving, subsequently drawing the severed stem in to the housing unit with the rotor. Chipping of the bole and limbs occurs with industrial helicoid knives as the tree passes through the rotor until it is completely broken down (Savoie et al. 2014). Chips are then expelled through the top chute to a collection unit of choice. The steps required of the tractor-pulled reconfigured forage-harvesting system in its optimized form to produce woody biomass from a SRWC plantation is described below, accommodated by Figure 6.

Figure 5: JF 192 Ny Vraa harvesting unit attached to a John Deere 7330 tractor.

- Step 1: The tractor/harvester operator and chip collection operator will approach one corner of the SRWC plantation with their respective equipment. The chip collection operator will be stationed behind the harvester for the duration of the operation to collect woody biomass as it is produced.
- Step 2: The harvester and chip van will travel at the same designated speed to harvest woody stems, produce biomass chips, and subsequently collect them. In this case the chip collection unit is very small, for research purposes. It is likely not representative of a commercial-scale chip collection unit.
- Step 3: The harvester and chip van will continue down the first lane of the stand, harvesting one single double-row, until the entire lane has been harvested. The harvesting system will then travel to the opposite end of the plantation, harvesting that entire double-row.

- Step 4: The harvester and chip van will harvest the plantation in concentric circles until the entire stand is gone. The harvester will idle as necessary to allow a filled chip collection unit to switch out for an empty one.

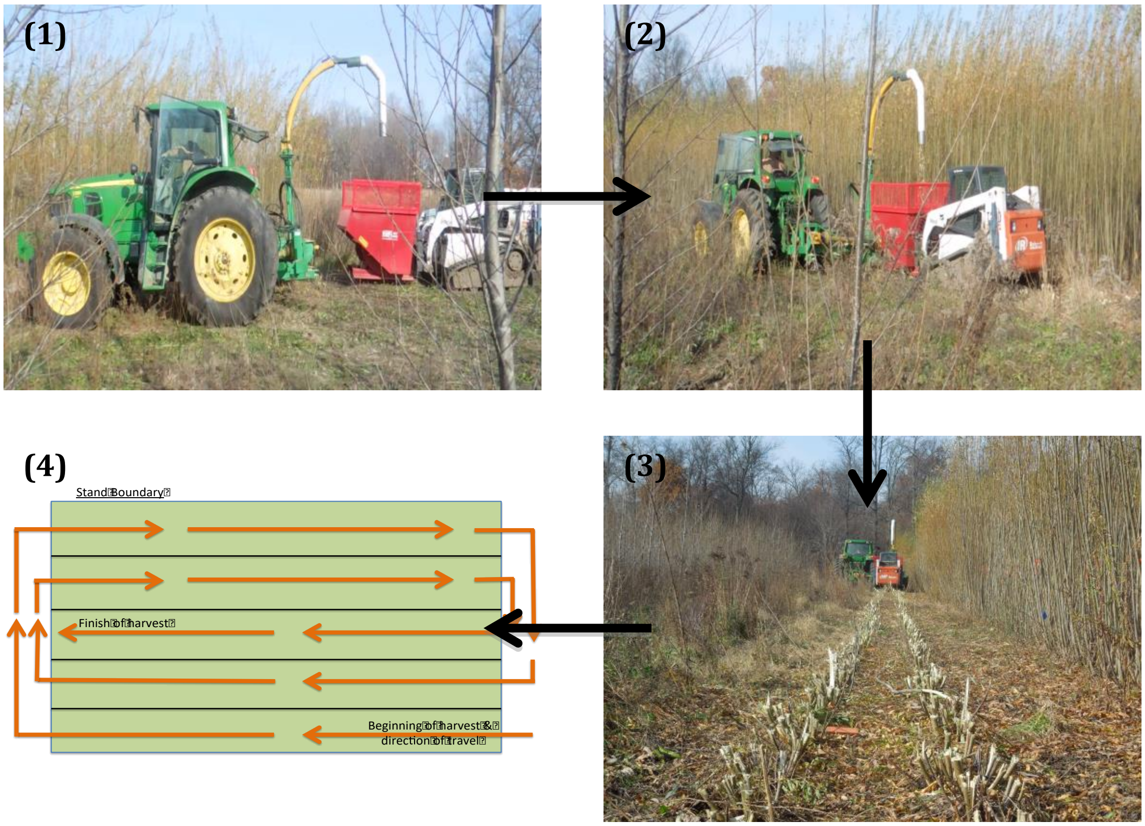

Figure 6: Tractor-pulled cut-and-chip harvesting system operations activities for harvesting SRWC.

Once a chip collection unit has been filled, it will withdraw from the harvesting unit and supply its payload to a chip loader. The chip loader will then fill an idling chip van for subsequent transport to an energy conversion facility. It is possible to reduce the number of machines within the supply chain, here, by having a chip van directly follow the harvesting unit in-field, instead of utilizing a chip collector and chip loader. Largely, though, this does not happen at the commercial-scale because the severed SRWC stems are often very sharp, quickly leading to punctured rubber tires that are unfit for field travel (Mitchell, 2016).

Currently, there has been limited inquiry regarding the productivity and efficiency of utilizing the JF 192 to produce woody biomass feedstock. One particular study stands out, though, documented through the publication of an American Society of Agricultural and Biological Engineering paper by researchers at the Agriculture and Agri-food Canada, and the Département des sols et de génie agroalimentaire from Université Laval (Savoie et al. 2013). Along with productivity information regarding a medium sized pull-type forage harvester, and a novel-designed cutting head, this paper evaluated the working capability of the JF 192 operating in a SRWC willow plantation. Mounted on a 105 hp tractor, the harvester operated at an average continuous harvest capacity of 12.78 wet tons/ PMH (converted from t WM/h) with an efficiency of 78 % as long as the harvested stems were ≤ 1.96 inches. Furthermore, the harvest conditions were considered to be relatively good (Savoie et al. 2013). This particular study did not include production cost ($/ton) or machine hourly rate information ($/SMH). The reliability of production rate information for this particular harvester should, thus, not be considered complete due to the little amount of information that has been provided within the recent body of scientific literature. Further quantitative references within the literature review focus on the medium-sized JF Z200 due to the larger research base with which to draw comparisons.

2.2.2.2. The self-propelled reconfigured forage-harvesting system

The self-propelled reconfigured forage harvesting system utilizes a harvester unit with attached cutting head to cut and produce woody biomass chips as well as at least one chip collection unit and one chip van. Like the tractor-pulled systems, the amount of active chip vans is adjusted accordingly so that pace can be kept with the harvester. A depiction of the harvesting unit can be seen below, in Figure 7. Figure 7 was provided by Eisenbies, Volk et al. (2014b). This particular model, known as the FR9090 with attached 130FB coppice header produced by CNH (referred to as the CNH model), has had extensive amounts of research conducted on it within the Northeastern regions of the U.S. assisted by faculty and staff at SUNY, making it popular within the U.S. marketplace.

Figure 7: Self-propelled reconfigured forage harvesting system (Case New Holland FR9090 harvester with 130FB coppice header).

Unlike the Ny Vraa harvester depicted in Figure 5, the CNH harvester utilizes a cutting head mounted directly in front of the base unit. A heavy-duty push-bar located above the cutting head bends the biomass stems over as the harvester travels down the lane it is currently harvesting. Two counter-rotating high-speed saw blades cut the biomass stems at their base as the harvester travels over them, subsequently chipping the biomass as it passes through the rotating saw blades with attached rotating star wheels. The biomass then passes through a series of paddle feedrolls that force the biomass through the harvester base unit to be expelled out the back through an attached chute.

The steps required of the self-propelled reconfigured forage-harvesting system in its optimized form to produce woody biomass from a SRWC plantation are described below, in

Figure 8. Pictures for figure 8 were provided by Eisenbies, Volk et al. (2014b). The process of harvesting woody biomass for the self-propelled harvester is very similar to that of the tractor-pulled harvester (Figure 6) though productivity values will differ.

- Step 1: The harvester operator and chip van operator will approach one corner of the SRWC plantation with their respective equipment. The chip van operator will be stationed behind or beside the harvester for the duration of the operation to collect woody biomass as it is produced.
- Step 2: The harvester and chip van will travel at the same designated speed to harvest woody stems, produce biomass chips, and subsequently collect them.
- Step 3: The harvester and chip van will continue down the first lane of the stand, harvesting one single double-row, until the entire lane has been harvested. The harvesting system will then travel to the opposite end of the plantation, harvesting that entire double-row.
- Step 4: In a similar fashion to the tractor-pulled harvester, the self-propelled harvester and chip van will harvest the plantation in concentric circles until the entire stand is gone. The harvester will idle as necessary to allow a filled chip van to switch out for an empty one.

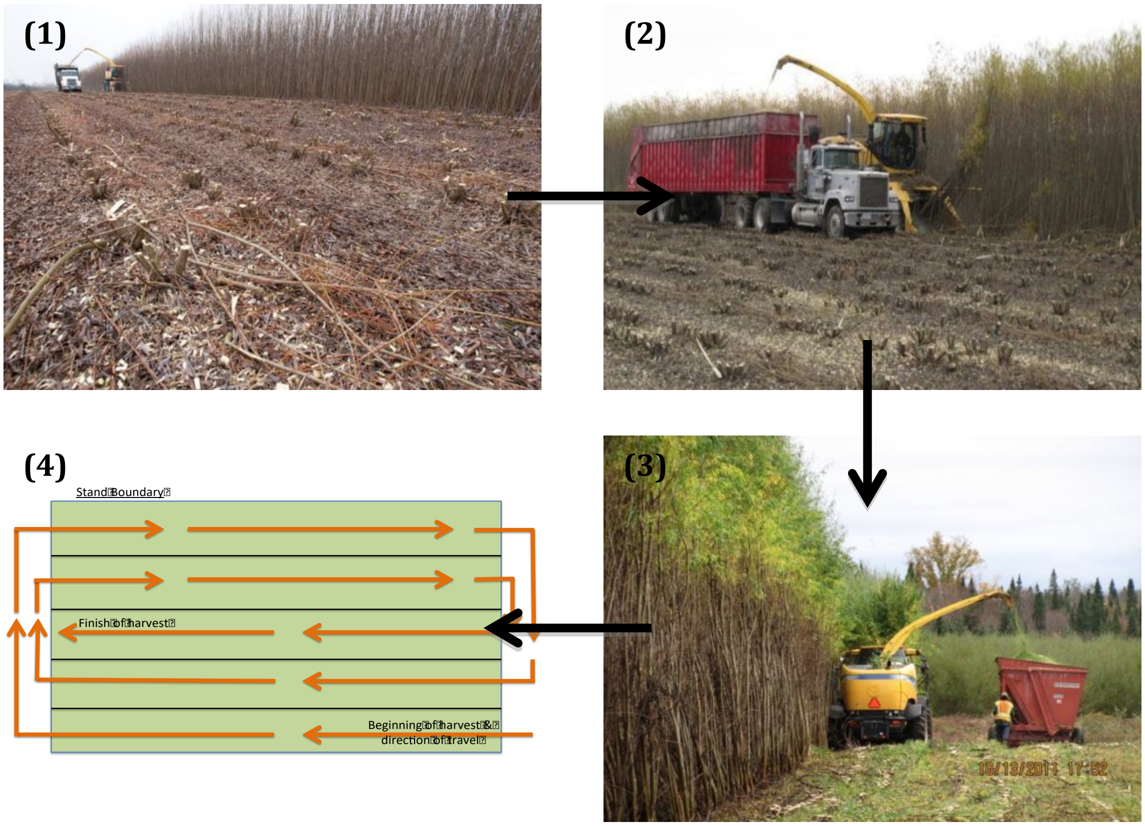

Figure 8: Self-propelled cut-and-chip harvesting system operations activities for harvesting SRWC.

A notable difference between the self-propelled and tractor-pulled cut-and-chip forage harvester operations activities descriptions (Figure 8 and Figure 6, respectively) are the utilization of an in-field chip van. As stated previously, this method of operation is not commonplace, because chip van tires generally cannot handle traveling over severed SRWC stems. The pictures depicted in Figure 8 represent research operations that took place at SUNY and, thus, cannot be considered necessarily representative of a commercial scale operation.

2.3. Tractor-pulled and self-propelled reconfigured forage harvesting system comparison

Tabled information pertaining to cost and productivity for both the tractor-pulled and self-propelled reconfigured forage harvester can be found in Table 1.

Table 1: Cut-and-chip forage harvester comparison information

Harvester Type[a]	Company & Model	Country of make	Upfront Capital Cost ($)	Mach. Lifetime (yr)	Operating/ Ownership Costs (excluding labor) ($/hr)	Maint. Costs ($/hr)	Prod. Cost ($/ODT)	Prod. Rate (ODT/PMH)[b]	Optimal Stem diam. (in)
Tractor-pulled (with tractor)	Ny Vraa & John Deere (JF Z200 & JD 8520)	Denmark, USA	252,000 (52,000)[c]	8	136.9	31.7 (18.2)	47.97	Not Available	0.63
Self-propelled	CNH (FR 9090 & 130FB)	Belgium	474,000	8	242.0	60.0	27.80	10.0-21.0	0.83

[a]Values to populate the table were taken from literature provided by: (Rummer and Mitchell 2012, Berhongaray, Kasmioui et al. 2013, Eisenbies, Volk et al. 2014a, Eisenbies, Volk et al. 2014b).
[b]PMH=Productive Machine Hour.
[c]Value in parenthesis represent cost of JF Z200 harvester without tractor.

As Table 1 demonstrates, the production cost associated with the CNH harvester is lower than the tractor-pulled Ny Vraa harvester at approximately $27.80/ODT, compared to the $47.97/ODT. While the upfront capital costs, ownership costs, and maintenance costs are higher, the cost to produce woody biomass feedstock is overall lower for CNH harvester than the Ny Vraa. The maximum harvestable stem diameter of the CNH harvester has been shown to be larger, as well, without a loss in

productivity. At amounts of up to 60% of the total input costs, though, harvesting woody biomass with use of reconfigured forage harvesting systems demonstrates a very large barrier to successful implementation. Because SRWC harvesting is largely subcontracted in areas where it is most popular (Nordic countries), purchasing a harvester is often excessively expensive for a single person. At an upfront capital cost of approximately $474,000 (converted from Euros), the self-propelled forage harvesting system provides a currently unfeasible logistic model for which it was designed for, the average farmer.
At a purchasing price of approximately $52,000, though, the Ny Vraa tractor-pulled JF Z200-HYDRO/E reconfigured forage harvester offers farmers with a much more feasible harvesting system that can be easily implemented in the Lake States region (Table 1). With the assumption that a tractor is readily available, the upfront capital requirements of the Ny Vraa harvesting system are nearly 100 percent less than the Case New Holland. Productivity aside, the tractor-pulled system reduces the barriers to entry in the production of woody biomass over that of the Case New Holland by costing significantly less and, thus, should be regarded as a viable harvesting tool.

2.4. Literature gaps within the tractor-pulled reconfigured forage harvesting system

Currently, literature has been lacking in providing accurate productivity estimates of the tractor-pulled reconfigured harvesting system, with specific emphasis on the affordable Ny Vraa design (Table 1). While simple dimensional analysis of all associated input costs and the production cost could provide a productivity value (in ODT/hr), this value would not accurately capture the production rate associated with actual use, in ODT/PMH. As a result, in order to successfully capture the working capability of this tractor-pulled reconfigured forage-harvesting system, further productivity analysis must be conducted while operating in a SRWC plantation. In doing so, a better understanding of the working capabilities this harvesting system will be provided so that potential stakeholder involvement can be expanded.

2.5. Woody biomass transportation, storage, and payment

Regardless of the harvesting system utilized, transportation of the produced biomass feedstock product must occur in order for the stakeholder to receive payment for their efforts; and because transportation is nonspecific of the harvesting system (a chip van is utilized regardless), this aspect of the supply chain was not a specific focus of the research. Unfortunately, though, transportation represents one of the most expensive aspects within the woody biomass supply chain and, as a result, must be addressed with regards to the validity of SRWC as a viable fuel source (Srivastava, Abbas et al. 2011). Subsequent storage is also incredibly important because it increases the overall higher HHV of the woody biomass, thereby making the biomass a more competitive fuel source with other stationary fossil fuels. For these reasons, the transport, storage, and payment of SRWC will be briefly addressed in subsequent sections.

2.5.1. Woody Biomass Transport

Often considered to be one of the most expensive aspects within the supply chain, transporting woody biomass is a relevant cost factor within the entire bio-energy system, not just the supply chain (Carlsson and Ronnqvist 2007, Abbas, Current et al. 2011). There are two primary factors that affect transportation: biomass bulk density, and travel time. The low bulk and energy density of woody biomass compared to other fossil fuels can greatly hinder the feasibility of the fuel source as a whole if transportation is not properly coordinated. Travel time is also a large economic variable that is dependent on the transport distance and speed of the hauling vehicle.

Mass and volume of the harvested biomass, as well as the hauling capacity of the carrying vehicle all affect feasibility variables within the transportation step of the supply chain. Increasing the bulk density of the biomass maximizes truck cycle capacity and optimizes the utilization of vehicle payload (Gold and Seuring 2011). In doing so, transportation costs are reduced and environmental emissions are decreased. Densification techniques applied to the harvested woody biomass are the primary ways to increase bulk density and make secondary transportation a more cost affective aspect within the supply chain (Tumuluru, Wright et al. 2010). The primary mode of densification, as stated previously, is grinding or chipping, which increases the surface area of the harvested biomass. Other densification techniques, such as thermochemical conversion (torrefaction/pyrolysis) or pelletization will generally occur at the energy conversion facility due to the energy, infrastructure, size, specificity, and cost of the required industrial equipment CITE. Instead of explicitly increasing the surface area, though, thermochemical conversion increases the feedstock energy density (BTUs/lb). Bulk density is increased as a secondary benefit because the undesirable hemicellulosic components of the biomass are removed.

The distance of a transportation route is dependent on where the harvest site is located in relation to the end-user (or storage facility). This variable is usually a fixed factor within the supply chain but can be influenced by where the biomass landing site is located and how the logging road was constructed in relation to main roadways. The speed of the hauling vehicle is affected by road properties, surrounding infrastructure, and the mode of transportation. Properly scheduling personnel and vehicles can also affect speed.

In Michigan, and the surrounding lake states, chipped/ground woody biomass is generally transported through chip vans that occur in multiple different types, including the walking bed or stationary type. In general, though, all chip vans are open-topped to allow for easy filling access via grinder/chipper conveyors subsequent to processing (Green, Sproule et al. 2006). If the woody biomass is not processed before transportation, it will generally be loaded on to the bunked trailers of a semi-truck. The bunks help keep the biomass in place while the truck is in motion and come in single or multi-pup configurations (Green, Sproule et al. 2006). This mode of transportation is generally limited due to the high cost of transporting biomass with such a low bulk density.

2.5.2. Woody Biomass Storage

Woody biomass for energy is primarily stored so that adequate amounts can be supplied to a conversion facility when the demand fluctuates. Proper storage also decreases moisture content, effectively reducing boiler retention time or conversion energy requirements (Tumuluru, Wright et al. 2010). Woody biomass has superior storage characteristics over other biomass forms in that it can be stored in a more cost effective and feasible manner. It generally has a longer harvesting period, which reduces storage stresses caused by the simultaneous harvest of annual crops (Hamelinck, Surrs et al. 2005). Generally speaking, the shorter the harvest season, the more storage units are required to appropriately buffer sudden surpluses (Hamelinck, Surrs et al. 2005). The beneficial effects created through storage are best realized through closed type warehouses situated adjacent to the conversion facility, where produced exhaust heat can be used to help dry the woody biomass (Afzal, Bedane et al. 2010).

The main risk associated with woody biomass storage is quality degradation, where the heating value decreases due to decomposition. The biomass at hand will then take up space without producing the necessary yield. This occurs the longer the biomass sits without being used, and is exacerbated if it is exposed to weather conditions outside of controlled ambient housed temperatures (Afzal, Bedane et al. 2010). The other main risk associated with biomass storage is yield loss due to a high number of storage steps. Dry matter loss is directly associated with the amount of storage steps and, thus, increases as more steps are taken within the supply chain (Garstang, Weekes et al. 2002). It is in best practice for the end user to move piled woody biomass as little as possible. Allowing harvested biomass to dry for multiple months adds additional logistic steps and ultimately a higher capital input due to the removal and subsequent return of harvesting equipment, but generally provides for a higher quality product.

2.5.3. Woody Biomass Payment

The current system for payment in the US values pulpwood and hog fuel on a per weight basis, meaning that quantity is valued over quality. The result is that conversion facilities in the U.S. will pay a higher price for wet and saturated biomass that may be contaminated, with an overall lower HHV, than clean bone-dry biomass with a higher HHV. While possibly easier for the logger, this devalued product increases the pretreatment costs for the conversion facility, making it more difficult for woody biomass to compete with other fossil fuels. Ultimately, conversion facilities are relating the biomass volume-to-weight relationship with a positive correlation, when it may be most beneficial to base the relationship with a negative correlation. Meaning, that for a specific volume of supplied biomass, a higher relative weight should devalue the product. European countries have been operating in this manner for a number of years. In doing so, their conversion facilities operation in a more efficient manner because the number of logistic steps associated with pretreatment at the conversion facility is reduced, storage retention time is reduced, and the supplied biomass product has a generally higher HHV at the factory gate.

2.6. Life Cycle Assessment

The purpose of the life cycle assessment (LCA), as defined by the International Organization for Standardization (ISO), is to compile and evaluate the inputs, outputs, and potential environmental impacts of a product system throughout its lifetime (cradle-to-grave), including everything from raw material acquisition through product disposal (International Organization for Standardization 2006). LCA guidelines are part of the ISO 14000 environmental management standards series. Assessments such as these have allowed for better comprehension of the possible impacts associated with the manufacture and utilization of different products. The LCA has, therefore, been considered to be of critical importance for environmental protection awareness.

Development of the LCA over the years has divided the analysis based on presented implications, which include the attributional LCA (ALCA), and the consequential LCA (CLCA) (Helin, Sokka et al. 2013). The ALCA seeks to “describe the environmentally relevant physical flows of a past, current, or future product system” (Curran, Mann et al. 2005, Djomo, Kasmioui et al. 2011). The CLCA, on the other hand, describes how “environmentally relevant physical flows would have been or would be changed in response to possible decisions” (Curran, Mann et al. 2005, Djomo, Kasmioui et al. 2011).

Regardless of the interpretation, though, all LCA's utilize the same basic framework to (help) standardize and report findings. This framework includes: a definition of goal and scope, an inventory analysis, impact assessment, and an interpretation of the results. The LCA process framework is iterative, as demonstrated by Figure 9 (International Organization for Standardization 2006):

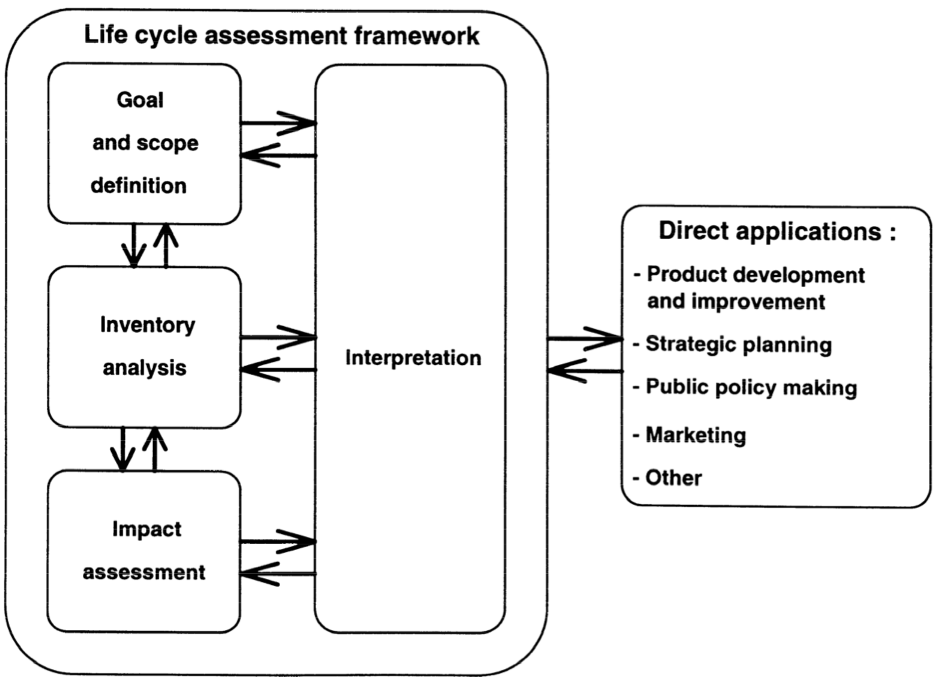

Figure 9: Life Cycle Assessment Framework provided by ISO 1040

Based on the components identified by ISO 14040 in Figure 9, and the methodology of (nearly) all LCA publications, the LCA framework components are described in detail below:

- Goal and scope definition: The goal clearly provides intended application of the study, the immediate need for the study, and the intended audience to reduce any type of ambiguity that could result from conducting the LCA. The scope provides a system boundary for which to begin and end the analysis.

- Inventory analysis: Quantifies the relevant inputs and outputs of the analyzed product system. The inventory analysis solely tracks measurable quantities directly associated to the LCA goal into, through, and out of the identified system boundary.
- Impact assessment: Takes the collected information from the inventory analysis and evaluates the significance of potential environmental impacts. The impact assessment generally associates the inventory data with specific environmental impacts while simultaneously attempting to comprehend them.
- Interpretation: Combines the findings of the inventory analysis and impact assessment to generate conclusions or recommendations that are consistent with the goal and scope. Comparisons with other production systems can occur here, too. The interpreted information will be presented for decision-makers and stakeholders to generate the most impact.

2.6.1. LCA of woody biomass production in SRWC plantations

Because SRWC plantations are often championed as being one of the most effective ways to produce woody biomass for bioenergy, the environmental effects, and the amount of produced energy from a cradle-to-farmgate or cradle-to-plant setting have been extensively analyzed around the world. Table 2, below, summarizes life cycle assessment publications pertaining to SRWC systems with utilized poplar and/or willow energy species over the past 20 years (with reference to 2016). Explicit focus of Table 2 was set on the harvesting systems utilized to produce the woody biomass. In this way, a better understanding of how past research groups analyzed the harvesting system supply chain could be had so that gaps in literature could be identified to further strengthen the necessity of the thesis objectives. The collected studies were not exhaustive of the available information, but were intended to provide an accurate snapshot of LCA's over the past two decades. While other short rotation energy crops, such as Miscanthus, American Sycamore, Eucalyptus, and Sweetgum were the focus of many studies over the past 20 years, the Lakes States region primarily researched the utilization of *populus* and *salix* species. As a result, these two species were a focus of this literature review while other species were excluded.

Table 2: Compiled woody biomass for bioenergy life cycle assessment information over the last two decades

Year	Author (s)	Research Location	SB[a] and FU[b]	Reference System	Energy Crop	Harvesting System	Focus on: Environ.	Energy
1997	Mann & Spath	U.S.	Cradle-to-plant; FU= 1 kWh	Grid electricity	*Populus,* other	Traditional (whole-tree)	✔	✔
1999	Rafaschieri et al.	Italy	Cradle-to-plant; FU=1 MW_e	Grid electricity	*populus*	N/a	✔	✔
2003	Lettens et al.	Belgium	Cradle-to-plant; FU= 1 ha	Grid electricity	*salix,* other	Modified maize chopper, generalized special whole-stem harvester	✔	✔
2005	Keoleian & Volk	U.S.	Cradle-to-plant; FU=1 kWh	Grid electricity	*salix*	Prototype self-propelled forage harvester	✔	✔
2007	Adler et al.	U.S.	Cradle-to-plant; FU=g CO_2e-C•$m^{-2}yr^{-1}$	Grid electricity	*populus*	Traditional (whole-tree)	✔	
2009	Goglio & Owende	Italy	Cradle-to-plant; FU=1 ha	Grid electricity	*salix*	Traditional (cut-to-length)	✔	✔
2009	Gasol et al.	Spain	Cradle-to-farmgate; FU= 3.93 TJ & 1 ha	Natural Gas	*populus*	N/a	✔	✔
2010	Di Nasso et al.	Italy	Cradle-to-plant; FU=1 GJ ha^{-1}	N/a	*populus*	Tractor-pulled cut-and-chip		✔
2011	Djomo et al.	Global	Multiple	Multiple	*Populus, salix*	Multiple	✔	✔
2011	Cherubini & Strømman	Global	Multiple[d]	Multiple	*populus, salix,* other	Multiple	✔	✔
2013	González-García et al.	Europe	Cradle-to-gate; FU= 1 m^3 felled roundwood yr^{-1}	N/a	*populus, salix,* other	Traditional (cut-to-length)	✔	✔
2013	Dillen et al.	Belgium	Cradle-to-plant; FU=1 ha	Grid electricity	*populus*	N/a		✔
2015	Vasquez Sandoval	U.S.	Cradle-to-gate; FU= 1 bone-dry metric ton biomass	Grid electricity	*populus*	CNH FR series forage harvester & attached coppice header,	✔	✔

[a]SB= system boundary
[b]FU= functional unit

2.6.2. LCA literature gaps

Based upon the conducted LCA literature reviews presented in Table 2, multiple knowledge gaps and methodological issues have presented themselves. In addressing them, and subsequently analyzing them through experimentation, the identified project objectives and project necessity will be further strengthened within the thesis. As noted from Mann and Spath (1997), Adler (2007), and Goglio & Owende (2009), LCA's have been conducted on the traditional harvesting system operating in SRWC plantations consistently throughout the last two decades. It should be noted, though, that all of these presented studies utilized existing literature or simulation software to generate productivity estimates of the traditional harvesting system. With harvesting and transportation accounting for up to 60% of the total energy input required to produce woody biomass, it should be considered imperative to generate the data in field where the analysis occurred. Furthermore, little to no information pertaining to the traditional harvesting system operating in a SRWC plantation existing in literature, assumptions must have been made to generate the environmental/energy data within these studies, ultimately reducing their effectiveness as a demonstrative tool.

Similar methodologies utilized to produce results from the traditional system were used with the tractor-pulled cut-and-chip reconfigured forage harvesting system. Di Nasso et al. (2010) employed reference literature for all energy inputs and outputs related to their analyzed harvesting system. They also forewent the comparison of a reference system, further limiting the validity of their LCA interpretation due to lack of context. In order to accurately capture the environmental and energy impacts associated with woody biomass production from the proposed harvesting systems operating in a SRWC plantation, a reduction in the number of removed steps and assumptions from the actual study that took place must be considered. While not always possible, doing provides more accurate net energy information for stakeholders interested in producing woody biomass for fuel, and better environmental loading estimates for lawmakers promoting woody biomass for fuel, therefore making the analysis more exact and ethical. As a result, it was considered vital to add LCA research to the existing body of literature that accurately captured the actual energy inputs and associated environmental effects created by utilizing the traditional and tractor-pulled reconfigured forage harvesting systems to produce woody biomass from SRWC plantations.

2.6.3. SRWC Carbon Sequestration

Aside from producing a reusable form of energy through their short growth period, SRWC have a capacity to sequester atmospheric carbon in to the soil, thereby providing a net-negative source for global warming potential (Potter et al. 1999). Documentation of carbon sequestration by woody crops is pertinent because the above ground biomass is utilized for combustion. An understanding of how net-negative carbon emissions are produced must, therefore, be provided. Sequestration comes largely in two forms: from applied residues (such as limbs and tops) following harvest, and from stored carbon within the crops' root system (Lemus and Lal, 2007). For intents and purposes of this thesis, though, it was assumed that the entire crop was harvested for bioenergy production, including all limbs and tops (hog fuel). Because the application of residues would add a logical step within the supply chain, thereby increasing input costs, and ultimately reducing system feasibility, it was excluded from the analysis.

The root biomass of crops, especially those of perennial woody crops, such as willow and poplar, stand to provide a sink for increasing soil organic carbon through their extensive root system and symbiotic dependence on the rhizosphere (Lynch and Whipps, 1991). Compared to switchgrass and corn, for example, willow increased the proportion of total system carbon by 14.4 and 15.6 %, respectively (Zan et al. 2001). Multiple studies have demonstrated varying degrees of root carbon sequestration, where the coarse woody roots (and stumps) either reach a nearly stable state over the plantation lifespan or continue to sequester accumulated carbon at a constant rate (Heller et al. 2003, Lemus and Lal 2007, Sartori et al. 2006, Zan et al. 2001). With an inconclusive consensus, it was assumed that carbon sequestration would occur at a steady rate over the plantation's lifespan. An average carbon sequestration rate of approximately 0.60 tons C AC^{-1} yr^{-1} was found from multiple studies (with a low of 0.11 tons C AC^{-1} yr^{-1} and a high of 1.33 tons C AC^{-1} yr^{-1}) for SRWC poplar and willow (Heller et al. 2003, Lemus and Lal 2007, Sartori et al. 2006, Zan et al. 2001).

In general, the amount of accumulated root biomass will not equal the amount of shoot biomass over the woody crop's lifespan. This is due to multiple different environmental and inherent plant factors, including: nutrient, water, oxygen, temperature and carbon allocation, as well as plant controls and root-shoot feedbacks (Friend et al. 1994). As such, the LCA incorporated an idealized biomass allocation model, where the amount of years within the harvest rotation was equal to the number of segmented bioenergy stands (Figure 10). In this way, the carbon released in to the atmosphere during combustion would be re-sequestered within a single year, while providing a consistent and steady supply of biomass throughout the SRWC plantation's lifetime.

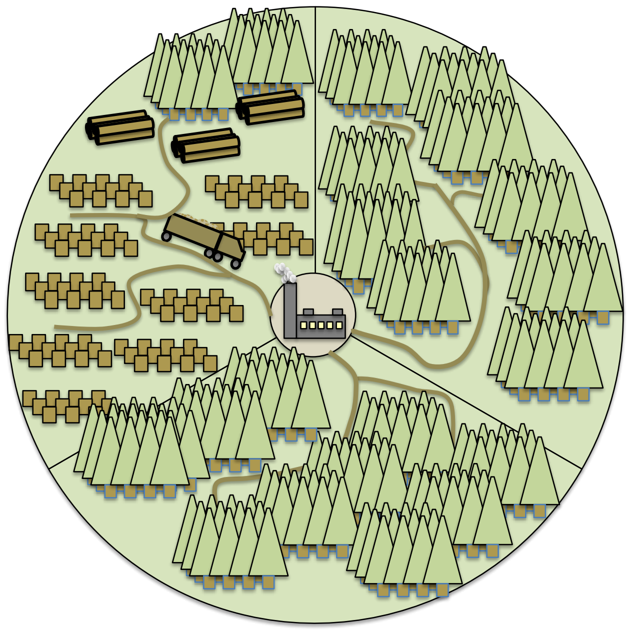

Figure 10: Idealized 3-year biomass allocation model utilized for the LCA.

If, for example, the rotation period were determined to be three years (Figure 10), the amount of available biomass would ideally be segmented in to three equal parts. Following harvest of 1/3 the available biomass, emitted carbon would be re-sequestered following one-year's growth, thereby providing a net-positive carbon producing model (or a net-negative carbon-emitting model). Available biomass would then rotation between all three sites on a per-year basis, providing a consistent biomass product of similar quality.

Furthermore, the cultivation of SRWC was assumed to have minimal effects on land use change due to the utilization of no-till planting practices and the accumulation of leaf litter during non-harvest years (Cherubini and Jungmeier 2010, Heller et al. 2003). Under the assumption that converted sites were not native grasslands or peat bogs, planted willow or poplar would ultimately increase the immediate amount of soil organic matter.

2.7. Economic Analysis

An aspect of classical economic theory concerns itself with the production and utilization of capital goods produced by people (Oxford University Press 2014). The economics of forestry, therefore, values wood and woody biomass as capital through its production and subsequent harvest. Although forests obviously have much deeper significance to society than the amount of money they produce, many investors own forested land solely for its financial returns. Furthermore, in order to compete with monetarily cheaper fossil fuel sources, understanding the potential economic benefits (or lack thereof) of using underexplored harvesting systems to produce SRWC biomass must be made through standard economic analyses. Providing such details will add a further dimension for which these systems can be compared to other established energy-producing systems. Without government subsidies, which are not covered in this thesis, an investor who plants, tends, and sells short rotation woody crops must ultimately be reimbursed for their time and effort, no matter how good their intentions are to produce environmentally friendly sources of energy. Without such returns, SRWC utilization will not persist in to the future.

From a mail survey of Michigan-based logging firms that detailed information on the outlook of the current logging sector within the state of Michigan, G.C. and Potter-Witter (2011) demonstrated that loggers have been facing significant difficulty in turning a profit and retaining their business in recent years. With numerous mill closures occurring throughout the state, utilizing woody biomass for bioenergy could provide new business to reinvigorate a once thriving industry. Of the logging firms who responded to the survey (109 respondents), 83 percent stated that logging residues (limbs and tops of harvested stems) are left on-site following a harvest operation, indicating that this is currently an underutilized resource with little to no market presence. In the very least, there is currently an available market with existing timber stands for additional supplementation of woody biomass for bioenergy generation.

The research results provided by G.C. and Potter-Witter was timely because Michigan's forest products industry is currently on the decline as a result of challenges due to limited timber availability/sale (private and public lands), high fixed and variable costs, sector downturns, foreign competition, and aging facilities (G.C. and Potter-Witter 2011). With an estimated loss of more than 30,000 Michigan jobs and $720 million in wages, providing the forest products industry with a supplemental form of income without increasing competition between firms will undoubtedly bolster an industry that is in need of help (Korpi, 2010; G.C. and Potter-Witter 2011). Table 3and Table 4 (page 45) provides selected information from the study conducted by G.C. and Potter-Witter summarizing the favorability of wood-based biofuel manufacturing with loggers in Michigan.

From Table 3 and Table 4, it can be noted that the general consensus between all 109 respondents is that wood-based biofuel manufacturing is considered to be a desirable endeavor. Similarly, logging firms generally consider non-merchantable timber to be a desirable form of wood utilization when asked about opinions on the introduction of new wood-using facilities within the state. Providing further diversified forms of income to loggers should be considered critical due to its influence on Michigan's local economy and population. In order to determine the true viability of such endeavors, though, economic assessments must be made.

Providing economic analyses of producing woody biomass for bioenergy with use of the traditional whole-tree harvesting system and the tractor-pulled cut-and-chip reconfigured forage harvesting system will also demonstrate the economic viability of participating in such pursuits. Ultimately, this information can be utilized to understand how woody biomass for bioenergy should best be sourced as the woody biomass for bioenergy industry continues to grow within the state.

Table 3: The favorability of wood-based biofuel manufacturing based on the type of wood-using firms in Michigan (G.C. and Potter-Witter, 2011)

Type of wood-using firms	Median response		X^2 value	*P* value
	Large mills	Small mills		
Pulp and paper manufacturing	Undesirable	Desirable	6.161	0.013
Wood pellet fuels	Neutral	Desirable	4.685	0.030
Hardwood sawmill	Very undesirable	Undesirable	3.223	0.073
Softwood sawmill	Undesirable	Undesirable	1.837	0.175
Veneer manufacturing	Neutral	Neutral	0.171	0.679
Particle board or other panel manufacturing	Undesirable	Neutral	3.354	0.067
Oriented-strand board manufacturing	Undesirable	Neutral	2.777	0.096
Direct-fired wood power generation	Desirable	Desirable	0.031	0.860
Wood-based biofuel manufacturing	Desirable	Desirable	1.390	0.238

Table 4: The favorability of wood-based biofuel manufacturing based on the type of wood use in Michigan (G.C. and Potter-Witter, 2011)

Type of wood use	Median response		X^2 value	*P* value
	Large mills	Small mills		
Roundwood	Neutral	Desirable	0.001	0.973
Nonmerchantable timer	Desirable	Desirable	0.009	0.922
Forest residue	Neutral	Desirable	0.000	0.988
Mill residue	Neutral	Desirable	0.387	0.534

3. GENERAL HARVESTING SYSTEM METHODOLOGIES

This thesis consisted of three different studies that developed a framework for quantifying how well the traditional and tractor-pulled reconfigured harvesting systems operated in SRWC plantations, consistent with the identified project objectives. Through these three studies, one journal publication was created. This publication focused on productivity estimation of the traditional harvesting system operating in a SRWC poplar plantation (from one field study). This journal article also included pertinent information related to the production cost of producing woody biomass with the traditional system as well as a net-energy ratio. This research was published within the International Journal of Forest Engineering, and was titled "A Traditional Ground-Based System for Woody Biomass Harvesting in Short Rotation Woody Crops (SRWC) Plantations - A Case Study in Michigan". This information was written in to a journal publication because it was lacking within the existing body of scientific literature, and was seen as most pertinent to amend. The remainder of the thesis built upon the first study by expanding collected production information to incorporate the tractor pulled reconfigured forage harvesting system (from one study) and subsequently contrasted both harvesting systems through an economic analysis and LCA. The collected information has been separated in to three parts, Harvesting System Evaluation, Economic Analysis, and Life Cycle Assessment to better convey each of the three thesis objectives.

This section describes the general methodologies of the thesis that overlap between all three of the identified objectives, including: the study area descriptions, harvesting system specifics, and working conditions.

3.1. Traditional Harvesting System

3.1.1. Study Area

The harvest study was conducted in a 7.8-ac stand of 7-year-old poplar hybrids at Michigan State University's Forest Biomass Innovation Center (FBIC), in Escanaba, Michigan, U.S.A (45°45'53.7"N, 87°11'01.7"W, Figure 11). The site was rectangular in shape, had no discernable slope, and was free of any impassable objects. Seven poplar hybrid types were planted in a randomized complete block design with 3 spacing treatments (8.0 x 5.0 ft, 8.0 x 6.0 ft, and 8.0 x 7.0 ft spaced plot-types within and between constructed rows) replicated four times each. Moreover, each different spacing treatment had three different randomly distributed harvest plot stockings throughout the stand. This plantation was setup to determine the effects of different tree spacing's on biomass yield. As such, a separate study was run concurrently with this study, but did not affect the analysis. In total there were 78 rectangular-shaped plots, which occupied approximately 1/10th AC each, at an average stand density of 880 TPA (Figure 12). Tree size ranged from 2.5 to 4.7 inches in diameter at breast height (DBH), where nearly all trees were single-stemmed. Average volume was approximately 1.6 m^3 per tree, or 1,537.0 ft^3 per AC (Jenkins et al. 2003). Average tree height at the time of harvesting was approximately 33.0 ft.

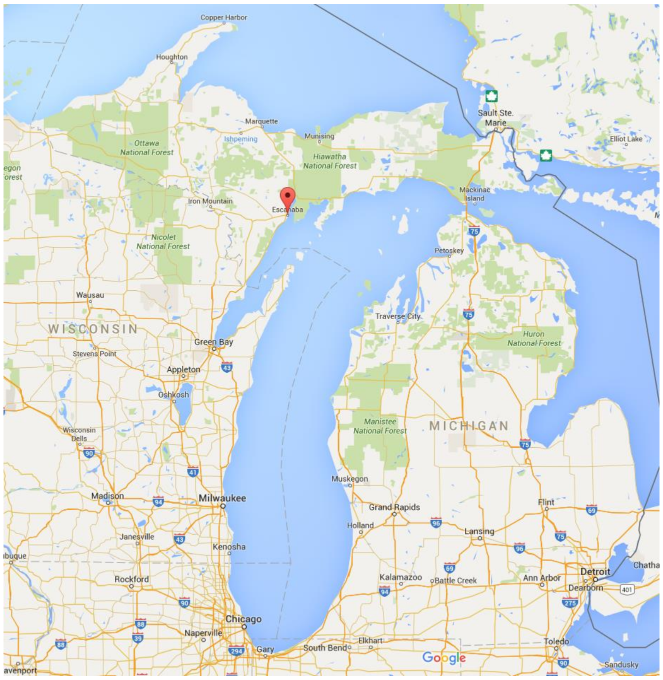

Figure 11: Location of SRWC harvest operation with use of the traditional harvesting system: Escanaba, MI.

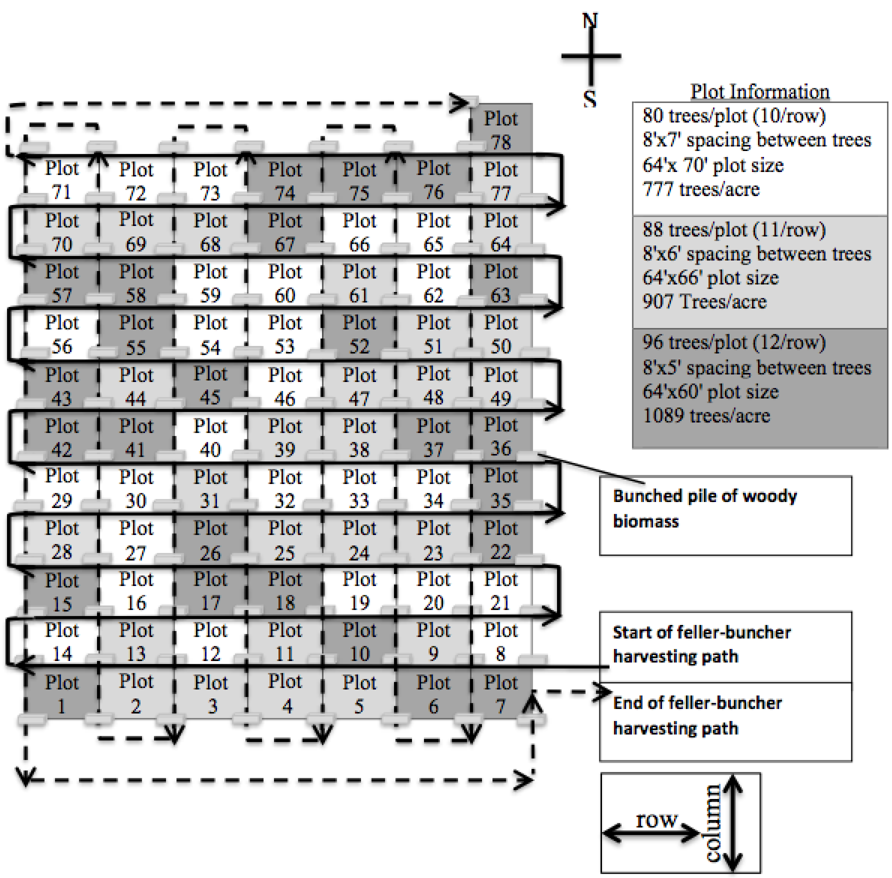

Figure 12: Overview of harvested study site with highlighted differences in stand density.

3.1.2. Harvesting system description & working conditions

A mechanized ground-based whole-tree harvesting system (traditional system) was used to harvest the stand, which included a feller-buncher, grapple skidder, log loader, and grinder (Figure 13). The scope of the analysis was centered on the harvesting system, subsequently ending at the farm gate. All biomass transport operations were not included in this study. A tracked John Deere® 653G feller-buncher with attached hot saw cut eight 213-meter-long swaths through the stand. Bunches of harvested trees were placed along each swath by the feller-buncher until the entire plantation was clear-cut. Due to the logistics involved with the collected data of the spacing study, harvesting with the feller-buncher occurred over two separate working days in September 2014. Operating in this manner did not affect the feller-buncher operator's harvest strategy or productivity estimation and continuous work was assumed. In total, the feller-buncher operated for 14.4 delay-free hours.

Following the clear-cut operation, bunched biomass piles were decked based upon logger recommendations until January 2015, when the ground was sufficiently frozen. The biomass was subsequently moved to the landing by a fixed-boom rubber-tired John Deere® 740A grapple skidder. A Hood® S-182 log loader was utilized at the landing to feed the harvested wood into a remote-controlled Peterson® 4700B grinder as it was gathered and deposited by the skidder. Chip van drivers volunteered to operate the grinder during feeding so as to ease the workload of the loader operator. Skidding, loading and grinding occurred simultaneously on one working day in January of 2015, where the skidder operated for a total of 4.1 delay-free hours and the loader-grinder operated for 3.6 delay-free hours. The contracted loggers were from Marvin Nelson Forest Products Inc., where operators had between 5-25 years related operations experience. All operators were adept at handling small diameter trees and were each present for the entire operation.

Figure 13: Traditional ground-based whole-tree harvesting system used in the study, including: (a) John Deere 653G feller-buncher, (b) John Deere 740A grapple skidder, (c) Hood S-182 log loader, and (d) a Peterson 4700B grinder.

3.2. Tractor-pulled reconfigured forage harvesting system

3.2.1. Study Area

The harvest study was conducted in a stand of 3-year-old willow hybrids at a Michigan State University extension site near Albion, Michigan (42.2467° N, 84.7533° W, Figure 14). The plantation was rectangularly shaped at a size of 1.1-acres, with a gentle slope of approximately 10% spanning its entire length. The site was set up in a traditional double-row configuration but was divided in to 80 equally sized rectangular plots (approximately 0.0137-acres each), with 16 plots per plantation row (Figure 15). Twenty different willow hybrid types were planted in a randomized complete block design, replicated four times each. Each plot contained three pair-rows with 13 multi-stemmed trees in each row (78 trees per plot) for a total density of 5,672 TPA. Hybrids were spaced 2.5ft between each tree width-wise within each double-row and 2ft between each tree length-wise. Each double-row was separated by approximately 4.92ft of space. Tree stems averaged 0.5-1.0 inch DBH, with multiple stems per tree.

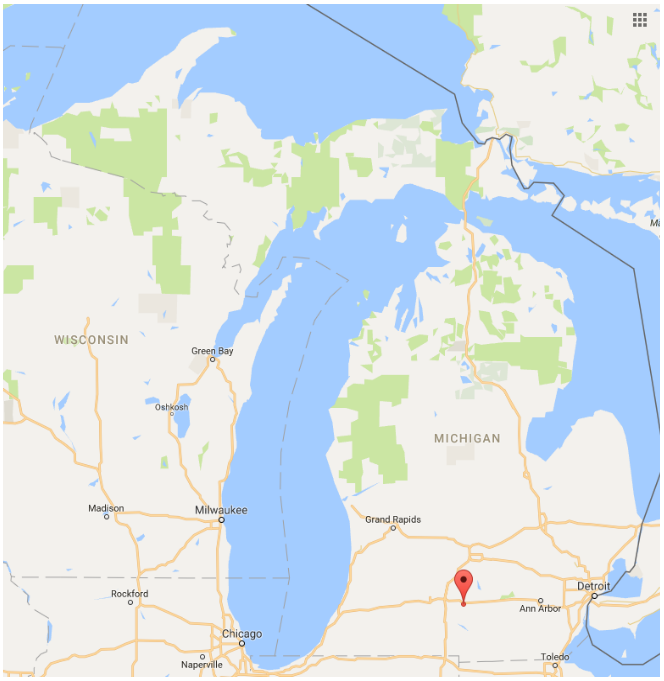

Figure 14: Location of SRWC harvest operation with use of the tractor-pulled cut-and-chip reconfigured forage harvesting system: Albion, MI.

Plot 80	Plot 79	Plot 78	Plot 77	Plot 76	Plot 75	Plot 74	Plot 73	Plot 72	Plot 71	Plot 70	Plot 69	Plot 68	Plot 67	Plot 66	Plot 65
Plot 49	Plot 50	Plot 51	Plot 52	Plot 53	Plot 54	Plot 55	Plot 56	Plot 57	Plot 58	Plot 59	Plot 60	Plot 61	Plot 62	Plot 63	Plot 64
Plot 48	Plot 47	Plot 46	Plot 45	Plot 44	Plot 43	Plot 42	Plot 41	Plot 40	Plot 39	Plot 38	Plot 37	Plot 36	Plot 35	Plot 34	Plot 33
Plot 17	Plot 18	Plot 19	Plot 20	Plot 21	Plot 22	Plot 23	Plot 24	Plot 25	Plot 26	Plot 27	Plot 28	Plot 29	Plot 30	Plot 31	Plot 32
Plot 16	Plot 15	Plot 14	Plot 13	Plot 12	Plot 11	Plot 10	Plot 9	Plot 8	Plot 7	Plot 6	Plot 5	Plot 4	Plot 3	Plot 2	Plot 1

N

Figure 15: Plot layout of the SRWC willow stand in Albion, MI.

3.2.2. Harvesting System Description

A single-pass tractor-pulled cut-and-chip reconfigured forage harvesting system was utilized to harvest the trees within the stand, which included a Ny Vraa JF192 harvester attached to a John Deere 7330 tractor (Figure 16). Produced chips were subsequently collected in a Komatsu CK35-1 Bobcat skid steer loader as they were expelled from the harvester. The harvest operator, who simultaneously drove the tractor and operated the JF192, utilized a traditional row-crop harvesting strategy where he harvested the outer-most double-rows of the plantation, harvesting in concentric circles, until the plantation was completely clearcut (Figure 17). The harvest operator began in the southeastern-most corner of the stand at Plot 1, harvesting the first lane in the double-rows of Plots 1-16, then moved to Plot 80 and subsequently harvested the outer-most lane in the double-row of Plots 80-65, all while a second operator controlled the skid steer loader to collect produced biomass chips. Following this, both operators would then move back to Plot 1 and begin harvesting the second lane in the first double-row. This procedure was followed for the duration of the operation until the entire plantation was harvested. The operators would harvest single rows of each double-row, working in concentric circles toward the center of the stand until there were no stems left to harvest. Both machine operators worked for the Michigan State University FBIC, and had at least 15 years experience operating farming machinery.

Figure 16: Tractor-pulled cut-and-chip reconfigured forage harvesting system used in the study, including: (a) John Deere 7330 tractor, (b) Ny Vraa JF192 harvester, and (c) a Komatsu CK 35-1 Bobcat skid steer loader.

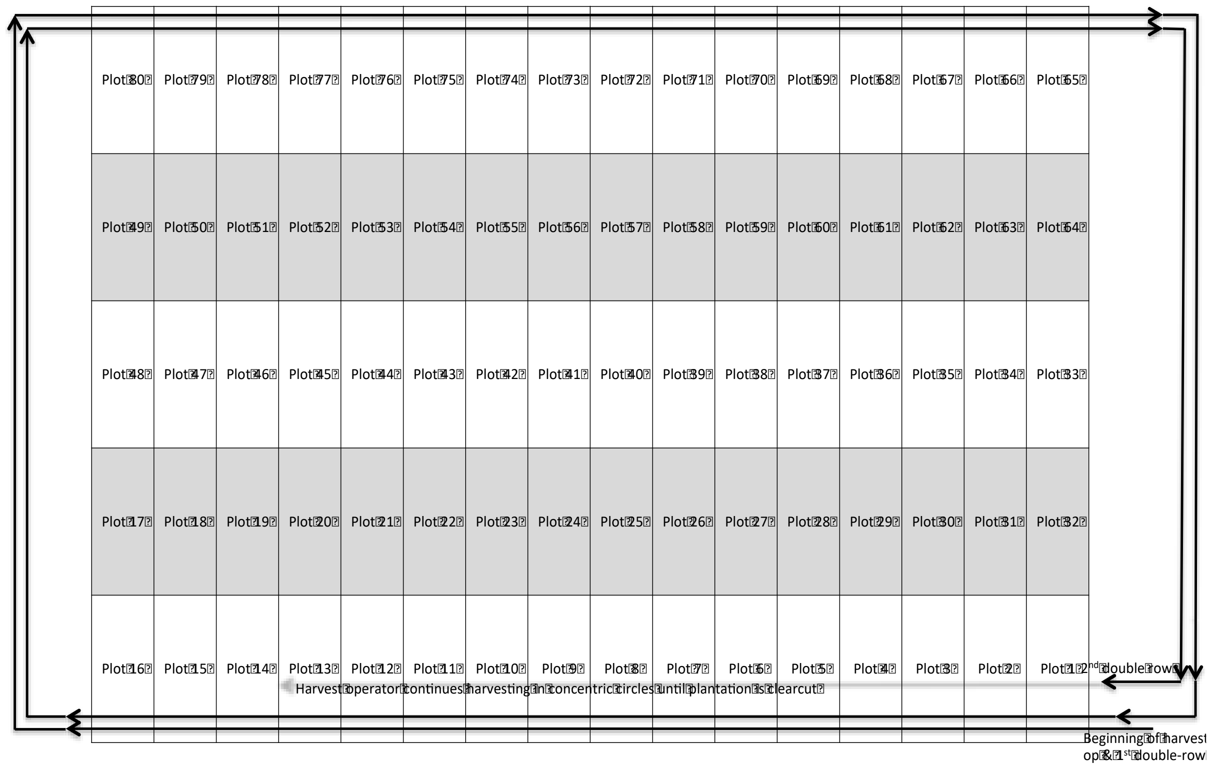

Figure 17: Harvesting pattern of the tractor-pulled reconfigured forage harvesting system in the SRWC willow plantation.

3.2.3. Working conditions and data collection

Felling took place on October 31st 2014, for approximately half of one working day. Information pertaining to stem DBH, MC, energy content and hybrid statistics were gathered from the inside 18 trees of the middle double-row of each plot (Figure 18), to minimize the effects due to edge. This resulted in idling from the machine operators as other FBIC workers were allowed to collect produced willow chip samples from the loader's bucket. Because this was not typical of a normal clear cut single-pass harvesting operation, productivity information was gathered only from the outside two double-rows of each plot, where operations were unbroken between plots.

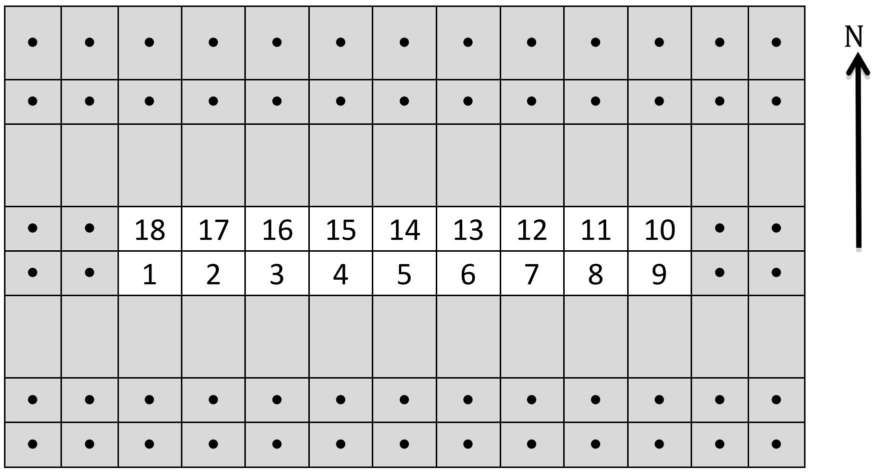

Figure 18: Individual plot layout, where inside 18 trees were harvested and collected for analysis.

Transportation was not analyzed in this study due to the focus on harvesting machine productivity and hybrid willow growth information. As a result, the skid steer operator was utilized as necessary to hold produced chips in his font-end loader bucket to assist workers in collecting biomass samples. Chips that were produced during the harvest of the outermost double-rows of each plot were collected by the skid steer loader and subsequently placed in a corner of the stand that would not hinder harvester movement.

4. HARVESTING SYSTEM EVALUATIONS: DATA COLLECTION & ANALYSIS

4.1. Traditional harvesting system

4.1.1. Cost and Productivity estimation

The machine hourly rates, measured in dollars per scheduled machine hour ($/SMH) were calculated for fixed and operating costs through methods introduced by Miyata (1980) (Table 5). Information on equipment purchasing, economic lifespan, interest, insurance, taxes, scheduled machine hours per year, lubrication, tires/chains, and repair/maintenance were obtained from the project contractor. Other information, including diesel consumption rate and equipment utilization rate, were gathered during the study from the analyzed harvest operation. Diesel prices were determined during the time period of the field study using local market information. Equipment salvage value was set at 20 % of the initial investment. In total, the machine hourly rate for the entire traditional harvesting system was calculated to be $284.00/SMH.

Table 5: Traditional harvesting system machine hourly cost ($/SMH) information provided from equipment information survey and calculations.

	Feller Buncher	Grapple Skidder	Log Loader	Grinder
Make/Model	John Deere 653G	John Deere 740A	Hood S-182	Peterson 4700B
Initial investment ($)	90,000	169,000	162,000	426,892
Economic lifespan (years)	5	5	5	5
Salvage value ($)	18,000	33,800	32,400	85,378.4
Machine Utilization (%)	98.93%	90.83%	35.82%	35.82%
Depreciation ($/SMH[a])	9.60	18.03	17.28	45.54
Interest ($/SMH)	2.73	5.36	3.82	11.22
Insurance ($/SMH)	0.43	0.32	0.58	2.16
Tax ($/SMH)	0.07	0.07	0.07	0.07
Maintenance ($/SMH)	6.13	2.93	1.13	10.67
Fuel ($/SMH)	18.86	14.32	4.94	19.53
Lube ($/SMH)	0.97	0.97	0.97	0.97
Labor[b] ($/SMH)	32.81	18.27[c]	32.81	0.0[d]
Total Hourly Cost ($/SMH)	71.60	60.27	61.59	90.15

[a]SMH: Scheduled machine hour.
[b]Labor costs include fringe and benefits.
[c]Lower labor cost of skidder operator due to shorter term of employment.
[d]Grinder was controlled remotely by the chip van driver.

Time and motion studies allowed for the development of machine production rate equations (in oven dry tons per productive machine hour, or ODT/PMH) for each piece of equipment. All timing measurements were taken with the use of a centi-minute flyback stopwatch. Independent variables of each machine’s elemental actions, as well as cycle repetition, were identified prior to the operations commencement. Due to time constraints, only a portion of the total number of machine cycles required to harvest the plantation was recorded. The number of collected cycles, though, was sufficient to gain statistical significance for all machine production rate equations.

A complete feller-buncher cycle began with movement to the first tree, included subsequent cuts to make a full accumulation, and ended with the placement of that accumulation on the ground to make a bunch, where multiple accumulations often constituted a single bunch. Move to tree distance, the number of cuts, and move to bunch distance were thus identified as variables for these elemental activities within a cycle. The "number of cuts" variable was based on the number of times the hot-saw was utilized to sever a tree stem/stems to subsequently make an accumulation, and distances for the feller-buncher were estimated visually based on track-length movements (13.0 ft) due to safety requirements. Time associated with swing movement of the boom was not included separately in this model but was instead incorporated in to the move to tree time and move to bunch time. The effect of edge on feller-buncher productivity was also not analyzed due to inherent plot variations and the small plot size of approximately $1/10^{th}$ AC.

A complete skidder cycle began with movement from the landing to a tree bunch and included subsequent grappling to make a full skid load, travel back to the general landing location, and ended with the placement of loaded trees on the ground near the log loader. Elemental activities within a skidding cycle were thus identified to include: moving empty to bunch, positioning at the bunch, grappling a pile of bunched trees, and traveling loaded to the landing. Intermediate travel from one bunch to a second did not occur during the operation. Distance estimation for the skidder was based on tire-to-tire lengths during movement (15.0 ft).

As biomass was brought to the landing by the skidder, the loader operator worked together with the grinder operator to pick up, and subsequently process, bunched trees to supply a chip van. Ground biomass was produced from a grinder grate size of approximately 5.0 ft in diameter. A complete cycle for the loader-grinder unit was defined as the time required for the loader to supply the grinder with a grapple of wood and process a complete stem in to ground biomass. DBH measurements of the collected biomass being grappled by the log loader were documented during the time motion study through visual estimation of the loader's extended grapple diameter and average poplar stem DBH. The loader-grinder average cycle time estimator utilized the product of tree DBH and the number of trees per cycle as the independent variable in the linear regression model, rather than either variable by itself. Because the grinder often ground more than one tree at a time, the product of the DBH and number of grappled trees per cycle better reflected the working capability of the grinder. Cycle time naturally increased as either DBH or the number of trees increased.

Multiple regression analysis using ordinary least squares estimators was performed in MATLAB R2014b (MathWorks 2014) to develop the predictive machine production rate equations. To validate the developed regression models, 33 % of all data collected for the feller-buncher and skidder were randomly reserved, while the remaining 67 % was used to develop the models and then predict the reserved data. A pair-wise two-sample T-test (α=0.05) was then used to assess the accuracy of the machine production equations. This method of analysis was not used on the loader and grinder due to small sample size. Instead, the entire data set was used to generate the predictive model. Calculation of predicted cycle times were generated from the developed regression models using averaged values for independent variables from the observed time and motion study (Pan et al. 2008b).

4.1.2. Net energy analysis

A net energy analysis was performed on the traditional harvesting system. The diesel fuel energy consumed during harvesting, skidding, loading, and grinding was compared with the gross energy output of the produced biomass. A net energy ratio was subsequently generated describing the harvesting systems overall energy efficiency.

Fuel consumption was measured by a GPI 11325-1 flow meter mounted on the fuel gun of the on-site fuel truck. Readings from the flow meter were recorded each time fuel tanks were filled, as well as before and after operations commenced. This ensured that no machine would function on a partially full tank. Fuel volume was converted to an equivalent heating value in British Thermal Units (BTUs) assuming that one gallon of diesel fuel was approximately equal to 137,000 BTUs, as described by Adams (1983). Energy content of harvested biomass was also expressed in BTUs. Recoverable heating values (RHV) for woody biomass energy output measurements were calculated with the formula described by Ince (1979) in equation [1]:

$$RHV = HHV \cdot (1 - MC_{wb}) - HL \qquad [1]$$

Where:

RHV=recoverable heating value, BTUs/pound

HHV= higher heating value, BTUs/pound

MCwb= wet-basis moisture content, percent

HL= heat loss, BTUs/pound

Average moisture content (MC) values were determined through random sampling of all seven non-harvested poplar hybrid types in September 2014. For each poplar hybrid type, one whole tree from one plot of each block in the stand (four blocks in total) was randomly selected without replacement for all three spacing types. With this, the moisture content was measured for 12 different trees for each of the seven hybrid types, from 12 different plots. In total, 84 MC measurements were taken. Each tree selected was marked with timber marking paint, felled with a chainsaw the morning before harvesting began, and subsequently ground in its entirety with a hammer mill once access was gained following the clear-cut operation. Procedures for determining MC followed the American Society of Testing and Materials E 871-82 guidelines (ASTM 2006), and took place at the FBIC. All dry samples were then placed in frozen storage until HHV testing took place on May 2015 at Michigan State University. Two separate samples for each hybrid poplar type were then randomly selected for testing. HHV evaluation was conducted based on methods described by ASTM standards (E 0711-087) (ASTM 2003) using oxygen bomb calorimetry. Each sample was tested three times to ensure statistical significance, and to generate a mean HHV for each sample. A one-way ANOVA analysis was performed to detect variance between samples, and to compare the mean HHV of each sample.

Heat loss assumptions followed the procedures described by Pan et al. (2008a), which were detailed by Ince (1979), where: the combustion heat recovery system was assumed to operate with 40 percent excess air and a stack gas temperature of 500°F. These values are fairly typical for an industrial system. Other assumptions included a constant conventional heat loss factor of 4 percent, the ambient temperature of the biomass was 68°F before combustion, and complete combustion occurred for each sample.

4.2. Tractor-pulled reconfigured forage harvesting system

4.2.1. Productivity estimates

Productivity estimation and calculation for the tractor-pulled reconfigured forage harvesting system was simpler when compared to the traditional harvesting system. Because a single-pass chipping harvester and loader was utilized simultaneously to create one harvesting system that functioned concurrently, there was no need to conduct a time and motion study to understand the dynamics between the different operating machinery.

Furthermore, conducting a time and motion study to develop a predictive linear regression model for the harvesting system's movement and actions was considered unnecessary due to the harvester's single-function, single-pass operating style: the produced regression equation would have only one independent variable.

System productivity (in ODT/PMH), based upon concurrent use of the harvesting unit (JD 7330 tractor and JF192 harvester) and skid steer loader (CK35-1), was estimated through the time required to simultaneously harvest the border rows of each plot of the plantation. Biomass weight for the productivity estimation was measured through the weight of each plot's 18 internal test trees (Figure 18). This calculation, thus, measured time and weight separately and subsequently combined them to generate a system productivity value. Conducting the analysis in this way allowed the field analyzers to gain accurate timing information from the harvesting unit without contributing to unproductive delay created from time-intensive in-field weight measurements. The weight of the 18 test trees within each plot were subsequently averaged on a per-tree basis and applied to the remaining 52 trees of the border rows that took part in the time trial (the remaining 8 trees in the middle double-row were completely discarded). It was assumed that the growth effects due to edge were negligible. The total time required to harvest each border row of a plantation lane was also averaged and applied to each corresponding double-row that was not measured for time to account for the total time to harvest the plantation. In this way, the time required to harvest the entire plantation could be measured through extrapolation from the time-trial data that was actually collected.

4.2.2. Cost estimates

The machine hourly rates, measured in dollars per scheduled machine hour ($/SMH) were calculated for all fixed and variable costs following methods introduced by Miyata (1980) with use of an equipment information survey and personal interviews (Table 6). Much information from the Albion harvest operation was obtained directly from the researchers at the FBIC who owned the equipment, including: purchasing details, economic lifespan, interest, insurance, taxes, scheduled machine hours per year, lubrication, tires/chains, and repair/maintenance. Diesel prices were determined during the time period of the field study using local market information. Equipment salvage value was set at 20% of the initial investment. The tractor, harvester, and loader utilized in the operation were purchased new from the manufacturer, allowing all Miyata assumptions to be true.

Table 6: Tractor-pulled reconfigured forage harvesting system machine hourly cost ($/SMH) information provided from equipment information survey and calculations.

	Harvesting Unit	Chip Collection
Make(s)/Model(s)	JD 7330, Ny Vraa JF192	Komatsu Bobcat CK 35-1
Initial Investment ($)	145,737	56,597
Economic Lifespan (Yrs)	5	5
Salvage Value ($)	23,317.92	9,055.52
Machine Utilization (%)	100	100
Depreciation ($/SMH[a])	15.55	6.04
Interest ($/SMH)	2.75	1.07
Insurance ($/SMH)	1.94	1.95
Tax ($/SMH)	0.00	0.00
Maintenance ($/SMH)	2.43	2.43
Fuel ($/SMH)	39.75	39.75
Lube ($/SMH)	0.01	0.01
Labor[b] ($/SMH)	42.00	42.00
Total Hourly Cost ($/SMH)	76.79	64.31

4.2.3. Net energy analysis

A net energy analysis was performed on the reconfigured forage harvesting operation by subtracting the diesel fuel energy consumed from all tractor usage, harvester usage, and all skid steer loader usage from the gross energy of the biomass produced. Fuel consumption was measured with a GPI 11325-1 flow meter mounted on the fuel gun of the on-site fuel truck. Readings from the flow meter were recorded each time fuel tanks were filled, as well as before and after operations commenced. This ensured that no machine would function on a partially full tank. Fuel volume was converted to an equivalent heating value in British Thermal Units (BTUs) assuming that one gallon of diesel fuel was approximately equal to 137,000 BTUs, as described by Adams (1983).

Energy content of harvested biomass was expressed in BTUs. Identical to the traditional harvesting system energy analysis for objective 1, RHV for woody biomass energy output measurements were calculated with the formula described by Ince (1979) in equation [1]. For reference:

$$RHV = HHV \cdot (1 - MC_{wb}) - HL \qquad [1]$$

Where:

RHV=recoverable heating value, BTUs/pound

HHV= higher heating value, BTUs/pound

$MCwb$= wet-basis moisture content, percent

HL= heat loss, BTUs/pound

Heat loss assumptions followed the procedures described by Pan et al. (2008a), which were detailed by Ince (1979), where: the combustion heat recovery system was assumed to operate with 40 percent excess air and a stack gas temperature of 500°F. These values are fairly typical for an industrial system. Other assumptions included a constant conventional heat loss factor of 4 percent, the ambient temperature of the biomass was 68°F before combustion, and complete combustion occurred for each sample.

MC values were determined for each plot of the plantation following chipping by the Ny Vraa harvesting unit. An FBIC worker would collect a thoroughly mixed sample of the biomass from each plot in a 12x7x17in paper bag. All samples were sealed for subsequent MC testing at the FBIC on November 1st 2014. MC calculations were taken from random samples of all 20 willow hybrid species that were selected once from all four of the randomly distributed plot types, resulting in each willow species being replicated four times each (random samples from all 80 plots were tested). Procedures for determining MC followed the American Society of Testing and Materials E 871-82 guidelines (ASTM 2006). All dry samples were then placed in frozen storage until HHV/RHV testing which took place on October 2015 at Michigan State University.

HHV/RHV calculations were taken from random samples of all 20 willow hybrid species following thorough mixing of each same-species sample from all four replicated plots. This resulted in 20 total samples for HHV/RHV testing. Evaluation was conducted based on methods described by ASTM standards (E 0711-087) (ASTM 2003) using oxygen bomb calorimetry. Each sample was tested two times to ensure statistical significance, and to generate a mean HHV/RHV for each willow species (eight tests per clone). A one-way ANOVA analysis was performed to detect variance between samples, and to compare the mean HHV/RHV of each sample.

5. HARVESTING SYSTEM EVALUATIONS: RESULTS & DISCUSSION

5.1. Traditional harvesting system

5.1.1. Productivity estimates

Cycle time regression equations (Table 7) from the time and motion study were found to have significant *p*-values ($p<0.05$, $\alpha=0.05$) for the developed feller-buncher and loader-grinder models. The cycle time equation for the feller-buncher showed that moving distance and the number of cuts per cycle had impacts on cycle time. The result was that overall stand density and overall tree size influenced cycle time. Operating in a stand with higher stem density or harvesting larger sized trees intuitively may reduce overall cycle time. With all other variables held constant, a stand with higher tree density (1,089 TPA vs. 777 TPA) would require shorter travel distances while being harvested, resulting in increased productivity represented through an overall shorter cycle time. Similarly, a stand with larger sized trees (4.7 in DBH vs. 2.5 in DBH) would require less cuts to make a full bunch, again increasing productivity through a decrease in cycle time.

The skidder's "Travel Empty Distance" was found to be statistically insignificant in predicting average cycle time because only one biomass bunch was being skidded per cycle. Both travel distance variables therefore suggested essentially the same thing, resulting in correlation, suggesting multicollinearity. Similarly, the number of trees collected to make a full skid load was also statistically insignificant in predicting average cycle time suggesting that the size of the biomass bunches created by the feller-buncher were properly made for the skidder's grapple diameter. In this study, the skidder cycle time was most influenced by the distance between bunched piles and the landing area. Model validation procedures showed statistically insignificance (p>0.05) between the observed and predicted cycle times for both the feller-buncher and the skidder.

Table 7: Delay-free average cycle time equations for traditional harvesting system machines.

Machine	Average cycle time estimator (centi-minute)	Associated *p*-value	Variable range	Mean	r^2	n[a]	Validation *p*-value[b]
Feller-buncher	= 8.766	0.001			0.85	125	0.36
	+ 0.564 (move to tree distance in feet)	<0.001	0 to 90	16.2			
	+ 8.816 (number of cuts per cycle)	<0.001	1 to 12	5.8			
	+ 0.325 (move to bunch distance in feet)	<0.001	0 to 82.5	14.0			
Skidder	=49.180	0.001			0.73	36	0.53
	+0.690 (positioning distance in feet)	<0.001	0 to 45	12.0			
	+0.467(travel loaded distance in feet)	<0.001	67.5 to 322.5	178.0			
Loader-Grinder	= 20.864	<0.001			0.28	32[c]	**[d]
	+ 0.239 (number of trees per cycle x DBH in inches)	0.001	13 to 54.6	31.4			

[a]*p*-value provided by two sample-t-test between predicted and observed cycle times.
[b]67 percent of the total observed data n was used for model training.
[c]100 percent of the total observed data n was used for model training.
[d]No *p-value* available.

The predicted production rate, in oven dry tons per productive machine hour, was calculated for the feller-buncher, skidder, and the loader-grinder by using average biomass weight per operation cycle divided by the predicted operation times per cycle (Table 8). Average biomass weight for the stand was calculated to be 15.45 ODT/AC based on results produced for all poplar hybrids (with a minimum of 6.20 ODT/AC, and a maximum of 28.10 ODT/AC). Production rates for the feller-buncher, skidder, and loader-grinder were determined to be 9.73, 34.32, and 39.07 ODT/PMH, respectively. These predicted production rates reflect how harvesting operations were affected by site conditions.

Table 8: Predicted delay-free average cycle time and production rate for the traditional harvesting system.

Machine	Cycle Time (min)	Production Rate (ODT/PMH)
Feller-Buncher	0.75	9.73
Skidder	1.50	34.42
Loader-Grinder	0.28	39.07

5.1.1.1. Unproductive delays

Unproductive organizational, mechanical, and personal delays are presented in Table 9 with associated total production times and utilization rates. Both the feller-buncher and skidder had a minimal amount of delay, which resulted in high utilization rates of 98.9 % and 90.8 %, respectively. Because the agricultural marginal land available for SRWC is often small in size within the Lake States region, the types of delay that are common to large-scale and balanced commercial timber harvesting operations were not present in this study. As a result, the high utilization rate of the feller-buncher can be attributed to the small stand size associated with the study. Mechanical and personnel delays normally associated with larger logging jobs did not occur in this small 7.8-AC stand.

Delays (and costs) associated with the frequent shifting between stands often seen in small harvest operations also did not occur. The only delay for the feller-buncher was an organizational delay caused by pausing to arrange the bunched tree piles to accommodate access through the stand.

Table 9: Unproductive delay summary for traditional system harvesting operation.

Machine	Organizational delay	Mechanical delay	Personal & others[a]	Total delay	Utilization rate
			(min)		(percent)
Feller-buncher	1.45 (100)[b]	0	0	1.45 (100)	98.9
Skidder	5.07 (64.4)	2.8 (35.6)	0	7.87 (100)	90.8
Loader-Grinder	18.49 (100)	0	0	18.49 (100)	35.8

[a] Other delay includes research delay.
[b] Value in parenthesis indicate % of total.

The skidder's high utilization can be attributed to the biomass being decked in field over the winter. As a result, all organizational delay between the skidder and feller-buncher was removed. Sources of organizational delay were due to the skidder needing to organize grapples, needing to pick up dropped stems, and waiting for the loader-grinder crane to clear its position from the landing location. The source of mechanical delay came from tire traction loss while attempting to pile skids at the landing.

The loader-grinder combination had the lowest utilization rate of the operation at 35.8 % because it functioned as a concurrent system with dependence on the skidder. The loader-grinder cycle was much faster than the skidder cycle so it often had to wait for the skidder to provide biomass. This accounted for 89.7 % of the total organizational delay. The other 10.3 % of the organizational delay was for cleaning the landing area to provide better access to the skidder. The loader-grinder did not experience any other type of delay, including delay associated to waiting for chip van operators.

5.1.2. Production cost estimates and the effect of utilization rate, the number of machines, and varied stand density on harvesting system productivity and cost.

The cost of biomass production was estimated to be \$20.23/ODT under actual conditions. The leading contributors to this cost were the feller-buncher, which had a relatively low productivity rate, and the grinder-loader, which had a relatively low utilization rate. Equipment utilization in the observed system was unbalanced. In this small study, the grinder-loader was idle more often than the other equipment. To better understand costs that might be typical of a large-scale operation, a sensitivity analysis was conducted on the traditional harvesting system. The effect of equipment utilization rate on the total production cost (\$/ODT) was determined by setting utilization rates of each piece of equipment to an equal level of 90, 80, 70, 60 and 50 percent with results presented in Table 10. In a more balanced system where operations achieve an overall utilization rate of 80 % (Smidt et al. 2009), a total production cost of \$16.26 can be realized. Although the utilization rate of the feller-buncher and skidder was higher in the actual condition, overall production costs decreased with a decrease in system utilization, suggesting that the loader-grinder's utilization rate had a large influence on production costs (Figure 19).

Table 10: Production cost of associated traditional system harvesting equipment (\$/ODT).

Utilization	Production Cost (\$/ODT)			
(%)	Feller-Buncher	Skidder	Loader-Grinder	Total
Actual[a]	7.45	1.93	10.85	20.23
50	14.73	3.51	7.77	23.79
60	12.28	2.93	6.47	21.68
70	10.52	2.51	5.55	18.58
80	9.21	2.20	4.85	16.26
90	8.18	1.95	4.32	14.45

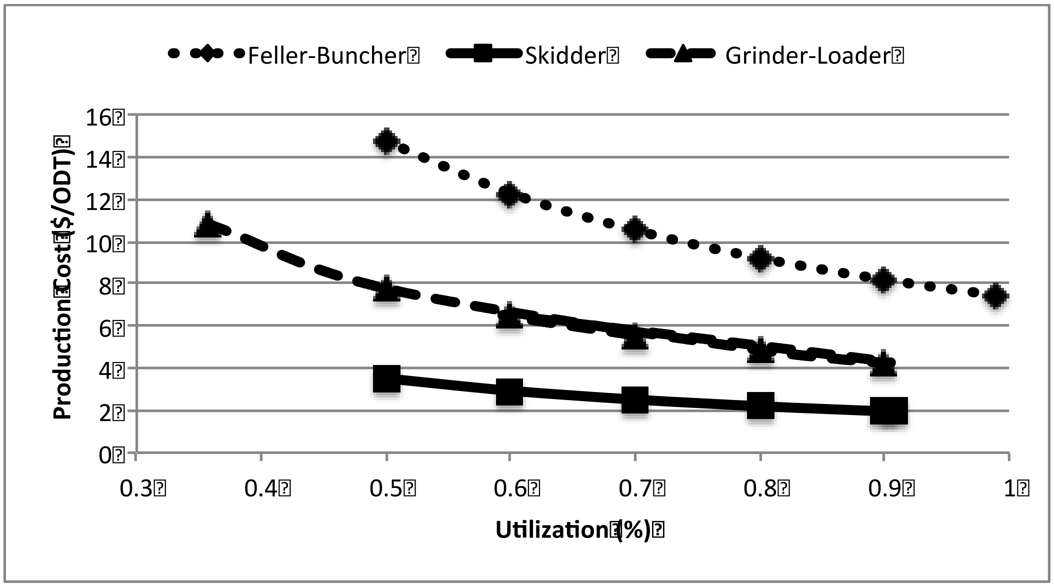

Figure 19: Production cost sensitivity analysis with changes in utilization rate for the traditional harvesting system.

Because the loader-grinder experienced a low utilization rate as a result of idling, a scenario was run to determine the effect of utilizing two skidders simultaneously to better provide ample amounts of feedstock. With this introduction into the harvesting system, the downstream loader-grinder utilization would subsequently double to approximately 71.6 %, assuming both skidders were each as productive as the individual skidder used in the actual operation. Under this assumption, the combined production rates for the two skidders would double to 68.63 ODT/PMH, while the per-ton costing would remain the same at $1.93/ODT. The loader-grinder production cost, on the other hand, would subsequently decrease to approximately $5.42/ODT, from $10.85/ODT. In total, production costs of the harvesting system would decrease from $20.23/ODT to $14.80/ODT as a result of these changes in the number of machines.

A second scenario was conducted by simulating a stand condition with doubled stem density (1,760 TPA). In this scenario, the space between trees was reduced by one half. The move-to-tree distance and move-to-bunch distance variables in the cycle time regression model were, thus, reduced by one half for the feller-buncher. With this change, feller-buncher cycle time decreased to 0.68 minutes, the production rate increased to 10.73 ODT/PMH, and the production cost decreased to \$76.76/ODT. The skidder and loader-grinder, though, experienced no change in productivity or cost because cycle time and utilization remained the same. In total, a doubling of the stand density would decrease production costs from \$20.23/ODT to \$19.54/ODT.

5.1.3. Net energy analysis

5.1.3.1. Energy input

Diesel fuel consumption for each piece of machinery in the traditional system, as well as the energy equivalent in BTUs, is shown in Table 11. A total of 230.8 gallons ($31.6*10^6$ BTUs) of diesel fuel was consumed by the equipment over the course of the operation. The feller-buncher consumed the most diesel fuel (45.0 %) because it had the longest operation time of 14.4 hours. The skidder, loader, and grinder each consumed less diesel fuel because they were able to complete their operations in approximately 4 hours.

The grinding unit also had relatively high diesel fuel consumption due to its 765 hp engine. The skidder had a higher direct diesel input than the loader even though both machines operated for approximately the same amount of time, most likely due to the skidders higher rate of utilization (Table 9).

Table 11: Direct diesel consumption for the traditional system harvesting operation.

	Feller-buncher	Skidder	Loader	Grinder	Total
Direct diesel input (gal)	103.9	23.8	20.8	82.3	230.8
Heating value[a] (MMBTUs)	14.23	3.26	2.85	11.28	31.62
Consumption (gal/hr)	7.20	5.95	5.20	20.58	38.92
Consumtion Rate[b] (gal/hr/hp)	0.036	0.029	0.032	0.030	N/a
Percent total	45.0%	10.3%	9.0%	35.7%	100.0%

[a]Produced ground woody biomass was not uniform in size.
[b]At an average loaded skid distance of 166ft.
[c] :137,000 BTUs per gallon diesel fuel.

5.1.3.2. Energy output & net energy ratio

The calculated mean higher heating value (HHV) from the 7 different poplar genotypes was determined to be approximately 8,517 BTU per oven dry pound (BTU/OD lb.) with a standard deviation of 660.60 BTU/OD lb., which was approximately 7.75 % of the mean. From equation [1], the total RHV was 2,902 BTU/lb., based on a stack gas heat loss due to moisture, hydrogen, and dry gas/excess air equal to 585.85, 356.74, and 489.06 BTU/lb. respectively. The conventional heat loss factor as part of the total heat loss was equal to 180.58 BTU/lb.

During the study, 265.06 green tons of ground woody biomass was produced from the poplar stand. The ground biomass had an average moisture content of 47.0 % and, thus, were equal to 140.48 oven dry tons. This was equivalent to a recoverable gross energy content of 815.40 MMBTUs. The net energy output was determined to be 783.78 MMBTUs after subtracting the energy inputs due to diesel consumption. The energy ratio between the net recoverable energy output and diesel fuel input was therefore approximately 24.8:1.

5.2. Tractor-pulled reconfigured forage harvesting system

5.2.1. Productivity estimates

Based on the average time required to harvest an entire plantation row (482.5 seconds) and subsequently travel the width of the plantation to harvest in the opposite direction (42 seconds), it took the tractor-pulled reconfigured forage harvesting system approximately 4.13 hours to harvest the entire 1.1 AC study site. In total, the harvesting system spent 4.02 hours (97.3%) of its time actually harvesting, while the remaining 0.11 hours were spent traveling between plantation lanes (minus the time required to collect chip samples). Although the operator was not actively harvesting while traveling between lanes, this was not considered to be a form of delay because it was a necessary component of producing biomass with this type of production system. With an average MC_{wb} of 43.50% for all plots within the stand, 7.18 ODT of biomass was produced. The result was an overall production rate of approximately 1.74 ODT/PMH with a utilization rate ≈100%. It should be noted, though, that a utilization rate this high might not be typical of a normal harvesting operation. Although the skid steer loader was separate from the harvesting unit (tractor and harvester), it was also considered to have a utilization of 100% because it did not hinder the movements and actions of the tractor and harvester.

5.2.1.1. Unproductive delay

The harvest operation that took place in Albion saw virtually no unproductive delay from the operating equipment, resulting in a very high utilization rate of approximately 100%. This can be attributed to the small size of the harvested plantation (1.1 AC). The result was that the operating machinery did not breakdown or experience any issues harvesting the willow stems. Similarly, the operators did not require breaks or need to stop operations over the duration of the time trial. Although a utilization rate of nearly 100% is good for operations productivity, it cannot be considered normal of a large-scale operation. With a standard and productive utilization rate set (arbitrarily) at 85%, the production rate will be more representative of a typical operation that is larger in size. As such, the production rate for the tractor-pulled reconfigured forage harvesting system would subsequently drop to 1.51 ODT/PMH with this lower utilization rate. Figure 20 represents this concept graphically with use of a sensitivity analysis with respect to harvesting system utilization. Table 12 displays the values of Figure 20 numerically as well as the resulting time required to harvest the entire plantation.

Table 12: Sensitivity analysis results on reconfigured forage harvesting system productivity.

Utilization Rate (%)	Total Harvesting Time (hrs)	Production rate (ODT/PMH)
1.00[a]	4.13	1.74
0.85	4.75	1.51
0.75	5.16	1.39
0.65	5.58	1.29
0.55	5.99	1.20
0.45	6.40	1.12

[a]Actual utilization rate

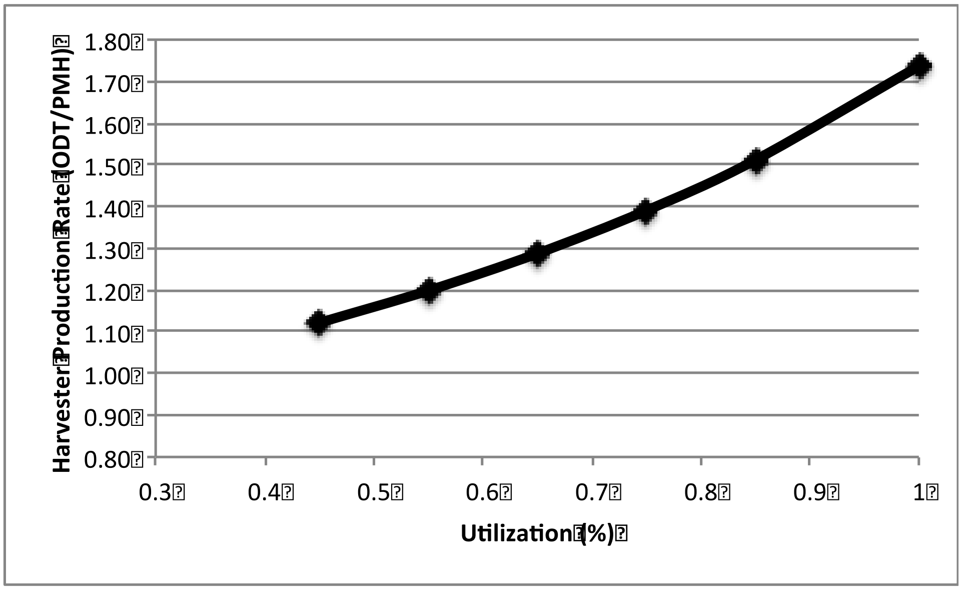

Figure 20: Production rate sensitivity analysis with changes in utilization rate for the tractor-pulled reconfigured forage harvesting system.

5.2.2. Production cost estimates

Based on a utilization rate of approximately 100% for the entire harvesting system, the cost of biomass production was estimated to be $40.72/ODT. Although the utilization rate was very high, this production cost compares favorably with published data from other studies (Table 1), where Berhongaray et al. (2013) determined the production cost of a Ny Vraaa JF Z200 & John Deere 8520 harvesting system to be approximately $47.97/ODT under similar conditions. At an arbitrarily balanced utilization rate of 85%, the production cost would be approximately $50.23/ODT. With the production rate held constant (at 1.74 ODT/PMH), a sensitivity analysis was conducted on the system production cost, to accompany Figure 21. Both the harvesting unit and the skid steer loader were set to an equal utilization of 85, 75, 65, 55, and 45 percent. Results are presented graphically in Figure 21, with numerical values in Table 13.

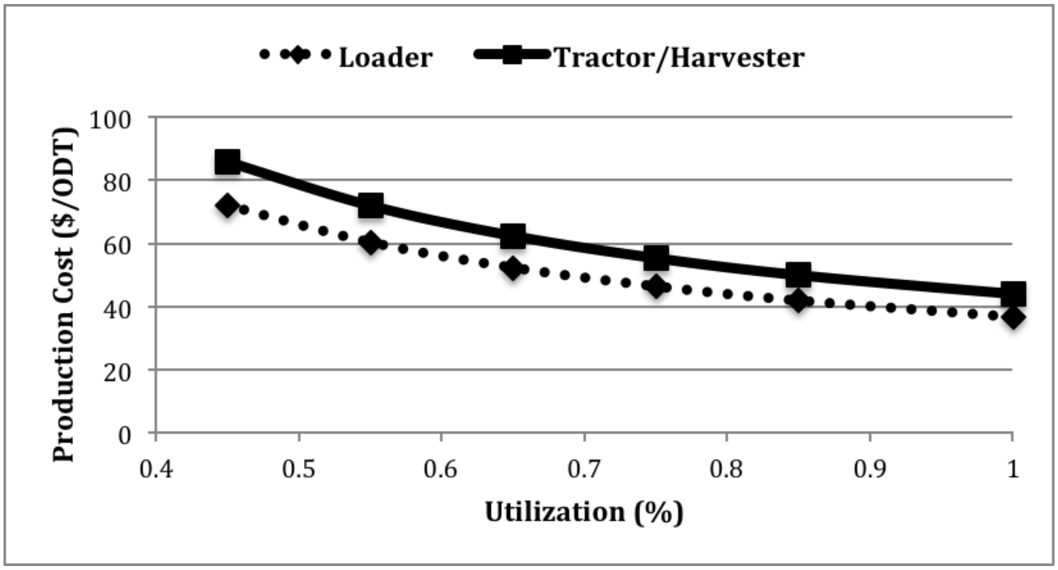

Figure 21: Production cost sensitivity analysis with changes in utilization rate for the tractor-pulled reconfigured forage harvesting system.

Table 13: Sensitivity analysis results on reconfigured forage harvesting system production costs.

Utilization (%)	Production Cost ($/ODT)		
	Tractor/Harvester	Loader	Total
1	44.18	36.99	81.17
0.85	50.23	42.07	92.31
0.75	55.62	46.59	102.21
0.65	62.66	52.49	115.15
0.55	72.26	60.55	132.80
0.45	86.12	72.18	158.30

5.2.3. Net energy analysis

5.2.3.1. Energy input

Diesel fuel consumption for each piece of machinery, as well as the energy equivalent in BTUs, of this reconfigured forage harvesting system is shown below in Table 14. A total of 5.50 gallons (753,500 BTUs) of diesel fuel were consumed by the equipment over the course of the entire operation. At 71 percent, the harvesting unit, made up of the tractor and harvester, consumed the most fuel due to the larger horsepower motor and the required intensity of work to produce woody biomass chips.

Table 14: Direct diesel consumption for the reconfigured forage harvesting system harvest operation.

	Harvesting Unit	Skid Steer Loader	Total
Direct diesel input (Grigal, Ohmann et al.)	3.90	1.60	5.50
Heating value[a] (BTUs)	534,300	219,200	753,500
Consumption (gal/hr)	0.94	0.39	1.33
Consumtion Rate (gal/hr/hp)	0.01	0.0[b]	N/a
Percent total	71%	29%	100%

[a]137,000 BTUs per gallon diesel fuel.
[b]Value too small to be represented through significant digits

5.2.3.2. Energy output

The calculated mean HHV from the 20 different hybrid willow genotypes was determined to be approximately 8,014 BTUs/OD lb. From equation [1], the average RHV was 2,903 BTUs/lb., based on an average stack gas heat loss due to moisture, hydrogen, and dry gas/excess air equal to 600, 400 and 500 BTUs/lb., respectively. The conventional heat loss factor as part of the total heat loss was equal to 200 BTUs/lb.

During the test 13.54 green tons of ground woody biomass was produced from the willow stand. The chipped product had an average moisture content of 43.5 percent and, thus, was equal to 7.65 oven dry tons. This was equivalent to a recoverable gross energy content of 78.66 MM BTUs. The net energy output was determined to be 13.90 MM BTUs after subtracting the energy inputs due to diesel consumption. The energy ratio between the net recoverable energy output and diesel fuel input was therefore approximately 18.4:1.

6. HARVESTING SYSTEM EVALUATIONS: SUMMARY & IMPLICATIONS

This chapter of the thesis evaluated the cost and productivity of utilizing a traditional ground-based harvesting system and the tractor-pulled cut-and-chip reconfigured forage harvesting system to produce woody biomass from a short rotation woody crop plantation.

The traditional system evaluation took place in a 7.8 AC spacing trial that compared seven poplar hybrid species. Trees ranged in size from 2.5 to 4.7 inches at breast height in an average stand density of 880 TPA. Multiple linear regression models were developed from a time and motion analysis to show machine productivity ranging from 9.73 ODT/PMH for the feller-buncher to 39.07 ODT/PMH for the loader-grinder, with the skidder at 34.32 ODT/PMH. Production cost for ground woody biomass at the farm gate was calculated to be $22.30/ODT, where farm gate refers to all incurred costs of producing woody biomass grindings from harvesting up until transportation. Transportation costs were not included in this analysis.

A net energy analysis was conducted on the traditional system to compare diesel fuel inputs and recoverable energy outputs of the harvested biomass. During the trial, 265.06 green tons of woody biomass was harvested at a MC of 47 %. This material had an average higher heating value of 8,517 BTU /OD lb. and a RHV of 2,902 BTU/OD lb. Over the course of harvesting, skidding, loading, and grinding 230.8 gallons of diesel fuel were used, resulting in a net energy ratio of 24.8:1.

The tractor-pull cut-and-chip reconfigured forage system evaluation took place in a 1.1 AC SRWC willow plantation. Trees ranged in size from 0.5 to 1.0 inches at breast height in a stand density of 9600 TPA. Time trial results demonstrated a harvesting system production rate of approximately 1.7 ODT/PMH. Production costs for ground woody biomass at the farm gate with the utilized harvesting system was calculated to be $141.1/SMH. Similar to the traditional harvesting system analysis, transportation costs were not included in this analysis.

A net energy analysis was conducted on the reconfigured system to compare diesel fuel inputs and recoverable energy outputs of the harvested biomass. During the trial, 13.54 green tons of woody biomass was harvested at a MC of 43.5 %. This material had an average higher heating value of 8,014 BTU /OD lb. and a RHV of 2,903 BTU/OD lb. Over the course of harvesting and collecting, 5.50 gallons of diesel fuel were consumed, resulting in a net energy ratio of 18.4:1.

From the information provided in Harvesting System Evaluation sections, summarized below in Table 15, both analyzed harvesting systems offer stakeholders feasible alternatives to the self-propelled reconfigured forage harvesting system (CNH information in Table 15 was retrieved from Table 1). The results demonstrate that the traditional harvesting system can produce woody biomass feedstock from a SRWC poplar stand in a manner that is arguable superior or equivalent to the CNH harvesting system. Although the traditional system's machine hourly rate of $283.6/SMH was higher from the provided metrics, it should be considered similar to the CNH harvesting system because labor costing was not included in the compared study. The results of this study indicate, therefore, that Lakes States loggers who currently own and utilize the traditional system can competitively produce biomass feedstock while forgoing the need to purchase expensive, state-of-the-art self-propelled cut-and-chip harvesting systems.

Table 15: Harvesting system evaluation summary of production rates, production costs, ownership costs, and net energy ratio.

	Harvesting System		
	Traditional	Tractor-pulled Reconfigured	CNH self-propelled
Production Rate (ODT/PMH)	9.7-39.1	1.7	10.0-21.0
Production Costs ($/ODT)	20.23	81.17	27.8
Machine hourly rate ($/SMH)	283.6	141.10	242.0[a]
Purchasing Price ($, new)	848,000	202,334	474,000[b]
Net Energy Ratio	24.8	18.4	N/a

[a]Owner/operator costs do not include labor.
[b]Includes capital cost of the harvesting unit only.

While its production rate and cost is left to be desired, the tractor-pulled cut-and-chip reconfigured forage harvesting system had the most superior machine hourly rate of all analyzed studies, at $141.1/SMH. Because it presents the lowest barrier to entry (at $202,334), this system may be the best solution for stakeholders who have none of the necessary harvesting equipment, but are interested in SRWC biomass production. Having included a necessary tractor within the metrics of Table 15, the machine hourly rate and purchasing price will beneficially drop even further if the owner/operator has purchased a tractor prior to purchasing a tractor-pulled harvesting unit. With an available tractor and fallow agriculture land at hand, the tractor-pulled cut-and-chip harvesting system presents a good option for farmers who are interested in producing SRWC biomass at a small-scale.

6.1. Study Limitations

The information presented from these case studies were not encompassing of all SRWC harvesting scenarios. All implications should, thus, be restricted to the demonstrated set of conditions. Because the analyzed poplar and willow stands were 7.8 AC and 1.1 AC in size, respectively, the utilization rate of all independently functioning equipment was uncharacteristically high. This had downstream effects on machine productivity and machine hourly rate values. A larger sized stand may exhibit lower machine utilization due to: an increased probability of machine breakdown, increased focus on biomass organization, and necessary operator stoppages. Furthermore, each analyzed stand consisted of only one SRWC species, at one particular age, variably spaced in a way that was conducive for research. With many different agronomic bioenergy crop options available, the demonstrated implications must remain within the context of the study to be considered as truthful and accurate.

7. ECONOMIC ANALYSIS: DATA COLLECTION & ANALYSIS

Although specific objectives will ultimately vary between individuals and stakeholders, it can be assumed that all involved parties will seek to maximize revenue from their produced timber crops (Grossman and Potter-Witter 1991). As a result, this portion of the thesis is concerned with presenting pertinent information related to the determination of SRWC economic feasibility. Through a consideration of woody crops strictly as a store for capital, the inclusion of more stakeholders will be considered, ultimately furthering woody biomass as a fuel alternative. All endeavors that are centralized around cash flow require an understanding of their economic potential. As such, the economic investigations of this thesis included: breakeven scenario analyses to explore different cost-optimizing opportunities available throughout the supply chain, benefit/cost analyses (through net present values, benefit/cost ratios, and internal rates of return) to quantitatively weight the benefits and costs associated with producing woody biomass for bioenergy, and hedonic regression to determine what, from the given metrics, most influenced biomass accumulation while the SRWC species were being grown and tended to. The following subsections of Chapter 7 will discuss these concepts in detail.

7.1. Breakeven scenario analysis

A breakeven analysis is utilized to determine the set of factors within an investment that will make it profitable, based on potential influential aspects within the investment. As such, a breakeven analysis was conducted on the traditional and reconfigured forage harvesting systems to determine what aspects within the supply chain would allow these systems, and their surrounding up/downstream supply chains, to return a profit or increase their return on investment. Because the biomass produced from these sites was done so for research purposes, operations were not always conducted with efficiency and cost-reduction as the main objective. With this in mind, multiple simulation scenarios were conducted coinciding with the breakeven analyses to provide insight about the system profitability. These simulation scenarios will help in identifying the most costly aspects within the supply chain and subsequently examine the effects on profit following achievable optimization procedures.

In total, five separate breakeven/simulation analyses were conducted for both the traditional harvesting and reconfigured forage harvesting systems. Such analyses included:

1. A scope-limited breakeven analysis encompassing all components associated with producing woody biomass feedstock, from harvesting up to the farm gate. This particular analysis included only field-observed data from both of the analyzed harvesting systems.
2. An expanded-scope breakeven analysis on both harvesting systems encompassing all inputs for research purposes: from site setup through delivery to the end user (the biomass conversion facility).
3. An expanded-scope generalized breakeven analysis conducted on both harvesting systems, from site setup through delivery to the end user. In this instance, case-study specific costing information was removed in place for literature-generated values. This analysis, therefore, utilized generalized hourly rates for all machinery within the analyzed supply chain, based on information provided by Miyata (1980) and the Food and Agriculture Association of the United Nations (1999).

4. A simulation scenario reducing the cost impacts of labor by removing research-related plantation setup/maintenance activities and introducing simulated cost-saving activities, including mechanical tree planting.
5. A simulation scenario that combined optimized labor inputs with increased stand density, from site setup through biomass delivery.

Cost estimation pertaining to site preparation, stand initiation, and site upkeep was provided from in-field data collected by FBIC researchers. The author collected cost estimation for the harvest operation, and loading/transport costs were estimated through simulations from a combination of author-collected in-field data and literature.

7.2. Benefit/cost analysis

To prioritize a potential investment, stakeholders must weigh the generated benefits relative to the incurred costs. These investments generally have an initial cost (or costs), which will give rise to future benefits over time. All other things aside, though, the most efficient investment minimizes costs and maximizes the potential benefits. To weigh the benefits and costs of an opportunity, a benefit/cost analysis is performed (Zhang and Pearse 2011).

Benefit/cost analyses do not distinguish between the advantages (or lack thereof) of different projects, but rather determines if an individual project presents a net benefit for the investor. Every opportunity is different, and because this type of analysis considers the feasibility of a stochastic biological system, comparisons between projects can be considered inappropriate. Among the multiple project priority criteria that have been identified for use in the benefit/cost analysis, via Zhang and Pearse (2011) and Klemperer (1996), net present values (NPV), benefit/cost ratios (B/C), and internal rates of return (*i*) were analyzed to determine how beneficial each of the two studied harvest operations would be for a potential investor. These project priority criteria were chosen over others because they provide investors with readily identifiable values for which to base a potential investment.

7.2.1. Net present value

The net present value, or net benefit, of an opportunity discounts all future benefits and costs to present time (Klemperer 1996; Zhang and Pearse 2011). Intuitively, the greater the gain in benefits over costs from a potential project will be reflected in the NPV calculation, allowing investors a quick and easy way to quantitatively understand a project's potential viability. In this instance, the larger the NPV value the better the investment. SRWC are considered to be a finite periodic series because they are often fertilized, coppiced, and harvested at regular periodic intervals for a finite period of time. Both of the analyzed plantations that were harvested for this thesis are expected to function in this manner. As such, finite periodic series NPV is expressed below in equation [2], where the woody crops are assumed be harvested and sold at the optimal rotation age for their specific use.

$$NPV = \sum_{q=0}^{t-y}\left[\frac{R_q}{(1+r)^q} - \frac{C_q}{(1+r)^q}\right] \qquad [2]$$

Where:

t = optimal rotation age of clearcut

y = an index for years from 0 to t

q = an index from 0 to t-y years between year y and clearcutting age t

R_q = the present value of all revenues

r = real interest rate

C_q = present value of all costs

In essence, equation [2] sums the difference between all discounted revenues R_q and costs C_q over time t starting at time 0. If the output from this calculation is positive, the investment opportunity can be considered to be beneficial for the investor.

7.2.2. Benefit/cost ratio

The benefit/cost ratio provides investors who have a fixed budget with a metric for which to measure the efficiency of expended funds (or potential expenditures). The ratio measures the economic efficiency of all utilized resources input to the system. Similar to the NPV calculation, a higher B/C ratio will generate maximum net benefits from limited investment funds (Klemperer 1996). The B/C ratio equation is simply a ratio of equation [2]. Following algebraic manipulation, though, the equation appears somewhat different and, thus, utilizes slightly different notation. The ratio also does not require the assumption of optimal rotation age. It can be found below in equation [3]:

$$\frac{B}{C} = \frac{\sum_{y=0}^{n} \frac{R_y}{(1+r)^y}}{\sum_{y=0}^{n} \frac{C_y}{(1+r)^y}} \qquad [3]$$

Where:

n = project life, years

y = an index for years

R_y = revenue in year y

r = real interest rate

C_y = cost in year y

7.2.3. Internal rate of return

The internal rate of return provides investors who are only interested in the return on the capital they invest with a value to determine the priority of a potential project. Many investors are familiar with IRR because it has the appeal of simplicity where a larger value is always better. The IRR (equation 4) provides a percentage rate for which the initial investment will grow over the course of the projects lifetime, based linearly on expected eventual benefits. This calculation differs from the previous two presented methods of investment prioritization in that all associated costs are accounted for and, thus, the return on invested capital is treated as residual.

$$\sum_{y=0}^{n} \frac{R_y}{(1+IRR)^y} - \sum_{y=0}^{n} \frac{C_y}{(1+IRR)^y} = 0 \qquad [4]$$

Where:

n = project life, years

y = an index for years

R_y = revenue in year y

IRR = internal rate of return

C_y = cost in year y

4] is the same as the traditional NPV calculation (equation 2), and must be subsequently rearranged to solve for IRR.

7.3. Hedonic regression

Hedonic regression analysis decomposes the output of a researched topic in to separate constituent variables, and then analyzes each variable for its contribution to that particular outcome through a multiple linear regression model (Zhang and Pearse, 2011). Because each analyzed site was utilized as a spacing study, meticulous records were kept pertaining to the performance of different SRWC species that were grown and tended to. Following their harvest, the performance metrics of these crops could subsequently be analyzed to determine how well they predicted the production of the produced biomass (in ODT/AC-yr). Such metrics for analysis included: the different clone genotypes, plot spacing treatments, the number of stems in a given plot, average plot DBH, and plot survival rate. The hedonic regression can provide useful information for predicting future output variables that have similar constituents with a similar range of variability. Regressions such as this have yet to be done for SRWC poplar and willow.

7.4. Harvesting system economic inputs

7.4.1. Traditional Harvesting System

7.4.1.1. System input overview

All system inputs utilized to produce a ground woody biomass product from a single 7-year rotation SRWC poplar plantation are presented below, in Table 16 (in $/ODT). Calculations for all fixed, operating and labor costs were generated from in-field data collected by the FBIC, time and motion analyses, or from simulated model data. This information can be found in Table 58 and Table 59 of Appendix B: Economic input background information. Further information can be found Table 5 and Table 6, as well.

The values that populate Table 16, below, reflect the actual condition of producing ground woody biomass for FBIC research purposes, with the addition of a simulated transport operation to make a complete supply chain. The presented data should be considered as documentation of field research experimentation. Subsequent scenario analyses examined potential optimization opportunities for the components within the presented supply chain.

Table 16: Itemized per-ODT system cost inputs for a single 7-year harvest rotation, with use of a traditional whole-tree harvesting system.

System Input	Fixed Cost ($/ODT)	Oper. cost ($/ODT)	Labor Cost ($/ODT)	Info. Source
Site Preparation & Stand Initiation: Year 0.0				
Tilling/Spading	0.33	0.91	3.0	FBIC
Poplar hand planting	0.0	0.0	161.44	FBIC
Herbicide Application[a]	0.13	3.82	2.10	FBIC
Site Upkeep: Year 1.0				
Herbicide Application[b]	0.0	0.02	5.83	FBIC
Insecticide Application	0.0	0.21	0.90	FBIC
Harvest Operation: Year 7.0				
Feller-Buncher	1.33 (5.33)[c]	2.70 (10.79)	3.41 (13.64)	Field coll.
Skidder	0.76 (3.05)	0.58 (2.34)	0.59 (2.34)	Field coll.
Loader	1.56 (6.22)	0.50 (2.01)	2.35 (9.39)	Field coll.
Grinder	4.22 (16.88)	2.23 (8.92)	0.0 (0.0)	Field coll.
Chip van transport	5.41 (21.65)	6.43 (25.72)	8.06 (32.24)	Sim
Post-Harvest Upkeep: Year 7.5				
Herbicide Application[d]	0.0	0.33	1.14	FBIC
Total per-ODT cost of single plantation rotation				
Itemized Total[e]	13.75 (53.59)	17.73 (55.72)	188.79 (234.27)	
System Total[f]	220.27 (343.59)			

[a]Scepter, pendulum and glyphosate application.
[b]Glyphosate application.
[c]Parenthesis= cost of system input (in $/ODT) for entire 28-year plantation lifespan.
[d]Credit 41 application.
[c]Itemized total on an hourly basis for a single harvest operation: fixed cost= $159.4/SMH, operating cost= $246.25/PMH, labor cost= $503.89.
[f]Total hourly cost of the supply chain= $840.7/SMH.

Sections 7.4.1.2-7.4.1.7, below, provide background into how the values of Table 16 was generated.

7.4.1.2. FBIC input assumptions

Input information for site preparation, stand initiation, and upkeep were provided from records kept by the FBIC. Specifically these records were research-related, and detailed metrics necessary for experimental silvicultural replication. As such, the FBIC employees did not document some specific details required for the economic analysis, due to their erroneous nature. Assumptions for specific details that were not collected for FBIC field experimentation were provided from researchers who were directly involved with the stand as “best-guess” estimates. All mechanical equipment utilized by the FBIC was assumed to have been purchased new under the Miyata methodology, while fuel information was taken from local market prices at the time of the operation. Fuel efficiency information was taken from data provided by Benjamin et al. (2000). Table 62 and Table 63**,** in Appendix B, provides a summary of all the FBIC data and assumptions utilized within the economic analysis.

Subsequent optimization scenarios sought to reduce the monetary impacts associated with site setup costs through utilization of a mechanical planter. Researchers at the FBIC and TRC provided productivity and cost estimates for the mechanical planter, found in Table 60 of Appendix B. Fixed and operating cost estimation for this equipment was not considered within the economic analysis due to its inconsequential operation time on an hourly basis.

7.4.1.3. Time and motion analysis input assumptions

Economic information for the harvesting system was generated through time and motion analyses. Linear regression models provided predicted productivity estimates for each piece of machinery (in ODT/PMH) that were subsequently utilized to forecast costs based on total operating time and the Miyata hourly costing methodology. Productivity and operating time for each piece of machinery within the harvesting system can be found, in summary, below in Table 17. Complete productivity estimation data for the traditional system can be found in Section 5.1.

Table 17: Traditional harvesting system productivity summary.

Machine	Predicted Productivity (ODT/PMH)	Total operating time (PMH)
Feller-Buncher	9.73	14.44
Skidder	34.32	4.09
Grinder/Loader	39.07	3.60

Breakeven scenario #5 (of Section 8.1.1.1) incorporated a stand density of 1,760 TPA, double the actual in-field calculated density of 880 TPA (averaged). With an increased stand density, machine productivity was subsequently affected as well. To reflect this, the average movement distance inputs (move-to-tree distance and move-to-bunch distance) of the feller-buncher multiple linear regression model was reduced by one half, due to harvested stems being twice as close as the actual condition. With this change, cycle time was reduced to 0.68 minutes and productivity was increased to 10.71 ODT/PMH. With this calculated production rate, the 7.8 AC stand would be harvested in approximately 26.2 hours under the same utilization rate of 98.9%.

With a plantation density doubled from its original, the skidder, loader, grinder, and chip van costing on a per-acre basis was assumed to double as well, though the per-ton cost of producing biomass would remain the same. Although the number of stems per acre would increase, the elemental activities of these four machines would not change. The skidder, loader, grinder, and chip van would subsequently operate at the same capacity, resulting the same levels of productivity. Each machine would thus be required to operate for approximately twice the amount of time because the number of stems doubled per acre.

7.4.1.4. Transport simulation input information

Data for the simulated transport operation was based on the average net weight payload of the eight chip vans that were filled during the course of processing the produced biomass within the harvesting operation (Table 18, below). This information was recorded through ticket payment slips following delivery to Verso Corporation, where the biomass was sold. With an average van weight of 33.13 green tons, approximately 1.0 van was required on a per-acre basis (0.975 calculated vans). Per-hour equipment costing estimation was calculated with the Miyata methodology from data supplied by the logging firm who conducted the operation (please see Table 58 in Appendix B for more information). One-way travel distances were assumed at 50 miles with a total two-way travel time of 2.5 hours one-way (Table 19), for an average speed of approximately 40 miles per hour. Additionally, biomass loading and unloading was assumed to take approximately 27 minutes and 20 minutes, respectively, based on in-field calculations and chip van driver experience.

Table 18: Payload of the chip vans required to transport harvested woody biomass in Escanaba, MI.

Chip Van Number	Payload Weight (green tons per van)
1	49.74
2	31.73
3	36.15
4	29.12
5	28.94
6	28.88
7	29.57
8	30.93
Total	265.06
Average	33.13

Table 19: Payload verification simulation.

	Highway	Pavement	Unpaved
Travel speed (mph)	55	4	1
Travel Distance (miles)	45	35	3
One-way travel time (hr)	1.23	0.11	0.34
Two-way total travel time estimation (hr)			2.53

7.4.1.5. Plantation input assumptions

The price of poplar saplings was not considered in this analysis under the assumption that clonal cuttings could be gathered from existing mature poplar trees and subsequently propagated at a nominal cost. With an existing source of mature poplar trees available, the cost of such saplings would likely be inconsequential to the operation. Furthermore, the cost of poplar parent tree initiation, care, and propagation was considered to be too far out of scope for the size of this particular analysis.

Within the stand density and labor optimization scenario, presented in section 8.1.1.1 (Scenario #5), stand density was doubled to 1760TPA. At this stand density it was assumed that competition between stems would not increase, thereby having no effect on biomass yield. Consequently, doubled stand density was assumed to double the biomass weight at the time of harvesting.

The FBIC ordered to have the SRWC poplar stand harvested at 7 years of age. It was assumed that, for purposes of the economic analysis, the stand would be harvested every 7 years, and be productive for 28 years in total. As a result, it was assumed that the stand would effectively produce equal amounts of biomass for 4 times over the plantation lifespan.

7.4.1.6. Biomass sales input assumptions

Produced biomass was assumed to be sold at a price of $30/green ton, as suggested by Kevin Rush Forest Products Inc., a provider of woody biomass feedstock to MSU's T.B. Simon power plant. Based on an average stand moisture content of 47.0% (calculated from the collected biomass, please see Section 5.1.3.2 for more details), the produced biomass was calculated to be sold at approximately $56.6/ODT. This value was utilized for all generated revenue and profit values at a normal stand density of 880TPA and a doubled stand density of 1760TPA.

7.4.1.7. Labor optimization assumptions

Breakeven scenario analysis #4 (of section 8.1.1.1) for the traditional harvesting system utilized an optimized labor force in order to reduce feedstock production costs. In this scenario, the harvesting system utilization was set to an equal rate of 80 % for all pieces of machinery following felling (skidder, loader, grinder), as suggested by Smidt et al. (2009), for a properly optimized harvesting system. Because harvested biomass was left decked in field over multiple months, the feller-buncher utilization rate was determined to be inconsequential to the downstream productivity of the harvesting system. Because of this, the feller-buncher utilization was left at its calculated rate of 98.9 %.

7.4.2. Reconfigured forage harvesting system

7.4.2.1. System input overview

All system inputs utilized to produce a chipped woody biomass product with a reconfigured forage harvesting system from a single 3-year SRWC rotation is presented below, in Table 20. Calculations for all fixed, operating, and labor costs were generated from in-field data, time and motion analysis, or from simulated models, and are presented in Table 63 and Table 62of Appendix B. Similar to the traditional system, the values that populate Table 20 reflect the actual condition of producing woody biomass for FBIC research purposes, with the addition of simulated loading and transport operations to make a complete supply chain. As such, the system cost total for this particular harvesting system may not reflect those of an actual optimized harvesting operation centered on profit generation. Instead, the presented data may best be considered as documentation of research field experimentation. Subsequent scenario analyses looked to examine potential optimization opportunities for the components within the supply chain.

Table 20: Itemized per-ODT system cost inputs for a single 3-year harvest rotation, with use of a reconfigured forage harvesting system.

System Input	Fixed Cost ($/ODT)	Op. cost ($/ODT)	Labor Cost ($/ODT)	Info. Source
		Site Preparation & Stand Initiation		
Tilling/Spading	2.6	7.1	70.2	FBIC
Cultivation	2.6	7.1	46.8	FBIC
Pesticide application[a]	0.3	3.8	2.9	FBIC
Willow hand planting	0.0	0.0	608.2	FBIC
Pesticide application[b]	0.0	3.8	2.9	FBIC
		Plantation Coppice: Year 0.5		
Coppice Cut	0.3	0.9	2.9	FBIC
		Harvest Operation: Year 3.0		
Harvesting Unit	10.2 (101.6)[c]	9.5 (95.5)	24.2 (241.6)	Field coll.
Biomass Collection	8.0 (79.7)	8.9 (88.9)	24.2 (241.6)	Field & sim.
Biomass Loading	0.5 (4.9)	0.8 (7.7)	2.5 (25.4)	Field coll.
Chip van transport	2.9 (28.9)	3.4 (34.4)	4.3 (43.1)	Sim.
		Post-Harvest Upkeep Year 3.5		
Pesticide Application[a]	0.3 (2.9)	3.8 (33.8)	2.9 (26.3)	FBIC
		Total per-ODT cost of single plantation rotation		
Itemized Total[d]	27.6 (223.8)	51.6 (285.4)	794.9 (1,314.8)	
System Total[e]	874.2 (1,824.0)			

[a]Glyphosate application.
[b]Simazine and Goal application.
[c]Parenthesis= cost of system input for entire 30-year plantation lifespan.

Sections 7.4.2.2-7.4.2.6, below, provide background into how the values of Table 20 was generated.

7.4.2.2. FBIC input assumptions

Similar to values utilized for the traditional system, stand initiation and stand upkeep inputs for the tractor-pulled cut-and-chip reconfigured system (Table 20) were based on records kept for research-related replication purposes at the FBIC. Reiterated, the FBIC researchers did not document some specific details required for the economic analysis due to their erroneous nature at the time of data collection. As a result, some information utilized to generate the economic analysis was done so through assumption-based calculation: All mechanical equipment utilized by the FBIC were assumed to have been purchased new under the Miyata methodology, fuel information was taken from local market prices at the time of the operation, and fuel efficiency information was taken from data provided by Benjamin et al. (2000).

Just as with the traditional system, subsequent optimization scenarios sought to reduce the monetary impacts associated with stand initiation costs through utilization of a mechanical planter. As such, this input information can be found in Table 62 and Table 63 of Appendix B. Researchers at the FBIC and TRC provided productivity and cost estimates for this equipment. Fixed and operating cost estimation for this equipment was not considered within the economic analysis due to its inconsequential operation time on an hourly basis.

7.4.2.3. Production rate calculation assumptions

The harvesting unit (JD 7330 tractor and Ny Vraa JF 192 willow harvester) production rate was calculated based on in-field time trial information taken at the time of the harvest operation. The operation time required to harvest the 1.1 AC plantation was reduced to a per-acre basis (3.75 PMH/AC). Delays related to FBIC record-keeping and Komatsue CK35-1 unloading was disregarded from the analysis due to their research related focus. This, consequentially, made the harvesting unit utilization rate approximately 100 % (delay free). It was assumed that, if the operation were of a commercial size, delay associated with wood biomass chip collection would not detrimentally influence productivity, due to proper machine scheduling.

Scenario #5 of the breakeven analysis incorporated a stand density of 19,200 TPA, double of the actual in-field calculated density of 9,600 TPA. It was assumed that a doubling of the stand density would not affect harvesting system productivity. Because the harvesting unit was single-pass and was designed to travel at a constant speed regardless of the number of stems present, an increase in the number of stems per acre would likely double productivity and, therefore, be inconsequential to the calculated machine hourly rate, as long as the number of rows present within the plantation remained the same.

7.4.2.4. Transport simulation input information

Data for the simulated transport operation was based on the average net weight payload of chip vans utilized to transport biomass from the Escanaba poplar harvest operation (please see Table 18 for more detailed information). This information was recorded through ticket payment slips following delivery to Verso Corporation, where the biomass was sold. With an average van weight of 33.13 green tons, approximately 0.4 vans were required on a per-acre basis. Willow chip size was assumed to be the same as the produced poplar grindings, in this case. Although the study site was approximately 1.1 AC in size, costing was scaled in on a per-ton basis in an assumption that the chip van operator would wait to transport biomass until a full payload was made. In a large-scale commercial operation, it would be unlikely that a logging firm/owner-operator would transport a payload so small due to the intensive capital requirements associated with biomass transport.

Per-hour transport equipment costing estimation was calculated with the Miyata method from data supplied by the logging firm who conducted the Escanaba harvest operation, as well. One-way travel distances were assumed at 50 miles with a total two-way travel time of 2.5 hours (Table 61 of Appendix B), for an average speed of approximately 40 miles per hour. Additionally, biomass loading and unloading was assumed to take approximately 27 minutes and 20 minutes, respectively, based on in-field calculations.

7.4.2.5. Plantation input assumptions

The price of willow saplings was not considered in this analysis under the assumption that clonal cuttings could be gathered from existing mature willow trees and subsequently propagated at a nominal cost. With an existing source of mature poplar trees available, the cost of such saplings would likely be inconsequential to the operation. Furthermore, the cost of willow parent tree initiation, care, and propagation was considered to be too far out of scope for the size of this particular analysis.

Within the stand density and labor optimization scenario (Scenario #5 of section 10.2.1.), stand density was doubled to 19,200 TPA. At this stand density it was assumed that competition between stems would not increase, thereby having no affect on biomass productivity. For this scenario, it was assumed that doubled stand density would also double biomass weight.

The FBIC ordered to have the SRWC willow stand harvested at 3 years of age. It was assumed that, for purposes of the economic analysis, the stand would subsequently be harvested every 3 years, and be productive for 30 years in total. As a result, it was assumed that the stand would effectively produce equal amounts of biomass for 10 times over the plantation lifespan.

7.4.2.6. Biomass sales input assumptions

Produced biomass was assumed to be sold at a price of $\$30/\text{ton}_{wb}$, as suggested by Kevin Rush Forest Products Inc., a provider of woody biomass feedstock to MSU's T.B.

Simon power plant. Willow moisture content was assumed to be equal to the moisture content of the Escanaba poplar, at 47% (calculated from the collected biomass, please see section 6.2.3. for more details), the produced biomass was calculated to be sold at approximately $56.6/ODT. This value was utilized for all generated revenue and profit values at a normal stand density of 9,600 TPA and a doubled stand density of 19,200 TPA.

8. ECONOMIC ANALYSIS: RESULTS & DISCUSSION

8.1. Traditional Harvesting System

8.1.1. Breakeven analysis

8.1.1.1. Breakeven scenarios

The following five scenarios detail the step-by-step procedure taken for analyzing the economic feasibility of producing, harvesting, and processing woody biomass feedstock from a SRWC poplar stand, where:

- Scenario #1 examined the profitability of utilizing solely the traditional whole tree harvesting system, including transport to an energy conversion facility, to generate an income.
- Scenario #2 expanded the scope from scenario #1 to determine the economic feasibility of the entire supply chain, from site setup through transport to an energy conversion facility. Economic values presented from scenario #2 were a record of the events that actually took place within the plantation for research purposes, with the addition of simulated transportation.
- Scenario #3 took the information from scenario #2 and replaced field collected case-specific costing items with generalized hourly rate estimates, based on information provided by Miyata (1980) and the Food and Agriculture Association of the United Nations (1999).
- Scenario #4 optimized the labor force utilized in scenario's 2 and 3, which was identified as the major profit-generating deficiency within these scenarios. This

scenario removed excess labor necessary for seedling hand planting and pesticide application, introduced mechanical planting machinery in to the supply chain, and balanced the harvesting system utilization, as well.

- Scenario #5 optimized the economic information presented in scenario #4 with a doubling of the original stand density, to 1760TPA. Under the assumption that this would not decrease biomass productivity, an increase in stand density was identified as an easily achievable method to increase profit margins.

a) Scenario #1: Scope-limited harvesting system scenario

The scope-limited harvesting system scenario considered the feasibility of utilizing only the traditional harvesting system to generate a profit. While the allocation of profits is not likely to occur in this manner outside of research, a demonstrated focus on the harvesting system provides insight on the minimum requirements necessary to generate an income for the logger.

Table 21 shows the cost (in $/ODT and $/AC), and resultant profit of producing a ground woody biomass feedstock product with the traditional whole tree harvesting system, including simulated transportation. Figure 22 and Figure 23 demonstrate the per-ton cost for the harvesting system based on costing type and machine type, respectively.

Table 21: Scenario #1 economic cost breakdown of producing SRWC poplar with the traditional harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Feller-buncher	1.3 (5.3)[a]	2.7 (10.8)	3.4 (13.6)	7.4 (29.8)	134.0 (535.1)
Skidder	0.8 (3.0)	0.6 (2.3)	0.6 (2.3)	1.9 (7.7)	34.8 (139.2)
Loader	1.6 (6.2)	0.5 (2.0)	2.3 (9.4)	4.4 (17.6)	79.4 (317.4)
Grinder	4.2 (16.9)	2.2 (8.9)	0.0 (0.0)	6.5 (25.8)	116.2 (464.6)
Chip Van Transport	5.4 (21.6)	6.4 (25.7)	8.1 (32.2)	19.9 (79.6)	358.4 (1433.8)
Per unit total cost[b]	13.3	12.4	14.4	40.1 (160.5)	722.8 (2,891.1)
Plantation lifespan total cost ($)	53.1	49.8	57.6	22,550.7	22,550.7
Per unit total revenue	--	--	--	226.4	4,077.9
Plantation lifespan total revenue ($)	--	--	--	31,807.2	31,807.2
Per unit total profit	--	--	--	65.9	1,186.7
Plantation lifespan total profit ($)	--	--	--	9,256.5	9,256.5

[a]Parenthesis= cost of system input for entire 28-year plantation lifespan.
[b]Itemized total on an hourly basis for a single harvest operation: fixed= $117.34/SMH, operating= $152.96/PMH, labor= $83.89/SMH. Total= $283.61/SMH.

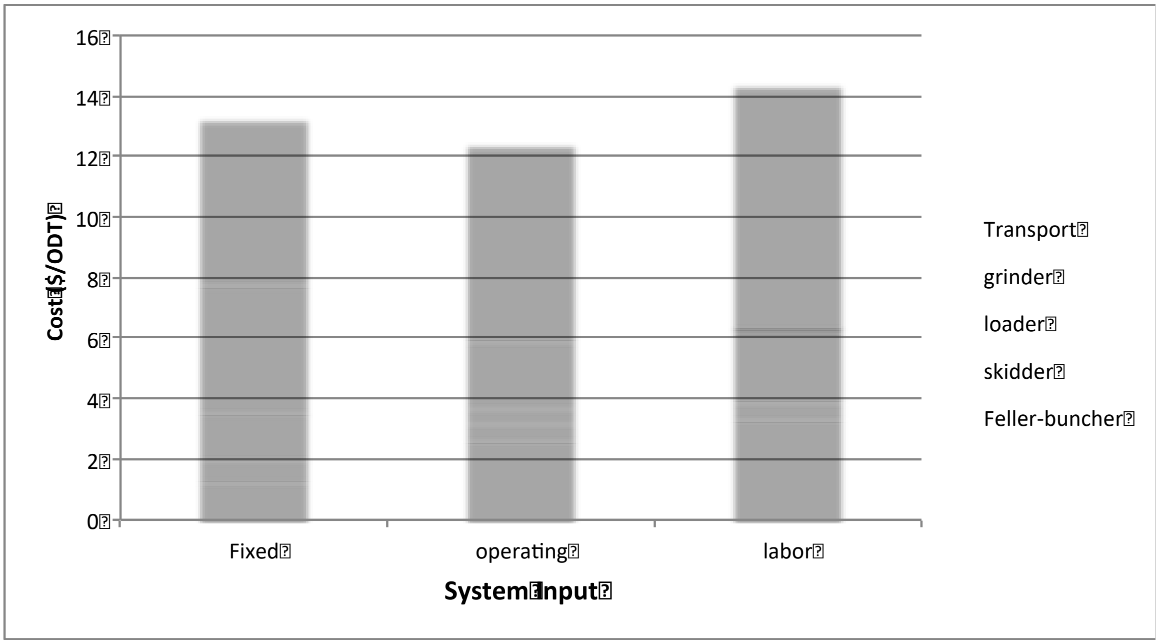

Figure 22: Economic breakdown of fixed, operating, and labor costs for Scenario #1 of the SRWC poplar operation.

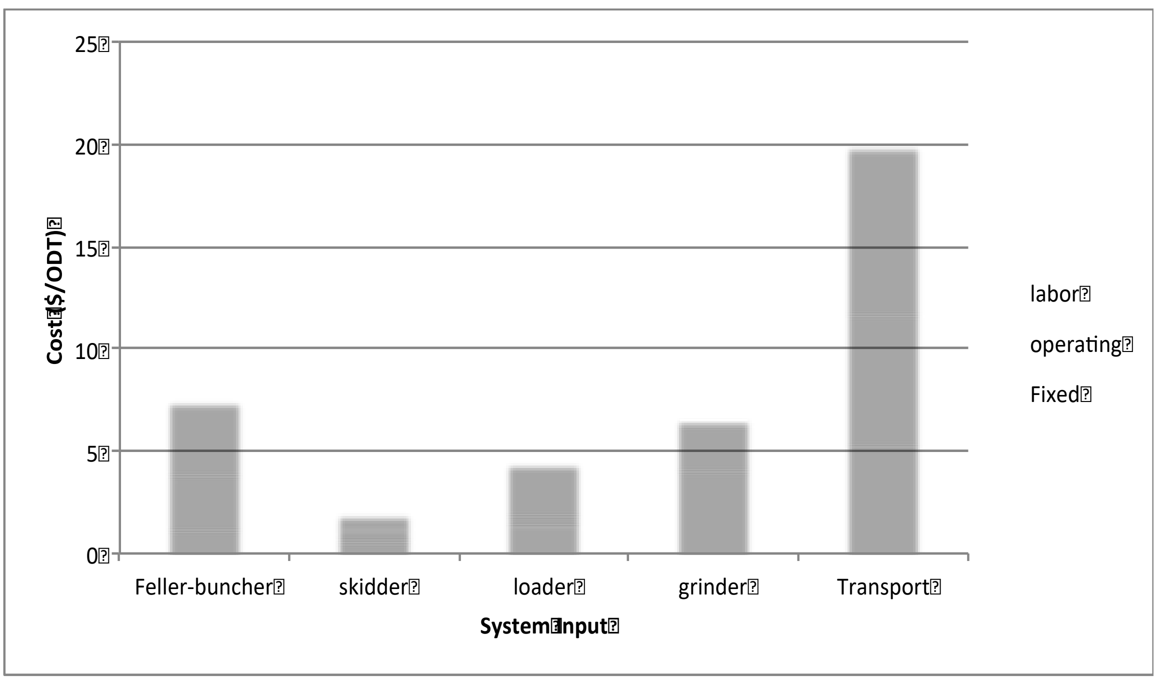

Figure 23: Economic breakdown for Scenario #1 based on system input items for the SRWC poplar operation.

As the scenario analysis demonstrated, a profit of approximately $65.9/ODT would be generated if the only monetary inputs were from operations associated with the traditional harvesting system ($160.5/ODT over the course of four harvest operations). In this case, transport was the largest contributing factor, at approximately $19.9/ODT, equating to nearly half of the total cost input (49.6%). Although disproportionately higher than the other components of the harvesting system, transport often accounts for upwards of 60% of biomass production costs. This simulated transport value was, thus, considered to be an accurate and feasible representation of an actual transportation operation.

With a generated profit of $65.9/ODT, a breakeven analysis was conducted on the harvesting system to determine the minimum sales price of the produced biomass (in $/ODT) and minimum stand density of the plantation (in TPA) required for the harvesting system to breakeven (Table 22). A breakeven analysis was also conducted on operator salary's to determine the maximum profit that could be had within the harvesting system. As Figure 22 demonstrated, labor was the largest overall cost input for the utilized machinery. Although not likely to be a practical solution to breaking even or increasing profit margins, an analysis of this type on the labor input demonstrated how sensitive it was to change within the harvesting system.

Table 22: Scenario #1 breakeven analysis for the SRWC poplar operation.

Breakeven Input	Breakeven Output
Plantation stand density (minimized, TPA)	704.0
Biomass sales price (minimized, $/ODT)	40.1
Operator salary (maximized, $/SMH)	317.4

As demonstrated in Table 22, the minimum plantation stand density required to breakeven with the traditional harvesting system was calculated to be 704.0 TPA. This analysis assumed that average biomass weight per tree was equal to the actual average biomass weight per tree. With SRWC stands reaching over 50,000 stems per acre, this demonstrated stem density should be considered quite low for a plantation of this type (Eisenbies et al. 2014b). Furthermore, at a minimum breakeven profit of $40.1/ODT, obtaining a profit within this scenario is readily feasible under the given scope.

b) Scenario #2: Complete supply chain base-case

Scenario #2, the complete supply chain base-case scenario, expanded the scope presented in Scenario #1 to encompass all inputs associated with woody biomass production, from site setup through product transport to an energy conversion facility. In short, the scope of this analysis should be considered encompassing from site setup to plant-gate. The expanded scope of Scenario #2 included such inputs as: tilling/spading, the hand planting of poplar clones, pesticide applications, insecticide application, and stand upkeep. Table 23 shows the cost (in $/ODT and $/AC), and resultant profit of producing a ground woody biomass feedstock product within this expanded scope. Although encompassing, Scenario #2 was a record of events that occurred at the FBIC for research purposes and should, thus, not be considered an optimized case of woody biomass production for bioenergy purposes. Figure 24 and Figure 25 demonstrate the per-ton cost for the supply chain based on costing type and system input type, respectively.

Table 23: Scenario #2 economic cost breakdown of producing SRWC poplar with the traditional harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	0.3	0.9	3.0	4.2	76.2
Hand planting	0.0	0.0	161.5	161.5	2,907.8
Site setup pesticide app. #1	0.1	3.8	2.1	6.1	108.9
Site setup pesticide app. #2	0.0	0.1	5.8	5.9	105.3
Insecticide app.	0.0	0.2	0.9	1.1	19.9
Feller-buncher	1.3 (5.3)[a]	2.7 (10.8)	3.4 (13.6)	7.4 (29.8)	134.0 (535.1)
Skidder	0.8 (3.0)	0.6 (2.3)	0.6 (2.3)	1.9 (7.7)	34.8 (139.2)
Loader	1.6 (6.2)	0.5 (2.01)	2.3 (9.4)	4.4 (17.6)	79.4 (317.4)
Grinder	4.2 (16.9)	2.2 (8.9)	0.0 (0.0)	6.5 (25.8)	116.2 (464.6)
Chip Van Transport	5.4 (21.6)	6.4 (25.7)	8.1 (32.2)	19.9 (79.6)	358.4 (1433.8)
Maintenance pesticide app.	0.0	0.3 (1.3)	1.1 (4.5)	1.5 (5.8)	26.3 (78.9)
Per unit total cost[b]	13.8	17.7	188.8	220.3 (343.6)	3,967.2 (6,188.2)
Plantation lifespan total cost ($)	53.6	55.7	234.3	48,267.8	48,267.8
Per unit total revenue	--	--	--	226.4	4,077.9
Plantation lifespan total revenue ($)	--	--	--	31,807.2	31,807.2
Per unit total profit	--	--	--	-117.2	-2,110.3
Plantation lifespan total profit ($)	--	--	--	-16,460.6	-16,460.6

[a]Parenthesis= cost of system input for entire 28-year plantation lifespan.
[b]Itemized total on an hourly basis for a single harvest operation: fixed= $150.20/SMH, operating= $197.59/PMH, labor= $167.89/SMH. Total= $515.66/SMH.

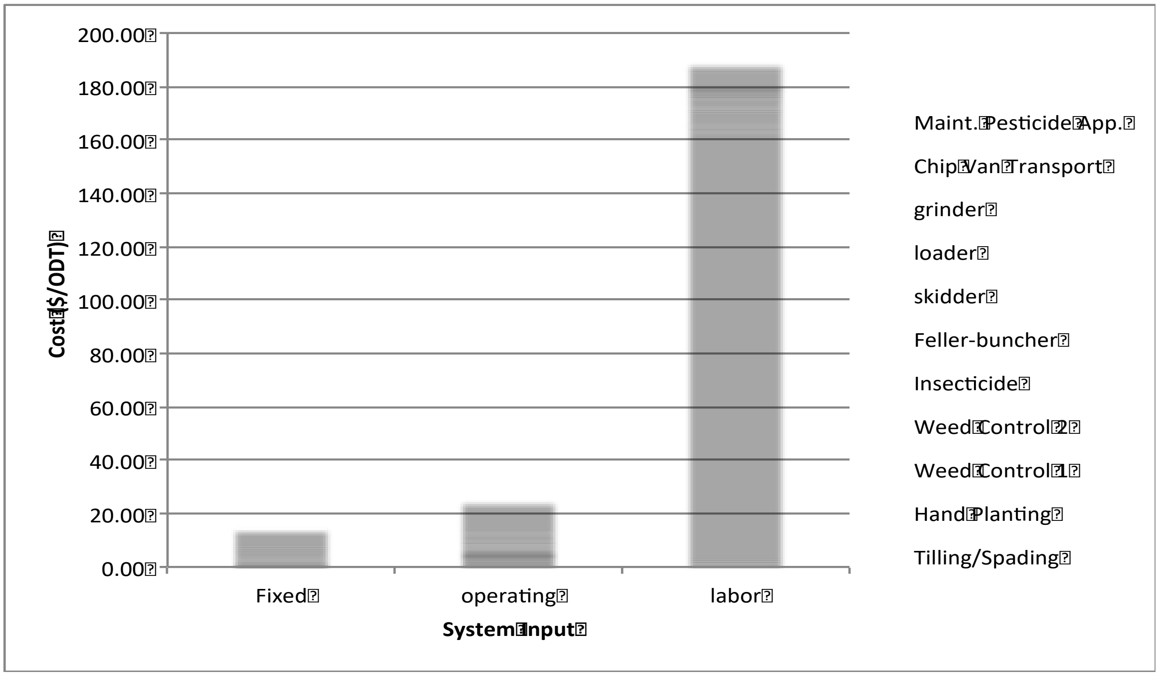

Figure 24: Economic breakdown of fixed, operating, and labor costs for scenario #2 of the SRWC poplar operation.

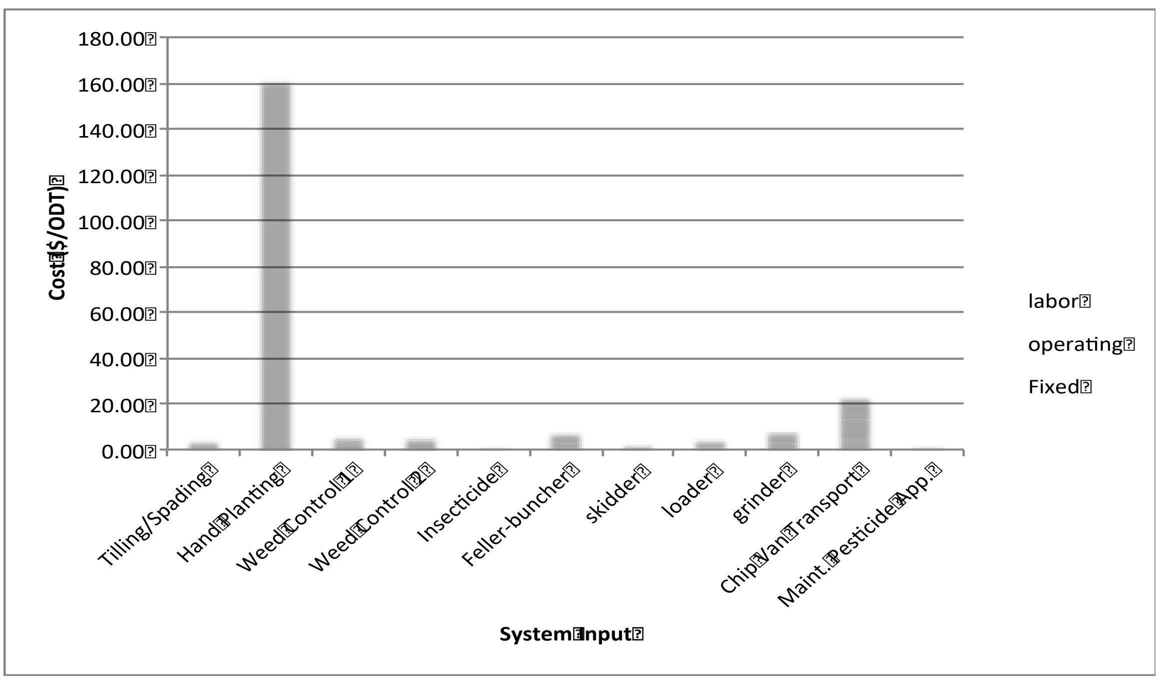

Figure 25: Economic breakdown for Scenario #2 based on system input items for the SRWC poplar operation.

As Table 23 demonstrates, a profit would not be generated under this particular set of circumstances. With a scope encompassing all inputs, from site setup to plant gate, a deficit of approximately -$117.2/ODT would be generated. The largest contributing cost in this scenario was the hand planting of poplar clones, at $161.5/ODT (accounting for 73.3% of all cost inputs), due to a disproportionately high labor cost (please see Figure 24 and Figure 25). Because of this, subsequent optimization scenarios (Scenarios 4 & 5) utilized mechanical planting equipment to reduce salary costing and the number of required individuals to complete the job, thereby increasing system economic feasibility.

A breakeven analysis was conducted the cost inputs of the supply chain to determine how plantation stand density, biomass sales price, and operator salary for Scenario #2 must be modified in order to attain a profit (Table 24).

Table 24: Scenario #2 breakeven analysis for the SRWC poplar operation.

Breakeven Input	Breakeven Output
Plantation stand density (minimized, TPA)	1,506.5
Biomass sales price (minimized, $/ODT)	85.9 (1,547.0)[a]
Operator salary (minimized, $/SMH)	11.8

[a]Minimum biomass price, in $/AC.

As demonstrated in Table 24, the minimum plantation stand density required to breakeven with the analyzed system boundary was calculated to be 1,506.5 TPA. This analysis assumed that average biomass weight per tree was equal to the actual average biomass weight per tree. Although this is an increase in plantation stem density, it is still within the feasible realm of commercial SRWC plantations, as demonstrated by Eisenbies et al. (2014b). The minimum breakeven biomass sales price, though, was calculated to be $85.9/ODT. With an assumed MC of 47 %, the minimum breakeven price of the produced biomass would be approximately $45.5/green ton, which is unlikely to occur in today's economy due to the low value that biomass for bioenergy is often sold for. The resultant operator salary, $11.8/SMH, is also not a feasible way to attain a profit. This operator salary is too low for skilled operators.

c) Scenario #3: Generalized complete supply chain base-case

Scenario #3 took the scope of Scenario #2 (the complete supply chain base-case) and applied generalized cost input values for all associated machinery required to setup, maintain, and harvest SRWC poplar for bioenergy generation. Instead of utilizing hourly rate values with specific operating cost information, provided by the logging firm and FBIC, this scenario produced costs through hourly rate estimation methods demonstrated by Miyata (1980) and the Food and Agriculture Organization of The United Nations (1999) (Table 25). As such, the cost information presented in Table 25 can be considered more representative of an actual SRWC production operation in the Lakes States region. Like Scenario #2, though, Scenario #3 utilized research related inputs and, thus, cannot be considered to have an optimized supply chain for SRWC production. Figure 26 and Figure 27 demonstrate the per-ton cost for the supply chain based on costing type and system input type, respectively.

Table 25: Scenario #3 economic cost breakdown of producing SRWC poplar with the traditional harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	0.3	1.1	3.0	4.4	79.8
Hand planting	0.0	0.0	161.5	161.5	2,907.8
Site setup pesticide app. #1	0.1	3.9	2.1	6.1	110.4
Site setup pesticide app. #2	0.0	0.1	5.8	5.9	105.3
Insecticide app.	0.0	0.2	0.9	1.1	19.9
Feller-buncher	1.3 (5.3)[a]	3.2 (12.7)	3.4 (13.64)	7.9 (31.7)	142.8 (571.1)
Skidder	0.8 (3.0)	0.9 (3.7)	0.6 (2.3)	2.3 (9.0)	40.8 (163.2)
Loader	1.6 (6.2)	1.1 (4.4)	2.4 (9.4)	5.0 (20.0)	90.1 (360.5)
Grinder	4.2 (16.9)	3.5 (14.2)	0.0 (0.0)	7.8 (31.0)	139.8 (559.3)
Chip Van Transport	5.4 (21.6)	10.0 (40.0)	8.1 (32.2)	23.5 (93.8)	422.5 (1,690.1)
Maintenance pesticide app.	0.0	0.3 (1.0)	1.1 (3.4)	1.5 (4.4)	26.3 (79.0)
Per unit total cost[b]	13.8	24.3	188.8	226.9 (369.0)	4,085.6 (6,646.4)
Plantation lifespan total cost ($)	53.6	81.2	234.3	51,842.0	51,842.0
Per unit total revenue	--	--	--	226.4	4,077.9
Plantation lifespan total revenue ($)	--	--	--	31,807.2	31,807.2
Per unit total profit	--	--	--	-142.6	-2,568.6
Plantation lifespan total profit ($)	--	--	--	-20,034.8	-20,034.8

[a]Parenthesis= cost of system input for entire 28-year plantation lifespan.
[b]Itemized total on an hourly basis for a single harvest operation: fixed= $150.20/SMH, operating= $144.65/PMH, labor= $167.89/SMH. Total= $462.73/SMH.

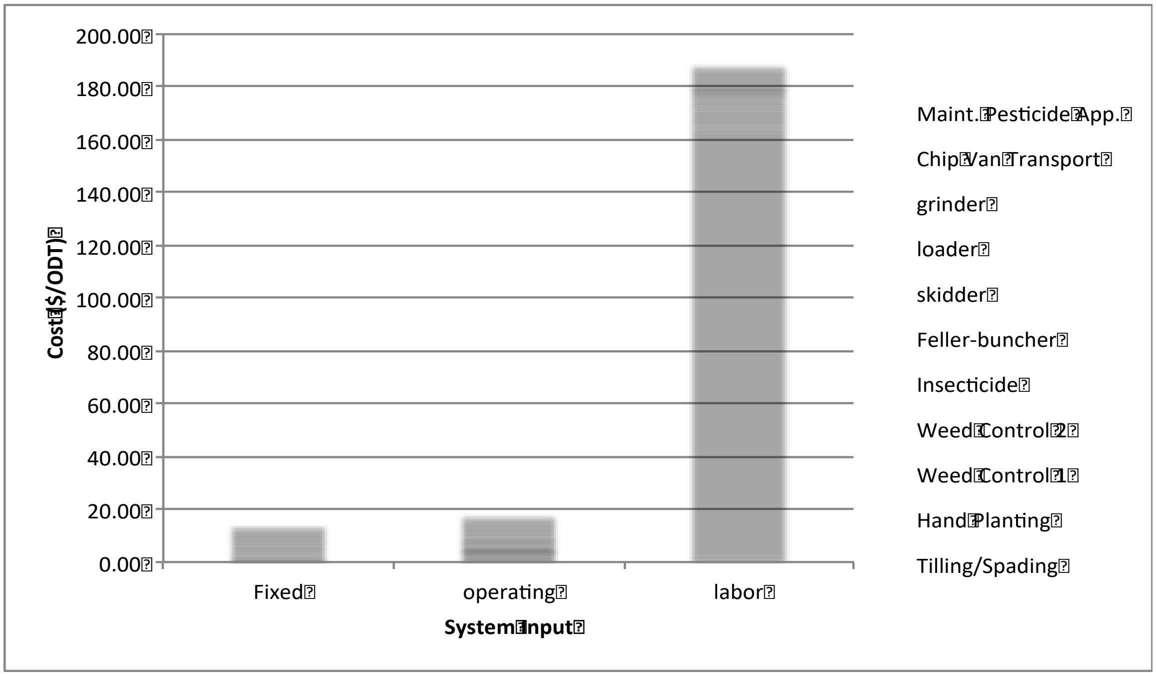

Figure 26: Economic breakdown of fixed, operating, and labor costs for scenario #3 of the SRWC poplar operation.

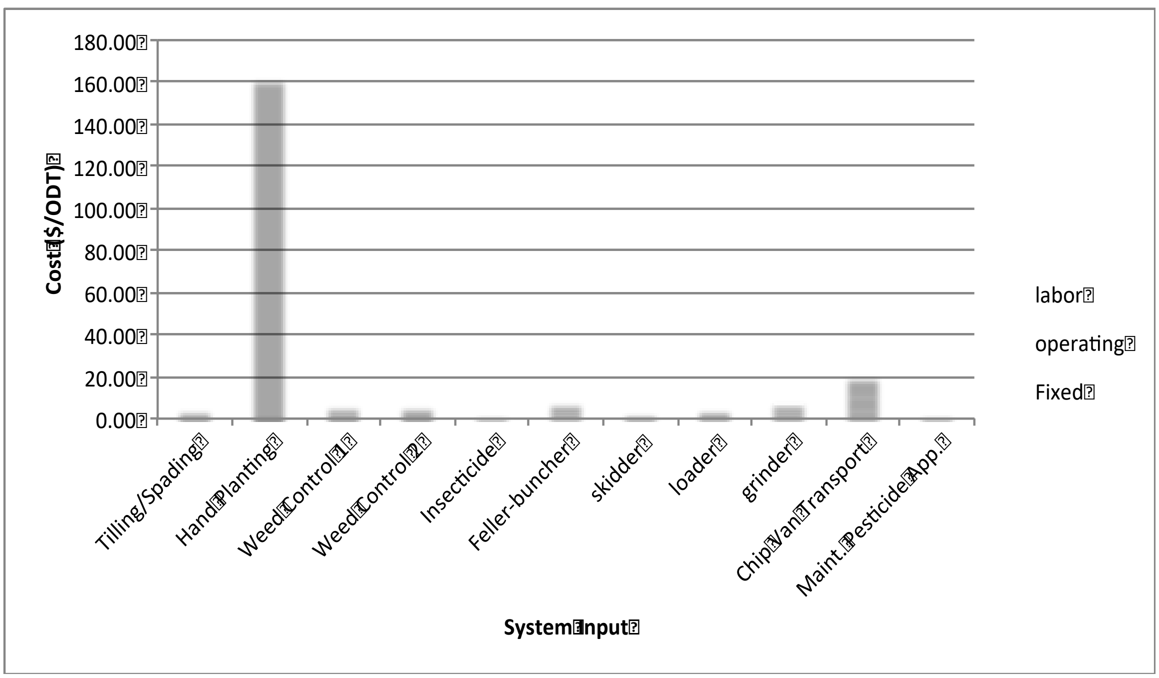

Figure 27: Economic breakdown for Scenario #3 based on system input items for the SRWC poplar operation.

With similar cost inputs to scenario #2, scenario #3 resulted in a loss of profit under this particular set of circumstances. With a scope encompassing all inputs, from site setup to plant gate, a deficit of approximately -$142.6/ODT would be generated (or -$20,034.8 in total over the plantation lifespan). As with scenario #2, the labor cost associated with the hand planting of poplar clones was the largest contributing in scenario #3, at $161.5/ODT (accounting for 71.2% of all cost inputs, Figure 26 and Figure 27). With generalized hourly rate estimation values that remove the specificity of scenario #2, scenario #3 further demonstrates the need to reduce labor costs.

A breakeven analysis was conducted for scenario #3 below, in Table 26, to determine the minimum plantation stand density, biomass sales price, and operator salary necessary to garner a profit within the supply chain.

Table 26: Scenario #3 breakeven analysis for the SRWC poplar operation.

Breakeven Input	Breakeven Output
Plantation stand density (minimized, TPA)	1,618.0
Biomass sales price (minimized, $/ODT)	92.3 (1,661.9)[a]
Operator salary (maximized, $/SMH)	17.1

[a]Minimum biomass price, in $/AC.

As demonstrated in Table 26, the minimum plantation stand density required to breakeven with the traditional harvesting system was calculated to be 1,618.0 TPA. This analysis assumed that average biomass weight per tree was equal to the actual average biomass weight per tree. Although this is an increase in plantation stem density, it is still within the feasible realm of commercial SRWC plantations, as demonstrated by Eisenbies et al. (2014b). The minimum breakeven biomass sales price, though, was calculated to be $92.3/ODT. With an assumed MC of 47 %, the minimum breakeven price of the produced biomass would be approximately $48.9/green ton, which is unlikely to occur in today's economy due to the low value biomass for bioenergy is often sold for. Although very similar, the generalized machine hourly rate values applied to scenario #3 increases the amount of revenue necessary to generate a profit, when compared to the case-specific input costs of scenario #2.

d) Scenario #4: Labor optimization scenario

Based upon the identified labor cost disparity from Scenario #2 and Scenario #3, Scenario #4 sought to reduce input costs through labor optimization. Such optimization steps included:

- Mechanical planting equipment with integrated use of existing farm tractor utilized elsewhere within the scenario. Mechanical planting reduced the number of operators from four to three and drastically reduced operation time (please see Table 60 of Appendix B for more details).
- Simultaneous site setup application of pesticides (Pendulum Aquacap and Scepter 70 DG) where one operator was assumed to be capable of applying both pesticide types.
- Removal of the second pesticide application that took place after the first year of poplar growth, under the assumption that the simultaneous pesticide application was sufficient to effectively inhibit weed growth.
- Setting the harvesting system utilization rate to 80 %, with exception to the feller-buncher (which was left at its in-field utilization of 98.9 % due to its independent operation).

With these identified optimization steps, Table 27 **,** Figure 28 and Figure 29 reflect the costs, revenue, and subsequent profit of producing a poplar feedstock product from site setup to factory gate. Although possible, reducing the hourly wage of employees was not seen as a viable way to increase profit margins. Skilled employee retention would likely decrease as wages decreased because workers would seek other employment opportunities that paid competitively. Without skilled and trained workers, the job could not be completed properly.

Table 27: Scenario #4 economic cost breakdown of producing SRWC poplar with the traditional harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	0.3	0.9	3.0	4.2	76.2
Mechanical planting	0.1	0.1	1.7	1.8	33.0
Simultaneous pesticide app.	0.1	3.8	1.2	5.2	92.8
Insecticide app.	0.0	0.2	0.9	1.1	19.9
Feller-buncher	1.3 (5.3)	2.7 (10.8)	3.4 (13.6)	7.4 (29.8)	134.0 (536.1)
Skidder	0.9 (3.5)	0.7 (2.7)	0.7 (2.7)	2.2 (8.8)	39.5 (158.0)
Loader	0.7 (2.8)	0.2 (0.9)	1.1 (4.2)	2.0 (7.9)	35.5 (142.1)
Grinder	1.9 (7.6)	1.0 (4.0)	0.0 (0.0)	2.9 (11.6)	52.0 (208.0)
Chip Van Transport	5.4 (21.6)	6.4 (25.7)	8.1 (32.2)	19.9 (79.6)	358.4 (1,433.8)
Maintenance pesticide app.	0.0 (0.0)	0.3 (1.0)	1.1 (3.4)	1.5 (4.4)	26.3 (79.0)
Per unit total cost	10.7	16.3	21.1	48.2 (153.6)	864.6 (2,766.7)
Plantation lifespan total cost ($)	41.3	50.0	62.3	21,580.4	21,580.4
Per unit total revenue	--	--	--	226.4	4,077.9
Plantation lifespan total revenue ($)	--	--	--	31,807.2	31,807.2
Per unit total profit	--	--	--	72.8	1,311.1
Plantation lifespan total profit ($)	--	--	--	10,266.8	10,266.8

[a]Parenthesis= cost of system input for entire 28-year plantation lifespan.

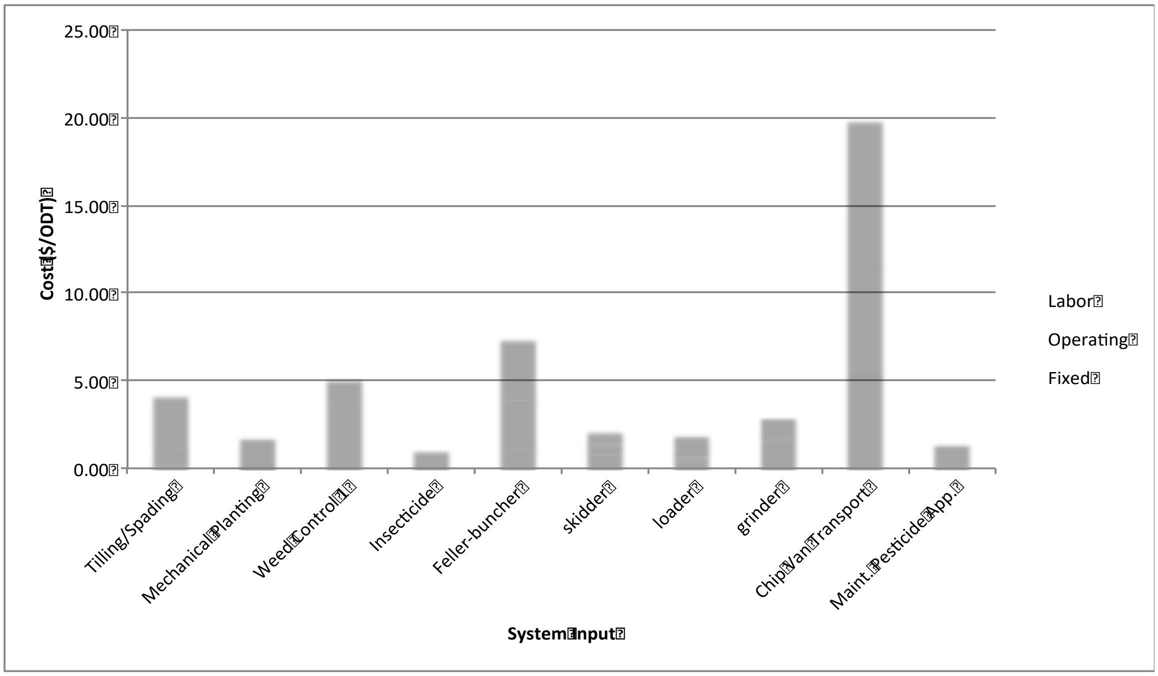

Figure 28: Economic breakdown of fixed, operating, and labor costs for scenario #4 of the SRWC poplar operation.

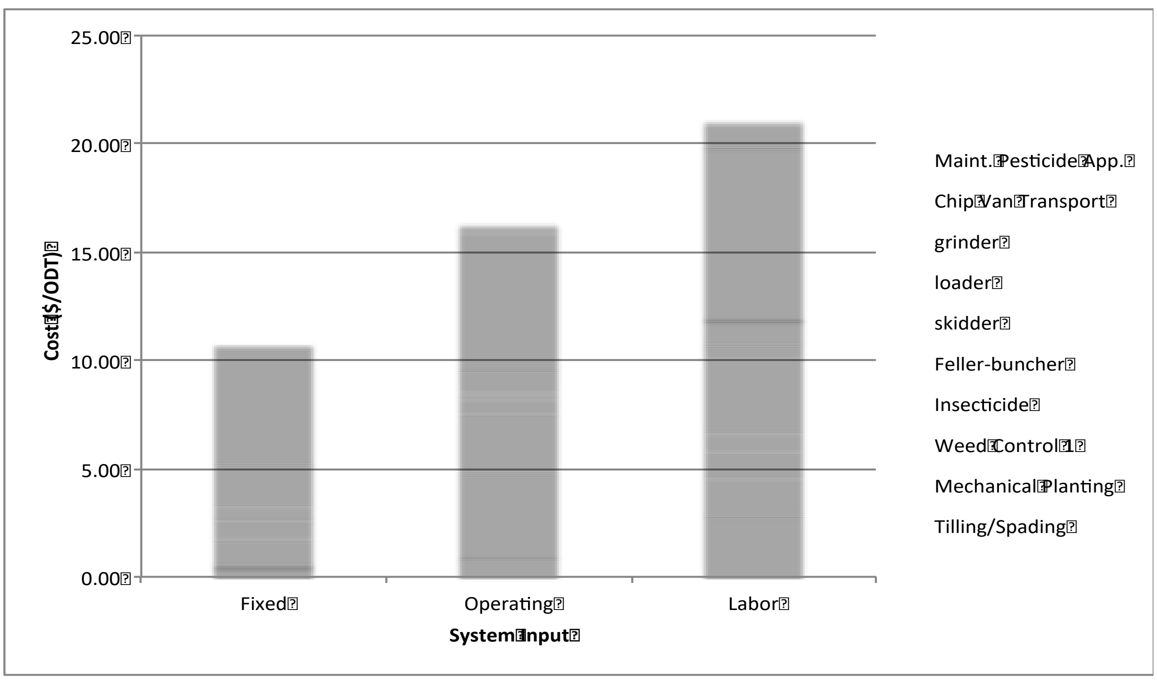

Figure 29: Economic breakdown for Scenario #4 based on system input items for the SRWC poplar operation.

As Table 27, Figure 28 and Figure 29 demonstrate, the disparity between the labor and fixed/operating costs was reduced as a result of the optimization scenario, where labor subsequently accounted for approximately 43.8% of all cost inputs. Although still the largest contributing factor, labor was not disproportionately higher than the fixed and operating costs, which accounted for 22.3% and 33.9% of the cost total, respectively. Because of this, the optimization scenario was considered to provide a balanced set of input costs within the given scope. Furthermore, the scenario also demonstrated that profit could be generated- where approximately $72.8/ODT was netted based on the given set of assumptions. Over the entire 28-year lifespan of the plantation, with 7.8 acres of available land, a total profit of $10,266.8 would be made.

The implications of this scenario demonstrate that efficient and cost-effective input operations are necessary to achieve a profit within the analyzed supply chain. Minor changes in labor resulted in disproportionately large influences in the profit outcome, thereby demonstrating the fragility of producing woody biomass feedstock for income.

a) Scenario #5: Combined Labor and stand density optimization scenario

Scenario #5 took the optimized labor condition presented in Scenario #4 and incorporated a stand density of 1760 TPA, which was twice as dense as the average density of the actual plantation (880 TPA). Under these given conditions, Table 28 and Figures Figure 30 and Figure 31 reflect the costs and subsequent profit of producing a poplar feedstock product from site setup to factory gate.

Table 28: Scenario #5 economic cost breakdown of producing SRWC poplar with the traditional harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	0.3	0.9	3.0	2.1	76.2
Mechanical planting	0.1	0.1	1.7	1.8	66.0
Simultaneous pesticide app.	0.1	3.8	1.2	2.6	92.8
Insecticide app.	0.0	0.2	0.9	0.6	19.9
Feller-buncher	1.2 (4.8)	2.5 (9.8)	3.1 (12.4)	6.8 (27.0)	234.4 (973.4)
Skidder	0.9 (3.5)	0.7 (2.7)	0.7 (2.7)	2.2 (8.8)	74.3 (297.1)
Loader	0.7 (2.8)	0.2 (0.9)	1.1 (4.2)	2.0 (7.9)	165.8 (663.1)
Grinder	1.9 (7.6)	1.0 (4.0)	0.0 (0.0)	2.9 (11.6)	263.6 (1,054.2)
Chip Van Transport	5.4 (21.6)	6.4 (25.7)	8.1 (32.2)	19.9 (79.6)	716.9 (2,867.5)
Maintenance pesticide app.	0.0 (0.0)	0.3 (1.0)	1.1 (3.4)	1.5 (4.4)	26.3 (79.0)
Per unit total cost[b]	10.7	16.2	22.5	49.3 (153.4)	1,745.0 (6,189.1)
Plantation lifespan total cost ($)	83.4	112.4	102.5	48,275.0	48,275.0
Per unit total revenue	--	--	--	226.4	8,155.7
Plantation lifespan total revenue ($)	--	--	--	63,614.4	63,614.4
Per unit total profit	--	--	--	178.0	1,966.6
Plantation lifespan total profit ($)	--	--	--	15,339.4	15,339.4

[a]Parenthesis= cost of system input for entire 28-year plantation lifespan.

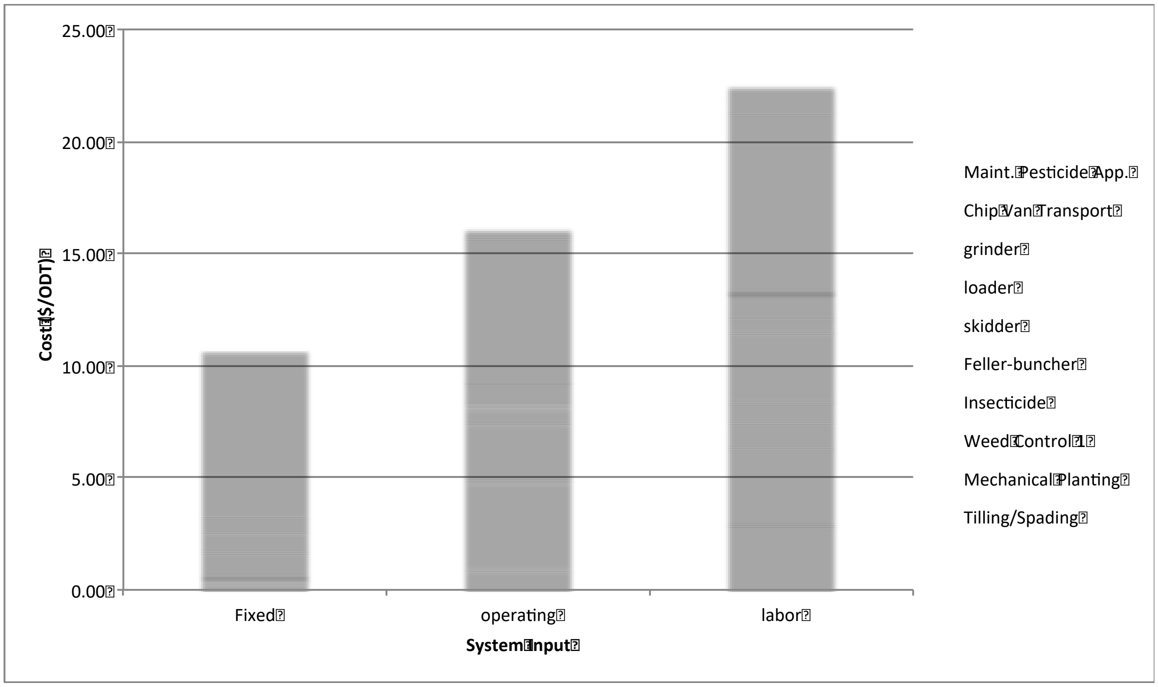

Figure 30: Economic breakdown of fixed, operating, and labor costs for scenario #5 of the SRWC poplar operation.

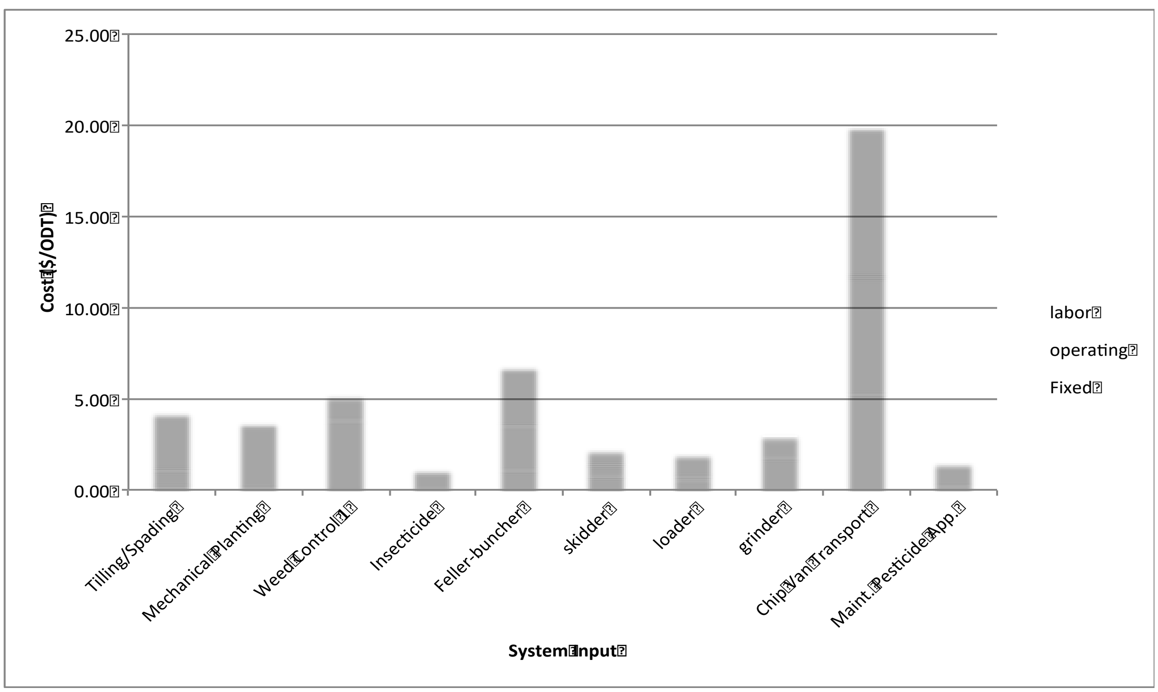

Figure 31: Economic breakdown for Scenario #5 based on system input items for the SRWC poplar operation.

As Table 28 demonstrated, a profit of $178.0/ODT was generated under the given set of conditions, with approximately $15,339.4 made in total over the course of the 28-year plantation lifespan. Although the input costs of this scenario were slightly higher than the inputs of Scenario #4, the economies of scale allowed for even more profit to be generated under the given set of assumptions.

8.1.1.2. Breakeven scenario analysis conclusion

The demonstrated breakeven scenario analyses, summarized below in Table 29, show that profit generation is achievable within the given scope of site setup through product delivery at the plant gate. It must be noted, though, that proper labor optimization steps are required to consider the system as a feasible economic endeavor. The removal of inefficient site setup practices, such as seedling hand planting, and the incorporation of balanced machine scheduling will significantly increase the chances for economic success within the given scope and circumstances.

Table 29: Breakeven scenario analysis summary for the analyzed SRWC poplar operation.

Breakeven Scenario	Total Cost ($)	Total Revenue ($)	Total profit ($)
Scenario #1	22,550.7	31,807.2	9,256.5
Scenario #2	48,267.8	31,807.2	-16,460.6
Scenario #3	51,842.0	31,807.2	-20,034.8
Scenario #4	21,580.4	31,807.2	10,266.8
Scenario #5	48,275.0	63,614.4	15,339.4

8.1.2. Benefit-cost analysis

Input values for the benefit-cost analysis can be found below, in Table 30.

Table 30: Benefit-cost analysis inputs for the SRWC poplar operation.

Input Variable	Input Value	Input Justification
t (years)	7	FBIC in-field
y (an index for years)	7	FBIC in-field
R_q (present value of all revenues)	**	Calculated
C_q (present value of all costs)	**	Calculated
r (real interest rate)	0.04	Benjamin et al. (2000)
R_y (revenue in year y)	**	Calculated
C_y (cost in year y)	**	Calculated

** Different input values utilized for each individual scenario. All Revenue and cost values (R_q, C_q, R_y, and C_y) can be found summarized in section **10.1.1.2.**

Based on these provided input values, the benefit-cost analysis was generated. Results for the analysis can be found below, in Table 31.

Table 31: Benefit-cost analysis outputs for the SRWC poplar operation.

Breakeven Scenario	NPV	B/C	IRR
Scenario #1	7,034.17	1.41	3.32[a]
Scenario #2	-12,508.69	0.66	N/a[b]
Scenario #3	-15,224.80	0.60	N/a[b]
Scenario #4	7,771.51	1.47	0.15
Scenario #5	11,656.70	1.32	0.18

[a]value was consistently the highest of the generated IRR but simultaneously nonsensical due to multiple possible solutions.
[b]IRR value not available because no profit was generated for the given scenario.

As Table 31 demonstrated, profit-generating scenarios produced a positive NPV, and a B/C value >1.0, while deficit inducing scenarios produced a negative NPV, and a B/C value <1.0. Although the labor-optimizing scenario (scenario #4) generated less profit than the combined labor and stand density optimizing scenario (scenario #5), as demonstrated by its lower NPV value, its B/C ratio was higher (1.47 compared to 1.32, respectively). This indicated that, overall, scenario #4 was the best investment under the given set of conditions. The benefits of scenario #4 (generated revenue) nonparametrically outweighed the costs when compared to scenario #5. From this analysis it can be concluded that, within the given set of conditions, labor optimization was the most important step for gaining a profit.

The internal rate of return was highest for scenario #1. Intuitively, this makes sense because the cost of harvesting was the only consideration within the scenario. Being the only associated investment, the percentage rate of the investment grew much faster to equal the value of the expected benefits, over the investment period, much faster than the other analyzed scenarios. In reality, the high *IRR* produced in scenario #1 is not likely to occur because there will be more investments associated with producing biomass feedstock, as demonstrated by scenario's #2 and #3. These scenarios show that no profit is garnered throughout the investment period, thereby producing no *IRR* value. The *IRR* of scenarios #4 and #5 were equal to 0.15 and 0.18, respectively, indicating similar returns on investment based on the necessary cost inputs and resultant profits.

8.1.3. Hedonic regression

Five constituent variables were developed in to a multiple linear regression model for predicting woody biomass production (in average ODT/AC-yr). Descriptive statistics for each of the five input variables, and the produced biomass output variable that was being predicted, can be found below, in Table 32. Input variables included: poplar clone type (variable 1) numerically analyzed categorically, plot spacing treatment type (variable 2), also numerically analyzed categorically, the number of poplar stems per plot (variable 3), plot DBH (variable 4) in inches, and stem survival rate (variable 5) as a percentage. All utilized variables had 78 total observations (n=78).

Table 32: Hedonic regression inputs for the analyzed SRWC poplar operation.

Variables to describe biomass production	Variable Name	Data Min.	Data Max.	Data AVG.	Data STDEV.
Clone type (numerical)	Var. 1	1.00	7.00	4.23	1.88
Plot spacing treatment (numerical)	Var. 2	1.00	3.00	2.00	0.82
Number of stems (per plot)	Var. 3	9.00	39.00	24.71	7.69
Plot DBH (in.)	Var. 4	2.53	4.71	3.47	0.55
Sampled Survival Rate (%)	Var. 5	0.28	1.00	0.80	0.21
Produced Biomass (AVG ODT/AC-yr)	Var. 6	0.36	4.97	2.42	1.08

Table 33, below, demonstrates results for the hedonic regression with the inclusion of all five input variables, as well as associated *p*-values, and variance inflation factors (VIF) for each constituent variable. Table 33 demonstrates that the *p*-value of variable 2 (plot spacing treatment) is most insignificant ($p > 0.05$) in predicting biomass production, at $p = 0.160$. A review of the VIF value for variables 3 and 5, though, demonstrated that the number of stems per plot or the sampled survival rate likely influenced the value of the other output coefficients.

Table 33: Hedonic regression output for all included variables of the SRWC poplar operation.

Output Variable	Biomass Production Estimation (ODT/AC-yr)	*p*-value	VIF	F-value	r^2
Biomass Prod.	Biomass prod. Per-AC per-yr = -3.973	<0.001		81.82	0.85
	- 0.059 (Var. 1)	0.040	1.17		
	- 0.125 (Var. 2)	0.160	2.14		
	+ 0.047 (Var. 3)	0.023	9.76		
	+ 1.327 (Var. 4)	<0.001	1.08		
	+ 1.396 (Var. 5)	0.057	8.97		

Table 34, a table of the variable correlation coefficients, demonstrated this to be true: variable 3 and variable 5 were highly correlated to each other, at 88% correlation. Intuitively, this makes sense: the number of stems per plot was directly linked to the survival rate of the live stems per plot. In essence, these two variables described the same thing.

Table 34: Correlation coefficients for all included variables of the SRWC poplar operation.

	Var. 1	Var. 2	Var. 3	Var. 4	Var. 5
Var. 1	1.00				
Var. 2	0.00	1.00			
Var. 3	0.17	-0.25	1.00		
Var. 4	-0.12	0.22	0.03	1.00	
Var. 5	0.06	0.09	0.88	0.12	1.00

Because both variables 3 and 5 produced large VIF values and simultaneously demonstrated high degree of correlation between each other, it was not possible to determine which, of the two variables, was influencing the output values of the other coefficients within the regression model. As a result, variable 2, the plot spacing treatment, was removed from the regression equation because of its highly insignificant *p*-value. In doing so, a subsequent restricted multiple linear regression equation was generated. Both the updated model and variable correlation coefficient table can be found below, in Table 35 and Table 36, respectively.

Table 35: Restricted hedonic regression output.

Output Variable	Biomass Production Estimation (ODT/AC-yr)	*p*-value	VIF	F-value	r^2
Biomass Prod.	Biomass prod. Per-AC per-yr = -4.043	<0.001		100.38	0.84
	- 0.070 (Var. 1)	0.013	1.08		
	+0.067 (Var. 3)	<0.001	4.83		
	+ 1.306 (Var. 4)	<0.001	1.05		
	+ 0.696 (Var. 5)	0.192	4.77		

Table 36: Correlation coefficients of the restricted hedonic regression analysis.

	Var. 1	Var. 3	Var. 4	Var. 5
Var. 1	1.00			
Var. 3	0.17	1.00		
Var. 4	-0.11	0.03	1.00	
Var. 5	0.06	0.88	0.12	1.00

The restricted regression output, following removal of the plot spacing treatment, continued to produce very high VIF values for both variables 3 and 5, at 4.83 and 4.77, respectively (Table 35). Furthermore, Table 36 demonstrated that variables 3 and 5 were, again, highly correlated to each other at 0.88. This regression iteration, though, demonstrated that the sampled survival rate of the planted poplar clones (variable 5), was a highly insignificant contributor for predicting biomass production estimation, at p = 0.192. With these produced results, it was inferred that the sampled survival rate was likely influencing the output values of the other regression coefficients. Variable 5 was, thus, removed from the regression equation.

Table 37, below, shows the resultant restricted multiple linear regression model for biomass production, with input variables 2 and 5 removed. Table 38 shows the correlation between the remaining variables. From these two tables, all p-values were significant, all VIF values were approximately around 1.0, and correlation between coefficients was also quite low. The r^2 value was also quite high for a biological system at 0.84. With this, variables 1, 3, and 4 (clone type, the number of stems per plot, and DBH) effectively predicted biomass production within the analyzed poplar stand. This regression model demonstrated that an increase in DBH and the number of stems per plot would increase the amount of biomass produced within the stand, per acre per year.

Table 37: 2nd iteration of restricted regression analysis.

Output Variable	Restricted Biomass Production Estimation (ODT/AC-yr)	p-value	VIF	F-value	r^2
Biomass Prod.	Biomass prod. Per-AC per-yr = -3.940	<0.001		131.960	0.840
	- 0.077 (Var. 1)	0.006	1.040		
	+ 0.084 (Var. 3)	<0.001	1.030		
	+ 1.330 (Var. 4)	<0.001	1.010		

Table 38: Correlation coefficients of the 2nd iteration of restricted regression analysis.

	Var. 1	Var. 2	Var. 3
Var. 1	1.00		
Var. 3	0.17	1.00	
Var. 4	-0.11	0.03	1.00

8.2. Reconfigured Forage Harvesting System

8.2.1. Breakeven analysis

The following five scenarios detail the step-by-step procedure taken for analyzing the economic feasibility of producing, harvesting, and processing woody biomass feedstock from a SRWC poplar stand, where:

- Scenario #1 examined the profitability of utilizing solely the reconfigured forage harvesting system, including transport to an energy conversion facility, to generate an income.
- Scenario #2 expanded the scope from scenario #1 to determine the economic feasibility of the entire supply chain, from site setup through transport. Economic values presented from scenario #2 were a record of the events that actually took place within the plantation for research purposes.
- Scenario #3 took the information from scenario #2 and applied generalized hourly rates for all utilized machinery within the analyzed supply chain, based on information provided by Miyata (1980) and the Food and Agriculture Association of the United Nations (1999).
- Scenario #4 optimized the labor force utilized in scenario's 2 and 3, which was identified as the major profit-generating deficiency within these scenarios. This

scenario removed excess labor for seedling hand planting, and introduced mechanical planting machinery in to the supply chain.

- Scenario #5 optimized the economic information presented in scenario #4 with a doubling of the original stand density, to 19,200 TPA. Under the assumption that this would not decrease biomass productivity, an increase in stand density was identified as an easily achievable method to increase profit margins.

8.2.1.1. Breakeven Scenarios

a) Scenario #1: Scope-limited harvesting system scenario

The scope-limited harvesting system scenario considered the feasibility of utilizing only the reconfigured forage harvesting system to generate a profit. While the allocation of profits is not likely to occur in this manner outside of research, a demonstrated focus on the harvesting system provides insight on the minimum requirements necessary to generate an income for the owner-operator.

Table 39 shows the cost (in $/ODT and $/AC), and resultant profit of producing a chipped woody biomass feedstock product with the reconfigured forage harvesting system, including simulated transportation. Figure 32 and Figure 33 demonstrate the-per ton cost for the harvesting system based on costing type and machine type, respectively.

Table 39: Scenario #1 economic cost breakdown of producing SRWC willow with the reconfigured forage harvesting system.

a) Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Harvesting Unit	10.6 (101.6)[a]	9.6 (95.5)	24.2 (241.6)	43.9 (438.7)	286.4 (2,864.0)
Bobcat Loader Chip Collection	4.6 (46.3)	7.9 (78.9)	24.2 (241.6)	36.7 (366.8)	239.5 (2,395.0)
Chip Van Transport	2.9 (28.9)	3.4 (34.4)	4.3 (43.1)	10.6 (106.3)	69.4 (694.3)
Per unit total cost	17.7	20.9	52.6	91.2 (911.9)	595.3 (5,953.3)
Plantation lifespan total cost ($)	176.7	208.7	526.3	6,548.7	6,548.7
Per unit total revenue	--	--	--	566.0	3,695.7
Plantation lifespan total revenue ($)	--	--	--	4,065.3	4,065.3
Per unit total profit	--	--	--	-345.8	-2,257.6
Plantation lifespan total profit ($)	--	--	--	-2,483.4	-2,483.4

[a]Parenthesis= cost of system input for entire 30-year plantation lifespan.

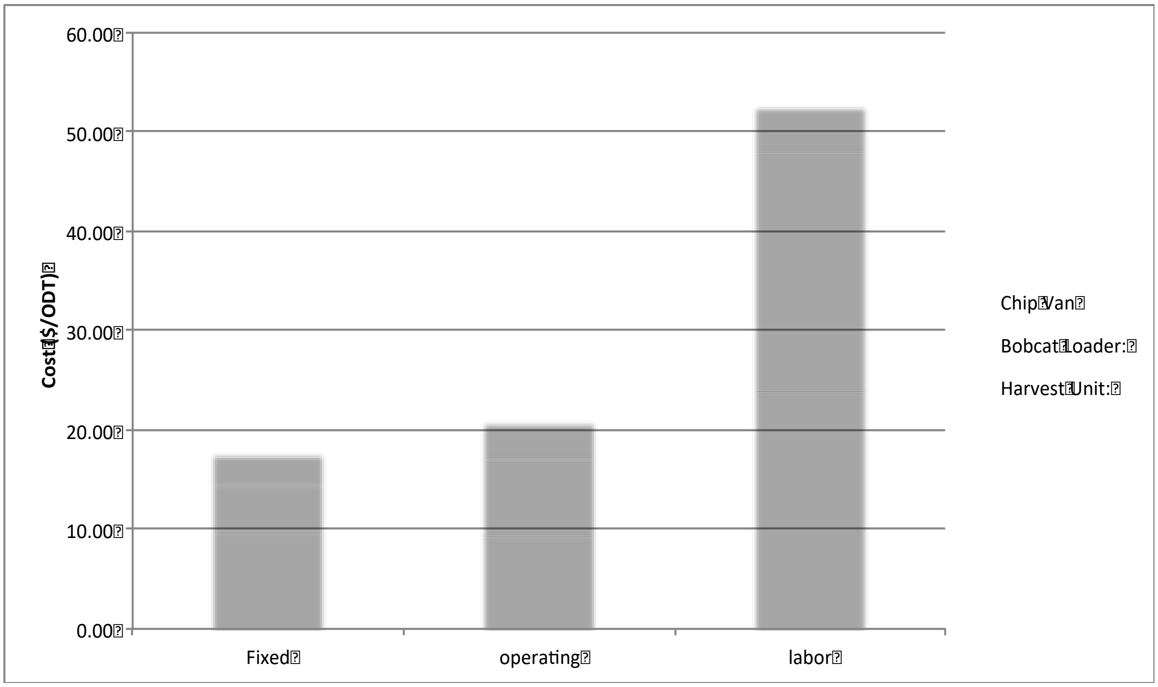

Figure 32: Economic breakdown of fixed, operating, and labor costs for scenario #1 of the SRWC willow operation.

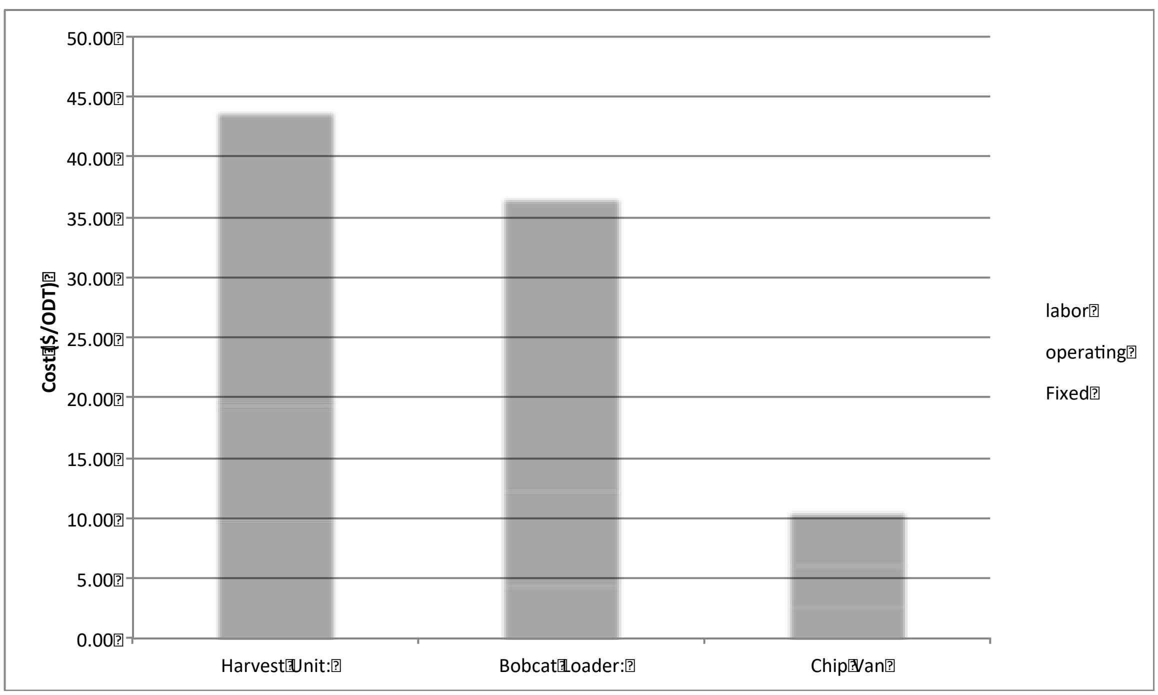

Figure 33: Economic breakdown for Scenario #1 based on system input items for the SRWC willow operation.

As the scenario analysis demonstrated, a profit of approximately -$345.8/ODT would be generated if the only monetary inputs were from operations associated with the harvesting system (-$2,483.4/ODT over the course of 10 harvest operations for the plantation lifespan). This means that the reconfigured system, analyzed at this particular scope, would not generate a profit. This was largely due to the low amount of biomass produced after three growing seasons (7.18 ODT). The harvesting system would not even fill one simulated chip van under these conditions (please see section 7.4.2.4 for more details), making harvest an unlikely option at the commercial scale. Coupled with a long operating time of approximately 4.14 hours, the labor costs associated with producing the biomass feedstock on a per-hour basis make the analyzed system unfeasible.

A breakeven analysis was conducted on the harvesting system to determine the minimum sales price of the produced biomass (in $/ODT), minimum stand density of the plantation (in TPA) required for the harvesting system to breakeven, and the minimum operator salary possible to attain a profit (Table 40). As Figure 32 demonstrated, labor was the largest overall cost input for the utilized machinery. Although not likely to be a practical solution to break even or increase profit margins, an analysis of this type on the labor input demonstrated how sensitive it was to change within the harvesting system.

Table 40: Scenario #1 breakeven analysis for the SRWC willow operation.

Breakeven Input	Breakeven Output
Plantation stand density (minimized, TPA)	13,483.1
Biomass sales price (minimized, $/ODT)	81.6 (532.9)[a]
Operator salary (maximized, $/SMH)	20.4

[a]Minimum biomass price, in $/AC.

As demonstrated in Table 40, the minimum plantation stand density required to breakeven with the reconfigured system was calculated to be 13,483.1 TPA. This analysis assumed that average biomass weight per tree was equal to the actual average biomass weight per tree. With SRWC stands reaching over 50,000 stems per acre, this demonstrated stem density should be considered quite low for a plantation of this type (Eisenbies et al. 2014b). At a minimum biomass sales price of $81.6/ODT, though, the reconfigured system is likely not economically feasible under the given scope. Furthermore, an operator salary of $20.4/SMH is unlikely in today's competitive market that requires skilled labor.

b) Scenario #2: Complete supply chain base-case

Scenario #2, the complete supply chain base-case scenario, expanded the scope presented in Scenario #1 to encompass all inputs associated with woody biomass production, from site setup through product transport to a hypothetical energy conversion facility. In short, the scope of this analysis could be considered from site setup to plant-gate. The expanded scope of Scenario #2 included such inputs as: tilling/spading, hand planting of willow clones, and pesticide applications.

Table 41 shows the cost (in $/ODT and $/AC), and resultant profit of producing a chipped woody biomass feedstock product with the reconfigured forage harvesting system with this expanded scope. Although encompassing, Scenario #2 was a record of events that occurred for research purposes and should, thus, not be considered an optimized case of woody biomass production for bioenergy purposes. Figure 34 and Figure 35 demonstrate the per-ton cost for the supply chain based on costing type and system input type, respectively.

Table 41: Scenario #2 economic cost breakdown of producing SRWC willow with the reconfigured forage harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	2.6	7.1	70.2	79.9	521.6
Plantation Cultivation	2.6	7.1	46.8	56.5	368.9
Hand planting	0.0	0.0	608.2	608.2	3970.9
Pesticide application[a]	0.3	3.8	2.9	7.0	45.7
Pesticide application[b]	0.0	6.3	5.8	12.2	79.4
Coppice cut	0.3	0.9	2.9	4.1	27.0
Harvesting Unit	10.6 (101.6)[c]	9.6 (95.5)	24.2 (241.6)	43.9 (438.7)	286.4 (2,864.0)
Chip collection	8.0 (79.7)	8.9 (88.9)	24.2 (241.6)	41.0 (410.2)	267.9 (2,678.3)
Chip Loading	0.5 (4.9)	0.8 (7.7)	2.5 (25.4)	3.8 (37.9)	24.8 (247.7)
Chip Van Transport	2.9 (28.9)	3.4 (34.4)	4.3 (43.1)	10.6 (106.3)	69.4 (294.3)
Upkeep pesticide application[a]	0.3 (2.9)	3.8 (33.8)	2.9 (26.3)	7.0 (63.0)	45.7 (411.5)
Per unit total cost	27.6	51.6	794.9	874.2 (1,824)	5,707.7 (11,882.2)
Plantation lifespan total cost ($)	223.8	285.4	1,314.8	13,070.5	13,070.5
Per unit total revenue	--	--	--	566.0	3,695.7
Plantation lifespan total revenue ($)	--	--	--	4,065.3	4,065.3
Per unit total profit	--	--	--	-1,253.8	-8,186.5
Plantation lifespan total profit ($)	--	--	--	-9,005.8	-9,005.8

[a]Glyphosate application.
[b]Simazine and Goal application.
[a]Parenthesis= cost of system input for entire 30-year plantation lifespan.

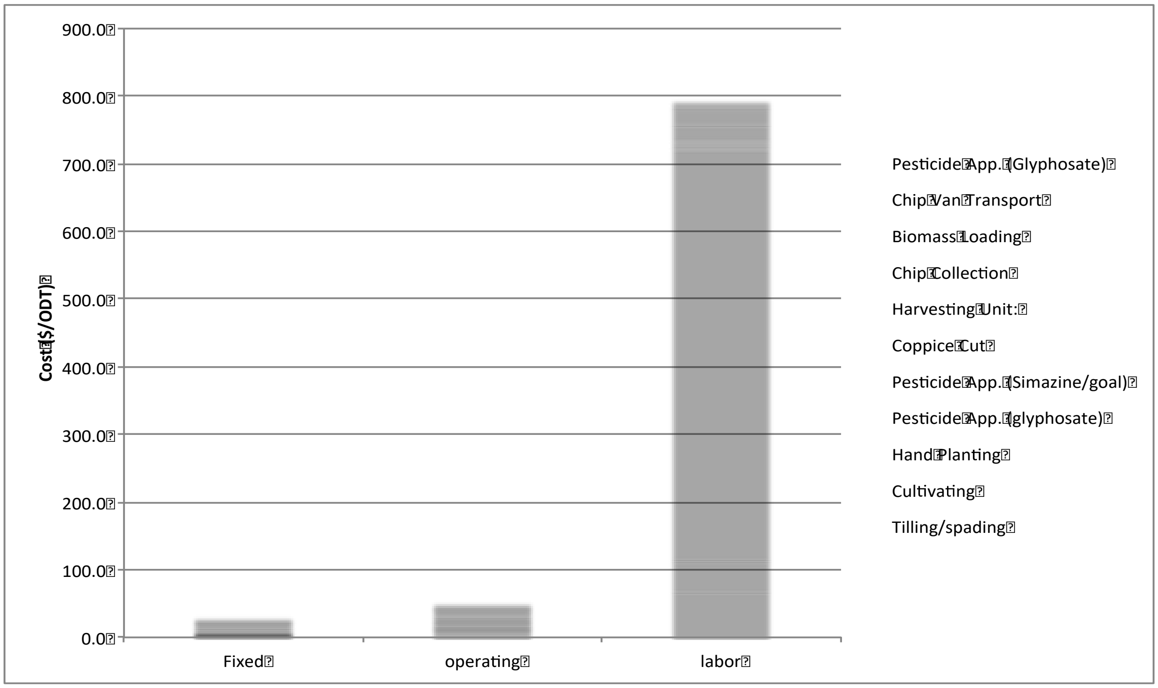

Figure 34: Economic breakdown of fixed, operating, and labor costs for scenario #2 of the SRWC willow operation.

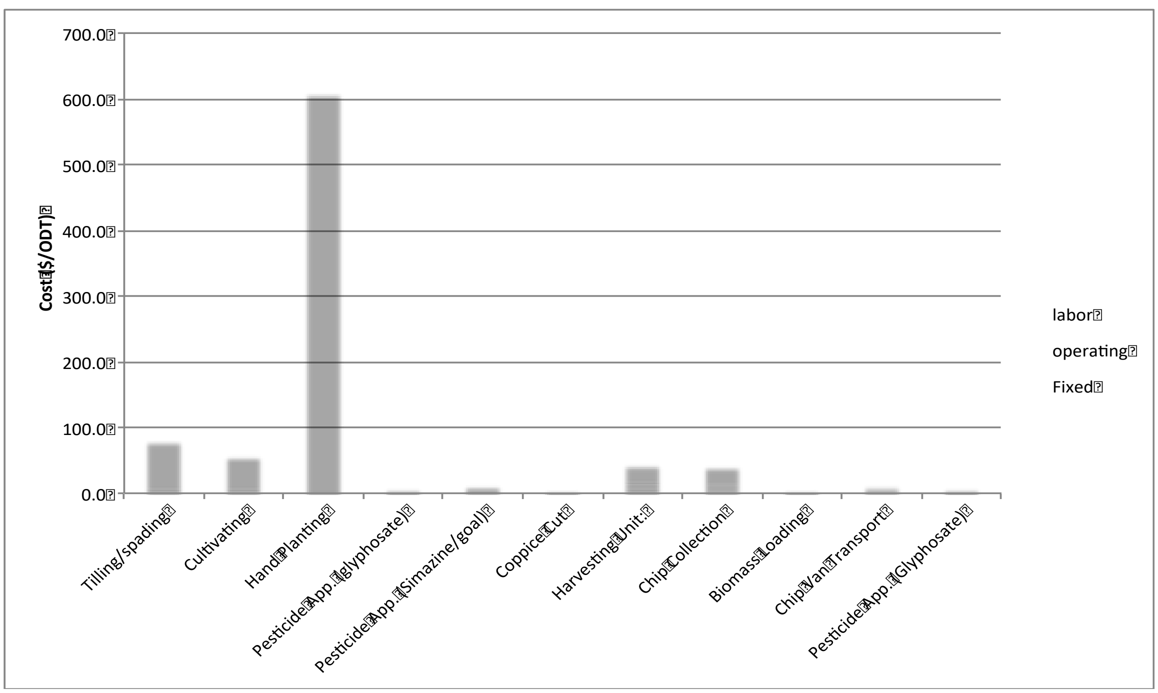

Figure 35: Economic breakdown for Scenario #2 based on system input items for the SRWC willow operation.

As Table 41 demonstrates, a profit would not be generated under this particular set of circumstances. With a scope encompassing all inputs, from site setup to the plant gate, a deficit of approximately -$1,253.8/ODT would be generated. The largest contributing cost in this scenario was hand planting willow stems, at $608.2/ODT (accounting for 33.3% of all cost inputs over the plantation lifespan), due to a disproportionately high labor cost (Figure 34 and Figure 35). Because of this, subsequent optimization scenarios (Scenarios 4 & 5) utilized mechanical planting equipment to reduce salary costing and the number of required individuals to complete the job, thereby increasing system economic feasibility. When compared to scenario #2 of the traditional harvesting system (**section 10.1.1.1.**), the per-ton costing of planting willow stems within the reconfigured system is much more expensive due to the high density of trees being planted per acre (9600 TPA, compared to 880 TPA)

Similar to Scenario #1, a breakeven analysis was conducted in Scenario #2 concerning plantation stand density, biomass sales price, and operator salary (Table 42).

Table 42: Scenario #2 breakeven analysis for the SRWC willow operation.

Breakeven Input	Breakeven Output
Plantation stand density (minimized, TPA)	30,867.9
Biomass sales price (minimized, $/ODT)	182.0 (1,188.3)[a]
Operator salary (maximized, $/SMH)	1.8

[a]Minimum biomass price, in $/AC.

Table 42 demonstrates that the minimum plantation stand density required to breakeven with the analyzed system boundary was calculated to be 30,867.9 TPA. This analysis assumed that average biomass weight per tree was equal to the actual average biomass weight per tree. Although this is an increase in plantation stem density, and creates a stand that is quite dense, it is still within the feasible realm of commercial SRWC plantations, as demonstrated by Eisenbies et al. (2014b). The minimum breakeven biomass sales price, though, was calculated to be $182.0/ODT. With an assumed MC of 47 %, the minimum breakeven price of the produced biomass would be approximately $96.5/green ton, which is unlikely to occur in today's economy due to the low value that biomass for bioenergy is often sold for. The resultant operator salary, $1.8/SMH, is also not a feasible way to attain a profit.

c) Scenario #3: Generalized complete supply chain base-case

Scenario #3 took the scope of Scenario #2 (the complete supply chain base-case) and applied generalized cost input values for all associated machinery required to setup, maintain, and harvest SRWC willow for bioenergy generation. Instead of utilizing hourly rate values with specific operating cost information provided by the FBIC, this scenario produced costs through hourly rate estimation methods provided by Miyata (1980) and the Food and Agriculture Organization of The United Nations (1999). As such, the presented cost information can be considered more representative of an actual SRWC production operation in the Lakes States region. Like Scenario #2, though, Scenario #3 utilized research related inputs and, thus, cannot be considered to have an optimized supply chain for SRWC production. Cost breakdown information is provided below, in Table 43 and Figure 36 and Figure 37.

Table 43: Scenario #3 economic cost breakdown of producing SRWC willow with the reconfigured forage harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	2.6	8.7	70.2	81.5	531.9
Plantation Cultivation	2.6	8.7	46.8	58.1	379.1
Hand planting	0.0	0.0	608.2	608.2	3970.9
Pesticide application[a]	0.3	4.0	2.9	7.2	47.0
Pesticide application[b]	0.0	6.3	5.9	12.2	79.4
Coppice cut	0.3	1.1	2.9	4.3	28.3
Harvesting Unit	10.2 (101.6)[c]	14.8 (148.3)	18.9 (188.8)	43.9 (438.6)	286.4 (2,863.9)
Chip collection	7.9 (79.4)	13.2 (132.1)	10.6 (106.3)	31.8 (317.7)	207.4 (2,074.4)
Chip Loading	0.5 (4.9)	1.0 (10.3)	2.0 (19.8)	3.5 (34.9)	22.8 (228.2)
Chip Van Transport	2.9 (28.9)	5.3 (53.4)	4.3 (43.1)	12.5 (125.4)	81.9 (818.5)
Upkeep pesticide application[a]	0.3 (2.9)	4.0 (35.6)	2.9 (26.3)	7.2 (64.8)	47.0 (470.1)
Per unit total cost	27.6	67.1	775.6	870.3 (1,752.9)	5,682.2 (11,444.7)
Plantation lifespan total cost ($)	223.4	408.4	1121.0	12,558.0	12,558.0
Per unit total revenue	--	--	--	566.0	3,695.7
Plantation lifespan total revenue ($)	--	--	--	4,065.3	4,065.3
Per unit total profit	--	--	--	-1,182.5	-7720.7
Plantation lifespan total profit ($)	--	--	--	-8,492.7	-8,492.7

[a]Glyphosate application.
[b]Simazine and Goal application.
[c]Parenthesis= cost of system input for entire 30-year plantation lifespan.

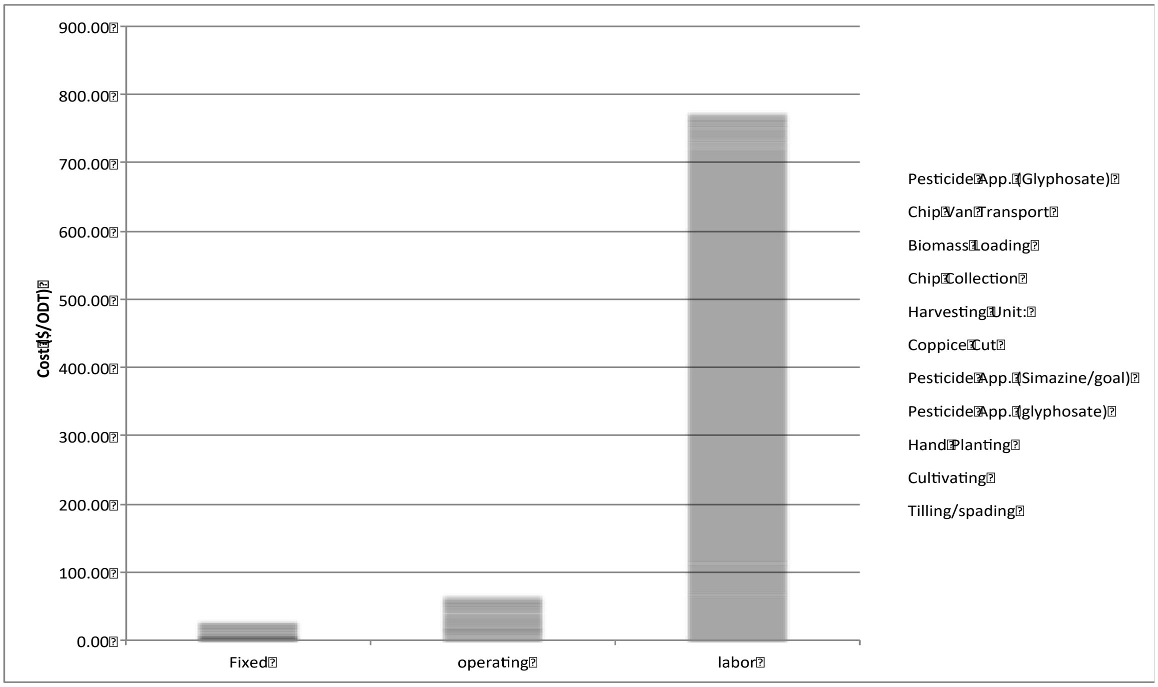

Figure 36: Economic breakdown of fixed, operating, and labor costs for scenario #3 of the SRWC willow operation.

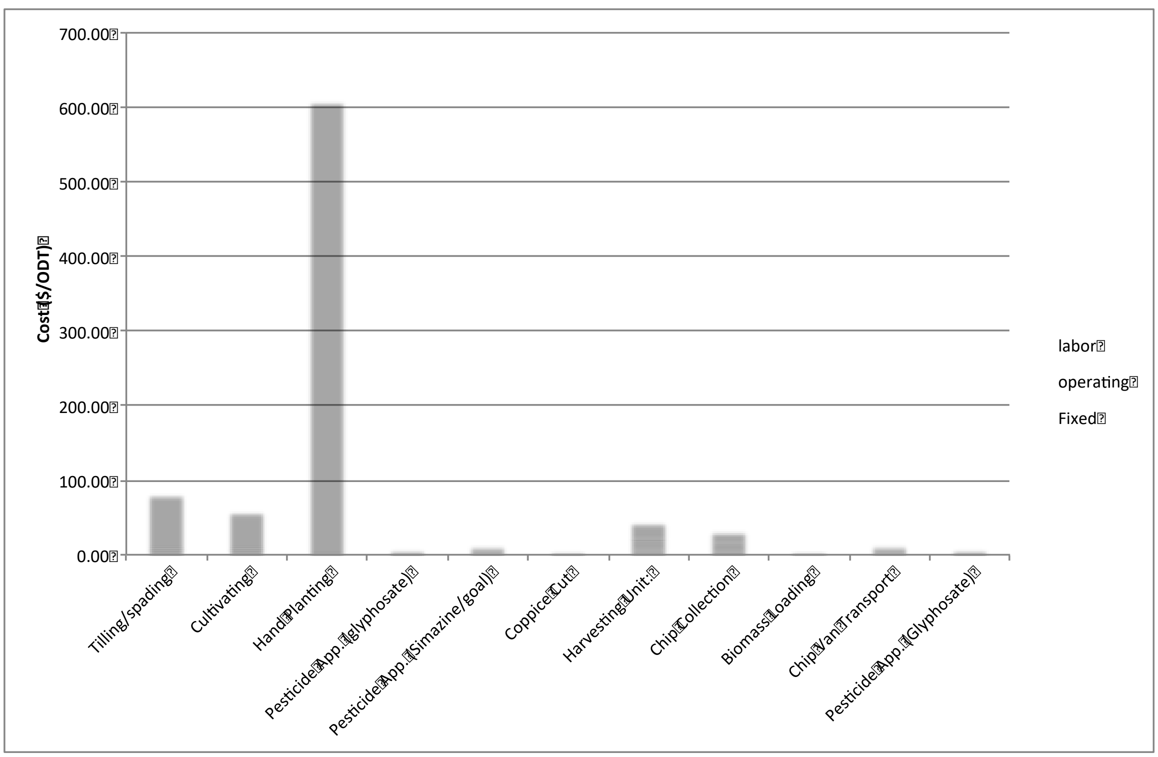

Figure 37: Economic breakdown for Scenario #3 based on system input items for the SRWC willow operation.

With similar cost inputs to scenario #2, scenario #3 results in a loss of profit under this particular set of circumstances. With a scope encompassing all inputs, from site setup to plant gate, a deficit of approximately -$1,182.5/ODT would be generated (or -$8,492.7 in total). As with scenario #2 (and the SRWC poplar scenarios), the labor cost associated with the hand planting of willow stems was the largest single cost input of scenario #3, at $608.2/ODT. With generalized hourly rate estimation values that remove the specificity of scenario #2, scenario #3 further demonstrates the need to reduce labor costs.

A breakeven analysis was conducted for scenario #3 to determine the minimum plantation stand density, biomass sales price, and operator salary necessary to garner a profit within the supply chain (Table 44).

Table 44: Scenario #3 breakeven analysis for the SRWC willow operation.

Breakeven Input	Breakeven Output
Plantation stand density (minimized, TPA)	29,657.8
Biomass sales price (minimized, $/ODT)	174.9 (1,141.7)[a]
Operator salary (maximized, $/SMH)	N/a[b]

[a]Minimum biomass price, in $/AC.
[b]A fluctuation in operator salary could not return a profit in this scenario.

As demonstrated in Table 44, the minimum plantation stand density required to breakeven with the traditional harvesting system was calculated to be 29,657.8 TPA. This analysis assumed that average biomass weight per tree was equal to the actual average biomass weight per tree. Although this is an increase in plantation stem density, it is still within the feasible realm of commercial SRWC plantations, as demonstrated by Eisenbies et al. (2014b). The minimum breakeven biomass sales price, though, was calculated to be $174.9/ODT. With an assumed MC of 47 %, the minimum breakeven price of the produced biomass would be approximately $82.2/green ton, which is unlikely to occur in today's economy due to the low value biomass for bioenergy is often sold for. Furthermore, this analysis demonstrated that a reduction in operator salary of any type would not be enough to generate a profit. Although slightly closer to breaking even than Scenario #2, both the base-case supply chain scenario and the generalized complete supply chain base case scenario demonstrate a need for system optimization. Being the largest single contributing cost input, labor was deemed to be most in need of a cost reduction in order to increase the system feasibility.

d) Scenario #4: Labor Optimization Scenario

Based upon the identified labor cost disparity from Scenario #2 and Scenario #3, Scenario #4 sought to reduce input costs through labor optimization. Such optimization steps included:

- Mechanical planting equipment with integrated use of existing farm tractor utilized elsewhere within the scenario. Mechanical planting reduced the number of operators from four to three and drastically reduced operation time (please see Table 60 of Appendix B for more details).
- The reduction of the number of cultivation operators to one and the number of tilling/spading operators to two.

With these identified optimization steps, Table 45 and Figure 38 and Figure 39 reflect the costs, revenue, and subsequent profit of producing a poplar feedstock product from site setup to factory gate. Although possible, reducing the hourly wage of employees was not seen as a viable way to increase profit margins. Skilled employee retention would likely decrease as wages decreased because workers would seek other employment opportunities that paid competitively. Without skilled and trained workers, the job could not be completed properly.

Table 45: Scenario #4 economic cost breakdown of producing SRWC willow with the reconfigured forage harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	2.6	7.1	46.8	56.5	368.8
Plantation Cultivation	2.6	7.1	23.4	33.1	216.1
Mechanical planting	1.9	5.2	51.5	58.6	382.5
Pesticide application[a]	0.3	3.8	2.9	7.0	45.7
Pesticide application[b]	0.0	6.3	5.8	12.2	79.4
Coppice cut	0.3	0.9	2.9	4.1	27.0
Harvesting Unit	10.2 (101.6)	14.8 (148.3)	18.9 (188.8)	43.9 (438.6)	286.9 (2,863.9)
Chip collection	8.0 (79.7)	8.9 (88.9)	24.2 (241.6)	41.0 (410.2)	267.8 (2,678.3)
Chip Loading	0.5 (4.9)	0.8 (7.7)	2.5 (25.4)	3.8 (37.9)	24.8 (247.7)
Chip Van Transport	2.9 (28.9)	3.4 (34.4)	4.3 (43.1)	10.6 (106.3)	69.4 (694.3)
Upkeep pesticide application[a]	0.3 (2.9)	3.8 (33.8)	2.9 (26.3)	7.0 (63.0)	45.7 (457.2)
Per unit total cost	29.5	62.1	186.1	277.8 (1,227.6)	1,813.8 (8,015.4)
Plantation lifespan total cost ($)	223.4	408.4	1121.0	8,816.9	8,816.9
Per unit total revenue	--	--	--	566.0	3,695.7
Plantation lifespan total revenue ($)	--	--	--	4,065.3	4,065.3
Per unit total profit	--	--	--	-884.1	-5,772.3
Plantation lifespan total profit ($)	--	--	--	-6,349.5	-6,349.5

[a]Glyphosate application.
[b]Simazine and Goal application.
[c]Parenthesis= cost of system input for entire 30-year plantation lifespan.

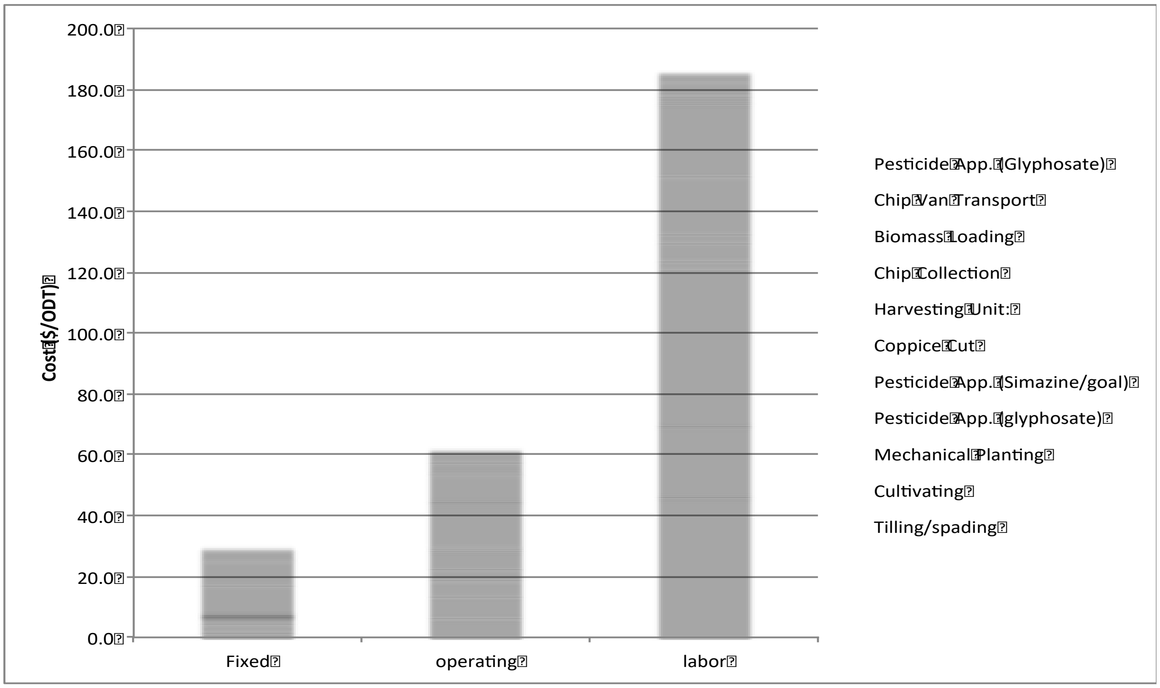

Figure 38: Economic breakdown of fixed, operating, and labor costs for scenario #4 of the SRWC willow operation.

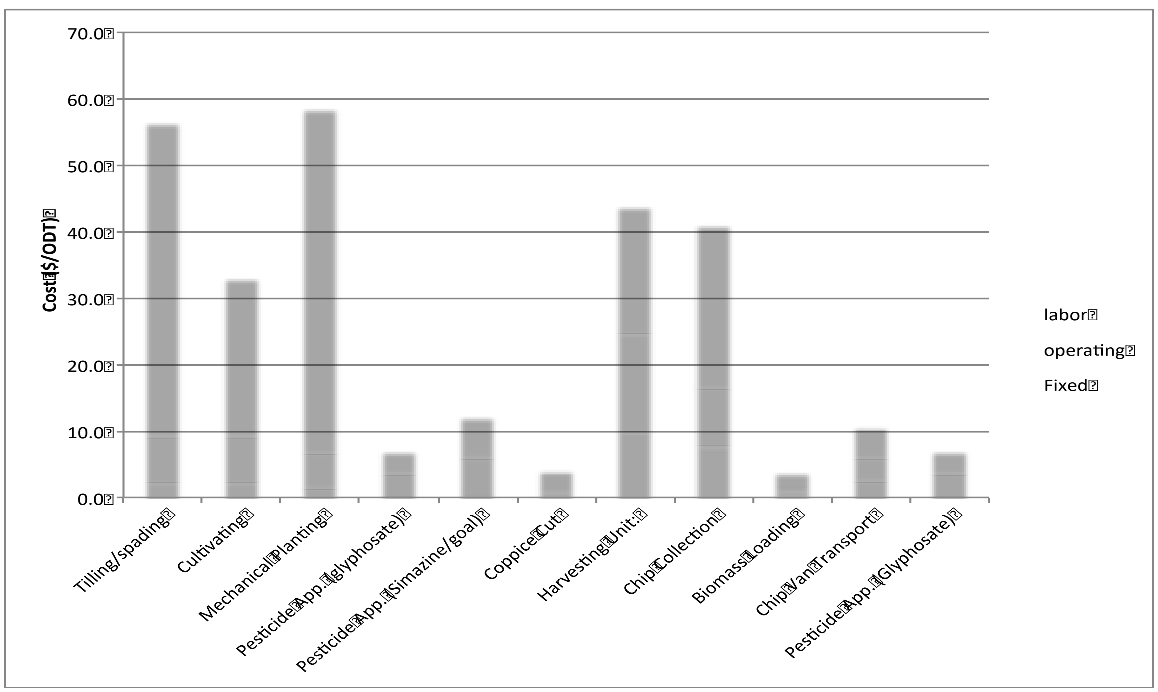

Figure 39: Economic breakdown for Scenario #4 based on system input items for the SRWC willow operation.

Although still the most expensive single component within the supply chain at $58.6/ODT, the mechanical planting of willow stems is now more comparable to the other cost input, as demonstrated by Figure 39. While still disproportionately accounting for the majority of all cost inputs, at approximately 67 % of the total, labor costs dropped as a result of the labor optimization. Still, though, profit was not generated in this scenario and, as a result, a breakeven analysis (Table 46**)** was conducted to determine how manipulations of stand density, biomass sales price, and operator salary would affect the supply chain.

Table 46: Scenario #4 breakeven analysis for the SRWC willow operation.

Breakeven Input	Breakeven Output
Plantation stand density (minimized, TPA)	20,823.3
Biomass sales price (minimized, $/ODT)	122.8 (801.6)[a]
Operator salary (maximized, $/SMH)	2.7

[a]Minimum biomass price, in $/AC.

e) Scenario #5: Combined Labor and stand density optimization scenario

Scenario #5 took the optimized labor condition presented in Scenario #4 and incorporated a stand density of 58,680 TPA, as demonstrated by SUNY researchers as being a feasible stand density for willow biomass crops (SV1, SX67, and Fish Creek hybrids) planted in Oregon. These densities were reported for SUNY's CNH forage harvesting system performance trials. For this scenario, though, it was assumed that biomass accumulation per tree at this density was equal to the per tree weight measured during the actual operation. Under these given conditions, Table 47 and Figure 40 and Figure 41 reflect the costs and subsequent profit of producing a willow feedstock product from site setup to factory gate.

Table 47: Scenario #5 economic cost breakdown of producing SRWC willow with the reconfigured forage harvesting system.

Input Item	Fixed Cost ($/ODT)	Operating Cost ($/ODT)	Labor Cost ($/ODT)	Total Cost ($/ODT)	Total Cost ($/AC)
Tilling/spading	2.6	7.1	46.8	56.5	368.8
Plantation Cultivation	2.6	7.1	23.4	33.1	216.1
Mechanical planting	11.6	32.0	314.1	58.6	382.5
Pesticide application[a]	0.3	3.8	2.9	7.0	45.7
Pesticide application[b]	0.0	6.3	5.8	12.2	79.4
Coppice cut	0.3	0.9	2.9	4.1	27.0
Harvesting Unit	13.6 (135.5)[c]	12.7 (127.4)	32.2 (322.4)	58.5 (585.3)	382.2 (3,821.7)
Chip collection	10.6 (106.4)	11.9 (118.6)	32.2 (322.4)	54.7 (547.3)	357.4 (3,573.8)
Chip Loading	1.5 (14.8)	2.4 (23.6)	7.8 (77.4)	11.6 (115.9)	75.7 (756.9)
Chip Van Transport	14.7 (147.4)	21.0 (210.0)	26.3 (263.2)	62.1 (620.7)	405.3 (4,052.5)
Upkeep pesticide application[a]	0.3 (2.9)	3.8 (33.8)	2.9 (26.3)	7.0 (63.0)	45.7 (411.5)
Per unit total cost	58.1	108.9	497.9	664.9 (2,403.3)	4,341.3 (15,691.4)
Plantation lifespan total cost ($)	424.4	570.6	2,403.3	17,260.6	17,260.6
Per unit total revenue	--	--	--	3,459.9	22,590.1
Plantation lifespan total revenue ($)	--	--	--	24,849.1	24,849.1
Per unit total profit	--	--	--	1,056.6	6,898.7
Plantation lifespan total profit ($)	--	--	--	7,588.5	7,588.5

[a]Glyphosate application.
[b]Simazine and Goal application.
[c]Parenthesis= cost of system input for entire 30-year plantation lifespan.

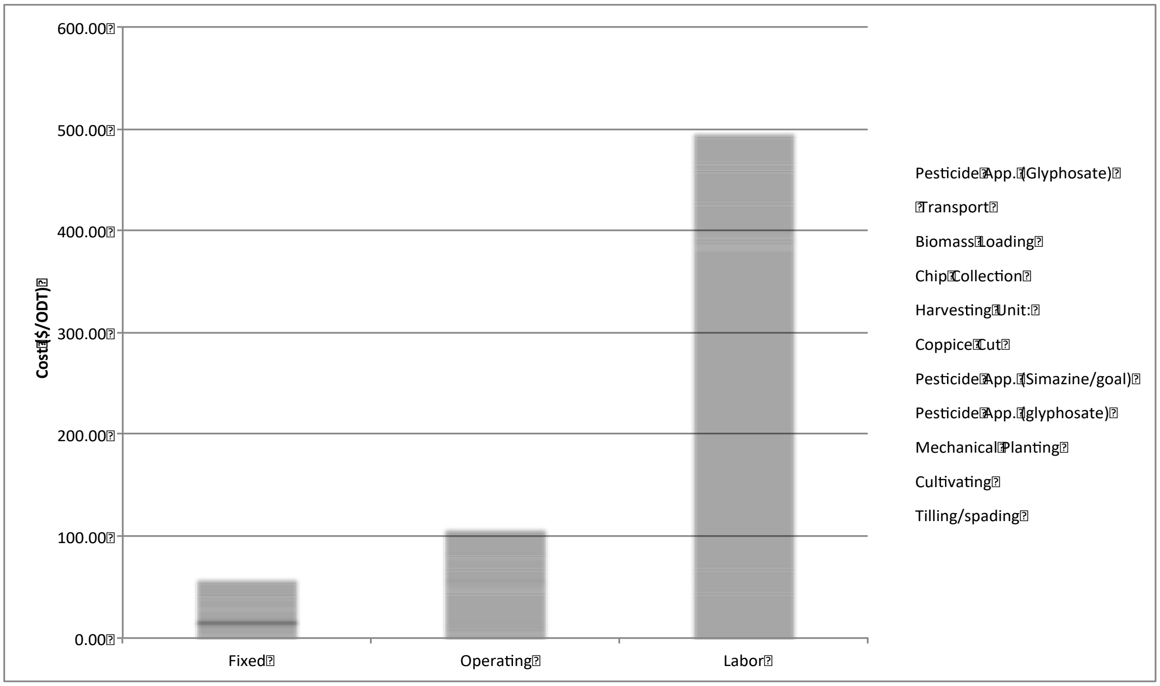

Figure 40: Economic breakdown of fixed, operating, and labor costs for scenario #5 of the SRWC willow operation.

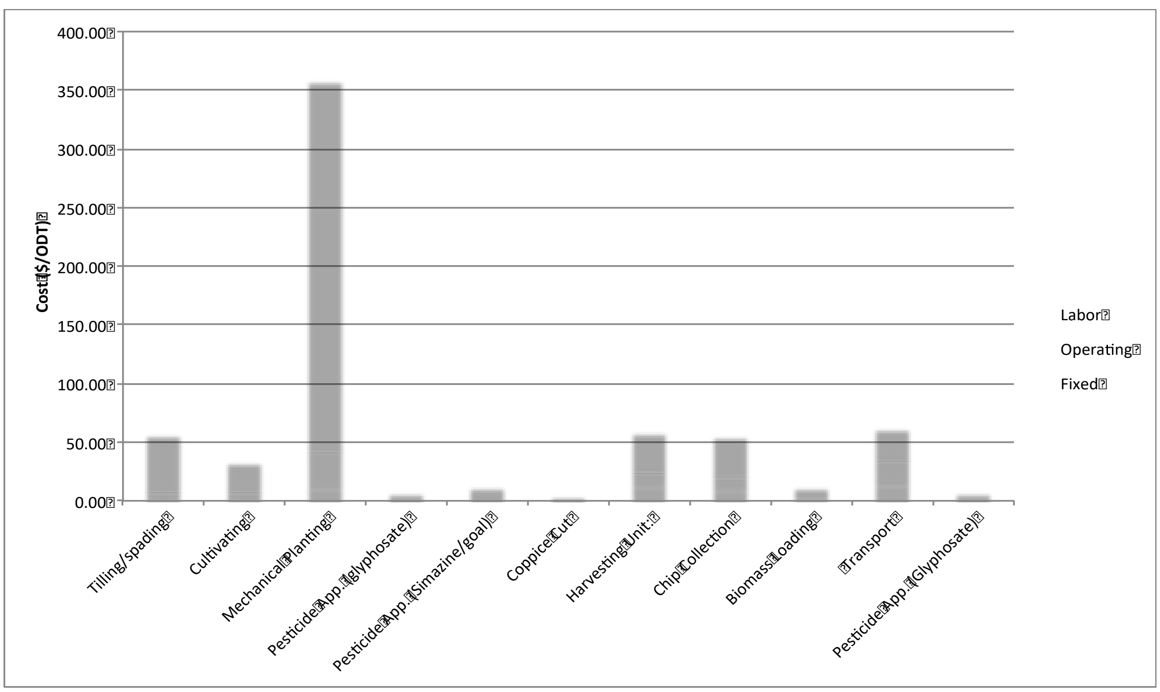

Figure 41: Economic breakdown for Scenario #5 based on system input items for the SRWC willow operation.

As Table 47 demonstrated, a profit of $1,056.6/ODT was generated under the given set of conditions, with approximately $7,588.5 made in total over the course of the 30-year plantation lifespan. Although the input costs of this scenario were higher than the inputs of Scenario #4, especially with mechanical planting (please see Figure 39 for further details), the economies of scale allowed for profit to be generated under the given set of assumptions.

8.2.1.2. Breakeven scenario analysis conclusion

The demonstrated breakeven scenario analyses, summarized in Table 48, show that profit generation is achievable within the given scope of site setup through product delivery at the plant gate. Generating a profit with the reconfigured harvesting system in this particular willow stand should be considered feasible, though is likely to be difficult under the given circumstances. As Scenario #5 demonstrated, a profit of approximately $7,588.5 would be made after 10 harvest operations have occurred over the 30-year plantation lifespan. It was assumed, though, that biomass accumulation increased linearly with the addition of more stems. This is likely to be an over-estimation for biomass productivity. All five scenarios demonstrated that labor was the largest contributing cost input, so it is of utmost importance to have optimized labor scheduling with these types of SRWC stands.

Table 48: Breakeven scenario analysis summary for the analyzed SRWC poplar operation.

Breakeven Scenario	Total Cost ($)	Total Revenue ($)	Total profit ($)
Scenario #1	6,548.7	4,065.3	-2,483.4
Scenario #2	13,070.5	4,065.3	-9005.2
Scenario #3	12,558.0	4,065.3	-8,492.7
Scenario #4	8,816.9	4,065.3	-4,751.6
Scenario #5	17,260.6	24,849.1	7,588.5

A major hindrance to profit generation for all presented scenarios was the time of harvest. With a harvest age of three years, the amount of accumulated biomass within the

SRWC willow stand was quite low when compared to the seven year-old SRWC poplar stand in Escanaba, on a per-acre basis. With similar site upkeep costs that occurred more frequently due to the short rotation cycle, the return on investment for the SRWC willow stand was much lower than that of the SRWC poplar stand. In order to increase the economic feasibility with this particular stand, decreasing the harvesting frequency of the stand is recommended. In doing so, there would be an increase in the amount of accumulated biomass per acre, and a decrease in the necessary upkeep costs associated with maintaining the stand following a harvest. In this case, Scenario #5 was able to overcome this issue with an incredibly high number of stems per acre.

8.2.2. Benefit/cost analysis

Input values for the benefit-cost analysis can be found below, in Table 49.

Table 49: Benefit-cost analysis inputs for the SRWC willow operation.

Input Variable	Input Value	Input Justification
t (years)	3	FBIC
y (an index for years)	3	FBIC
R_q (present value of all revenues)	**	Calculated
C_q (present value of all costs)	**	Calculated
r (real interest rate)	0.04	Benjamin et al. (2000)
R_y (revenue in year y)	**	Calculated
C_y (cost in year y)	**	Calculated

** Different input values utilized for each individual scenario. All Revenue and cost values (R_q, C_q, R_y, and C_y) can be found summarized in section ***10.2.1.2.***

Based on these provided input values, the benefit-cost analysis was generated. Results for the analysis can be found below, in Table 50.

Table 50: Benefit-cost analysis outputs for the SRWC willow operation.

Breakeven Scenario	NPV	B/C	IRR
Scenario #1	-2,007.0	0.62	N/a[a]
Scenario #2	-7,277.8	0.31	N/a
Scenario #3	-6,863.6	0.32	N/a
Scenario #4	-3,840.2	0.46	N/a
Scenario #5	6,132.9	1.44	0.104

[a]IRR value not available because no profit was generated for the given scenario.

From Table 50, profit-generating scenarios produced a positive NPV, and a B/C value >1.0, while deficit inducing scenarios produced a negative NPV, and a B/C value <1.0. In this instance, scenario #5 was the only scenario to generate a profit, therefore it was the only scenario to produce a positive NPV and a B/C value >1.0. As stated in Section 10.2.1.2 (the breakeven scenario analysis conclusion), the input costs associated with harvesting and maintaining a site with a short rotation period decreased the profitability of the entire supply chain. If the willow stems were allowed to mature to an older age, input costs would largely remain constant while the profit per-acre would increase. In essence, the benefits of each scenario would increase while the associated costs would decrease. The B/C ratio would, therefore, increase as well.

9. ECONOMIC ANALYSIS: SUMMARY & IMPLICATIONS

Summarized results for the breakeven analysis scenarios and the benefit-cost analysis for both SRWC poplar and willow operations can be found below, in Table 51 and Table 52.

Table 51: Economic analysis summary for SRWC poplar operation.

Breakeven Scenario	Total Cost ($)	Total Revenue ($)	Total profit ($)	NPV	B/C	IRR
Scenario #1	22,550.70	31,807.20	9,256.50	7,034.17	1.41	3.34
Scenario #2	48,267.80	31,807.20	-16,460.60	-12,508.69	0.66	N/a[a]
Scenario #3	51,842.00	31,807.20	-20,034.80	-15,224.80	0.60	N/a
Scenario #4	21,580.40	31,807.20	10,266.80	7,771.51	1.47	0.15
Scenario #5	48,275.00	63,614.40	15,339.40	11,656.70	1.32	0.18

Table 52: Economic analysis summary for SRWC willow operation

Breakeven Scenario	Total Cost ($)	Total Revenue ($)	Total profit ($)	NPV	B/C	IRR
Scenario #1	6,548.70	4,065.30	-2,483.40	-2,007.00	0.62	N/a[a]
Scenario #2	13,070.50	4,065.30	-9005.20	-7,277.80	0.31	N/a
Scenario #3	12,558.00	4,065.30	-8,492.70	-6,863.60	0.32	N/a
Scenario #4	8,816.90	4,065.30	-4,751.60	-3,840.20	0.46	N/a
Scenario #5	17,260.60	24,849.10	7,588.50	6,132.90	1.44	0.10

Considering a supply chain scope encompassing site setup through product delivery, both the SRWC poplar and SRWC willow operations were unable to generate a profit under actual conditions. Given that these stands were planted and utilized for research purposes, both operations were highly receptive to optimized labor input strategies, which greatly increased their economic feasibility, as demonstrated in each respective operation's scenario #4 (Table 51 and Table 52). The use of mechanical planting techniques and simultaneous operation activities, where applicable, is recommended to reduce input costs, thereby increasing profit margin potential. Regardless of SRWC feedstock type, optimized labor strategies such as these should be considered essential for all stakeholders participating in woody biomass feedstock production.

Based on the presented analysis of the two disproportionate SRWC production operations, the economies of scale also greatly influenced profit potentials. At a relatively sparse density of 880 TPA, in a stand size of 7.8 AC, harvested at 7 years of age over the course of a simulated 28-year lifespan, the poplar plantation was able to achieve economic success much more feasibly than the willow operation that was planted at a higher density of 9,600 TPA, in a stand size of 1.1 AC, that was harvested at 3 years of age over the course of a simulated 30-year plantation lifespan. This was demonstrated in Table 31 and Table 50, with the presented NPV and B/C values that were generally lower for the willow operation. Utilizing a small 1.1 AC plantation that was harvested at such a high frequency required more cost inputs than a larger plantation that was harvested less frequently, on a per-ton basis. This issue was exacerbated in that the plantation rotation time of 3 years reduced the amount of accumulated biomass that was available to be sold for revenue. With higher per-unit cost inputs, and lower revenue outputs, the SRWC willow plantation was not able to generate a profit without intensive optimization strategies.

The cost inputs required to harvest with use of the tractor-pulled cut-and-chip reconfigured forage harvesting system was higher than for the traditional harvesting system, as well. Largely due to a low estimated productivity of 1.92 ODT/PMH for the harvesting unit, it cost the reconfigured system approximately $99.3/ODT to produce a woody biomass feedstock (please see Table 41 for complete cost breakdown information regarding the harvesting unit, chip collector, chip loader, and chip van). The traditional system, on the other hand, cost approximately $40.1/ODT, including biomass transportation (please see Table 21 for complete cost breakdown information). With such a high cost associated with harvesting, input costs to produce a feedstock product every 3 years greatly increased for the SRWC willow operation under utilization of the reconfigured forage harvesting system.

Within the given parameters, woody biomass production (in ODT/AC-yr) was predicted for the analyzed Escanaba poplar plantation through utilization of a hedonic regression model. Following two restriction iterations, the regression model looked as such:

Biomass production (ODT/AC-yr) = -3.94 -0.077(Var.1) + 0.084(Var.3) + 1.33(Var.4)

Where:

Var.1 = clone type, numerically sorted.

Var.2 = the number of counted stems per plot.

Var.3 = Average plot DBH.

This regression model demonstrated that an increase in DBH and the number of stems per plot would increase the amount of biomass produced within the stand, per acre per year. The clone type utilized also had a statistically significant impact on the amount of biomass accumulation.

10. LIFE CYCLE ASSESSMENT: DATA COLLECTION & ANALYSIS

10.1. LCA framework

10.1.1. Goal and scope definition

The goal of this LCA was to determine and contrast the environmental impacts associated with cultivating, harvesting, and utilizing SRWC poplar and willow for bioenergy generation purposes, within the state of Michigan. For purposes of this particular study, the highlighted focus was on the particular harvesting system utilized to produce the biomass feedstock, where the SRWC poplar feedstock was produced utilizing the traditional whole-tree harvesting system, and the SRWC willow feedstock was produced utilizing the reconfigured forage harvesting system. The cultivation system boundary included: site preparation through tilling and spading, the planting of saplings, weed and pest control, and coppice cutting (Figure 42). The harvest operation referred to all necessary activities involved with clear-cutting the plantation, producing a chipped or ground feedstock product, and subsequent transport of that product to an energy conversion facility. Utilization of the feedstock assumed direct combustion without thermochemical upgrading procedures or densification. Investigated environmental impacts of this LCA included: global warming potential (GWP), measured in lb. of carbon dioxide equivalence (CO_2-e/lb.), and eutrophication potential of water, measured in lb. of nitrogen equivalence (N-e/lb.).

Included within the project scope was input product utilization and maintenance. This LCA did not include contributions associated with raw material acquisition or the manufacturing of input products necessary to produce and utilize the woody biomass feedstock. Raw materials transformed into a product (such as harvesting equipment) and subsequently distributed to an end user were also not considered in this assessment. This analysis also did not investigate the environmental impacts associated with site depletion, including: loss of soil organic matter and loss volatiles present within the soil. Ash waste recycling and disposal following combustion was also not analyzed. Analysis of volatiles subsequent to biomass combustion was also not included within the LCA.

10.1.2. Functional Unit

The functional unit for this LCA was one-kilowatt hour (kWh) of produced electrical grid energy, with respect to a delivered biomass feedstock product from the analyzed SRWC poplar and willow stands.

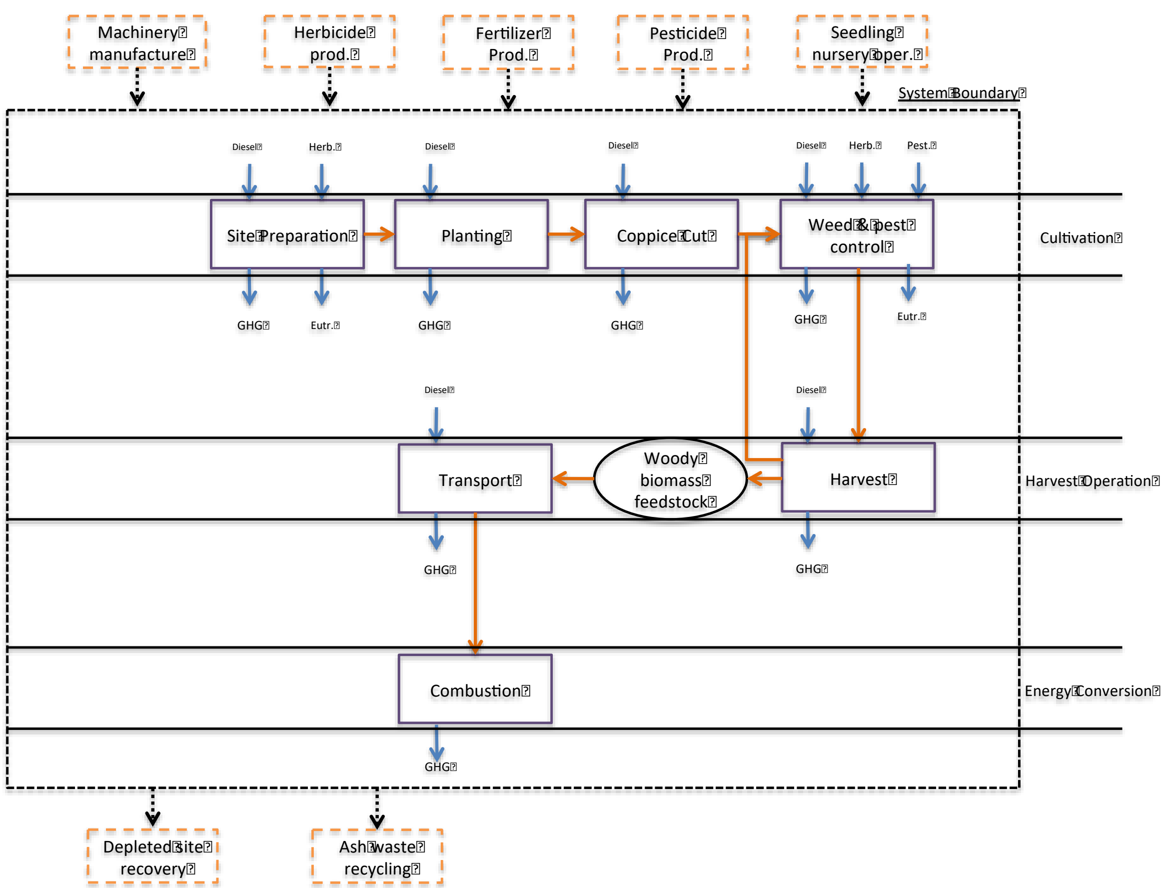

Figure 42: LCA systems flow diagram with included system boundary.

10.1.3. Inventory analysis

The information utilized to generate the inventory analysis came from multiple sources, namely in-field FBIC site records and data generated through time and motion analysis. Both of these information sources were site specific and were an occurrence of actual events that took place to produce the poplar/willow feedstock products. Data that was not collected in field was generated through simulation and was subsequently fact-checked against existing literature to ensure accuracy. Table 53 and Table 54 below, exhibit all analyzed inputs that went in to each plantation.

Table 53: SRWC poplar plantation inventory inputs, Escanaba, MI.

Item	System input value	Unit	Data source/comments
Site Preparation & Stand Initiation			
Tilling/spading	15.4	gal diesel	FBIC: 55hp tractor, 10hr op. time
Herbicide application:	6.16	gal diesel	FBIC: 55hp tractor, 4hr op. time
• Scepter 70 DG (tractor)	0.34	gal	FBIC: Imazaquin- 5.6oz/AC (1.35g/cm^3)
• Pendulum (tractor)	5.85	gal	FBIC: Pendimethalin- 3qts/AC (1.17g/cm^3)
• Glyphosate (manual)	0.26	gal	FBIC: 0.256 pints/AC (1.7g/cm^3)
Poplar Sapling Planting	2.94	gal diesel	TRC: 55hp tractor, 1tree/sec planting speed
Harvest Operation			
Feller-buncher	103.90	gal diesel	Time and motion
Skidder	23.80	gal diesel	Time and motion
Loader	20.80	gal diesel	Time and motion
Grinder	82.30	gal diesel	Time and motion
Chip van(s)	318.20	gal diesel	Miyata (1980) assumption, simulated
Plantation Upkeep			
Coppice cut	0.00	gal diesel	No coppice cut occurred in operation
Insecticide application (manual)	0.26	gal	FBIC: No provided info on app rate- assumed
Herbicide application (manual)	0.26	gal	FBIC: 0.256 pints/AC (1.7g/cm^3)
Biomass combustion for bioenergy			
Higher heating value input	8,517.00	BTU/lb.	Site collected samples- bomb calorimetry
Power plant efficiency	35.00	%	Assumed- TB Simon Power Plant
Boiler Capacity	21.00	mW	TB Simon Power Plant

Table 54: SRWC willow plantation inventory inputs, Albion, MI.

Item	System input value	Unit	Data source/comments
Site Preparation & Stand Initiation			
Tilling/spading	5.60	gal diesel	FBIC: 55hp tractor, 4hr op. time
Herbicide application:	2.31	gal diesel	FBIC: 55hp tractor, 1.5hr op. time
• Simazine (tractor)	0.91	lb.	FBIC: 1lb per 1.1AC
• Goal (tractor)	0.46	gal	FBIC: Oxyfluorfen, 0.5 gal per 1.1AC
• Glyphosate (tractor)	1.82	lb	FBIC: 2lb per 1.1AC mixed with water
Willow Sapling Planting	4.50	gal diesel	TRC: 55hp tractor, 1 tree/sec planting speed
Harvest Operation			
Harvesting unit	3.90	gal diesel	Field collected: 155hp tractor, 4.14 hr op. time
Chip collector	3.90	gal diesel	Simulated/field collected: 155hp tractor, min. delay
Loader	0.57	gal diesel	Simulated/field collected: 87HP bobcat loader
Chip van	7.40	gal diesel	Simulated: Scaled for size of operation
Plantation Upkeep			
Coppice cut	0.77	gal	FBIC: 55hp tractor, 0.5hr op. time
Insecticide application	0.00	gal	No insecticide applied in the operation
Herbicide application (manual)	1.82	lb	FBIC: 2lb per 1.1AC mixed with water
Biomass combustion for bioenergy			
Higher heating value input	8,014.00	BTU/lb.	Site collected samples- bomb calorimetry
Power plant efficiency	35.00	%	Assumed- TB Simon Power Plant
Boiler Capacity	21.00	mW	TB Simon Power Plant

10.1.4. Environmental Impact assessment

The environmental impact assessment for both the SRWC poplar and willow plantations can be found below, in Table 55 and Table 56. Information related to GWP can be found presented first while eutrophication potential (eutr.) values can be found subsequent, in parenthesis.

Table 55: SRWC poplar plantation inventory assessment, Escanaba, MI.

Item	GWP (Eutr.)	Unit
Site Preparation & Stand Initiation		
Tilling/spading	342.4 (0.0)	lb. CO_2-e (lb. N-e)
Herbicide application via tractor:	137.0 (0.0)	lb. CO_2-e (lb. N-e)
• Scepter 70 DG (tractor)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
• Pendulum (tractor)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
• Glyphosate (manual)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
Poplar Sapling Planting	65.3 (0.0)	lb. CO_2-e (lb. N-e)
Harvest Operation		
Feller-buncher	2,309.9 (0.0)	lb. CO_2-e (lb. N-e)
Skidder	529.1 (0.0)	lb. CO_2-e (lb. N-e)
Loader	462.4 (0.0)	lb. CO_2-e (lb. N-e)
Grinder	1,829.7 (0.0)	lb. CO_2-e (lb. N-e)
Chip van	7,074.9 (0.0)	lb. CO_2-e (lb. N-e)
Plantation Upkeep		
Coppice cut	0.0 (0.0)	lb. CO_2-e (lb. N-e)
Insecticide application (manual)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
Herbicide application (manual)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
Biomass combustion for bioenergy		
Combustion	252.7 (0.0)	tons CO_2-e (lb. N-e)
Total GWP (Eutr).	259.0 (0.0)	tons CO_2-e (lb. N-e)

Table 56: SRWC willow plantation inventory assessment, Albion, MI.

Item	GWP (Eutr.)	Unit
Site Preparation & Stand Initiation		
Tilling/spading	124.5 (0.0)	lb. CO_2-e (lb. N-e)
Herbicide application via tractor:	51.4 (0.0)	lb. CO_2-e (lb. N-e)
• Simazine (tractor)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
• Goal (tractor)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
• Glyphosate (tractor)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
Willow Sapling Planting	100.4 (0.0)	lb. CO_2-e (lb. N-e)
Harvest Operation		
Harvesting unit	86.6 (0.0)	lb. CO_2-e (lb. N-e)
Chip collector	86.6 (0.0)	lb. CO_2-e (lb. N-e)
Loader	12.8 (0.0)	lb. CO_2-e (lb. N-e)
Chip van	164.6 (0.0)	lb. CO_2-e (lb. N-e)
Plantation Upkeep		
Coppice cut	17.1 (0.0)	lb. CO_2-e (lb. N-e)
Insecticide application (manual)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
Herbicide application (manual)	0.0 (0.0)	lb. CO_2-e (lb. N-e)
Biomass combustion for bioenergy		
Combustion	12.2 (0.0)	tons CO_2-e (lb. N-e)
Total GWP (Eutr.)	12.5 (0.0)	tons CO_2-e (lb. N-e)

Input chemical GWP/eutrophication potential values populated within Table 55 and Table 56 were generated through the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) 2.0 (Bare, 2011). System input chemicals that were not included within the TRACI model, including Scepter 70 DG (Imazaquin) and BT insecticide (*Bacilius thuringiensis*), were generated through information provided in MSDS data sheets. All chemicals utilized to produce the woody biomass feedstock, though, had no influence on GWP or eutrophication potential within the given project scope.

All data collected on diesel fuel usage throughout the analyzed input operations were converted to lb. CO2-e through the Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel report (EPA, 2005). This report provided that the carbon content per gallon diesel was approximately 2,778.0 g/gal (6.12 lb./gal), under the assumption that

99.0 % of the carbon within the fuel was oxidized during combustion. This LCA followed the same set of assumptions. Furthermore, increases in eutrophication potential to water from the combustion of fossil fuels was found to be 0.0 lb. N-e for all utilized machinery.

Because the T.B. Simon Power Plant was identified as the hypothetical end-user of the produced woody biomass feedstock, GWP due to combustion was generated through equations provided in the T.B. Simon Power Plant Greenhouse Gas Monitoring Plan. These equations were originally described in the Environmental Protection Agency's Electronic Greenhouse Gas Reporting Tool (E-GGRT). As part of the EPA GHG Monitoring Plan (under 40 CFR 98.3(g)(5)), suppliers of fossil fuels or industrial greenhouse gasses that emit ≥25,000 metric tons per year CO_2-e are subject to GHG reporting. The T.B. Simon Power Plant falls under this category. As such, the identified greenhouse gasses that were emitted through combustion of biomass included: CO_2, CH_4, and N2O. The calculation for these three gasses were as follows described in Equation [5], Equation [6], and Equation [7]:

$$CO_2 = 1.0 \cdot 10^{-3} \cdot Fuel \cdot HHV \cdot EF\ CO_2 \quad [5]$$

$$CH_4 = 1.0 \cdot 10^{-3} \cdot (HI)_A \cdot EF\ CH_4 \quad [6]$$

$$N_2O = 1.0 \cdot 10^{-3} \cdot (HI)_A \cdot EF\ N_2O \quad [7]$$

Where:

CO_2/CH_4/N_2O = Annual mass emission for the specific fuel type (metric tons).

$1.0 \cdot 10^{-3}$ = Conversion factor from kilograms to metric tons.

Fuel = mass of the wood biofuel combusted per year (short tons).

$(HI)_A$ = Cumulative annual heat input from the biomass fuel (MMBTU).

EF CO_2 = Woody biomass specific default CO_2 emission factor (provided at 93.80 kg CO_2/MMBtu).

EF CH_4 = $3.2 \cdot 10^{-2}$ kg CH_4/MMBtu.

EF $N_2O = 3.2 \cdot 10^{-3}$ kg N_2O/MMBtu.

CO_2, CH_4, and N_2O were the only emission sources subject to GHG reporting requirements (40 CFR Part 98 (C)). Furthermore, this analysis only included these three chemicals for GWP contribution during combustion under the assumption that other volatilized chemicals resulted in negligible GWP contributions. Within the context of this analysis, the combustion of woody biomass did not result in any influence on eutrophication potential, as well.

Carbon sequestration due to the root development of the analyzed SRWC poplar and willow was estimated through values provided by Zan et al. (2001), where it was demonstrated that the rate of root carbon sequestration for willow on a 3-year period was approximately 0.56 ton C AC^{-1} yr^{-1}. This value was generated from an average of two site locations, in southwestern Quebec, at a root/soil depth of 1.96 ft, and plantation density of 4,453 stems/AC. Assuming a linear relationship between sequestered carbon and produced biomass, there would be approximately 0.25 lb. $tree^{-1}$ yr^{-1}. For the purposes of this analysis, it was assumed that both poplar and willow sequestration rates were the same.

11. LIFE CYCLE ASSESSMENT: RESULTS & DISCUSSION

11.1. Interpretation

Values from the environmental impact assessment were given context related to the functional unit by putting GWP outputs for both analyzed SRWC operations in lb. of per-unit CO_2-e per kWh, based on the amount of produced biomass for each stand (Figure 43). As Figure 43 demonstrated, the lbs of CO2-e/kWh due to combustion were slightly higher for the poplar operation. This was due to having a slightly higher MC of 47 % (compared to 43.5 %), which influenced the necessary amount of feedstock required to supply the power plant, based on the biomass HHV. In total, biomass combustion accounted for >97.0 % of the total emissions related to GWP for both biomass production operations.

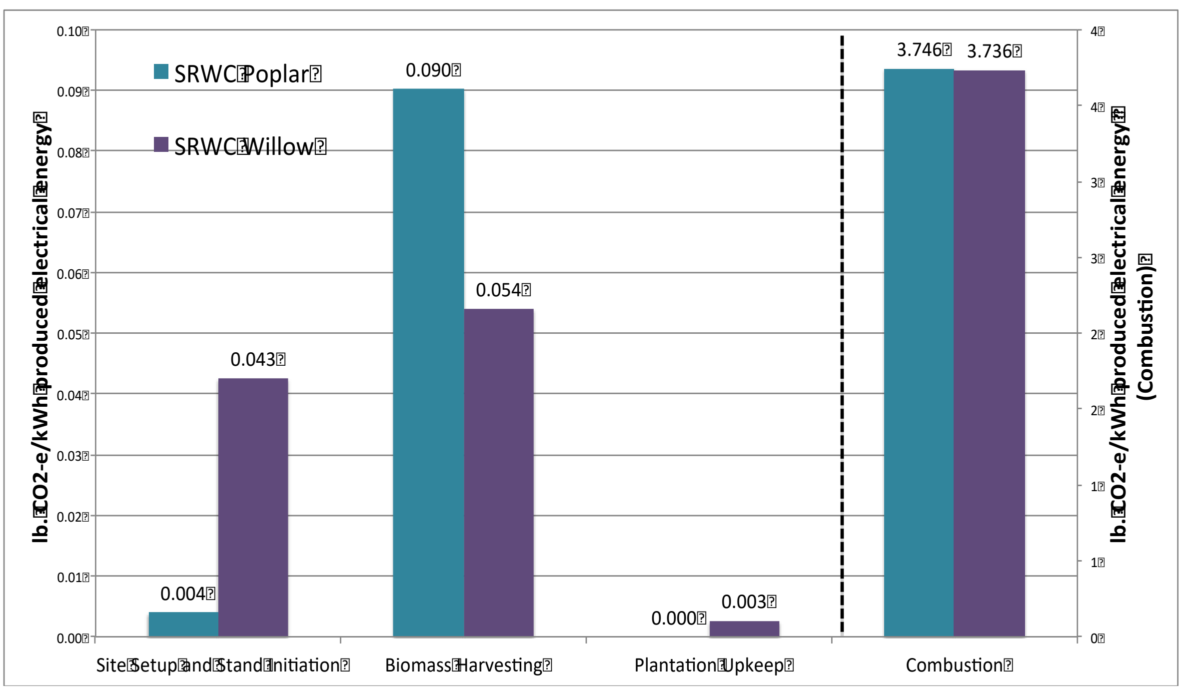

Figure 43: Itemized per-unit kWh GWP contributions for the two analyzed SRWC poplar and willow production operations.

When analyzed on an equivalent HHV and MC of 8018.06 BTUs/lb. and 43.5 %, though, the poplar harvesting operation generated combustion-related GWP at a nearly equivalent level to the willow harvesting operation, as demonstrated below in Figure 44. This shows that biomass quality created the difference associated with combustion-related GWP.

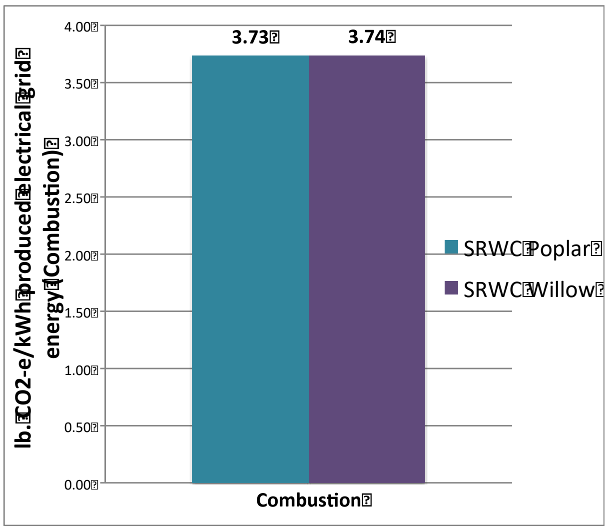

Figure 44: GWP contributions (in lb. CO2-e/kWh) for the SRWC poplar and willow operations with equal MC and HHV.

Although largely inconsequential to the total GWP contribution, the Site Setup and Stand Initiation category was higher in its per-unit lb. CO_2-e for the willow operation at 0.043 CO_2-e/kWh, compared to 0.004 lb. CO_2-e/kWh for the poplar operation. This was a product of three system inputs, as demonstrated by the life cycle inventory assessment (Table 54), where:

- The willow operation required a coppice cut to encourage sapling recruitment/growth while the poplar operation did not.

- The number of stems per acre was substantially higher for the willow operation (9,600 TPA compared to 880 TPA), thereby increasing the per-acre gasoline requirement associated with mechanical planting.
- Due to economies of scale, the tilling/spading and herbicide application of the poplar operation was only roughly 3 times higher than the willow operation. For a stand that was 7.1 times the size of the willow plantation, the poplar plantation benefited from requiring a similar amount of work that had a higher return on investment.

Figure 43 demonstrated that the reconfigured forage harvesting system produced slightly less per-unit GWP contributions when compared to the traditional system. At a 60.0 % reduction in GWP on a per-unit basis, approximately 0.054 lb. CO_2-e/kW was generated compared to 0.090 lb. CO_2-e/kW, for the reconfigured forage harvesting system and traditional harvesting system, respectively. Within the bounds of the presented scope, the reconfigured forage harvesting system was, thus, the environmentally superior harvesting system. At a difference of approximately 0.036 lb. CO_2-e/kWh, though, either harvesting system should be considered as a viable solution to producing woody biomass feedstock because of the inconsequential total system GWP contributions. Accounting for >97.0 % of all analyzed GWP contributions, the direct combustion of woody biomass was largely the only influential factor within the entire system. Figure 45, below, presents the itemized GWP contributions with the inclusion of net lb. CO_2-e/kWh based on different reported carbon sequestration rates (Heller et al. 2003, Lemus and Lal 2007, Sartori et al. 2006, Zan et al. 2001). Collected sequestration rates were presented based on low, mean, and high sequestration rates of 0.11, 0.60, and 1.33 tons C AC^{-1} yr^{-1}, respectively, due to the high degree of variation within the reported literature data. It was assumed that both crops would sequester at the same rate for purposes of this analysis.

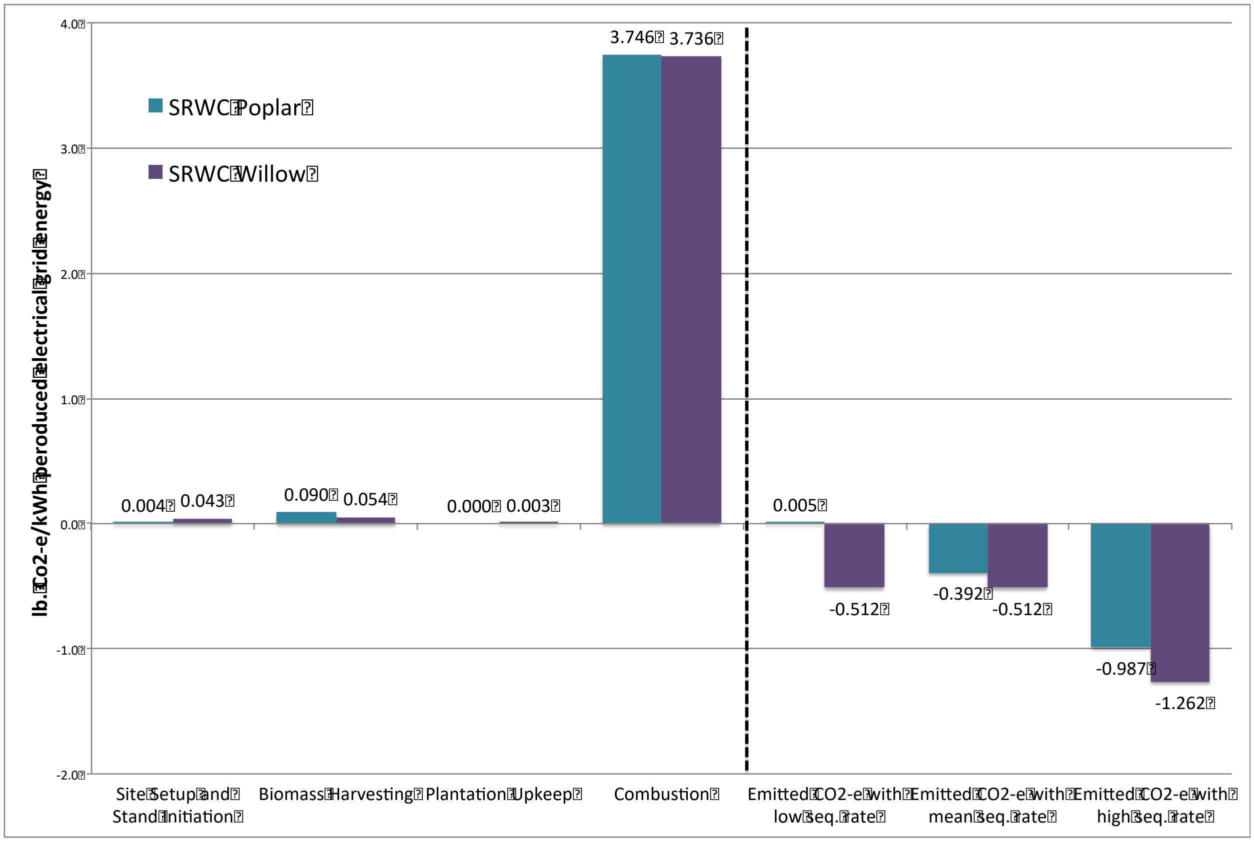

Figure 45: Itemized per-unit kWh GWP contributions with included carbon sequestration for the two analyzed SRWC operations.

11.1.1. Sensitivity analysis

In order to better understand how the functional unit influenced the GWP contributions of the two analyzed woody biomass feedstock production systems, a sensitivity analysis was conducted relating fluctuations in:

- Required electrical grid energy inputs (in kWh) with resultant GWP outputs (in tons of CO_2-e) based on the amount of supplied biomass.
- Woody biomass quality inputs through changes in MC, with resultant GWP outputs (in tons of CO_2-e).

- Woody biomass quality inputs through changes in HHV (in BTUs/lb.), with resultant GWP outputs (in tons of CO_2-e)

Specific focus of GWP contributions were related to biomass amount and quality because of combustion's inordinate affect on greenhouse gas emission production within the conducted LCA scope. Such an analysis provides insight to what aspects of the supplied biomass most affect GWP contributions when combusted. Results for both operations are presented below, in Figure 46 and Figure 47:

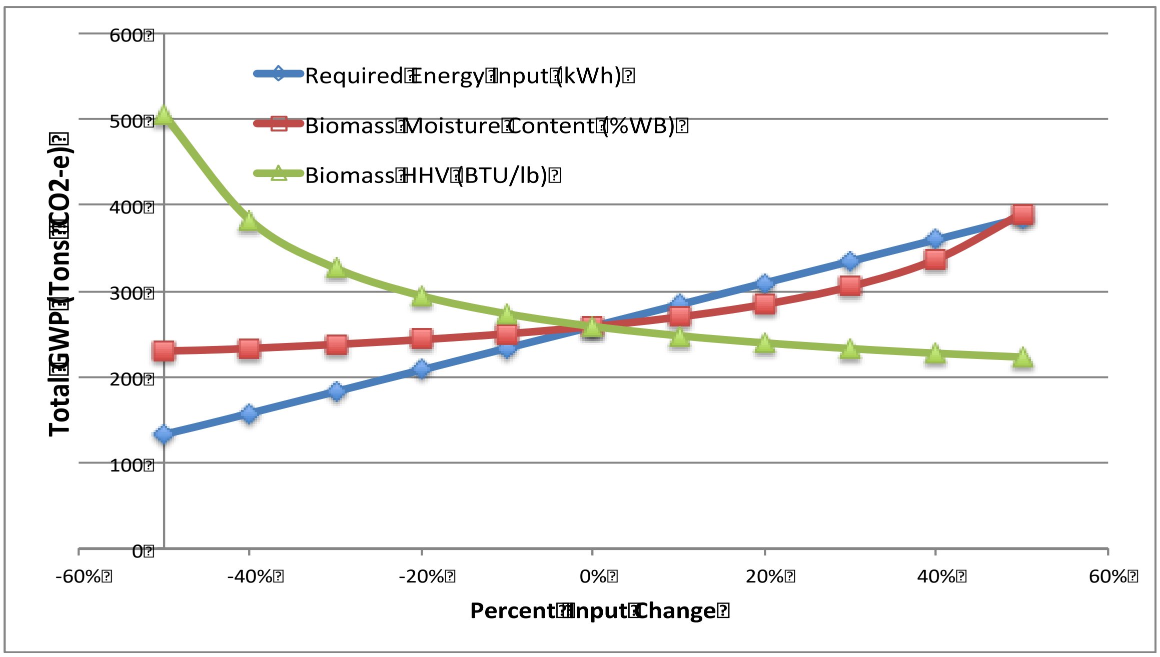

Figure 46: Sensitivity analysis relating biomass feedstock quality input categories with system GWP outputs for the SRWC poplar operation.

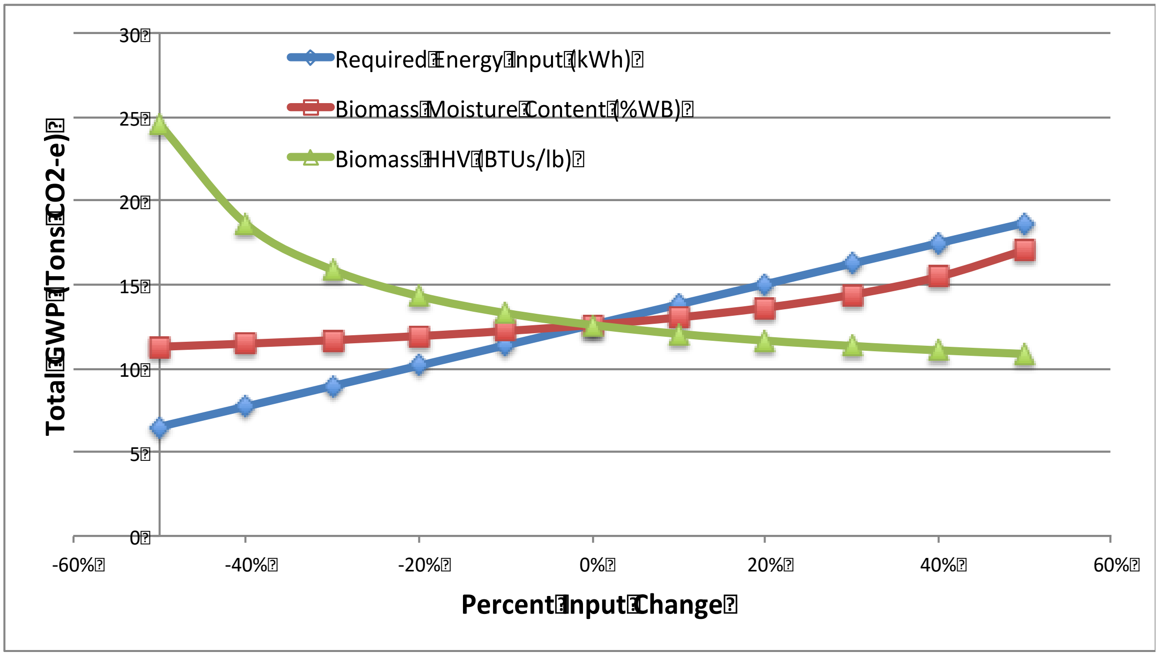

Figure 47: Sensitivity analysis relating biomass feedstock quality input categories with system GWP outputs for the SRWC willow operation.

As both Figure 46 and Figure 47 demonstrated, all three tested categories were sensitive to change. Biomass HHV, though, most influenced the system global warming potential, exhibiting exponential GWP behavior at a 50.0 % decrease in the percent input change of HHV. Among other components, MC was a contributing factor for biomass HHV (Equation 1); HHV therefore had the largest influence on biomass quality. Intuitively, increasing the biomass HHV decreased the system GWP because less biomass feedstock was required to meet the necessary kWh. Being just one component of HHV, MC was slightly less sensitive to change. With increased moisture, more feedstock combustion was required to produce the same amount of kWh, thereby increasing GWP contributions.

A second sensitivity analysis was conduced with specific focus on each harvesting system utilized to produce the biomass feedstock. Contributions to GWP through released greenhouse gasses of both the traditional and reconfigured forage harvesting systems were analyzed with fluctuations in individual machine productivity (in ODT/PMH). Results can be found below in Figure 48 and Figure 49**.** The analysis assumed each machine's operation activity was disjointed from the other machines within the supply chain (resulting in a staged harvesting operation, having no downstream effect on production rates).

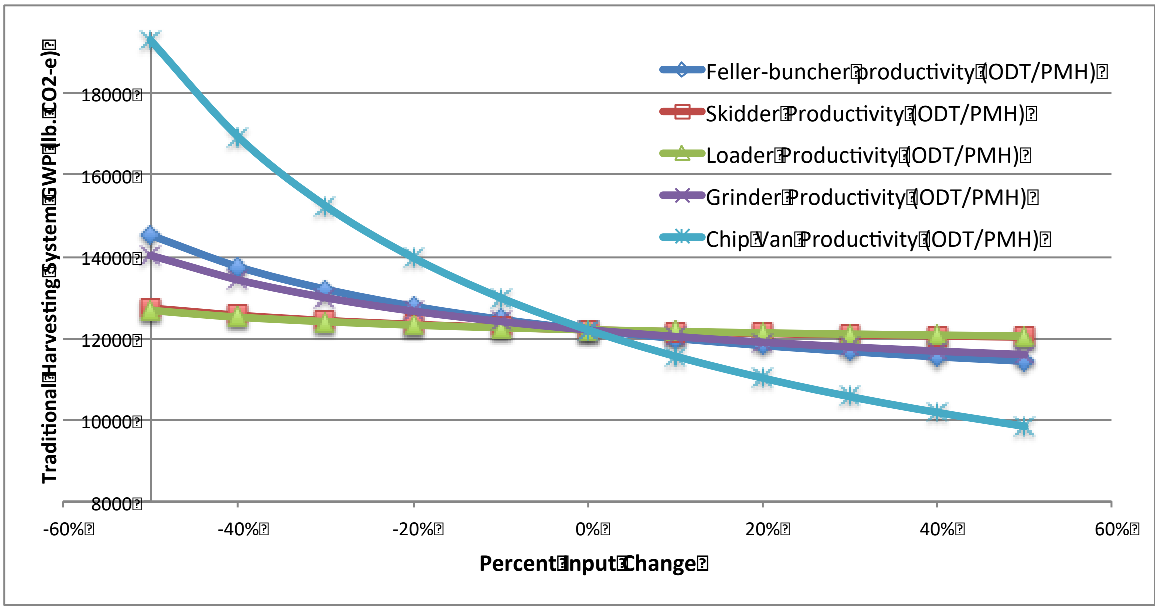

Figure 48: Sensitivity analysis relating machine productivity with system GWP outputs for the traditional harvesting system.

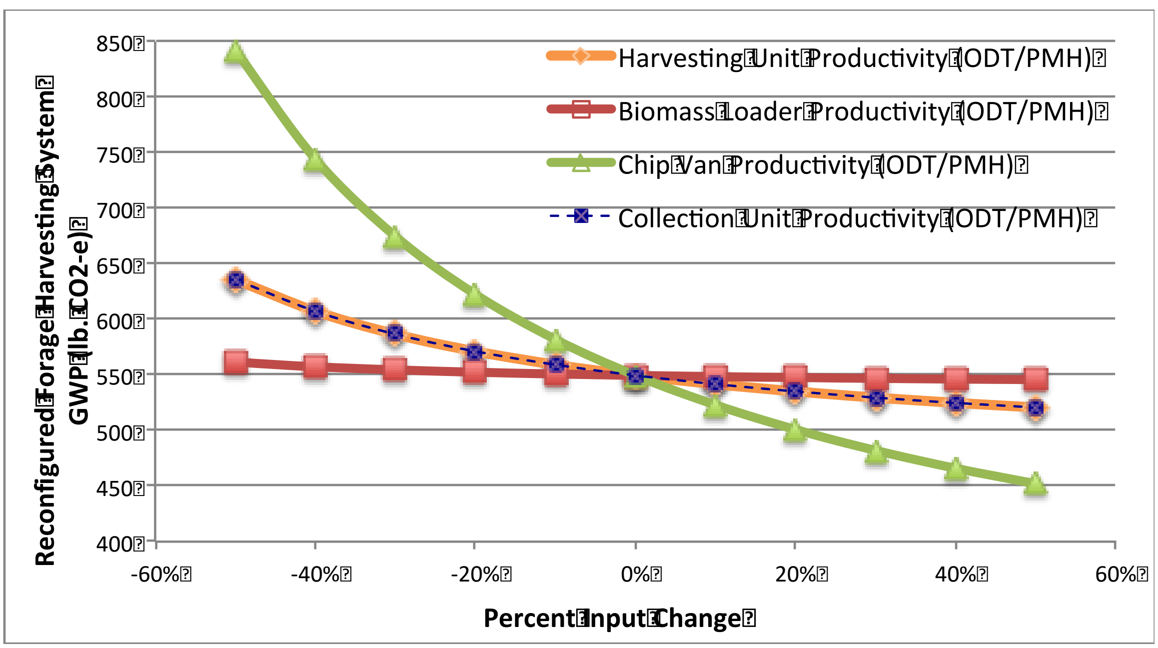

Figure 49: Sensitivity analysis relating machine productivity with system GWP outputs for the traditional harvesting system.

Both Figure 48 and Figure 49 demonstrated that chip van productivity was the most sensitive component to contributing GWP for both harvesting systems. From an environmental standpoint, it is, therefore, of utmost importance to optimize the supply chain logistics associated with woody biomass transport, regardless of how the feedstock was produced. An inefficient transport operation will likely influence GWP more than any other aspect of either harvesting system.

Figure 48 also demonstrated that the feller-buncher GWP of the traditional harvesting system was sensitive to percent changes in its productivity. Because the feller-buncher was shown to harvest SRWC stems at an inefficient level when compared to the skidder, loader, and grinder (Table 8), this sensitivity output further establishes the feller-buncher as the limiting factor of the traditional harvesting system when utilized unproductively.

For clarification purposes, the harvesting unit and collection unit of the reconfigured forage harvesting system, in Figure 49, exhibited the same GWP contributions with each percent change in productivity because they were singularly dependent upon each other during operation activities. Furthermore, with a simulated collection unit that utilized the same equipment as the in-field monitored harvesting unit (JD 7330 tractor), GHG emissions were the same for both analyzed categories.

12.LIFE CYCLE ASSESSMENT: SUMMARY & IMPLICATIONS

Total GWP contributions for both SRWC operations can be found summarized below, in Table 57.

Table 57: Itemized GWP contributions for the SRWC poplar and willow operations.

SRWC Type	Site setup and stand initiation (lb. CO2-e/kWh)	Harvesting (lb. CO2-e/kWh)	Plantation upkeep (lb. CO2-e/kWh)	Combustion (lb. CO2-e/kWh)	Total (lb. CO2-e/kWh)
Poplar	0.004	0.090	0.000	3.746	3.840
Willow	0.043	0.054	0.003	3.736	3.836

In complete, 3.840 and 3.836 lb. CO_2-e/kWh was produced for both the poplar and willow harvesting operation, respectively. This disparity of GWP with respect to the functional unit (kWh) was overwhelmingly due to differences in biomass quality. With respect to only the utilized harvesting systems, the willow feedstock production with use of the reconfigured system produced less lb. CO_2-e/kWh when compared to feedstock production with use of the traditional system. This suggests that the reconfigured machinery constitutes the better harvesting system, solely from an environmental standpoint. All else aside, though, either harvesting system should be considered as a viable solution to feedstock production because of their inconsequential system-wide GWP contributions. Within the analyzed scope, both SRWC feedstock operations also produced negligible additions of N-e resulting in no increase in system eutrophication potential. It should be noted, though, that an extended LCA scope incorporating fertilizer production and use would likely produce increases in N-e.

While recommendations about superiority related to environmental impacts can be made between the two utilized harvesting systems, it should be noted that this LCA was not encompassing of all SRWC production and harvesting scenarios. The presented analysis represented data from singular small-scale operations that were inherently different from each other. All implications should, thus, be restricted to the demonstrated set of conditions. In order to confidently make further conclusions that extend the bounds of the presented scope, further LCA analysis must be conducted from other multiple sources. This LCA should be considered as just one “data point” of many when analyzing the implications of producing SRWC feedstock with different harvesting systems.

13.CONCLUSIONS

This thesis evaluated the qualities of short rotation woody crop harvesting systems based on quantitative production metrics, economics, and environmental impacts associated with biomass feedstock for bioenergy production.

System evaluation results demonstrated a production rate, production cost, and machine hourly rate of 9.7-39.1 oven dry tons/productive machine hour (ODT/PMH), $20.23/ODT, and $283.6/scheduled machine hour (SMH), respectively, for the traditional system, and 1.7 ODT/PMH, $81.17/ODT, and $141.10/SMH for the reconfigured system, respectively. Although the machine hourly rate was beneficially lower for the reconfigured harvesting system, the beneficially higher production rate and lower per-ton production cost of the traditional harvesting system indicate that it is better suited for SRWC harvesting. The extremely low measured production rate of 1.7 ODT/PMH indicates that utilization of the small JF 192 harvester within the reconfigured forage harvesting system may not produce an adequate amount of feedstock within a timely manner.

Through scenario-based breakeven analyses within the economic analysis, it was determined that the traditional harvesting system could reach a practical breakeven point more feasibly than the reconfigured system, through labor optimization and stand initiation simulations, at an equal biomass sales price of $60/ODT. Because these stands were initiated for research purposes, though, both operations could not generate a profit under actual circumstances. With introduced labor optimization strategies, where mechanical planting was implemented and research related operations were removed, the SRWC willow operation attained a net present value of 7,771.5, a benefit-cost ratio of 1.47, and an internal rate of return of 0.15, respectively. The SRWC willow harvesting operation, on the other hand, could not attain a profit solely with this introduction. Following a further optimization step of increased stand density to 1,760 TPA and 58,680 TPA for the SRWC poplar and willow, respectively, the SRWC poplar operation attained a net present value of 11,656.7, a benefit-cost ratio of 1.32, and an internal rate of return of 0.18, respectively. The SRWC willow operation attained a net present value of 6,132.9, a benefit-cost ratio of 1.44, and an internal rate of return of 0.1, respectively. This analysis demonstrated that the SRWC willow operation required an incredibly high degree of efficiency to be considered as a feasible endeavor.

The life cycle assessment determined that the reconfigured forage harvesting system produced slightly less GWP contributions than the traditional system at 0.054 lb. CO_2-e/kWh and 0.090 lb. CO_2-e/kWh, respectively. With biomass feedstock combustion accounting for >97.0 % of all GWP contributions, though, both harvesting systems negligibly influenced their overall respective operations. Furthermore, considering the entire supply chain scope, both operations produced net-negative CO_2-e emissions due to carbon sequestration through root biomass accumulation, at an average sequestration rate from identified literature sources (-0.392 lb. CO_2-e/kWh and -0.512 lb. CO_2-e/kWh for the poplar and willow operation, respectively). Within the identified system boundary of the LCA, eutrophication potential was also non-present for both operations, at 0.0 lb. N-e. Both the reconfigured forage harvesting system and the traditional harvesting system should, thus, be considered as viable harvesting systems from an environmental standpoint

APPENDICES

Appendix A: MATlab code for predictive models

MATlab code utilized to generate the predictive production rate equations and values for each piece of machinery within the traditional ground-based whole-tree harvesting system.

- Feller-buncher:

```
%% Harvesting Production Rate
close
clear all
data=xlsread('poplar_fellerbuncher_data1');
data = data(randperm(size(data,1)),:); %Randomize the data

%% Enter in Data
TreeDist=data(:,3);
CutNumber=data(:,6);
MovetoBunch=data(:,9);

TreeDistTime=data(:,2);
CutNumbTime=data(:,5);
MovetoBunchTime=data(:,8);

%% Split Randomized Data in to Sections (2/3 vs 1/3)

TreeDistTwoThird=TreeDist(1:125);
TreeDistOneThird=TreeDist(126:187);


CutNumberTwoThird=CutNumber(1:125);
CutNumberOneThird=CutNumber(126:187);


MovetoBunchTwoThird=MovetoBunch(1:125);
MovetoBunchOneThird=MovetoBunch(126:187);

twothirds=[TreeDistTwoThird CutNumberTwoThird MovetoBunchTwoThird];
%The data was then moved over to excel, separated, saved, and then brought
%back in to matlab for analysis (as can be seen below).
%% Calculating Delay Free Average Cycle Time
data=xlsread('Rand_Poplar_OneThird_Final');
Dist=data(:,3);
TreeNumber=data(:,6);
BunchDist=data(:,9);
T2=data(:,12); %Collected Observed Data, summed total time per cycle

%Generated Linear Model Using Stata
%T1=8.765653+8.466335.*(Dist)+8.815661.*(TreeNumber)+4.875863.*(BunchDist)
T1=8.765653+0.564423.*Dist+8.815661.*TreeNumber+0.3250575.*BunchDist
T1min=T1/100

TMean=mean(T1)
Tstdev=std(T1)
T1minsMean=mean(T1min)
```

```
%% T2(Observed Data)
T2Mean=mean(T2)
T2stdev=std(T2)

%% Two Sample Ttest between Predicted-T and Observed-T
[h,p,ci,stats] = ttest2(T1,T2)
figure
boxplot(T2)
figure
boxplot(T1)
%% Caluclation of Predicted Cycle Time utilizing Averaged Data

%CompleteData=xlsread('Randomized_Poplar_Data1');
CompleteData=xlsread('Rand_FB_TwoThird_Final'); %utilizes 2/3 of data even
though data states its complete

DistComplete=CompleteData(:,3);
TreeNumberComplete=CompleteData(:,6);
BunchDistComplete=CompleteData(:,9);

DistCompleteMean=mean(DistComplete)
TreeCompleteMean=mean(TreeNumberComplete)
BunchDistCompleteMean=mean(BunchDistComplete)

%PredCycleTime=8.765653+8.466335.*(DistCompleteMean)+8.815661.*(TreeCompleteM
ean)+4.875863.*(BunchDistCompleteMean)
PredCycleTime=
8.76565306+0.5644234.*DistCompleteMean+8.81566093.*TreeCompleteMean+0.3250575
3.*BunchDistCompleteMean
PredCycleTime_Min=PredCycleTime/100


%% Calculation of Predicted Feller Buncher Production Rate

%Plot Acreage calculation
Tree_total=6864; %total number of trees on the study site
Tree_per_acre=6864/7.8; %the study site was 7.48 acres in size

%Harvested Biomass Weight Based on Averages
%ODTavgPerYear=2.4214444; %Value provided by Brad in poplar excel doc
%ODTavg=ODTavgPerYear*7;
ODTavg= 140.48; % based on weight of chip vans

%Calculation
%FB_Production_Rate_Tons=1/((Tree_per_acre/ODTavg)/TreeCompleteMean) %in
ODT/cycle
FB_Prod_Rate_PerCycle=(TreeCompleteMean/Tree_total)*ODTavg
%FB_Production_Rate_lb=FB_Production_Rate_Tons*2000

% PMH Conversion-The time the machine is scheduled to work for an hour in
% oven dry tons

%ProdRate_ODTperPMH=(FB_Production_Rate_Tons/PredCycleTime_Min)*60 %in short
```

```
tons
ProdRate_ODTperPMH=(FB_Prod_Rate_PerCycle/PredCycleTime_Min)*60

%Time to harvest stand
HarvestTime=1/(((ProdRate_ODTperPMH)/ODTavg))


%% Double Stand Density Harvest Time Calcs
DistMean2=DistCompleteMean/2;
BunchDistMean2= BunchDistCompleteMean/2;

%PredCycleTime2=8.765653+8.466335.*(DistMean2)+8.815661.*(TreeCompleteMean)+4
.875863.*(BunchDistMean2)
PredCycleTime2=
8.76565306+0.5644234.*DistMean2+8.81566093.*TreeCompleteMean+0.32505753.*Bunc
hDistMean2
PredCycleTime2_min=PredCycleTime2/100
%Prod Rate Calc
Tree_per_acre2=(6864*2)/7.8; %No loss of accumulation was assumed
ODTavg2=ODTavg*2;

%FB_Production_Rate_Tons2=((Tree_per_acre2/ODTavg2)/TreeCompleteMean); %in
ODT/cycle
ProdRate_ODTperPMH2=(FB_Prod_Rate_PerCycle/PredCycleTime2)*100*60 %in short
tons

%Time to harvest stand
%HarvestTime2=1/(((ProdRate_ODTperPMH2/0.989)/ODTavg2)/7.8) %Utilization rate
of 98.9%
HarvestTime2=1/(((ProdRate_ODTperPMH2)/ODTavg2))
HarvestTimePerAC2=HarvestTime2/7.8

return % stops code here
```

- Skidder:

```
%% Calculation of Delay-Free Skidding Production Rate
% Enter in data and randomize
close
clear all
data=xlsread('poplar_skidder_data');
data = data(randperm(size(data,1)),:); %Randomize the data

%% Assign Values to Data

TravelEmpDist=data(:,3);
PositionDist=data(:,5);
TreeNumber=data(:,7);
TravelLoadDist=data(:,9);
TotalTime=data(:,11);

TravelEmpDistTime=data(:,2);
PositionDistTime=data(:,4);
TreeNumberTime=data(:,6);
TravelLoadDistTime=data(:,8);
```

```
%% Split Randomized Data in to Sections (2/3 vs 1/3)- 54 total observations
% 2/3 of data will be used for linear regression to create a generic EQ
% 1/3 of data will be used in a T-test to test for statistical significance
TravelE_twothird=TravelEmpDist(1:36);
TravelE_onethird=TravelEmpDist(37:54);

Position_twothird=PositionDist(1:36);
Position_onethird=PositionDist(37:54);

TreeNum_twothird=TreeNumber(1:36);
TreeNum_onethird=TreeNumber(37:54);

TravelL_twothird=TravelLoadDist(1:36);
TravelL_onethird=TravelLoadDist(37:54);

TotalTime_twothird=TotalTime(1:36);
TotalTime_onethird=TotalTime(37:54)


twothirds=[TravelE_twothird Position_twothird TreeNum_twothird
TravelL_twothird TotalTime_twothird];
onethirds=[TravelE_onethird Position_onethird TreeNum_onethird
TravelL_onethird TotalTime_onethird];
%The data was then moved over to excel, separated, saved, and then brought
%back in to matlab for analysis (as can be seen below). If this was not
%done, matlab would create a new set of random numbers everytime the
%program was ran.

%% Calculation of Delay Free Average Cycle Time
data1=xlsread('Rand_Skidder_OneThirdV2')

TravelEmpDist1=data1(:,3);
PositionDist1=data1(:,5);
TreeNumber1=data1(:,7);
TravelLoadDist1=data1(:,9);
T2=data1(:,11);

%Created Linear Model From Stata
%T1=49.51184+(0.1821115).*(TravelEmpDist1)+1.202895.*(PositionDist1)+0.213039
7.*(TreeNumber1)+(0.2766338).*(TravelLoadDist1)
%T1=64.93638+(0.4069093).*TravelEmpDist1+(1.322248).*PositionDist1
T1=49.18072+0.6901818.*PositionDist1+0.4685417.*TravelLoadDist1
T1min=T1/100;

T1mean=mean(T1)
T1stddev=std(T1)
T1minmean=mean(T1min)

%% T2: Observed Data
T2mean=mean(T2);
T2stddev=std(T2);

%% Two Sample Ttest between Predicted-T and Observed-T
```

```
[h,p,ci,stats] = ttest2(T1,T2)
figure
boxplot(T2)
figure
boxplot(T1)

%% Calculation of Pedicted Cycle Time Utilizing Averaged Data

%CompleteData=xlsread('Rand_Skidder_CompleteV2')
CompleteData=xlsread('Skidder_TwoThird_Final') %Name states that data is
complete though only 2/3 was used (so that I did not have to change all var
names)

TravelEmpDistCom=CompleteData(:,3);
PositionDistCom=CompleteData(:,5);
TreeNumberCom=CompleteData(:,7);
TravelLoadDistCom=CompleteData(:,9);

TECMean=mean(TravelEmpDistCom)
PDCMean=mean(PositionDistCom)
%TNCMean=mean(TreeNumberCom)
TNCMean=40 %Approximately double the number of observed trees, which was an
underestimate
TLDCMean=mean(TravelLoadDistCom)

%PredCycleTime=49.51184+((0.1821115).*(TECMean))+(1.202895.*(PDCMean))+(0.213
0397.*(TNCMean))+((0.2766338).*(TLDCMean))
%PredCycleTime= 64.93638+(0.4069093).*TECMean+(1.322248).*PDCMean
PredCycleTime=49.18072+0.6901818.*PDCMean+0.4685417.*TLDCMean
PredCycleTime_min=PredCycleTime/100

%% Calculation of Predicted Skidder Production Rate

%Plot Acreage calculation
Tree_total=6864; %total number of trees on the study site
Tree_per_acre=6864/7.8; %the study site was 7.48 acres in size

%Harvested Biomass Average Weight
%ODTavgPerYear=2.4214444; %Value provided by Brad in poplar excel doc
%ODTavg=ODTavgPerYear*7;
ODTavg= 140.48; % based on weight of chip vans

% Calculation of Skidded OVEN DRY TONS
%Skidder_ProductionRate_Tons=1/((Tree_per_acre/ODTavg)/TNCMean) %in ODT/cycle
Skidder_ProductionRate_Tons=(TNCMean/Tree_total)*ODTavg/PredCycleTime_min*60
%Skidder_ProductionRate_lb=Skidder_ProductionRate_Tons*2000

% PMH Conversion-The time the machine is scheduled to work for an hour in
% oven dry tons
%ProdRate_ODTperPMH=(Skidder_ProductionRate_Tons/PredCycleTime_min)*60 %in
short tons

%Production Time
Prod_Time=ODTavg/Skidder_ProductionRate_Tons
Prod_Time2= ODTavg/Prod_Time
```

```
return
```

- Loader-Grinder:

```
%% Calculation of Delay-Free Chipping Production Rate
% Enter in data and randomize
close
clear all
data=xlsread('poplar_chipper_data1');
%data=xlsread('poplar_chipper_data2');
data = data(randperm(size(data,1)),:); %Randomize the data

%% Assign Values to Data

LoadTime=data(:,2);
TreeNumb=data(:,3);
TreeDBH=data(:,4);


%% Checking for Outliers in Data

CutsDBH=[TreeNumb.*TreeDBH];
boxplot(CutsDBH);
fprintf('75th Quartile: Q3=60\n25th Quartile: Q2=39\nOutliers= 100, 125\nDue
to the presence of outliers, this data will be culled. Y=72, Y=18, & Y=45
will also be culled.')

%75th quartile: Q3=60
%25th quartile: Q2=39
%Outliers= 100, 125

%% Five data Points removed to give data a better fit, Data entered in
clear
data=xlsread('Chipper_Culled_Final_Correction');
%data = data(randperm(size(data,1)),:); %Randomize the data

LoadTime=data(:,2);
T2=LoadTime;
TreeNumb=data(:,3);
TreeDBH=data(:,4);
%CutsDBH=[TreeNumb.*TreeDBH];
CutsDBH=data(:,5); %with 35% correction factor

%TreeNumbHoriz=TreeNumb';
%TreeNumbXDBH=TreeDBH*TreeNumbHoriz;
%x=diag(TreeNumbXDBH)

%% Calculation of Delay Free Average Cycle Time
% Because data set is so small, it will not be separated based on 2/3 1/3

%Created Linear Model from Stata
%T1=20.86366+0.1550278.*(CutsDBH)
T1=20.85366+0.2385043.*(CutsDBH) %Updated Reg Model with 35% correction
```

```
factor
T1mean=mean(T1)
T1stddev=std(T1)

%% T2: Observed Data
T2mean=mean(T2);
T2stddev=std(T2);

%% R^2 value of culled data set

p=polyfit(LoadTime,CutsDBH,1);
yfit=polyval(p,LoadTime);
yresid=CutsDBH-yfit;
ssresid=sum(yresid.^2);
sstotal=(length(CutsDBH)-1).*var(CutsDBH);
rsq=1-ssresid/sstotal

%% Two Sample Ttest between Predicted-T and Observed-T
[h,p,ci,stats] = ttest2(T1,T2)
%figure
%boxplot(T2)
%figure
%boxplot(T1)

%% Calculation of Predicted Cycle Time Utilizing Averaged Data
TreeNumbAVG=mean(TreeNumb);
CutsDBHAVG=mean(CutsDBH);

%PredictedCycleTime=20.86366+0.1550278.*(CutsDBHAVG);
PredictedCycleTime=20.86366+0.2385043.*(CutsDBHAVG) %Updated Reg Model with
35% correction factor
PredCycleTime_min=PredictedCycleTime/100

%% Calculation of Predicted Chipper Production Rate

%Plot Acreage calculation
Tree_total=6864; %total number of trees on the study site
Tree_per_acre=6864/7.8; %the study site was 7.48 acres in size

%Harvested Biomass Average Weight
ODTavgPerYear=2.4214444; %Value provided by Brad in poplar excel doc
%ODTavg=ODTavgPerYear*7; %7 years total for total operation
%ODTavg=18.1124
ODTavg= 140.48; % based on weight of chip vans
% Calculation of Prod Rate in OVEN DRY TONS
%Chipper_ProductionRate_Tons=1/((Tree_per_acre/ODTavg)/TreeNumbAVG) %in
ODT/cycle
%Chipper_ProductionRate_lb=Chipper_ProductionRate_Tons*2000
Chipper_ProductionRate_Tons=(TreeNumbAVG/PredCycleTime_min)*(ODTavg/Tree_tota
l)*60

% PMH Conversion-Part of scheduled operating time during which a machine
% actually operates
%ProdRate_ODTperPMH=((Chipper_ProductionRate_Tons/PredictedCycleTime)*100*60)
%in short tons
```

```
%ProdRate_ODTperPMH=Chipper_ProductionRate_Tons*0.3582 %Utilization for the
grinder was 35%

%Harvesting time
Processing_Time= (PredCycleTime_min/TreeNumbAVG)*Tree_total/60
```

Appendix B: Economic input background information

Table 58: Machine hourly rate input information for the SRWC poplar operation.

Machine Make/Model	Tractor (John Deere 5320)	Auger (43cc engine size)	Chip Van
Machine usage	Tilling/spading, weed control	Hand planting	Biomass transport
Purchasing price ($)	25,000.00	200.00	200,000.00
Hours on equipment when purchased (hrs)	0.00	0.00	0.00
Horsepower (hp)	55.00	1.30	400.00
Economic Life (yrs)	5.00	5.00	5.00
Interest ($/yr)	1,250.00	10.00	10,000.00
Insurance ($/yr)	3,500.00	0.00	3,500.00
Taxes ($/yr)	0.00	0.00	0.00
Scheduled machine hours (hrs/yr)	1,800.00	1,800.00	1,500.00
Fuel use (gal/hr)	4.00	0.50	12.00
Fuel price ($/gal)	2.65	2.65	2.65
Miyata generalized[a] fuel price ($/PMH)	10.60	--	31.80
Lubricant usage (gal/yr)	30.00	0.50	23.50
Lube price ($/gal)	15.00	15.00	61.80
Miyata generalized lube price ($/PMH)	3.90	--	11.80
Repair/ maintenance ($/yr)	3,500.00	20.00	3,500.00
Miyata generalized repair/maint. ($/yr)	2,000.00	--	16,000.00
Labor costing ($/SMH)	42.00	42.00	42.00
Utilization Rate (%)	1.00	1.00	0.95
Fixed hourly cost ($/SMH)	4.60	0.00	28.20
Operating hourly cost ($/SMH)	12.80	1.30	33.50
Labor hourly cost ($/SMH)	42.00	42.00	42.00

[a]Utilized within scenario #3 of the economic analysis.

Table 59: Site setup and maintenance information for the SRWC poplar operation.

Input Info	Tilling and Spading	Hand Planting	Scepter 70DG Pesticide	Pendulum Aquacap Pesticide	Glyphosate Pesticide (year 0)	Glyphosate Pesticide (year 1)	BT Insecticide	Credit 41 Herbicide
Machine Req. (name)	JD 5320	Auger	JD 5320	Manual	Manual	Manual	Manual	Manual
Machine fuel eff. (gal/hp-hr)	0.03	0.03	0.03	N/a	N/a	N/a	N/a	N/a
Machine Op. time (hrs)	10.00	4.00	4.00	N/a	N/a	N/a	N/a	N/a
Number of laborers (#)	1.00	5.00	1.00	1.00	1.00	1.00	1.00	1.00
Total Op. time (hrs)	10.00	21.60	4.00	4.00	3.00	19.50	3.00	3.80
Herb./pest. Price ($/gal)	N/a	N/a	181.34	72.00	10.29	10.29	112.00	24.00
Herb./pest. app. rate (gal/AC)	N/a	N/a	0.04	0.75	0.03	0.03	0.03	0.24

Table 60: Mechanical planting time trial information (from TRC).

	Function overview	Travel speed (ft/sec)	Planting rate (trees/sec)	Required operators (#)
Mechanical planter	Direct integration to tractor drive shaft (JD 5320)	1.50	1.00	2.00

Table 61: Biomass transport payload information.

Input Info	Chip Van
Payload fill weight average (tons)	33.13
One-way travel distance (miles)	50.00
Average speed (mph)	40.00
Van filling time (PMH)	0.45
Van unloading time (PMH)	0.34

Table 62: Machine hourly rate input information for the SRWC willow operation.

Machine Make/Model	Tractor (John Deere 5320)	Harvesting Unit (John Deere 5320 + Ny Vraa JF 192)	Chip Collector (John Deere 7330 + Chip bin)	Front End Loader (Komatsu CK35-1)	Chip Van
Machine usage	Tilling/spading, weed control	Woody biomass harvest & process	Chipped Biomass Collection	Biomass loading	Biomass transport
Purchasing price ($)	25,000.00	145,737.00	110,517.00	56,597.00	200,000.00
Hours on equipment when purchased (hrs)	0.00	0.00	0.00	0.00	0.00
Horsepower (hp)	55.00	155.00 (gross)	155.00	86.00	400.00
Economic Life (yrs)	5.00	5.00	5.00	5.00	5.00
Interest ($/yr)	1,250.00	7,286.90	5,525.90	2,829.90	10,000.00
Insurance ($/yr)	3,500.00	3,500.00	3,500.00	3,500.00	3,500.00
Taxes ($/yr)	0.00	0.00	0.00	0.00	0.00
Scheduled machine hours (hrs/yr)	1,800.00	1,800.00	1,800.00	1,800.00	1,500.00
Fuel use (gal/hr)	4.00	5.00	5.00	4.00	12.00
Fuel price ($/gal)	2.65	2.88	2.65	2.88	2.65
Miyata generalized fuel price ($/PMH)	10.60	13.25	13.25	10.60	31.80
Lubricant usage (gal/yr)	30.00	30.00	30.00	30.00	23.50
Lube price ($/gal)	15.00	15.00	15.00	15.00	61.80
Miyata generalized lube price ($/PMH)	3.90	4.90	4.90	3.90	11.80
Repair/ maintenance ($/yr)	3,500.00	3,500.00	3,500.00	3,500.00	3,500.00
Miyata generalized repair/maint. ($/yr)	2,000.00	11,659.00	8,841.40	4,527.80	16,000.00
Labor costing ($/SMH)	42.00	42.00	42.00	42.00	42.00
Utilization Rate (%)	1.00	1.00	1.00	1.00	0.95
Fixed hourly cost ($/SMH)	4.60	17.65	13.86	8.04	28.20
Operating hourly cost ($/SMH)	12.80	16.59	15.44	13.71	33.50
Labor hourly cost ($/SMH)	42.00	42.00	42.00	42.00	42.00

[a]Utilized within scenario #3 of the economic analysis.

Table 63: Site Setup and Maintenance Operation Information for the SRWC willow operation.

Input Info	Tilling & Spading	Hand Planting	Glyphosate pest. (year 0, post harvest)	Simazine Pesticide	Goal Pesticide	Coppice Cut
Machine Req. (name)	JD 5320	Manual	JD 5320	Manual	Manual	JD 5320
Machine fuel eff. (gal/hp-hr)	0.03	N/a	0.03	N/a	N/a	0.03
Machine Op. time (hrs)	4.00	N/a	0.50	N/a	N/a	0.50
Number of laborers (#)	2.00	4.00	1.00	1.00	1.00	1.00
Total Op. time (hrs)	4.00	26.00	0.50	1.00	1.00	0.50
Herbicide price ($/lb)	N/a	N/a	10.28	72.00	79.58[a]	N/a
Herbicide app. rate (lb/AC)	N/a	N/a	1.80	0.75	0.45[b]	N/a

[a]Price in $/gal

[b]Application rate in gal/acre.

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