COST PREDICTION AND LIFE CYCLE ASSESSMENT OF WOODY BIOMASS SUPPLY-CHAIN IN MICHIGAN

By

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ABSTRACT

COST PREDICTION AND LIFE CYCLE ASSESSMENT OF WOODY BIOMASS SUPPLY-CHAIN IN MICHIGAN

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As a state with rich forest resources and a good transportation system, Michigan is in a position to promote the use of woody biomass for bioenergy production. To achieve sustainable development in Michigan's woody biomass supply chain, the goals this research were to: 1) to develop a cost prediction model in Excel using Visual Basic for Application (VBA) programming language; 2) to perform cradle-to-grave Life Cycle Assessment (LCA) to account for the GHG emissions, energy return on investment, and nutrient removal; and 3) to design an eco-efficient (Define) woody biomass supply chain with minimal logistic cost and GHG emissions in Michigan.

Five woody biomass production systems were monitored to develop predictive regression equations for different harvesting machines and to predict the total production cost of woody biomass in Michigan. Based on the predictive machine productivity equations and machine hourly cost obtained from each studied system, a spreadsheet model was developed in Excel 2016 using VBA programming language.

In order to better understand field storage of woody biomass, 5 studies were conducted to monitor the biomass quality (biomass Higher Heating Value (HHV) and biomass moisture content) change under different storage forms (wood logging residues piles and wood chips piles). The results indicated that storing woody biomass in logging residue pile could effectively reduce the biomass moisture content and maintain the HHV at a stable level. On the contrary, increases in moisture content were observed in all wood

chips piles. Based on the above findings, an improved operations system structured with linear programming was developed for minimizing the total cost of woody biomass preprocessing, storage, and transportation. The operation details suggested by the improved operations system can be used as a guideline of real operations to achieve the lowest possible operations cost.

To evaluate the total GHG emissions, energy return on investment and nutrient removal in each studied biomass production system, five cradle-to-grave LCAs were performed. Results suggested that over 90% of GHG emissions were from the combustion stage, which can be effectively reduced by increasing biomass HHV and decreasing biomass moisture content. Including soil carbon sequestration in LCA can largely offset the total global warming effect caused by woody biomass production and utilization. However, a better approach is needed to estimate soil carbon sequestration to avoid uncertainties caused by vegetation types, considered soil depth, and time duration.

A multi-criteria optimization framework was developed to design a woody biomass supply chain with minimal GHG emissions and production cost in Michigan. The trade-off between rising cost and reducing GHG emissions was that by increasing the cost by 1.46 ¢/kWh, the total GHG emissions could be reduced by 0.66 kg CO2-eq/kWh. The sensitivity analysis indicated that biomass HHV and biomass moisture content had a larger impact on the optimized solutions and the trade-offs, as compared to the transportation distance. This again, confirmed that in order to improve the efficiency and sustainability of the woody biomass supply chain, future research efforts should be spent on improving the HHV and decreasing the moisture content of woody biomass.

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KEY TO ABBREVIATIONS

ADP: abiotic depletion potential

BTU: British Thermal Unit

CTL: cut-to-length harvesting system

DBH: diameter at breast height

EROI: renewable energy return on investment

FS: natural forest stand

FBIC: Forest Biomass Innovation Center

GHG: greenhouse gas

GT: green ton

GWP: global warming potential

HHV: higher heating value

ISO: International Standards Organization

KBS: Kellogg Biological Station

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

MC: moisture content

MSU: Michigan State University

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

SRP: short rotation poplar

SRWC: short rotation woody crop

SRW: short rotation willow

TRC: Tree Research Center

U.S.: United States

WT: whole tree harvesting system

Yr: year

CHAPTER 1 INTRODUCTION

1.1 Woody biomass as a renewable energy source

Woody biomass was defined as "the trees and woody plants, including limbs, tops, needles, leaves, and other woody parts, grown in a forest, woodland, or rangeland environment, that are the byproducts of forest management" (USDA Forest Service, 2008). It can be produces from various forest management and production processes such as non-timber tree removal, timber harvesting, landfill diversion and dedicated plantations (Shelly, 2011). Annually, United States produces about 14 million dry tons of wood debris and waste, 87 million dry tons of woody milling residues, and 64 million dry tons of harvesting residues (White, 2010). Woody biomass can be used to produce a wide range of wood products like lumbers, paper and pulp, furniture, and building materials. Historically, it has been used to produce heat and electrical energy in combined heat and power (CHP) plants. There are about 178 biomass power plants in the U.S., with a total capacity of 20,156 MW (Biomass Magazine, 2017). Overall combustion efficiency of CHP plants varies from 65-85% and highly depends on wood characteristics such as ash content, moisture content and the higher heating value of the wood fuel (Clarke et al., 2012).

In the past decades, due to the growing need of reducing the dependence on fossil-based fuels, renewable energy has become the world's fastest-growing energy sources (Zanchi et al., 2012; REN21, 2012; EIA, 2015). From 2008 to 2017, the total annual electric power produced from renewable energy sources (excluding hydroelectric and solar) has risen from 1.25E+08 MW to 3.34E+08 MW (EIA, 2018a). As one of the most important renewable energy sources, wood and wood-derived biomass supplied about 19%

of total U.S. renewable energy consumption in 2016 (Figure 1). About 69% of the bioenergy produced from woody biomass was consumed to produce power and heat for industrial applications such as wood and paper production (EIA, 2018b).

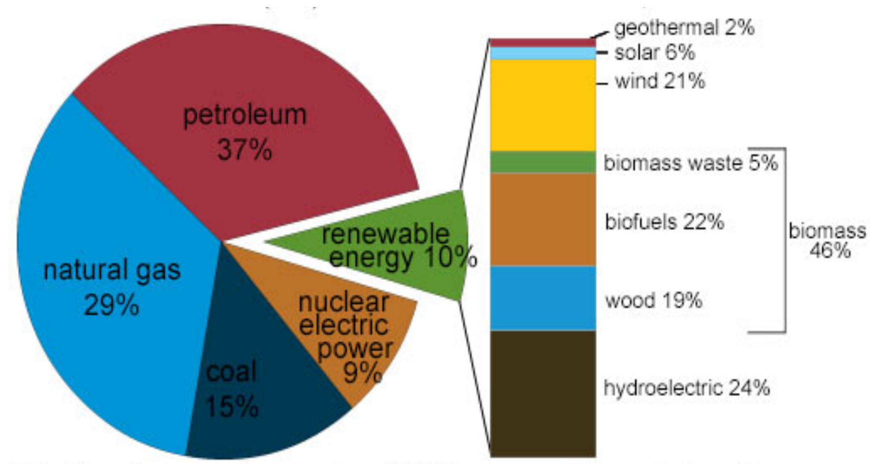


Figure 1. U.S. energy consumption by energy source (EIA, 2017)

Besides heat and electricity, woody biomass can also be utilized to produce biofuels such as bioethanol and bio-methanol (Galbe and Zachhi, 2002). Compared to petroleum-based fuels, biofuels have many environmental advantages: 1) high availability; 2) reduction of greenhouse gases (GHG) emissions; 3) biodegradability; 4) carbon sequestration (Balat, 2011). From 2010 to 2016, the annual volume requirement suggested by EPA for cellulosic biofuel production has grown from 6.5 million gallons to 206 million gallons (Schnepf and Yacobucci and, 2010). There are several techniques to covert woody biomass to biofuels, e.g. fermentation, digestion, gasification, liquefaction, enzymatic conversion and pyrolysis (McKendry, 2002; Papari and Hawboldt, 2015). Compared to enzyme conversion, pyrolysis requires shorter time and less pretreatment like stem explosion and hydrolysis (Mettler et al., 2012). Pyrolysis is a thermo decomposition process that can convert green woody biomass into bio-oil under inert atmospheric conditions (Sinha et al., 2000). Based on different heating rates, temperature and processing time, pyrolysis is categorized as slow pyrolysis, moderate pyrolysis and fast pyrolysis (McKendry, 2002; Papari and Hawboldt, 2015). The energy recovery rate of fast pyrolysis with hybrid poplar (29.4-34.2%) has been concluded to be higher than other biochemical conversion techniques (Dou et al., 2017). Biofuel yield from fast pyrolysis can be up to 80%, but it is highly depends on feedstock type, chemical composition and reaction conditions (Mettler et al., 2012; Papari and Hawboldt, 2015).

Besides conversion techniques, the long-term potential for using woody biomass as bioenergy resource also largely relies on its availability (Demirbaş, 2003). Based on the 2016 Billion-Ton report, around 82 million to 88 million dry tons of woody biomass are available annually in U.S. at the price of $60 per dry ton (USDOE, 2016). One dry ton of woody biomass can produce about 70 gallons of biofuels (Bracmort et al., 2011). This indicates a good potential of woody biomass to be a primary biofuel feedstock. In order to ensure the year-round operation of biofuel processing plants, it is critical to have reliable and consistent supply of woody biomass. In the past two decades, SRWC such as hybrid poplar and hybrid willow have been largely grown for cellulosic biofuel production because of their high growth rates, high quality (high carbohydrate and low ash content), and flexible harvest period (Hinchee et al., 2011; Emerson et al., 2018). For instance, hybrid poplar production increased from 211 acres to 2,554 acres from August to November 2014 (US Department of Energy, 2016). To increase the biomass yield and improve the biomass chemical composition of SRWC, many research studies have been done to develop new breeds (Volk et al., 2011; Shield et al., 2014). Another key obstacle to maintain the year-round supply of SRWC is the leaf removal. Leaves that are included in the harvested biomass can affect both the initial and final fuel qualities after storage

(Eisenbies et al., 2015). In addition, Dou et al. (2017) has reported that bio-oil produced from whole tree coppice wood chips had 25.3% lower C content compared to those produced from no-leaf coppice. In order to remove the low quality parts such as leaves and bark, a low cost technique, air classification has been tested by Emerson et al. (2018) for hybrid poplar and shrub willow samples. Their results indicated that with majority of leaves removed, the ash content could be reduced by 28.6% for hybrid poplar and 17.7% for shrub willow.

Michigan has rich forest resources and the forest cover is over 53 percent. Extensive studies have been done to estimate and assess the woody biomass availability in MI (Jakes and Smith, 1983; MacFarlane, 2009; Mueller et al., 2010; Zhang et al., 2018). With a broad base of 18.6 million acres of timberland, about 20 million dry tons of forest biomass can be produced as bioenergy feedstock annually (Cook, 2010). These rich forest resources bring significant economic benefits to Michigan's economy, especially the Upper Peninsula. There are more than 1,400 forest products manufacturing facilities, 1,700 units of forest products manufacturing business, and about 200,000 jobs are supported by these forest-based industries (Michigan Department of Natural Resources, 2003). The annual electricity produced from woody biomass ranks fourth nationally in 2015 (Michigan Biomass, 2017). Presently there are 10 biomass-based power facilities in MI, producing 209 MW power annually with 1.86 million dry tons of woody biomass (Auch, 2016). With the woody biomass availability of 20 million dry tons, MI has a good opportunity to increase use of woody biomass. Hence, the total logistic cost of producing woody biomass in MI becomes a key question. In addition, the environmental impacts caused by different kinds of forest harvesting operations in MI such as CO_2 emissions and soil nutrient depletion should be studied more.

1.2 Key challenges in woody biomass supply chain

The potential of using woody biomass as an alternative bioenergy source highly depends on the combined cost of logistics and the quality of the produced biomass. There are five important components in woody biomass supply chain, including biomass harvesting, collection, pre-processing, storage and transportation. The supply chain planning of woody biomass can be very challenging due to several factors such as the biomass availability, the consumers demand and all kinds of regulations and policies (Soylu et al., 2006). To achieve the eco-efficiency in Michigan's woody biomass supply chain, which is defined as 'maintaining or increasing the value of economic output while simultaneously decreasing the impact of economic activity upon ecological systems' (Braungart et al., 2007), there are several key challenges to consider about: 1) production costs estimation; 2) fuel qualities monitor during storage; 3) life-cycle impacts; 4) total cost minimization, trade-off between GHG emissions and total logistics cost.

1.2.1 Prediction of production costs

Due to the traditional harvesting strategy and the undeveloped biomass supply chain, the costs of using woody biomass are mainly higher or close to fossil fuels and coals (Dunnett et al., 2007; Perlack et al., 2011; Caputo, 2014;). In U.S., compared to \$2.37/MMBTU for coals, the average price of using woody biomass for electric power purpose is at \$2.69/MMBTU (EIA, 2014). There are many reasons can lead to high production cost, such as high capital investment on harvesting machines, inappropriate harvesting season, difficult harvesting site conditions, low travel distance and lack of operation management (Ghaffariyan et al., 2012a; Harril and Han, 2012; Strandgard, 2014).

Cost prediction in woody biomass supply chain is important to determine the economic feasibility of using woody biomass for energy purpose (Alam et al., 2012). Several cost analysis models such as BioSum 3.0, Auburn Harvest Analyzer (AHA) and FRCS-North have been developed to provide logistic cost predictions. Since transportation costs have always been accounted for an essential part of the total costs, linear programming models and GIS-based forest biomass data are used to reduce transportation costs in European Countries and Canada (Ranta, 2002; Ranta, 2005; Panichelli and Gnansounou, 2008).

Besides cost prediction, determination of the effective factors in biomass supply chain and developing their corresponding time prediction models are also important to improve the production efficiency (Alam et al., 2012). For instance, harvester productivity can be affected by many factors such as tree size, spacing, ground slope and roughness (Ghaffariyan et al., 2012b; Wright et al., 2010). Harril and Han (2012) found a noticeable relationship between transportation cost and road type that every 50 m increase of spur road can increase the total transportation cost in $0.08/ODT. Many research trials monitored that the overall productivity decreased as the slope increased (Bolding and Lanford, 2002; Acuna and Kellogg, 2009; Spinelli et al., 2010).

Due to the differences in tree species, stand density, site and terrain conditions, productivities of woody biomass supply chain in Lake States such as Illinois, Indiana, Michigan and Ohio are expected to be different from Western U.S. For instance, ground slope is smaller in Lake States compared to Western States, which might reduce the harvesting and biomass collecting time and cost. Also, the lower ground elevation in Lake States makes biomass hauling and transportation easier than in Western States. Consider about the impacts of terrain condition and forest transportation road types on the production cost, there is a need to develop a cost prediction model based on Michigan collected data.

1.2.2 Fuel quality change during storage

Storage is a key component within the woody biomass supply chain, especially when year-round harvesting is impossible. Storage is complicated because of the changing seasonal availability of woody biomass and the varied demand of energy plants throughout the year (Sokhansanj et al., 2006; Lin and Pan, 2013). Meanwhile, different storage methods will produce biomass at various quality levels, which can significantly affect the transportation and energy conversion efficiency (Jirjis, 2001; Casal et al., 2010).

The most common way in northern United States to store green biomass is to directly process wood into chips and store these in piles before being utilization (Lin and Pan, 2013). This storage method poses several problems such as dry matter loss, moisture content (MC) increase, and energy content reduction (Fredholm and Jirjis, 1988; Hornqvist and Jirjis, 1999; Jirjis 2001; FRL, 2002; Afzal et al, 2010). Store wood residues in bundles, as the second option, can produce high quality biomass feedstock with low biomass MC, higher energy content, and low ash content (Lehtikangas, 2001; Pettersson and Nordfjell, 2007; Afzal et al., 2010). Yet, the bundling technology is associated with several problems such as high capital investment and low productivity caused by saw binding, materials handling, twine spool collapse, and slow movement at the harvesting site (Rummer et al. 2004; Leinonen, 2004; Harrill, 2010). In order to ensure a year-round supply of high-quality biomass feedstock, it is necessary to further study the fuel quality during the storage period.

1.2.3 Life-cycle impacts assessment

1.2.3.1 Greenhouse gas (GHG) emissions

Another key question in woody biomass supply chain is how to correctly assess and minimize the GHG emissions. Historically, it was assumed that the carbon emitted into the air from biomass production and combustion can be offset by tree carbon sequestration. Therefore, woody biomass has been recognized as "carbon neutral" and "environmentally friendly" and has been recommended to produce in a large scale to replace fossil fuel (Lippke et al., 2004; Puettmann and Wilson, 2007; Solomon et al., 2007). However, it takes a long term for the immediately emitted carbon dioxide and other greenhouse gas to be sequestered by forest again; the global warming effect caused by the carbon flux during this long term has normally been underestimated (Searchinger et al., 2009; Cherubini et al., 2011; Sedjo, 2011 and 2013).

Under In 2010, 90 scientists has expressed their concerns on carbon neutrality of woody biomass and stated that using woody biomass might not necessarily stop global warming (Sedjo, 2013). UK Department of Environment Climate Change has reported that although utilizing wood residues could result in a low net GHG emission, however harvesting round wood from natural forest or plantation could lead to very high emissions (Stephenson and MacKay, 2014). In short rotation woody crops plantation, N_2O emissions occur at cultivation stage from N fertilizer application, leaf litter decomposition and other maintenance practices (Crutzen et al., 2016; Bouwman et al., 2010). N_2O emissions were reported to be 4.6 and 5.9 Mg ha^{-1} of CO_2 equivalents in willow and poplar plantation (Nikièma et al., 2012).

1.2.3.2 Soil carbon sequestration

Soil organic carbon is the one of the most important carbon pool on earth. It majorly forms from decomposition of detritus such as leafs, dead roots and leachates from living roots. The formed soil organic carbon will be stored in the topsoil (0-25 cm) and gradually transport to subsoil (25-100 cm). Over 50% of the carbon is stored in soil organic matter, which is more stable compared to debris and litter (Brandão et al., 2013; Helin et al., 2013). Qin et al. (2016) suggested that including soil organic carbon (SOC) sequestration in LCA could significantly influence the total GHG footprints of bioenergy production systems. However, SOC changes are highly impacted by regional climate conditions, management practices, vegetation type, soil depth, and time period considered. For instance, Freibauer et al. (2004) have reported that reduce tillage and increase surface residue return could increase soil C by 0.4-0.6 t C $ha^{-1}yr^{-1}$. Surface litter cover has been demonstrated to increase microbial activities, thus to increase SOC accumulation rates (Tolbert et al., 2002). Besides management practice, change of vegetation type can also impact SOC change by directly change the microbial communities (Freibauer et al., 2004; Xue et al., 2016; Qin et al., 2016). Previously, most studies have assumed that majority of accumulated SOC is in top soil (0-30cm), yet, to fully assess the soil C inventory, SOC in deeper profile (0-100cm) should also be included (Knops and Bradley, 2009; Follett et al., 2012; Qin et al., 2016). Another key factor is the time horizon with the SOC because SOC change tends to decrease with time until the soil C reach the equilibrium level (Guo and Gifford, 2002; Stewart et al., 2007). As suggested by Qin et al. (2016), there are high uncertainties with SOC changes rates in different perennial crops production systems. Due to these challenges and uncertainties in accounting soil carbon, majority LCA studies have not included soil C sequestration in their inventory data (Koerber et al., 2009; Petersen et al., 2013).

1.2.3.3 Nutrient removal

Other environmental concerns for woody biomass supply chain include increased removal of forest debris, threats to wildlife and biodiversity, nutrients loss and soil compaction (Evans and Pershel, 2009). Among all the concerns, the nutrient removal or nutrients loss caused by the forest harvesting projects was widely expressed from the prospect of the environment sustainability (Staaf and Olsson, 1991; Vanguelova et al., 2010; Hall and Richardson, 2001). For instance, whole tree harvesting system has been reported to remove 44% of K and have a long-term negative impact on soil nutrition of K and P (Duchesne and Houle, 2008;Vanguelova et al., 2010). Soil nutrient and fertility loss were shown to cause 3-7% reduction in future tree growth up to 33 years after harvesting (Achat et al., 2015).

The negative impact caused by whole tree harvesting system is site sensitive, in some regions that originally have low soil organic matter content, the reduction of soil C and cation exchange capacity is more obvious (Thiffault et al., 2006). Several states in U.S. have developed biomass harvesting guidelines since 2007 and offered suggestions for how to avoid the impacts of intensive forestry harvesting operations in Minnesota (MFRC, 2007), Wisconsin (Herrick et al., 2009) and Maine (Benjamin, 2010). A better understanding of the nutrients removal caused by forest harvesting system in Michigan has become an impotency to limit the nutrient depletion caused by utilization of woody biomass.

Life-cycle assessment (LCA) has been largely adopted to count and study the environment impacts including carbon emission and nutrients removal in many bioenergy production systems (Di Nassi o Nasso et al., 2010; Bracomrt, 2015; Vasquez Sandoval, 2015). GHG emissions in woody biomass production system in Michigan and Lake States have rarely been studied. A correct and comprehensive LCA that includes all life stages of woody biomass supply chain can provide a clear picture of the energy and mass flow in a woody biomass bioenergy production system. With the help of LCA, better decisions can be made in promoting woody biomass utilization, and in improving the system performance in terms of minimizing GHG emissions (Puettmann, 2006).

1.2.4 Cost minimization, trade-off between GHG emissions and cost

In addition to the cost analysis and the LCA, many mathematical models for optimization were widely used to implement cost-effective bioenergy production (Gunasekaran et al., 2004; Bredstro ̈m et al., 2004; Parker et al., 2010; Shabani and Sowlati, 2013a). As woody biomass transportation cost accounts for the largest part of the total cost and energy consumption (Eriksson and Bjo ̈rheden, 1989; Allen et al., 1998; Alam et al., 2012), the developed model mainly focus on location selection and woody biomass collection to minimize the logistic cost. However, reducing the cost and reducing the carbon emissions could be two conflicting objectives. Only focus on cost minimization might lead to a production system with high carbon footprints. Therefore, it is critical to include both the economic and environmental objectives when optimizing the woody biomass supply chain, more importantly, to understand the trade-off between the total production cost and total carbon emissions.

Multi-criteria optimization has been commonly used to support decision making with multiple competing criteria in renewable energy production systems. Afgan and Carvalho (2008) have evaluated the economic, environmental and social performance of five different renewable energy production systems using multi-criteria optimization method. The method examined the sustainability index of the five renewable energy production systems in scenario cases with different weight assigned to indicators such as electricity cost, efficiency, CO_2 emissions and NO_x emissions. Ayoub et al. (2009) proposed a multi-level optimization model to determine the bioenergy generation plan using different energy sources, with optimized energy efficiency, minimized total cost and CO_2 emissions for Japan. However, only a few multi-criteria optimization studies have been published in woody biomass supply chain. Kanzian et al. (2013) has formulated a multi-criteria optimization problem to minimize the CO_2 emissions and to maximize the profit for large-scale forest energy supply networks in Austria. The optimized biomass production strategy suggested by the model can double the profit with only 4.5% increase in CO_2 emissions. In order to sustainably utilize woody biomass as a bioenergy source in Michigan and U.S., there is a great need to combine environmental and economic demands and develop a multi-criteria optimization framework.

1.3 Hypothesis

1) The productivity and production cost of woody biomass supply chain can be effectively predicted by multi-linear regression equations and machine price survey collected from loggers in MI;

2) Life cycle assessment can reveal the environmental impacts such as total global warming potential and nutrient removal caused by different woody biomass supply chain in MI;
3) A multi-criteria optimization model can be applied to provide an optimized woody biomass production strategy with minimal cost and minimal total global warming potential, and to examine the trade-off between the total global warming potential reduction and cost increase in the woody biomass supply chain in MI.

1.4 Goal and objectives

As a state with high availability of woody biomass, Michigan has a high potential to replace fossil fuels. To use the forest resources sustainably, the goal of this Ph.D. project is to develop a spreadsheets cost prediction model in Excel using VBA programming language, to perform LCA to account for the GHG emissions and nutrient removal from biomass cultivation to combustion, and to design an eco-effecient woody biomass supply chain with minimal logistic cost and GHG emissions in Michigan.

The specific objectives of this Ph.D. project were:

1) Predicting the cost of the entire biomass supply chain consists of harvesting, biomass collecting, handling and transportation, based on the cost analysis of different harvesting systems (Whole-tree harvesting system, Cut-to-length harvesting system and Single-pass cut-and-chip harvesting system) in Michigan;

2) Use LCA to project the total GHG emissions and to illustrate nutrients flow (N, P, K) in harvesting, biomass collecting, biomass handling (grinding/chipping), transportation and combustion phases in Whole-tree harvesting system, Cut-to-length harvesting system and Single-pass cut-and-chip harvesting system in Michigan;

3) Provide an optimized logistic strategy which can minimize the total logistic cost and GHG emissions using multi-criteria optimization method, and to examine the impacts of transportation distance and carbon tax policy on the biomass production strategy.

CHAPTER 2 LITERATURE REVIEW

2.1 Cost analysis and models in woody biomass harvesting, processing and transportation

Harvesting systems contain four stages include timber harvesting, primary transportation, loading, and secondary transportation (Conway, 1982). Determination of the effective factors in each stage and developing their corresponding time prediction models can help to improve the efficiency of managing the process of harvesting operations (Mohammad et al., 2012). Timber harvesting includes felling (severing the standing tree from the stump) and processing (often called bucking, limbing, or topping) (Johnson et al., 2012). Feller-buncher is a harvesting machine normally used in a whole-tree harvesting system, with a cutting or felling head that can gather and cut one or several trees at a time (Hakkila, 1989; Adebayo et al., 2007; Spinelli et al., 2002). The selection of different types fell-buncher depends on the site condition. For instance, in mountainous Western U.S., track mounted feller-buncher with felling head and short boom are more commonly used. In the south U.S., where the sites are more flat with slope less than 25%, 4-wheel rubber tired drive-to-tree feller-buncher is appropriate to use (Jaffe and Obrien, 2009; Mitchell, 2008).

The other commonly used felling machine is harvester. They are utilized in cut-to-length harvesting systems. For steep ground with slope ranging from 35-45%, track-mounted harvester is normally selected, and rubber tired harvester will be selected for flatter ground with slope less than 25% (Jaffe and Obrien, 2009). Harvesters have lighter cutting head and longer booms compared to feller-buncher and they can move vertically and horizontally (Jaffe and Obrien, 2009).

Productivity of harvesting machines has widely been studied using different methods in North America (Tufts and Brinker, 1993; Kellogg and Bettinger, 1994; MCNeel and Rutherford, 1994; Landford and Stokes, 1995; Tufts, 1997). In these studies, time and motion studies are conducted in order to investigate the main contributing factors that affect work productivity and to establish a base for cost calculation (Nurminen et al. 2006). For instance, hourly productivity and hourly cost for the feller-buncher in a Central Appalachian hardwood forest were reported to be about 428.9 to 2267.7 ft3 per productive machine hour (PMH) and $99.68/PMH (Long et al., 2002). In Michigan, the productivity and hourly cost of feller-buncher were estimated to be 5.95-28 BDT/PMH and $51.52-$51.64/PMH (Pan and Srivastava, 2013). The most influencing factors for the productivity of harvesting machines were summarized to be: 1) environmental conditions such as forest stand and harvesting site and 2) operational factors such as ground conditions, operators motivation and skill, operational layout, etc. (Jirouðek et al. 2007; Mizaras et al., 2008).

Skidding and forwarding operation, indicating the transportation of unprocessed forest residues from harvesting site to the centralized locations. In the skidding process, tracked skidder or wheeled are used based on specific purpose. Tracked skidder is normally used when there is a big load of materials and the ground slope is steep. Wheeled skidder has smaller size and higher speed, and is suitable to be used in less steeper ground. Skidder can also be categorized as grapple skidder and cable skidder depends on their grapple mechanism. The grapple skidder can pick up more than one tree at a time; while the cable skidder has a skid line with chokers attached. Skidders generally come with either a grapple or a cable drum, now many modern skidders come with both (Forest and Rangelands). The productivity and hourly cost of skidder have been estimated by many previous studies in different regions (Wang et al., 2008; Goychuk et al., 2011; Borz et al., 2013; Lotfalian et al., 2011). It has been indicated that the most influencing factors on the productivity of skidding or forwarding process are: skidding distance, piece size, load volume, winching distance and slope of the trail (Egan and Baumgras, 2003; Sabo and Porsinsky, 2005).

There is also a loading process involves in the movement of logs or residue in the first stage transportation (Johnson et al., 2012). The loader cost has been projected to range from 125 to 150 $/SMH and the transportation cost ranged from 70 to 115 $/SMH (Perez et al., 2012). In field processing, there are different machines that can be used to reduce size and homogenize the forest residues such as biomass bundler, baler, and chipper. The biomass bundler is commonly used in cut-to-length harvesting systems to process slashes into a slash bundle or a compressed residue log (Gallagher, 2010, Martin, 2008). The major problems in producing biomass bundles with a slash bundler is the low productivity and the high hourly cost due to delays caused by saw binding, materials handling, twine spool collapse, and slow movement at the site (Patterson et al., 2008; Harrill, 2010; Rummer et al. 2004; Leinonen, 2004).

Another machine developed to handle forestry logging residues is Bio-baler. The benefits of using Bio-baler include reduction in fire hazard, decrease in herbicide application, and wildlife enhancement (Klepac and Rummer, 2009). However, the cost per unit for Bio-baler ranges from $17.60/green ton to 36.75$/green ton, which will largely decrease its economic feasibility (Klepac and Rummer, 2009).VTo reduce the size of woody biomass, chipper or grinder is utilized in the harvesting site. One of the most commonly used chipper is the disk chipper, which equipped with a revolving heavy disk with straight knives (Naimi et al., 2006). The other type of commonly used chipper is the drum chipper, which has a large drum where the knives are mounted (Van Loo and Koppejan, 2007). The productivity of the chippers will be decreased as knives become dull, meanwhile, the fuel consumption will be increased (Zamora Cristales, 2013).

Compared to chippers, grinders are less sensitive to the cleanness of the material. The main factor that drives the in-feed speed is the size of the biomass piece (Zamora Cristales, 2013). The most popular grinders are horizontal grinder and tub grinder. The two types grinders differ in their in-feed system, residues are fed into the grinder horizontally in horizontal grinder while in tub grinder residues are fed in a rotating tub (Zamora Cristales, 2013). Grinders can also be classified into stationary grinder and mobile grinder depends on where they are operated (Hummel et. al. 1988). The average productivities of grinders have been estimated to range from 32.5 Gt/PMH to 70 Gt/PMH (Zamora Cristales, 2013; Rawlings et al., 2004; Aman et al., 2010). Results obtained from Harrill and Han (2010) and the related thesis by Harrill (2010) had also been used to model the cost and production of the grinders.

The biomass transportation involves highway truck-tractors and chip vans, which has been commonly used in the United States to ship chips for the pulp and paper industry (Zamora Cristales, 2013; Johnson et al., 2012; Rawlings 2004). However, because of the adverse road condition, smaller trucks such as Hook-lift truck are favorable to transport the biomass (Harrill et al., 2009). To eliminate the high cost associated with slash collection and transportation, a roll-off trucking system has been evaluated in northern California, which was recommended for short hauling distance and loose material (Han et al., 2010). For distance larger than 50 km, a truck-and-trailer unit is preferred (Wolfsmayr and Rauch, 2014; Spinelli and Hartsough, 2001). The transportation cost of transportation from forest to mill has been studied by many researchers, and the most effective variables have been decided to be the transport distance, load volume and load weight. (Asikainen, 1995 and 1998; Moll and Copstead, 1996; Sikanen et al., 2005; Nurminen and Heinonen, 2007; Mo˙ller and Nielsen, 2007).

The transportation cost of forestry harvesting system is normally calculated based on the hauling distances in different types of roads (Mo˙ller and Nielsen, 2007). The classification of the road type is based on the transportation speed in each road type in average mph. For instance, 25 mph in paved road, 55 mph in gravel road, 45 mph in dirt road, and 55 mph in state highway (Michigan State Police).

2.2 Existing forestry-based biomass economic models

2.2.1 Fuel Reduction Cost Simulation (FRCS)

The FRCS is a spreadsheet application developed by Pacific Northwest (PNW) Research Station, with Microsoft® Excel® from 2002 to 2007. It can be used to estimate the costs of fuel reduction treatments if given the site condition and the harvest system configuration. This model uses the cost estimating approach developed by Miyata (1980) and combine machines into systems following the approach introduced by Hartsough et al (2001). As described above, this model can simulate the total cost by the information given; however, it cannot decide what system will be best fit for the harvesting site, which is one of its key limitations. Another limitation is the equipment production rates used in the model were from studies in Pacific Northwest, further modifications is necessary to improve the accuracy for lake states such as Michigan, Wisconsin or Minnesota.

2.2.2 Harvest Cost-Revenue (HCR) Estimator

This software is developed to provide cost of harvesting small-diameter ponderosa pine in Southwest United States. It can simulate stand-level producing cost and revenue for logging contractors and forest planners to design the fuel reduction plan and final financial profits.

2.2.3 My Fuel Treatment Planner (MyFTP)

This model is another spreadsheets application developed by Pacific Northwest Research Station at 2002 with Microsoft® Excel®. It is designed for providing the harvesting cost, revenue, economic impacts and total biomass production of fuel reduction project in national forest district or similar size unit. This application can only be valid when the volume of the estimated trees volume is smaller than 50 ft^3. The sample data files and cited scenarios in this model were all from Western U.S. model, therefore this spreadsheets is suggested to be used for the dry-forest types in Western United States.

2.2.4 BioSum 3.0

The BioSum 3.0 is software developed and tested by PNW Research Station. This software is designed to explore alternative landscape-scale treatment scenarios that achieve a certain management objective. It combined forest inventory data, treatment cost model, fuel treatment model and raw material hauling cost model (Fried et al. 2005). As an effective tool to optimize the woody biomass supply chain and achieve the largest benefits, it has been successfully used in Oregon, California and New Mexico with a wide range of forest bioenergy-facilities. It is still under modification and not currently available online. More information will be updated later after it is officially published.

2.2.5 Auburn Harvest Analyzer (AHA)

Auburn Harvest Analyzer (AHA) is designed by Shawn Baker and Dale Greene from the Center for Forest Business, Warnell School of Forestry and Natural Resources at the University of Georgia. AHA is a spreadsheet template that can only be used to estimate the whole-tree harvesting costs of merchantable tree or round wood. It was developed based on a whole-tree harvesting system included a Hydro-Ax 511 feller-buncher, a CAT 518 skidder and a 210 Prentice loader.

2.2.6 USDA Forest Service Region 6 Forest Products Web Page: Logging Systems and Economic Programs

This website contains spreadsheets models that can calculate logging and hauling cost, evaluate residual value and project economics for 19 National Forests in Oregon and Washington. The biomass harvesting cost estimation model can handle logging systems and equipment include skyline, mechanized, tractor, shovel and helicopter systems. The hauling cost estimation model only handle transportation cost of log truck.

2.2.7 Biomass Site Assessment Tool 3.0 (BioSAT 3.0)

BioSAT model is developed to estimate marginal, average and total cost of producing and delivering agricultural residues, logging residues and mill residues within 80 miles hauling distance. The model is based on data collected from 33 Eastern Unite States. In this model, stumpage and delivered wood cost on Michigan, Minnesota and

Wisconsin are cited from loggers' surveys conducted by Timber Mart North. Harvesting cost for merchantable trees is determined by AHA cost model; and logging residues cost is estimated using FRCS model. Trucking cost is calculated using the Trucking Cost Model for Transportation Managers developed by North Dakota State University at 2003, which did not classify different transportation road types (e.g. dirt road, paved road or highway).

2.2.8 Forest Residue Transportation Costing Model (FoRTSv5)

FoRTSv5 is a spreadsheet calculator designed by U.S. Forest Service Southern Research Station to decide loading cost and transportation cost of moving woody biomass from the harvesting site to the feedstock buyer. There are two stages transportation considered in the model: the biomass hauling process from the forest to landing site, and from the landing site to the end-user. Although it was developed at Southern U.S., the intermediate values such as the machine cost, production rate and fuel consumption rate can be modified by users to better suit their own conditions.

In conclusion, there were many cost analysis models developed to estimate costs of different harvesting systems (Whole tree or Cut-to-length) with different harvesting purposes (forest thinning or clear cut). Yet, most of the developed models were produced and can only be applied at Southern or Western U.S., which cause a concern for users in Lake States. In Lake States, terrain conditions and major tree species are different compared to Southern and Western U.S., which could result in different biomass volume and weight harvested during certain machine harvesting hours. Furthermore, none of above-discussed models have combined harvesting with transportation stage to provide a complete cost prediction for the whole woody biomass supply chain. This indicates a research need to develop a comprehensive cost prediction tool for Lake States, which considers all stages in woody biomass supply chain, use the same cost calculation method as previous discussed models (Miyata 1980), but with machine model information and productivity collected from Michigan based field study.

2.3 Woody biomass storage

Owing to increasing energy demands and the need to reduce greenhouse emissions, there is a strong necessity to decrease dependence on fossil-based fuels (REN21 2012, Zanchi et al. 2012). Biomass materials such as trees, grasses, and agricultural crops have thus become imperative alternative energy resources (US Department of Energy [USDOE] 2004). Among all of these materials, woody biomass is one of the most feasible choices because of its relatively low cost and high availability (USDOE 2004). Approximately 87 million dry tons (short tons) of wood residues and 64 million dry tons of forest harvest residues are produced in the United States every year, which accounts for approximately 2 percent of the total energy consumed (USDOE 2004, White 2010). In Michigan, there are over 1,400 forest products manufacturing facilities and 1,700 units that are working in the forest products manufacturing business, which implies a high availability of forest residues that can be used for bioenergy generation (Michigan Forest Products Council 2010).

2.3.1 Wood chips storage

Green biomass is usually directly processed into wood chips by mills or other wood-using facilities and is stored on-site before being transported to a power plant or a biofuel refinery (Lin and Pan 2013). This introduces many problems and concerns, such as a risk of self-ignition, health issues caused by the release of high concentrations of allergenic microspores, and most important, dry matter loss followed by the decrease of the biomass quality (Fredholm and Jirjis 1988, Jirjis 1995). Previous studies showed that the dry matter loss in a large green chip pile was approximately 12 percent during a 7-month storage period (Hornqvist and Jirjis 1999). A dry matter loss of 26 percent was also found in large bark piles throughout a 6-month storage period (Fredholm and Jirjis 1988). In addition, the dry matter loss in the large bark pile resulted in a 20 percent reduction in energy content (Fredholm and Jirjis 1988), thus lowering the energy yield and the value of woody biomass feedstock.

Wood chip quality control during storage is a key consideration because woody biomass with a high, constant, and uniform fuel quality is always desired (Lehtikangas and Jirjis 1998, Afzal et al. 2010). Wood chip piles, compared with bundled and unchipped logging residues, pose more challenge such as dry matter loss, increment in moisture content (MC), and reduction in energy content (Fredholm and Jirjis 1988; Tho¨rnqvist and Jirjis 1990; Jirjis 1995, 2001; Garstang et al.2002; Afzal et al. 2010). Because of these concerns, the duration of wood chip storage is normally suggested to be less than 6 months. Kofman and Spinelli (1997) suggest that willow from short rotation coppice should be delivered immediately to heating plants after harvest to avoid difficulty in storage. In Michigan, the typical storage period of wood chips is around 60 to 70 days (Scott Robbins, Director of SFI and Public Affairs in Michigan Forest Products Council, personal communication, October 15, 2013). However, no study is available to validate these suggestions for wood chip storage in Michigan. In addition, a key yet unresolved issue is how to predict the MC in a biomass pile without frequent measurement (Erber et al. 2012). This is also the problem for biomass higher heating value (HHV) estimates, because all existing models to predict the HHV of woody biomass use independent variables such as fixed carbon content, volatile matter content, and ash content, which all require additional testing (Iyer et al. 2002, Channiwala and Parikh 2002, Parikh et al. 2005).

Several factors exist that can affect woody biomass MC. They are air movement in the pile, relative air humidity, and monthly cumulative rainfall (Jirjis 1995, 2001; Garstang et al. 2002; Afzal et al. 2010). Using these weather factors can be a possible solution to predict woody biomass MC and HHV. However, to our knowledge, no previous research has been documented regarding this type of predicting model.

2.3.2 Logging residue storage

Several studies highlighted that the storage of logging residue in bundles can produce high-quality biomass feedstock with low moisture content (MC), increased higher heating value (HHV), and low ash content (Lehtikangas 2001, Pettersson and Nordfjell 2007, Afzal et al. 2010). Patterson et al. (2008) reported that the MC of biomass bundles decreased by 10 to 25 percent within 1 month after piling. Meanwhile, Karha and Vartiamaki (2006) found that the reduction of MCs resulted in a 12 to 28 percent increase in energy content per unit volume. The major problems in producing biomass bundles with a slash bundler is the low productivity and the high hourly cost due to delays caused by saw binding, materials handling, twine spool collapse, and slow movement at the site (Leinonen 2004, Rummer etal. 2004, Patterson et al. 2008, Harrill 2010). This makes the economic feasibility of using the savings from transporting low MC and highly compacted biomass to pay for the cost of bundling operations questionable.

Previous studies found that woody biomass is better stored in a loose form, allowing more air movement to take place within the pile (White et al. 1983, Thornqvist 1985, Sampson and McBeath 1987, Jirjis 2005, Afzal et al. 2010). With the increased interests in developing wood-based renewable energy production in Michigan, ensuring a year-round supply of high-quality woody biomass feedstock with consistently low MC and high HHV without incurring extra processing cost becomes imperative.

2.4 Life Cycle Assessment (LCA) in forestry

2.4.1 Categories and key steps of LCA

LCA is a standard approach developed in the late 1960s to account the environmental impacts or potential in all life stages of producing a product or operating a process (Jensen et al. 1997; Guinée et al. 2011; Rebitzer et al. 2004; Finnveden et al. 2009; Sedjo, 2013; Klein et al., 2015). The primary goal of LCA is to prove and improve the environmental soundness of any product or production process (ISO, 2006; Heinimann, 2012). Since renewable energy sources are promising alternatives to reduce our dependence on fossil fuels, thousands of LCA have been performed globally in the past 20 years (Amponsah et al., 2014).

There are typically two types of LCA: “attributional” LCA (ALCA) and “consequential” LCA (CLCA) (Sedjo, 2013; Vasquez Sandoval, 2015). ALCA is performed to understand “the environmentally relevant physical flows of a past, current or potential future product system” (Currant et al., 2005; Sedjo, 2013). CLCA is developed to decide the consequence of possible decisions that would have been made (Poeschl et al., 2012a; Vasquez Sandoval, 2015). The two types of LCA provide different information, an ALCA can report total carbon emissions from woody biomass supply chain while a CLCA can show the possible consequences of mainly using woody biomass for energy production in Michigan.

Based on the methodology provided by Curran (2006) and framework described in ISO 14040 (2006), key steps of LCA can be summarized as below:

1) Define the goal(s) and scope of the project: In this step, the primary goal of the project, major assumptions, data quality assurance procedures, system boundary and function units of the LCA will be decided.

2) Life-cycle inventory (LCI): All input and output data will be collected in this phase to show the energy and material flow, and greenhouse gas (GHG) emissions throughout the life cycle of the evaluated system. The inventory data will be presented in units related to function units defined.

3) Life-cycle impact assessment (LCIA): The impacts caused by previously identified resources or GHG emissions will be assessed to review their contribution to impact categories such as global warming, acidification and eutrophication.

4) LCA interpretation: The results will be interpreted in terms of project objectives and functional units. Comparison with other production systems can be made in this phase, and conclusions will be drawn.

2.4.2 LCA in forest products

In the past 20 years, several LCAs of wood products have been performed, attempting to evaluate their resulted environmental impacts, especially carbon footprints. The accessed wood products processing systems include wood boards (Rivela et al., 2007; González-García et al., 2009a), paper pulp (González-García et al., 2009b), writing paper (Dias et al., 2007), floor coverings (Petersen and Solberg, 2003; Nebel et al., 2006) and furniture (González-García et al., 2011).

In U.S., the Consortium for Research on Renewable Industrial Material (CORRIM) started a large project to assess the material flows and the environmental consequences for kiln-dried softwood lumber (Puettmann et al., 2010), plywood (Wilson and Sakimoto, 2005), laminated veneer lumber (Wilson and Dancer, 2005), oriented-strand board (Kline, 2005), particleboard (Wilson, 2008a), and medium-density fiberboard (Wilson, 2008b). CORRIM concluded that wood used in long-term products such as construction material could provide a great reduction in fossil fuel use and emissions. Later on, Puettmann and Wilson (2005) published the first cradle-to-gate scope LCA for wood products and made a comparison between their report and CORRIM 2004 report. The comparison indicates that wood products used 1/3 of their energy consumption from renewable resources and the rest from fossil fuels when the system boundary includes all cradle-to-gate stages (Puettmann and Wilson, 2005).

2.4.3 LCA in Short Rotation Woody Crop (SRWC) systems

Short rotation woody crops such as *Populus, Salix* and *Eucalyptus* are gaining interests because their high productivity, and flexibility in harvest time (Hinchee et al., 2009). Since they are largely promoted to offset GHG emissions, many LCA studies are carried out globally to quantify the environment impacts and to chase the energy flow in their production systems.

Table 1 summarizes part of the documented LCA studies focus on SRWC systems in recent 13 years. Although most of them reach the same conclusion that SRWC could significantly reduce GHG emissions, large differences in reported energy ratio and GHG emissions level was found. For example, the energy ratio and total CO_2 emission in short rotation willow plantation reported by Goglio and Owende (2009) are 19.3 and 134 kg CO_2 Gj^{-1} electricity produced, whereas the values reported by Keoleian and Volk are 55.3 and 10.5 Mg CO_2 ha^{-1} (equivalent to 19.48 kg CO_2 Gj^{-1}). Djomo et al. (2011) have published a literature review, in which they compiled 26 LCA studies on energy ratio and GHG emissions of short rotation woody crops (poplar and willow). They highlighted that GHG emissions varied from 0.6 to 10.6 g CO_2Eq $MJ^{-1}_{biomass}$ (or 39 to 132 g CO_2Eq kWh^{-1}); and energy ratios for willow and poplar production systems varied from 16 to 79 and 13 to 55. This difference is due to different project goals, raw materials and research locations in the two studies. It indicates that LCA is very case specific and relevant for the geographic location where the life cycle inventory data are collected. Therefore, to evaluate the environmental impacts of SRWC production systems in Michigan and lake States, it is necessary to develop a LCA model that covers from cultivation to combustion stage.

Table 1. LCA studies in short rotation woody crop plantations

Year of study	Author(s)	Energy crops	Region	Research focus		Scope
				Environmental Impact	Energy	
2005	Keoleian and Volk	Willow	U.S.	✔	✔	Cultivation to energy generation
2007	Adler et al.	Poplar	U.S.	✔		Cultivation to energy generation
2009	Goglio and Owende	Willow	Italy	✔	✔	Cultivation to energy generation
2009	Gasol et al.	Poplar	Spain	✔	✔	Cultivation to energy generation
2010	Nassi o di Nasso et al.	Poplar	Italy		✔	Cultivation and harvesting
2011	Djomo et al.	Poplar and willow	Global	✔	✔	Literature review
2011	Cherubini and Strømman	Poplar and willow	Global	✔	✔	Literature review
2012	González-García et al.	Willow	Sweden	✔	✔	Cultivation to energy generation
2012	Nikiema et al.	Poplar and willow	U.S.	✔		Cultivation
2013	Dillen et al.	Poplar	Belgium		✔	Cultivation to transportation
2014	Caputo et al.	Willow	U.S.	✔	✔	Cultivation to transportation
2015	Vasquez Sandoval	Poplar	U.S.	✔	✔	Cultivation and harvesting

2.4.4 LCA in other forest production systems

Besides SRWC, there are other forest production systems such as spruce, pine and eucalypt stands that are originally planted for pulp production purpose or other industrial uses. In these forest production systems, trees certainly did not receive management practices like fertilization or herbicide application as intensively as in SRWC production system. The environment impacts caused by these not intensively managed forest production systems were not well studied, especially in U.S. (Kilpeläinen et al., 2011; González-García et al., 2014; Cherubini and Strømman, 2011). In a literature review completed by Cherubini and Strømman (2011), there are 13 out of 94 studies done in evaluating environmental impacts of forest wood production, compared to 27 studies done in SRWC production systems. Among the 13 studies in forest production system, only two studies: Pimentel and Patzek (2005) and William et al. (2009) are from U.S. Pimentel and Patzek (2005) compared the ethanol production and energy used in using corn, switch grass and wood. William et al. (2009) reviewed environmental impacts include greenhouse emissions, soil health and quality, water use and water quality in agricultural residues and forest residues production systems.

Walker et al. (2010) carried out an LCA study called Manomet that aimed to evaluate GHG emissions and potential impacts caused by utilizing forest biomass in Massachusetts. However, this study only involved one single harvest site with one single plot that allows no room for any change in future markets or prices. The approach used in Manomet was adopted in a Canadian study conducted by McKechnie et al. (2011), which involved a 5.3 million ha mature natural forest as a carbon sink. They combined LCA analysis with forest carbon modeling to provide a more accurate picture of forest carbon dynamic. Their major finding was that it might take up to 100 years to see the carbon mitigation benefit of the forest.

Later on, Sedjo and Tian (2012) published the conceptual Timber Supply Model (TSM) analysis using a well-known dynamic optimization forest management model to examine the effect of changing wood biomass demand on the existing forest and the amount of carbon captured by the forest system (Daigneault et al. 2012; Sohngen et al. 1999; Sedjo and Sohngen 2013). The TSM model used an unconstrained approach to maximized the profit in wood biomass market and to foresees the change in forest harvest plan corresponding to widespread demand increases for wood.

Handler et al. (2014) published an LCA that analyzed GHG emissions and energy input in harvesting and transportation stages (truck and railway transport) in roundwood supply chain in Michigan. This study is based on previous published peer-reviewed literature, national database, and a Michigan loggers' survey. Handler et al. (2014) claimed that Michigan roundwood supply chain has smaller environment burden compare to similar production systems from other regions.

Table 2 summarized some other LCA studies that have been done in U.S. It is noticeable none of them covers the whole woody biomass supply chain start from cultivation, end at biomass utilization stage. Besides the incomplete life scope, the results reported are widely different. Even though all published studies follow similar LCA procedure, critical issues are raised regarding about how the LCA procedure is exactly adopted in each study. As discussed by Heinimann (2012) and Klein et al. (2015), there were large differences found in scope definition, system boundaries, and the function units in many previous published studies. In 22 different peer-reviewed LCA reports, the Global Warming Potential (GWP) reported were at a range from 6.3-67.1 kg CO_2 equiv. m^{-3} ob (median = 17.0; n= 36) from site preparation to plant gate (Klein et al., 2015). These large variations not only made those studies very site-specific, but also created difficulties in cross-comparing these results to standard LCA studies (Cherubini, 2010).

Table 2. LCA studies in forest production systems (non-SRWC)

Year of study	Author(s)	Region of study	Goal and scope
2005	White et al.	Wisconsin	LCA of forestry harvesting
2006	Sonne	Northwest Pacific, West side of the Cascade Mountains in Washington and Oregon	Greenhouse gas emissions from forestry harvesting operation
2010	Oneil et al.	Minnesota, Maine, Missouri, West Virginia, Pennsylvania; Idaho, Montana, Washington	Carbon emissions and environmental toxicity from establishment to harvesting
2011	Neupane et al.	Maine	LCA of wood chips used for biofuel production
2012	Johnson et al.	Western and Southern U.S.	LCA of biomass collection and processing
2013	Saud el al.	West Virginia	Carbon emissions of harvesting

Another concern is that for woody biomass from mature forests and non-SRWC stand, there is no available LCA model developed to estimate environmental impacts caused by all life stages in a woody biomass supply chain. By 2015, there are over 20 millions acres of forested land in Michigan, and 19.3 millions acres of them are timberland (Pugh et al., 2016). Similarly for other Lake States, the land areas of non-SRWC forest stands are much larger than SRWC plantations. This indicates a great need of developing a LCA framework to assess the life impacts in the complete woody biomass supply chain, including cultivation, harvesting, biomass collection, biomass handling, transportation and combustion stages, especially in forest stands. This LCA framework should be applied to access the environmental impacts in the wood biomass supply chain on Michigan and other regions.

2.4.5 Soil carbon sequestration and sources of uncertainties

Carbon pool in forest biomass production systems include many components such as the aboveground biomass, belowground biomass, soil organic carbon, dead wood residues and litter (Figure 2). Based on EPA's report (EPA, 2008), 59% of the net CO_2 in US are sequestrated in the forest ecosystems, while 16% of the net CO_2 are stored in soil. Soil organic carbon majorly forms from decomposition of detritus such as leafs, dead roots and leachates from living roots. It it sequestrated into the soil by two major ways: humification and microphotosynthesis (Sedjo and Sohngen, 2012). The formed soil organic carbon will be stored in the topsoil (0-25 cm) and gradually transport to subsoil (25-100 cm). Over half of the carbon is stored in soil organic matter, which is more stable compared to debris and litter (Brandão et al., 2013; Helin et al., 2013). Qin et al. (2016) suggested that including SOC sequestration in LCA could significantly influence the total GHG footprints of bioenergy production systems. However, it is challenging to include SOC because there are high uncertainties in accounting SOC changes. Therefore, majority LCA studies have not included soil C sequestration in their inventory data (Koerber et al., 2009; Petersen et al., 2013).

The large uncertainty in SOC changes rate is because SOC are highly impacted by many factors such as regional climate conditions, soil management practice, vegetation type, soil depth and time period considered, C: N ratio of plant debris and so on (Lal, 2005). Soil C storage ability various from different biomes and forest zones. Boreal/taiga can store 471 Mg C/ha of soil, while temperate can only store 100 Mg C/ha of soil (Lal, 2005). In tropical forests, temperate forests, and boreal forest, Soil C stock density varies from 122 to 296 Mg C/ha (Prentice, 2001).

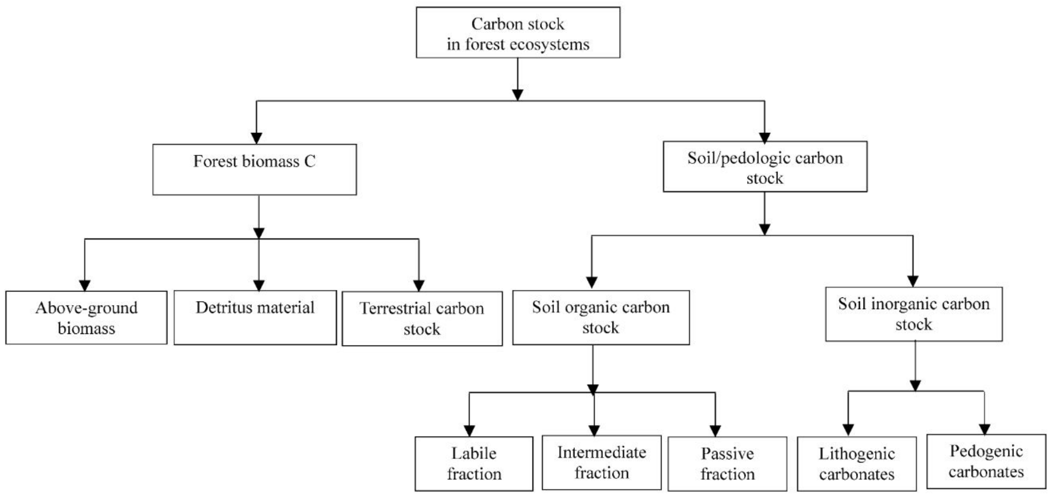


Figure 2. Components of terrestrial carbon stock (Lal, 2005)

Extensive studies have been conducted to evaluate the impact of forest ecosystems and land use change on the soil carbon storage and soil carbon dynamics (Hansen et al., 1993; Johnston et al., 1996; Zan et al., 2001; Rothstein et al., 2004; Schulp et al., 2008; Arevalo et al., 2011; Lockwell et al., 2012; Rytter et al., 2015; Winans et al., 2015). Freibauer et al. (2004) reported that reduce tillage and increase surface residue return could increase soil C by 0.4-0.6 t C $ha^{-1}yr^{-1}$. Surface litter cover has been demonstrated to affect the soil nitrogen balance and increase microbial activities, thus to increase SOC accumulation rates (Tolbert et al., 2002; Helmisaari et al., 2011). On the other hand, Lippke et al. (2011) concluded that soil C accumulation is not significantly impacted by management practice, but only driven by soil moisture, soil nitrogen content and climatic conditions.

As different vegetation can result in different organic matter inputs, root systems, and microbial communities, the impact of land use change on soil C stock has been largely studied. Guo and Gifford (2002) did a mega analysis of soil C stock changes following different land use changes based on 74 publications, which suggested that land use change caused significant increases or decreases in SOC stocks. Xue et al. (2016) studied the effects of land conversion from hayfields-to-willow and hayfields-to-hybrid poplar on soil microbial communities and soil properties after 3 years in Michigan and Wisconsin. The results indicated that total soil C decreased in one of the two study sites, and did not change in the other site. Qin et al. (2016) reported an overall 6-14% SOC gain in land that was converted from cropland to energy crop plantation, which 9-35% SOC losses were observed in lands that were converted from grassland and forest to corn field. They have also pointed out that SOC change rates slow down after 10 years of land conversion, which indicated time duration considered for SOC change is also important.

As discussed above, SOC stock can be largely impacted by the accounting method (e.g. depth, time duration considered) and many environmental factors, which all contribute to the large uncertainties and differences found in the reported soil C values. Todd-Brown et al. (2013 and 2014) reported a large variance range of 510 to 3040 pg C in predicted soil C stocks by 11 Earth system models. Tian et al. (2015) found the SOC estimations by 10 terrestrial biosphere models vary from 425 to 2111 Pg C (1 Pg = 10^{15} g). To effectively estimate and reduce the uncertainties in SOC stocks, many soil C modelling studies have utilized Markov Chain Monte Carlo (MCMC) technique (Heath and Smith, 2002; Verbeeck et al., 2006; Shi et al., 2018).

2.5 Nutrient removal caused by forest harvesting systems

Carbon neutrality, GHG emissions and energy balance in woody biomass production systems are always the key focus in about 90% LCA study. Nutrients loss in forest production system has rarely been quantified in LCA studies. Yet, the removal of fine woody materials can cause significant negative impacts to nutrients cycles and soil productivity (Martin et al. 2000, Watmough and Dillon 2003; Walker et al., 2010). Nutrients removal assessment is critical for soil nutrients protection and forest productivity maintenance, it should be considered as an important part of LCA study.

2.5.1 Intra-specific variability of N, P, K in different parts of trees

Intra-specific variability between different parts of the same tree has been widely studied. Tharakan et al. (2003) reported that nutrients (N, P, K) concentrations in wood and bark parts varied significantly among 7 hybrid poplar clones ($P < 0.05$). Leaf nitrogen concentrations were analyzed to be significantly different among the four clones (Karačić and Weih, 2006). Tharakan et al. (2003) reported that nutrients (N, P, K) concentrations in wood and bark parts varied significantly among 30 hybrid willow clones ($P < 0.05$). The average N and P content in leaf among 6 willow varieties were reported to be statistically the same ($P > 0.05$) and the concentration of K was found to increase significantly with the leaf biomass production ($P < 0.05$) (Hangs, 2013).

Tree foliar chemistry database have been established in both U.S. and Canada. Pardo et al. (2004) has built a report database of foliar nutrients data from 218 articles and publications in the Northeastern United States. In Canada, Paré et al. (2013) has compiled 12,800 nutrient concentration values for different components of 30 most common Canadian tree species. From their database, noticeable difference can be found in reported values, which might be differed by species, studied regions, treatments and nutrients measurement techniques.

2.5.2 Established aboveground tree biomass estimation equations

Given the nutrients allocations in each species, the estimated aboveground tree weight becomes a key component to know the total nutrients contents in a tree (Lambert et al., 2005; Pacala et al., 2001; Jenkins et al., 2003). "Aboveground tree biomass", as defined by Jenkins et al. (2003), refers to "the weight of that portion of the tree found above the ground surface, when oven-dried until a constant weight is reached". The total aboveground biomass in each plot can be estimated by summing the biomass values of each tree including all tree components in a plot, and expressed in a per-unit-area basis such as Mg ha^{-1} or kg m^{-2}. "Tree components" refer to the different parts of a tree such as foliage, merchantable stem, roots, or branches (Jenkins et al., 2003).

Pearson et al. (1983) has estimated the aboveground and belowground tree biomass including bole, branch, foliage, root crown and lateral root biomass of Lodgepole pine (Pinus contorta) using a combination of dimension analysis and sampling in southeastern Wyoming. Tritton and Hornbeck (1982) have estimated biomass above ground weight for major tree species in the Northeast of U.S. based on 178 sets of published equations. Similarly, TerMikaelian and Korzukhin (1997) have developed compilations of equations to estimated 65 tree species in U.S. In Michigan, 32 hardwood tree species included American basswood (*Tilia Americana L.*), American beech (*Fagus grandiolia Ehrh.*), black cherry (*Prunus serotina Ehrh.*), slippery elm (*Ulmus rubra Muhl.*) and sugar maple (*Acer saccharum Marsh.*) were studied to illustrate the impact of wood density and whole-tree factors on biomass equations (MacFarlane and Ver Planck, 2012).

Jenkins et al. (2003) compiled all available diameter-based allometric regression equations for estimating total aboveground and component biomass, defined in dry weight terms, for trees in the United States. Also, they applied a modified meta-analysis based on the published equations to develop a set of consistent, national-scale aboveground biomass regression equations for U.S. species. As concluded, the equations developed in this study were analyzed to generally agree with the biomass (±30%) estimated by the U.S. forest inventory data for eastern U.S. species. This study is the first one that compiled and analyzed all available biomass literature in a consistent national-scale framework.

The traditional way of predicting tree biomass is to fell, measure and weight the target trees, which is also called destructive sampling. On the other hand, functional branch analysis (FBA) has been reported to be a promising, non-destructive method to evaluate tree biomass (MacFarlane et al., 2014). It enables users to compute tree biomass by using fractal branching rules, woody density of tree volume components (Van Noordwijk and Mulia, 2002; MacFarlane et al., 2014). Besides whole tree biomass, FBA has also been applied to estimate tree component biomass based on standing tree measurements (Salas et al., 2004; Smith, 2001; Santos-Martin et al., 2010).

2.5.3 Sources of uncertainties in tree biomass equations

Estimating aboveground biomass (AGB) is very species-specific (Ketterings et al., 2001). There are four major steps for developing AGB estimation based on allometric equations: (1) choosing a suitable model to estimate the AGB (e.g.

polynomial function or power function); (2) choosing suitable values for any adjustable parameters in the equation; (3) measuring the input variables by field experiment (e.g. tree height and tree diameter); and (4) using the allometric equation to calculate the AGB of individual trees and to get the summation estimates (Brown, 1997; Ketterings et al., 2001; Chave et al., 2004).

Each of the four steps can bring uncertainties in different levels and lead to error propagation when estimating the AGB. Many studies are conducted to evaluate the uncertainties listed above (Laurance et al., 1999; Clark and Clark, 2000; Phillips et al., 2002; Shettles et al., 2016). The uncertainty due to measurement error and allometric model selection error were about 16% and 31% (Chave et al., 2004). The difference caused by allometric equations will be larger through the tree diameter increase (Laurance et al., 1999). 16% difference in AGB was found due to landscape-scale environmental variability, and there was no effect of soil type on AGB detected (Clark and Clark, 2000). Relative contributions for measurement, model and sampling error were 5%, 70% and 25%, respectively when using terrestrial laser scanner, and 11%, 66% and 23%, respectively using the traditional inventory measurements as inputs into the models (Shettles et al., 2016).

2.5.4 Quantifying the uncertainties using Monte Carlo analysis

Nutrients removal can be estimated by multiplying nutrients (N, P and K) concentrations in removed biomass with weight of removed biomass. However, as discussed above, there are many uncertainties in AGB estimations and tree nutrients concentrations results, due to the biological variations such as intra-specific variability in different parts of trees. Therefore, it is necessary to quantify the uncertainty in nutrients removal estimations.

Monte Carlo analysis has been widely used to understand the impact of risk and uncertainties in LCA studies, forest measurements and models and nutrients budge estimations (Yanai et al., 2012; Caputo et al., 2013; Zamar et al., 2015; Eyvindson and Kangas, 2016). It consists of randomly sampling values from a given probability density distributions of each input parameters to the model. These randomly sampled values are fed into the mathematical model and used to calculate a value for the output (risk) and to develop a discrete approximation to the output distribution (Burmaster and Anderson, 1994). Monte Carlo analysis is expected to provide results such as: (1) the uncertainty in estimated nutrients removal caused by each nutrient concentration estimate; (2) sensitivity analysis of estimated results to each nutrients concentration estimation, (3) graphical results and probabilistic results, which can illustrate the distribution of results based on nutrients concentrations estimation.

2.6 Optimization in woody biomass supply chain

Unlike the steady state operation of fossil fuel, the supply chain of woody biomass can be highly complex because its reliance on several activities such as the biomass availability; the consumers' demand; the logistic costs of biomass harvesting, storage and delivery; the landowner objectives; and also different laws, all kinds of regulations and policies (Soylu, 2006). For over 3 decades, many optimization models and methods have been used to solve the planning problems in woody biomass supply chain, such as strategic, tactical and operational planning. Strategic planning is a systematic process that defines the future strategy of using or allocating the forest resource in a long period such as 50 to 100 years. Tactical planning can provide a detail plan to decide the harvesting area, harvesting system, transportation distance and so on for a shorter time of several months to one year. Operational planning is the process that defines the harvesting system or plan for a specific harvesting area to reduce the operation cost and increase the product value. The typically used models in woody biomass supply chain include dynamic programming, integer programming, linear programming and non-linear programming.

Forty-nine studies were reviewed to summarize the optimization models developed in woody biomass supply chain since 1997. The reviewed studies were categorized based on the aspects they focus on, including economic, environmental and social. The main indicators for economic optimization model are the capital cost and production cost. For environmental optimization models, the most used indication is the total GHG emissions. The jobs created by the bioenergy production system are the main considered social criterion. In the 63 reviewed studies, 47 of them are single objective optimization models with the objective of cost minimization (Figure 3). The other 12 studies are bi-objective optimization models, aiming to minimize both cost and GHG emissions. Three out of the 12 studies were purely focused on woody biomass supply chain, the remaining nine studies considered agricultural crop as well. There are four studies conducted to optimize cost, environmental and social aspects in bioenergy production systems using agricultural crops and woody biomass as feedstock.

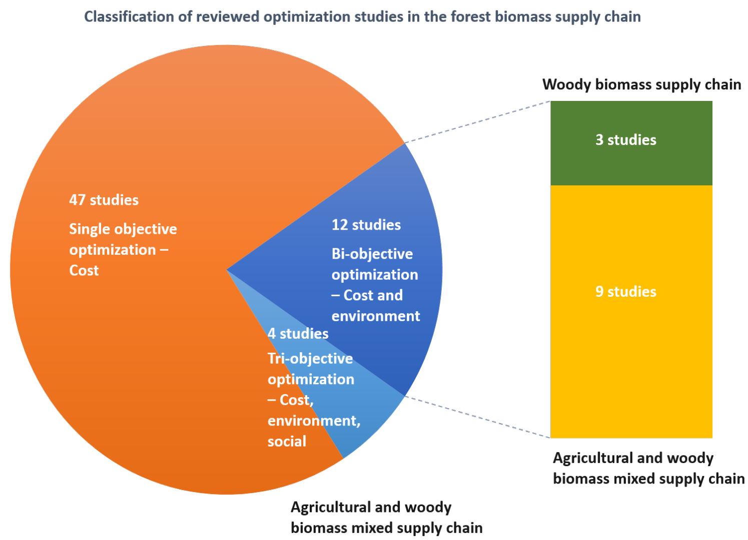


Figure 3. Classification of reviewed optimization studies in biomass supply chain

2.6.1 Single objective optimization models

2.6.1.1 Strategic planning

Strategic optimization models generally aim to provide information for long-term decision-making. Many studies have been published to analyze the economic feasibility of producing bioenergy using woody biomass in different regions (Nagel, 2000; Kaylen et al., 2000; Tittmann et al., 2010; Wetterlund and Söderström, 2010; Difs et al., 2010; Börjesson and Ahlgren, 2010; Huang et al., 2009; Yagi and Nakata, 2011; Schmidt et al., 2010a; Upadhyay et al., 2012; Keirstead et al., 2012; Kong et al., 2012; Fernández et al., 2015; Cambero et al., 2015; De Meyer et al., 2016). Results showed that with the advanced biomass conversional techniques, the biofuel price could be competitive with gasoline (Nagel, 2000; Tittmann et al., 2010). Scenario analysis and sensitivity analysis were applied in these studies to reveal the impacts of many factors such as biomass availability, energy price, market and policy change, and production scales on the bioenergy production cost.

As it is necessary for stakeholders to make decisions to allocate their investment and biomass flow strategies, many studies have focused on the design of the biomass supply chain networks (Chineses et al., 2005; Frombo et al., 2009 a and b; Feng et al., 2010; Parker et al., 2010; Schmidt et al., 2010 aandb; Elia et al., 2011; Zhang et al., 2016; Lim and Lam et al., 2016). The developed models plan the size and the optimal location of facilities, the feedstock combinations, the conversion processes, the harvested area, the transportation methods, and the best transportation routes with minimal cost or maximum profit. With careful supply chain management, the supply cost of biofuel can be reduced to $15.68 to $22.06/GJ, comparable to the cost of coal ($16/GJ) and compressed natural gas ($16.95/GJ) (Elia et al., 2011).

Facility locating has gained many interests because it can largely affect the transportation cost and the efficiency of the whole bioenergy production system. Thus, several optimization models have been developed to identify the optimal location of bio-refinery or power plant in Italy (Freppaz et al., 2004), Austria (Schmidt et al., 2009), Greece (Rentizelas and Tatsiopoulos, 2010), Sweden (Leduc at al., 2010 a and b), Finland (Natarajan et al., 2014), Colombia (Duarte et al., 2014), and U.S. (Kim et al., 2011 a and b). Factors such as plant capital investment, conversion efficiency, feedstock cost and industrial competition are summarized to be the most influential in the bioenergy production cost.

2.6.1.2 Tactical planning

Tactical supply chain models provide detail plan at the operational level to realize the strategies, such as harvesting schedule, distribution network and transportation method at certain region (Gunnarsson et al., 2004; Kanzian et al., 2009; Rauch and Gronalt, 2010; Shabani et al., 2012 and 2014). As woody biomass transportation cost accounts for the largest part of the total cost and energy consumption (Eriksson and Bjo¨rheden, 1989; Allen et al., 1998; Alam et al., 2012), the developed tactical optimization tools primarily focus on two categories: location selection and woody biomass collection. The location selection models mainly emphasized on finding the best location for single or multiple processing facilities over large-scale biomass supply chain (Zhang et al., 2011). The optimization models for woody biomass collection aimed to estimate the feedstock availability and to reduce cost of biomass procurement (Ranta, 2002; Ranta, 2005; Panichelli and Gnansounou, 2008). For instance, Lautala et al. (2012) have published a cost minimization model to minimize the cost for woody biomass transportation using railroads in Michigan and Wisconsin.

2.6.2 Bi-objective optimization models

While economic aspects of woody biomass supply chain have always been the major focus, recently the environmental impacts of renewable energy production systems are getting more concerns. Thereby, numerous supply chain models have been developed to minimize the environmental burden and analyze the trade-off between cost and GHG emissions. Nagurney et al. (2006) presented a framework for decision makers to determine the optimal carbon taxes should be applied to electric power plants that use renewable energy resources in different scenarios.

To minimize the environmental impacts of the bioenergy supply chain, LCA was largely used to provide the environmental indicators in many multi-objective optimization models (Steubing et al., 2012; Sacchelli et al., 2014; Pérez-Fortes et al., 2014). Zamboni et al., (2009) have developed a multi-objective environmental optimization model to apply in a corn-based bioethanol system in Italy. You and Wang (2011) presented a county-level optimization model to determine the optimal biomass (agricultural, energy crops, and wood residues) supply chain design under economic and environmental criteria in Iowa. Santibañ ez et al. (2011, 2015 and 2016) developed three different multi-objective optimization models to address different needs in the bio-refinery supply chain in Mexico using multi-feedstock. Multi-objective optimization framework has also been used to determine the conversion technologies, facility size, location, and raw material in a global scale (Giarola et al. 2011 and 2013).

There are only a few studies focus on multi-criteria optimization in woody biomass supply chain. For instance, Steubing et al. (2012) developed a strategy to determine the optimal size and location of a bioenergy plant that converts wood to synthetic natural gas in Switzerland. The minimal cost can be achieved when the plant size is around 100-200 MW, however if the environmental performance is considered, the optimal plant size is determined to be 90 MW. Kanzian et al. (2013) have formulated a model to maximize the profit and minimize the CO_2 emissions in a wood-based supply chain in Austria, with decision variables of pre-processing location, transportation mode, volume and terminal. The results suggested that with 4.5% increase in CO_2 emissions, the profit can be increased to more than twice. A strategic multi-objective optimization framework was developed to design the optimal supply chain networks with maximum Net Present Value (NPV) and minimal GHG emissions, for woody biomass supply chain in 20 years horizon (Cambero et al., 2016). This model was applied in a case study in

British Columbia, Canada. The results indicated that converting woody biomass to pellet and bio-oil and export to Europe could achieve the highest NPV and lowest GHG emissions. However, optimization model that considers both economic and environmental impacts of woody biomass supply chain in U.S. lacks (Shabani et al., 2013b), which indicates a great need for future study.

2.6.3 Tri-objective optimization models

Besides economic and environmental aspects, social aspect of woody biomass supply chain is also important due to its effects on society such as household income and job creations (McKay, 2006). The social criterion considered in the study published by Čuček et al. (2012) is "Social footprint", which is defined as the risk of using farmlands to the bioenergy production instead of food production. In the model developed by Sacchelli et al. (2014), social indicators include risk of negative profit for sawmills, negative profit for logging companies, and negative profit for energy plants. You et al. (2012) and Yue et al. (2014) presented two multi-criteria optimization models to minimize the economic (annualized cost), environmental (GHG emissions), and social objectives (the number of the accrued local jobs) in multi-feedstock biomass supply chain in Illinoi. However, in these two models, the harvesting, collection and pre-processing cost of woody biomass were combined into the biomass acquisition cost, which was a simulated value cited from previous study.

CHAPTER 3 WOODY BIOMASS PRODUCTION COST PREDICTION

3.1 Introduction

In the past decades, due to the growing need to reduce dependence on fossil-based fuels, renewable energy has become the world's fastest-growing energy sector (Zanchi et al., 2012; REN Renewables, 2012; EIA, 2015). From 2008 to 2017, the total annual electric power produced from renewable energy sources (excluding hydroelectric and solar) has risen from 1.25E+08 MW to 3.34E+08 MW (EIA, 2018a). As one of the most important renewable energy sources, wood and wood-derived biomass supplied about 19% of total U.S. renewable energy consumption in 2016 (Figure 1). About 69% of the bioenergy produced from woody biomass was consumed to produce power and heat for industrial applications such as wood and paper production (EIA, 2018b). In order to promote the use of woody biomass as a renewable energy resource, it is critical to evaluate its production cost.

Due to the traditional harvesting strategy and the undeveloped biomass supply chain, the costs of using woody biomass are tend to be higher than those of fossil fuels like coal (Dunnett et al., 2007; Perlack et al., 2011; Caputo, 2014). In U.S., compared to \$2.37/MMBTU for coal, the average price of using woody biomass for electric power is \$2.69/MMBTU (EIA, 2014). There are many reasons for high production costs, such as high capital investment of harvesting machines, inappropriate harvesting season, difficult harvesting site conditions, long travel distance, and lack of operation management (Ghaffariyan et al., 2012a; Harrill and Han, 2012; Strandgard, 2014).

Cost predictions for woody biomass supply chains are important to determine the economic feasibility of using woody biomass for bioenergy (Alam et al., 2012).

Extensive cost analysis and models such as BioSum 3.0, Auburn Harvest Analyzer (AHA) and FRCS-North have been developed to provide logistic cost predictions estimate woody biomass production cost. Transportation cost is a major factor influencing final production cost. Galik et al. (2009) have claimed that transportation cost could vary from $10-$30 per dry ton, even under 50 miles distance. Linear programming models and GIS-based forest biomass data were used to reduce transportation costs in the woody biomass supply chain (Ranta, 2002; Ranta, 2005; Panichelli and Gnansounou, 2008).

Besides cost prediction, determining the limiting factors in the biomass supply chain and developing their corresponding time prediction models are also important to improve the production efficiency (Alam et al., 2012). For instance, harvester productivity can be affected by many factors such as tree size, spacing, ground slope and roughness (Bolding and Lanford, 2002; Acuna and Kellogg, 2009; Wright et al., 2010; Ghaffariyan et al., 2012b). Bolding and Lanford (2002) reported that travelling distance and hauling weight affected the forwarder productivity in CTL harvesting system. Harrill and Han (2012) found a noticeable relationship between transportation cost and road type that every 50 m increase in transportation distance can raise the total transportation cost by $0.08/ODT.

Due to the differences in tree species, stand density, site and terrain conditions, productivity of woody biomass supply chains in the Lake States, including Illinois, Indiana, Michigan and Ohio, might be different from the Western U.S. For instance, the ground slope is gentler in the Lake States compared to the Western States, which may contribute to reducing the harvesting, and biomass collecting time and cost. Because of the impacts of terrain conditions and forest transportation road types on the production cost, there is a need to develop a cost prediction model based on the data collected in Michigan. In this study, five forest harvesting projects in Michigan were monitored to estimate the productivity and production cost of producing woody biomass. Based on data collected from time and motion studies, multiple linear regression equations were developed for each machine at each studied site.

3.2 Methodology

3.2.1 Study sites and harvesting systems

Five woody biomass harvest projects were monitored using time and motion techniques at different sites in Michigan from 2012 to 2014. Whole tree (WT) harvesting systems were investigated at four sites: Delton, East Lansing, Escanaba and Albion. Delton (Site 1) was located in the Kellogg Biological Station, Lux Arbor reserve, Michigan. The stand was dominantly stocked with Douglas-fir trees, mixed with Norway spruce, white spruce and other hardwood species. The total harvesting area was 33.33 acres. The average tree DBH at Site 1 is 5.36 inches. East Lansing (Site 2) was at the Sandhill Research Area, south of the Michigan State University Tree Research Center, East Lansing, Michigan. The harvesting site was a 28.55-acre mixed-species forest stand with hardwoods such as poplar, oak, black locust (*Robinia pseudoacacia*) and softwoods like spruce, larch, and Engelmann spruce (*Picea engelmannii*). The average tree DBH at Site 2 was around 8.5 inches.

Site 1 and Site 2 were harvested by a WT harvesting system: a wheeled hot-saw feller-buncher (Hydro Ax 511EX) that felled and bunched trees, and a rubber-tired grapple skidder (John Deere 648G) that skids the trees from the stump to the landing.

Harvesting prescriptions were 70% thinning for Site 1 and clear-cut for Site 2. The harvested wood was pre-processed to wood chips by a whole-tree chipper with an attached loader (Trelan 21L chipper).

Site 3 was a 7.8-acre, 7-year-old hybrid poplar plantation at Michigan State University's Forest Biomass Innovation Center (FBIC), in Escanaba, MI. The average tree DBH was 4 inches. A WT harvesting system, including a feller-buncher (John Deere® 653G feller-buncher), grapple skidder (John Deere 740A), log loader (Hood S-182), and grinder (Peterson 4700B) was used to harvest the entire stand.

Site 4 was located at Albion, MI. A single-pass, cut and chip harvesting system was operated to evaluate the total biomass yield in a 1.1 acres (site length L_1=112.5 ft.; site width W_1=416 ft.), 3-year old hybrid willow plantation (stand density = 5,808 trees/acre). The average tree DBH at Site 4 was about 0.75 inch. There were 80 plots (plot length L_2 = 22.5 ft.; plot width W_2 = 26 ft.) in this plantation in total and 16 plots in each line (**Fig. 4a**). In each individual plot, there are 3 pair-rows with 13 trees in each row (**Fig.4b**). Pair rows were planted 2.5-ft apart (SR_1=2.5 ft.) and the distance between two pair-rows was 5 ft (SR_2=5 ft.). This harvesting system consisted of three equipment items: a John Deere 7330 tractor to power the willow harvester, a Ny Vraa JF192 willow harvester and a Komatsu CK35-1 bobcat to hold the wood chips. In this harvesting project, only 32 of the 80 plots were harvested, in a direction from plot 17 through plot 32 and from plot 49 to plot 64 (marked red in **Fig. 4a**). In harvesting each plot, only the 18 trees in the center pair-rows were selected to record the biomass yield (circled trees in **Fig. 4b**).

A Cut-to-Length (CTL) harvesting system was studied at Site 5, Gwinn, Michigan.

The harvest site was a 56-acre, 29 years old Jack pine (*Pinus banksiana*) plantation. Since this study focused on using the by-product of the CTL harvesting system such as limbs and tops, this study only estimated the logging residues collecting cost. The forwarder used at Site 5 was a Ponsse Buffalo forwarder with 15 tons of loading capacity.

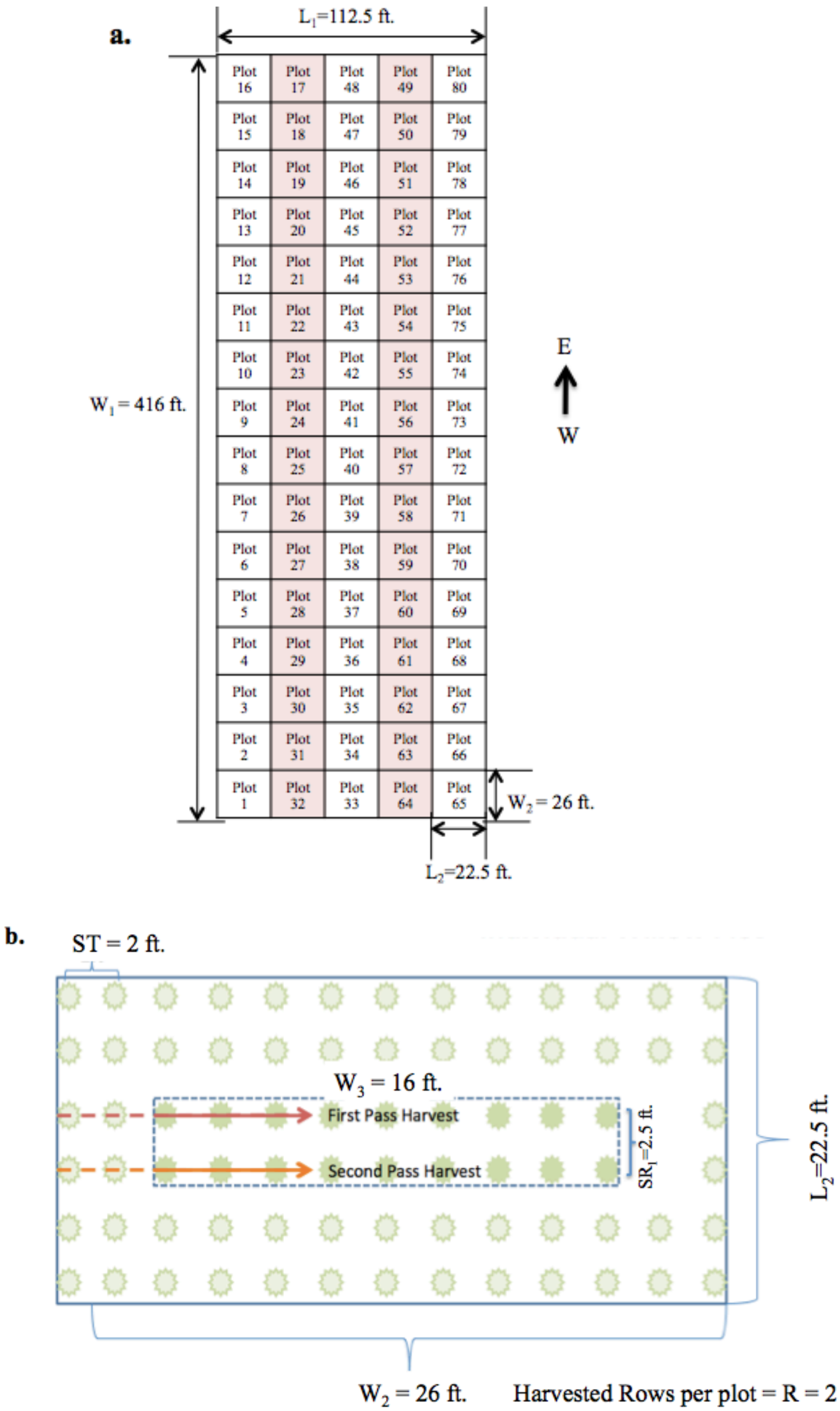


Figure 4 a and b. Plots layout at Site 4 and tree layout in each plot

3.2.2 Cycle time estimation and productivity calculation

Multiple linear regression equations were developed for the feller-buncher, skidder, and forwarder to predict cycle time in centi-minutes (1 centi-minute = 0.01 minute), using the independent variables such as the DBH of trees, travel distance and loaded swing degree, etc. The collected time-motion study data were tested for normality and outliers, and then used to develop predictive equations by multiple regressions with ordinary least squares estimators in Stata 12.0. 33% of all collected data were reserved and the remaining 67% of the collected data were used to develop the predictive equations. To validate the developed equations, the reserved data were used to generate predicted values and a two-sample t-test ($\alpha=0.05$) was used to compare the predicted values with collected data. A validation p-value larger than 0.05 indicated the difference between the predicted value and observed data was insignificant, and the developed equation capably predicted harvesting productivity. To estimate the cycle time of feller-buncher, skidder, and forwarder the average observed values for each independent variable were used in the regression equations.

For the feller-buncher, a complete cycle started from movement to the first tree, subsequent cuttings to make a full bunch, and ended with the placement of that tree bunch on the ground (Pan et al., 2008). Move-to-tree distance, the number of cuts per cycle, and move-to-bunch distance were defined as variables for these elemental activities within a cycle.

Regarding the skidder, a complete cycle started from moving from the landing site to a tree bunch and subsequent grappling to make a full skid load, return to the landing site, and ended with the placement of loaded trees on the landing site (Pan et al., 2008). Elemental activities within a skidding cycle were defined to be: travel empty distance, positioning distance, number of trees per cycle, and traveling loaded distance.

For the forwarder, a complete cycle started from the movement from the landing site to logging residue piles and subsequent grappling to make a full load, travel back to the landing site and unloading biomass on the ground near the loader (Pan et al., 2008). The included variables in predicting forwarding cycle time were: travel empty distance, intermediate travel distance in feet, number of grapples per cycle, travel loaded distance, and number of unloading grapples.

For the loader-grinder/loader-chipper unit, a complete cycle was defined as the time required for the loader-grinder/loader-chipper to process woody biomass to fill a full truckload. For Site 1, Site 2, Site 3 and Site 5, an average cycle time (mins) was presented based on all recorded cycle time values.

Site 4 was a 3-year-old hybrid-poplar plantation and was harvested by a reconfigured harvesting system consisting of a Ny Vraa JF 192 harvester, a John Deere 7330 tractor and a Komatsu CK 35-1 to collect chips. The productivity of the harvesting system was estimated by dividing the total harvested biomass dry weight by the total recorded work time, which was a method also adopted in other studies (Schweier and Becker, 2012; Berhongaray et al., 2013).

3.2.3 Harvesting and pre-processing costs

The machine hourly cost in dollars per scheduled machine hour ($/SMH) was estimated using the standard machine rate calculation methods reported by Miyata (1980). The information of machine make and model, purchase price, horsepower, scheduled machine hours (hr/yr) and labor cost has been collected from equipment owner (Table 3). The economic life span of each machine was assumed to be 5 years; the salvage value was set to be 20% of the original purchase price; the utilization rate of feller-buncher, skidder, forwarder was assumed to be 80%; the utilization rate of loader, and grinder was assumed to be 80% (Carter et al., 2017), the utilization rate of truck/van was assumed to be 95%. The machine hourly cost in dollars per productive machine hour ($/PMH) was converted to production cost in $/PMH using the method in Mitaya (1980). The production rate (ODT/PMH) of each machine was determined by dividing the total produced dry weight of biomass (ODT) by the each predicted cycle time (PMH). Production cost in $/ODT was computed by dividing the machine hourly cost ($/PMH) by the productivity (ODT/PMH).

3.2.4 Transportation costs

Multiple regression analyses using ordinary least squares estimators were used to develop the prediction models that estimate the travel times based on all data collected at Site 1, Site 2, and Site 5. For truck/van, a complete cycle started from loading wood chips to the empty truck, followed by hauling a full tank of woody biomass to the end user and ended at the end user's gate. The prediction model for travel time was based on travel distance in miles for each road type, including forest/dirt road, gravel road, paved road and highway. In this study, forest/dirt road refers to an unpaved road with single lane and hard dirt surface; a gravel road refers to unpaved road covered with gravel and single lane; a paved road was defined as the road with durable surface pavement and double lane; and highway referred to the main road that connected towns or cities. The travel speed on forest/dirt road, gravel road, paved road and highway were set to be less than 10 mph, 10-30 mph, 30-45 mph and 45-65 mph. Roads in all study sites were properly planned and constructed to assume smooth woody biomass transportation.

The multiple linear regression equation can be written as:

$$Truck\ travel\ time\ (hrs) = \alpha_0 + \alpha_1(dirt\ road\ distance) + \alpha_2(gravel\ road\ distance) + \alpha_3(paved\ road\ distance) + \alpha_4(highway\ distance)$$

Where α_0 = intercept;

α_1 = coefficient of the variable "dirt road distance";

α_2 = coefficient of the variable "gravel road distance";

α_3 = coefficient of the variable "paved road distance";

α_4 = coefficient of the variable "paved road distance".

Table 3. Machine hourly rate ($/SMH) calculated based on data obtained from equipment owners

Machine categories:	Feller-buncher	Skidder	Forwarder	Harvester	Bobcat	Loader	Grinder[d]	Truck + van
Horse power (hp)	170	200	159	155	86	150	765	148
Make/Model	John Deere 653G	John Deere 740A	Bison S15	JD 7330	Komatsu CK35-1	Hood S-182	Peterson 4700B	-
Initial investment	$90,000.00	$169,000.00	$120,000.00	$145,737.00	$56,597.00	$152,000.00	$426,000.00	$200,000.00
Economic lifespan	5	5	5	5	5	5	5	5
Salvage value (% of Initial investment)	20%	20%	20%	20%	20%	20%	20%	20%
Scheduled Machine Hours (hrs)[a]	1800	1800	1800	1800	1800	1800	1800	1800
Utilization rate (%)	80%	80%	80%	80%	80%	80%	80%	95%
Average annual investment (AAI) ($/year)	$61,200.00	$106,470.00	$75,600.00	$99,101.16	$38,485.96	$95,760.00	$268,380.00	$126,000.00
Depreciation ($/SMH)	$32.89	$15.02	$10.67	$12.95	$5.03	$13.51	$37.87	$17.78
Interest (%)	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%
Insurance (%)	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Tax (%)	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%
Maintenance (% of Depreciation)	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%
Fuel ($/PMH[b])	$23.58	$17.90	$17.90	$14.40	$11.52	$17.90	$17.90	31.76
Lube ($/PMH)	$1.23	$1.21	$1.21	$0.31	$0.31	$1.21	$1.21	0
Labor[c] ($/SMH) (with fringe benefit)	$35.00	$35.00	$35.00	$35.00	$35.00	$35.00	$35.00	$35.00
Machine hourly cost ($/SMH)	$70.92	$79.92	$71.33	$72.81	$54.58	$76.94	$124.98	$100.24

[a]SMH: Scheduled machine hour.

[b]PMH: Scheduled machine hour.

[c]Labor costs include fringe and benefits.

[d]Grinder was remotely controlled remotely by the chip van driver.

3.2.5 Biomass weight estimation

For study sites (Site 1, Site 2, and Site 3) that were harvested by the WT harvesting system, whole tree dry weight and stem wood dry weight were estimated using equations developed by Jenkins (2003):

$$bm = Exp(\beta_0 + \beta_1 \ln dbh)$$

Where

bm = total aboveground biomass (kg) for trees 2.5 cm and larger in dbh;

dbh = diameter at breast height (cm);

Exp = exponential function;

ln = natural log base "e" (2.718282);

For Site 1: β_0 = -2.2304 and β_1 = 2.4435;

For Site 2 and Site 3: β_0= -2.2094 and β_1 = 2.3867.

$$ratio = Exp(\delta_0 + \frac{\delta_1}{dbh})$$

Where

ratio = ratio of component to total aboveground biomass for trees 2.5 cm and larger in dbh;

dbh = diameter at breast height (cm);

Exp = exponential function;

ln = natural log base "e" (2.718282);

For Site 1: δ_0 = -0.3737 and δ_1 = -1.8055;

For Site 2 and Site 3: δ_0 = -0.3065 and δ_1 = -5.4240.

3.3 Results

3.3.1 Site 1

3.3.1.1 Regression equations and operation cycle time prediction

The multiple linear regression equations were developed for the feller-buncher, skidder and truck/van used in Site 1 (Table 4). All included variables have a p-value smaller than 0.05, indicating that they were significant in predicting cycle times. In the equations developed for the feller-buncher and skidder, the validation *p*-value larger than 0.05 suggested that there was no significant difference existed between predicted values and the observed values. Based on the mean value of each independent variable, the average predicted cycle time for the feller-buncher and skidder at Site 1 were calculated to be 89.80 centi-minutes (0.90 minute) and 233.74 centi-minutes (2.33 minutes). The total cycle time for loading and hauling biomass to the end user was estimated to be 2.36 hrs (based on 0.30 miles of dirt road, 0 miles of gravel road, 1.75 miles of paved road and 73.20 miles of highway). For the chipper and loader, the average monitored delay-free cycle time was 4,069 centi-minutes (40.69 minutes).

3.3.1.2 Cycle stem wood weight

The feller–buncher cuts, on average, 3 trees per operation cycle. Based on an average observed tree DBH of 5.36 inches, the stem wood weight per tree was estimated to be 38.23 kg (about 0.04 ODT) using the equations developed by Jenkins et al. (2003), and the harvested biomass weight per cycle was about 0.13 ODT. For the skidder, the number of trees collected in each complete cycle was averaged to be 12 (number of trees), which was calculated as 0.51 ODT. For the loader-chipper unit, the average biomass processed per cycle was about 17.87 ODTs. The average biomass weight transported per cycle for truck/ van was also estimated to be 17.87 ODTs.

3.3.1.3 Machine hourly rate and production cost

The productivity and production cost of each machine were presented in **Table 5.** Based on the machine cycle time and cycle stem wood weight produced, the productivity of the feller-buncher, skidder, loader-chipper, and truck van were determined to be 8.45 ODT/PMH, 13.13 ODT/PMH, 26.35 ODT/PMH, and 7.57 ODT/PMH, respectively. The machine hourly rate for the feller-buncher, skidder, chipper/loader and truck/van were 51.52 $/PMH, 54.88 $/PMH, 113.72 $/PMH, and 70.57 $/PMH (Pan and Srivastava, 2013). The production cost of biomass harvesting, collecting, pre-processing and transportation were determined to be 6.10 $/ODT, 4.18 $/ODT, 4.32 $/ODT, and 9.32 $/ODT.

Table 4. Delay-free average cycle time equations for harvesting machines at Site 1.

	Average cycle time estimator	Variable range	Associated *p*-value	Mean	r²	n	Validation *p*-value
Feller-buncher (Hydro Ax 511 EX)							
Cycle time (centi-mins)	=29.14		0.000		0.59	186	0.95
	+ 0.60 (move to tree distance in feet)	0 to 168	0.000	41.23			
	+ 7.20 (number of cuts per cycle)	1 to 6	0.000	3			
	+ 0.36 (move to bunch distance in feet)	0 to 120	0.000	39.81			
Skidder (John Deere 648 G Skidder)							
Cycle time (centi-mins)	=73.67		0.000		0.92	54	0.97
	+ 0.34 (travel empty distance in feet)	63 to 672	0.000	149.52			
	+ 0.28 (loaded distance in feet)	294 to 1,008	0.000	390.12			
Truck/van							
Total predicted time (hr)	=0.40		0.002		0.91	21	-
	+1.13 (dirt road in miles)	0.23 to 1.00	0.001	0.38			
	+0.05 (gravel road in miles)	0.00 to 1.20	0.000	0.45			
	+0.09 (paved road in miles)	0.80 to 4.20	0.000	3.14			
	+0.02 (highway in miles)	20.00 to 121.40	0.000	48.73			

Table 5. Productivity and production cost at Site 1.

	Feller-buncher	Skidder	Chipper/ Loader	Truck/Van
Production rate (ODT/PMH)	8.45	13.13	26.35	7.57
Production cost ($/ODT)	6.10	4.18	4.32	9.32
Percent of the total production cost (%)	25.50%	17.47%	18.06%	38.96%

3.3.2 Site 2

3.3.2.1 Regression equations and operation cycle time prediction

The multiple linear regression equations developed for the feller-buncher, skidder and truck/van at Site 2 are presented in Table 6. All the included variables have a *p*-value smaller than 0.05, indicating that they were significant in predicting cycle times. In the equation developed for feller-buncher and skidder, the validation *p*-value larger than 0.05 suggests that there was no significant difference existing between the predicted values and the observed values. The average predicted cycle times for the feller-buncher and skidder at Site 2 were 44.40 centi-minutes (0.44 minute), 307.65 centi-minutes (3.07 minutes). The loading and transportation time was estimated to be 1.20 hours based on the transportation distance (0.40 miles of dirt road, 0 mile of gravel road, 4.00 miles of paved road and 0 mile of highway). For chipper and loader, the average monitored delay-free cycle time was 4,581 centi-minutes (45.81 minutes).

3.3.2.2 Cycle stem wood weight

In each production cycle, the feller-buncher can harvest 2 trees on average, which was estimated to be 0.22 ODT based on an average DBH of 8.5 inches. The skidder can collect about 10 trees per cycle, which was equal to about 1.12 ODT per cycle. For the chipper attached with loader, the average biomass processed per cycle was about 19.70 ODT. The average biomass weight transported per cycle for truck/van was also estimated to be 19.70 ODT.

3.3.2.3 Machine hourly rate and production cost

The productivity and production cost of each machine are presented in Table 7**.** The productivities of the feller-buncher, skidder, loader-chipper unit and truck/van were determined to be 29.72 ODT/PMH, 21.89 ODT/PMH, 25.80 ODT/PMH, and 16.42 ODT/PMH, respectively. Because Site 2 shared the same harvesting system with Site 1, they have the same machine hourly rate. The machine hourly rate of the feller-buncher, skidder, chipper/loader and truck/van were 51.52 \$/PMH, 54.88 \$/PMH, 113.72 \$/PMH, and 70.57 \$/PMH (Pan and Srivastava, 2013). Therefore, biomass harvesting, collecting, pre-processing and transportation costs were estimated to be 1.73 \$/ODT, 2.51 \$/ODT, 4.41 \$/ODT, and 6.92 \$/ODT, respectively.

Table 6. Delay-free average cycle time equations for harvesting machines at Site 2.

	Average cycle time estimator	Variable range	Associated *p*-value	Mean	r^2	n	Validation *p*-value
Feller-buncher (Hydro Ax 511 EX)							
Cycle time (centi-mins)	=10.59		0.000		0.78	94	0.52
	+ 0.84 (move to tree distance in feet)	9 to 27	0.000	11.36			
	+ 7.37 (number of cuts per cycle)	1 to 5	0.000	2			
	+ 0.89 (move to bunch distance in feet)	0 to 18	0.000	10.71			
Skidder (John Deere 648 G Skidder)							
Cycle time (centi-mins)	=111.23		0.000		0.87	65	0.21
	+ 0.22 (travel empty distance in feet)	231 to 882	0.000	428.40			
	+ 0.23 (travel loaded distance in feet)	0 to 1197	0.000	444.23			
Truck/van							
Total predicted time (hr)	=0.40		0.002		0.91	21	-
	+1.13 (dirt road in miles)	0.23 to 0.50	0.001	0.38			
	+0.05 (gravel road in miles)	0.00 to 1.20	0.000	0.45			
	+0.09 (paved road in miles)	0.80 to 4.20	0.000	3.14			
	+0.02 (highway in miles)	20.00 to 121.40	0.000	48.73			

Table 7. Productivity and production cost at Site 2.

	Feller-buncher	Skidder	Chipper/ Loader	Truck/Van
Production rate (ODT/PMH)	29.72	21.89	25.8	16.42
Production cost ($/ODT)	1.73	2.51	4.41	6.92
Percent of the total production cost (%)	11.11%	16.12%	28.32%	44.44%

3.3.3 Site 3

3.3.3.1 Regression equations and operation cycle time prediction

The multiple linear regression equations developed for all machines employed at Site 3 are presented in Table 8. All the included variables have a *p*-value smaller than 0.05, indicating that they were significant in predicting cycle times. In the equations developed, the validation *p*-value larger than 0.05 suggested that there was no significant difference between predicted values and the observed values. The average predicted cycle time for the feller-buncher and skidder in Site 3 were 74.02 centi-minutes (0.74 minute) and 143.85 centi-minutes (1.44 minutes). The average observed cycle time for the loader-grinder was 36.67 minutes. Based on the travel distance (1 mile of dirt road, 0 miles of gravel road, 4 miles of paved road, and 45 miles of highway), the loading and transportation time was estimated to be 2.79 hours.

3.3.3.2 Cycle stem wood weight

The whole tree dry weight at Site 3 was estimated to be 0.03 ODT, using average DBH = 4 inches and equations developed by Jenkins et al. (2003). Therefore, cycle stem wood weights produced by the feller-buncher and skidder were 0.18 ODT (6 trees per cycle) and 0.86 ODT (28 trees per cycle). In each work cycle for loader-grinder, 17.56 ODT of woody biomass was processed. For the truck/van, the cycle stem wood weight was 17.56 ODT and the productivity was 6.29 ODT/PMH.

3.3.3.3 Machine hourly rate and production cost

The productivity and production cost of each machine at Site 3 were presented in Table 8**.** Biomass harvesting, collecting, pre-processing and transportation productivities were calculated to be 14.59 ODT/PMH, 35.83 ODT/PMH, 28.73 ODT/PMH, and 6.29 ODT/PMH. The machine hourly rate of the feller-buncher, skidder, chipper/loader and truck/van were estimated to be 70.92 $/SMH (or 86.10 $/PMH assuming utilization rate = 80%), 79.92 $/SMH (or 95.92 $/PMH assuming utilization rate = 80%), 203.14 $/SMH (or 244.46 $/PMH assuming utilization rate = 80%), and 100.24 $/SMH (or 101.66 $/PMH assuming utilization rate = 95%), respectively. Therefore, biomass harvesting, collecting, pre-processing and transportation costs were 5.90 $/ODT, 2.68 $/ODT, 8.51 $/ODT, and 16.16 $/ODT.

Table 8. Delay-free average cycle time equations for harvesting machines at Site 3.

	Average cycle time estimator	Variable range	Associated *p*-value	Mean	r^2	n	Validation *p*-value
Feller-buncher (John Deere 653 G)							
Cycle time (centi-mins)	= 8.76		0.001		0.85	125	0.36
	+ 0.57 (move to tree distance in feet)	0 to 90	0.000	16.40			
	+ 8.82 (number of cuts per cycle)	1 to 12	0.000	5.80			
	+ 0.33 (move to bunch distance in feet)	1 to 82	0.000	14.43			
Skidder (John Deere 740A)							
Cycle time (centi-mins)	=19.49		0.001		0.78	54	0.87
	+ 0.08 (travel empty distance in feet)	120 to 432	0.000	264.67			
	+ 0.35 (positioning distance in feet)	0 to 72	0.000	19.56			
	+ 1.78 (number of trees per cycle)	15 to 35	0.000	27.98			
	+ 0.16 (travel loaded distance in feet)	144 to 516	0.000	290.89			
Grinder/Loader (Peterson 4700B)							
Cycle time (centi-mins)	=20.86		0.001		0.28	32	-
	+ 0.24 (number of trees per cycle x DBH)	13.00 to 54.60	0.000	31.40			
Truck/van							
Total predicted time (hr)	=0.40		0.002		0.91	21	-
	+1.13 (dirt road in miles)	0.23 to 0.50	0.001	0.38			
	+0.05 (gravel road in miles)	0.00 to 1.20	0.000	0.45			
	+0.09 (paved road in miles)	0.80 to 4.20	0.000	3.14			
	+0.02 (highway in miles)	20.00 to 121.40	0.000	48.73			

Table 9. Productivity and production cost at Site 3.

	Feller-buncher	Skidder	Chipper/ Loader	Truck/Van
Production rate (ODT/PMH)	14.59	35.83	28.73	6.29
Production cost ($/ODT)	5.90	2.68	8.51	16.16
Percent of the total production cost (%)	17.74%	8.06%	25.59%	48.60%

3.3.4 Site 4

3.3.4.1 Productivity

The total working time for the reconfigured harvesting system to harvest the 1.1 acre 3-years old hybrid willow plantation was 4.13 hours, with 4.02 hours of actual harvesting time and 0.11 hours travel time between lanes in the plantation. A total of 7.18 ODT of biomass was harvested and processed into wood chips. The overall productivity of this configured harvesting system was estimated at 1.74 ODT/PMH. Based on a hauling distance of 50 miles (0.5 mile of forest/dirt road and 49.5 miles of highway), total loading and transportation time was calculated to be 1.96 hrs. A full truckload of wood chips was about 18.72 ODT. Therefore, the transportation productivity was estimated to be 9.55 ODT/PMH.

3.3.4.2 Machine hourly rate and the production cost

Machine hourly rate of the reconfigured system was determined to be 132.69 $/SMH, with a cost of 75.75 $/SMH from the harvesting unit and 56.94 $/SMH from the chip collector. Assuming a utilization rate of 80%, the total production cost was estimated to be 85.27 $/ODT (88.89% of the total production cost). The machine hourly rate truck/van was 100.24 $/SMH (or 101.66 $/PMH assuming utilization rate = 95%) and the production cost of biomass transportation was 10.65 $/ODT (11.11% of the total production cost).

3.3.5 Site 5

3.3.5.1 Regression equations and operation cycle time prediction

The developed multiple linear regression equations for the forwarder and the transportation stage are presented in Table 10. The predicted cycle time of the forwarder was determined to be 1,569.13 centi-minutes (15.69 minutes). For the transportation stage, the average cycle time was calculated to be 2.04 hours based on a total transportation distance of 50.33 miles (0.35 mile of forest/dirt road, 0.5 mile of gravel road, 3.31 mile of pave road and 46.17 miles of highway).

3.3.5.2 Productivities of forwarder and truck/van

The overall production rate of forwarder was calculated to be 5.49 ODT/PMH based on total recorded delay free work time of 15.98 hrs and total recorded collected biomass weight of 87.73 ODT. The average biomass dry weight in each truck/van work cycle was determined to 17.55 ODT. Thus the productivity of the truck/van was estimated to be 8.60 ODT/PMH.

3.3.5.3 Machine hourly rate and production cost

The machine hourly rate calculated for the forwarder and the truck/van was 71.33 \$/SMH and 100.24 \$/SMH. Assuming a utilization of 80% for the forwarder and 95% for the truck/van, the production costs were 85.19 \$/PMH and 101.66 \$/PMH. Therefore the total production cost of this biomass production system was 27.34 \$/ODT, with 15.52 \$/ODT (56.77% of the total cost) from forwarding process and 11.82 \$/ODT (43.23% of the total cost) from transportation process.

Table 10. Delay-free average cycle time equations for harvesting machines at Site 5.

	Average cycle time estimator	Variable range	Associated *p*-value	Mean	r²	n	Validation *p*-value
Forwarder (Bison S15)							
Cycle time (centi-mins)	= 242.7		0.003		0.89	57	0.76
	+ 0.46 (travel empty distance in feet)	0 to 1345.13	0.000	423.56			
	+ 0.56 (intermediate travel distance in feet)	66.3 to 691.05	0.000	211.65			
	+ 22.32 (number of grapples per cycle)	11 to 40	0.000	25.23			
	+ 0.40 (travel loaded distance in feet)	15.3 to 1364.25	0.000	419.48			
	+ 27.77 (number of unloading grapples)	5 to 17	0.001	10.16			
Truck/van							
Total predicted time (hr)	=0.40		0.002		0.91	21	-
	+1.13 (dirt road in miles)	0.23 to 0.50	0.001	0.38			
	+0.05 (gravel road in miles)	0.00 to 1.20	0.000	0.45			
	+0.09 (paved road in miles)	0.80 to 4.20	0.000	3.14			
	+0.02 (highway in miles)	20.00 to 121.40	0.000	48.73			

3.4 Discussions

3.4.1 Cycle time predictions for harvesting machines and woody biomass transportation

In the linear equations developed for the feller-buncher, skidder, and forwarder, all dependent variables have validation *p*-values smaller than 0.05, which means they can effectively produce estimates. However, as suggested by Kozak and Kozak (2003), the significant *p*-values of the indepent variables might not necessarily demonstrate that these equations are the best predicting equations. To validate these developed equations, 33% of the collected field data were used to make predicted data. The validation outcomes suggested that there was no significant difference (*p*-value <0.05) between the observed and predicted data, and the developed equations can be used in harvesting projects with similar site conditions.

For different machines, significant cycle time estimators could be different. For instance, Bolding et al. (2009) used the non-merchantable pieces and merchantable pieces per bunch as the predictors for feller-buncher productivity; skidding distance and trees per skidding cycle as the predictors for estimating the skidder's working cycle time. Li et al. (2006) used tree DBH and travel distance between harvested trees to predict the hourly production rates for a feller-buncher in West Virginia, and average extraction distance and payload size for estimating the production rates for the skidder and forwarder. In this study, for the feller-buncher cycle time prediction, move-to-tree distance, number of trees per cycle, and move-to-bunch distance were found to be significant at sites 1, 2 and 3. For estimating the skidder cycle time, travel empty distance and loaded distance were determined to be significant predictors at Site 1 and

Site 2; while at Site 3, position distance and trees collected per cycle were also tested to be significant. At Site 5, the significant cycle time estimators for the forwarder included the travel empty distance, intermediate travel distance, number of grapples per cycle, travel loaded distance and number of unloading grapples. The cycle time predicting equations in this study were developed and validated using field-base data collected from harvesting projects in Michigan. These equations cannot be representative of all biomass-harvesting projects in Michigan and can only be applied in harvesting projects that have similar site conditions (tree DBH, ground slope and etc.). The model user should also be cautioned that these predicting equations were developed based on independent variables with limited data range, whereas out-of-range input could lead to prediction errors. In future if similar regression models are reported, users are supposed to determine which assumptions of the models are more feasible to their study. Also, they will need to understand the improvements or differences of the new equations compared to our models, and decide wisely if the changes are applicable to their study.

The hauling time of woody biomass largely affected by the combination of the delivery distance and road types (Pan et al., 2007; Harrill and Han, 2012; Keefe, 2014; Anderson and Mitchell, 2016), which was confirmed by this study. In this study, the multiple linear regression equation developed for truck/van indicated that every 0.1 mile increase in forest/dirt road distance could raise about 0.11 hr (or 6.78 minutes) in transportation time, while 0.1 mile increase in highway distance only caused 0.001 hr (or 0.12 mins). This suggested that the hauling distance in forest/dirt road had larger influence in total traveling time compared to distance on the highway. In addition, to reduce hauling time and transportation cost of woody biomass, more effort should be spent on reducing the off-highway transportation distance.

3.4.2 Woody biomass harvesting production cost

The estimated total production costs of producing woody biomass at the 5 sites were 23.92, 15.57, 33.25, 95.92 and 39.16 \$/ODT. The highest production cost at Site 4 was mainly due to its lowest biomass productivity and additional cost from the front-end loader. The production cost at Site 4 was also higher than the costs (49.66 -\$57.30 \$/ODT) reported in other short rotation woody crop production systems (Walsh et al., 1996; Tharakan et al., 2005; Volk et al., 2006; Schweier and Becker, 2012). This was mainly because of the additional cost from the front-end loader which functioned as a chip collector, if it was substituted with an attached trailer to collect chips, the production cost can be lowered to 43.82 \$/ODT.

WT harvesting systems generally achieved lower production cost (23.92 \$/ODT at Site 1 and 15.57 \$/ODT at Site 2) than CTL harvesting systems (39.16 \$/ODT at Site 5). WT harvesting system at Site 3 had a slightly higher biomass production cost (39.84 \$/ODT) than CTL harvesting systems because of its higher transportation cost. The reported production costs in this study were generally lower than the values reported by Zhang et al. (2016). The main reason for this difference was that the machine hourly production rates in Zhang et al. (2016) was cited from a Michigan loggers' survey. Based on a validation study done by Pan and Srivastava (2013), the machine hourly production rate in the Michigan logger' survey deviated from the real field-based production rates. In particular, the production rate in clearcut hardwood stand case was underestimated, and the production rate in 70% cut softwood stand was overestimated.

The reason accounting for this phenomenon was the fact that the logger's survey did not consider tree size as one of the factors, while it was significant in predicting cycle time for feller-buncher, skidder and forwarder (Pan and Srivastava, 2013).

3.5 Conclusion

In this study, five woody biomass production systems were monitored to predict the productivity and production cost of utilizing woody biomass in the State of Michigan. Effective cycle time estimators were illustrated in predictive regression equations for the studied machines. The predicted cycle time for each machine was used with the machine hourly rate to calculate the machine productivity and hourly production cost. The obtained results suggested that due to the higher hourly productivity, WT harvesting systems generally achieved lower production cost (15.57 \$/ODT ~ 33.25 \$/ODT) than CTL harvesting systems (39.16 \$/ODT). Among the five evaluated studied sites, Site 5, the 3-year-old hybrid willow plantation harvested by a reconfigured harvesting system resulted in the highest production cost of 95.92 \$/ODT, owing to the low biomass yield per acre and the additional hourly cost from the chips collector. Overall, it can be concluded that producing woody biomass from natural forest stands with the WT harvesting system was the most economical way of utilizing woody biomass as it has the highest productivity and lowest cost.

CHAPTER 4 BIOMASS STORAGE AND FUEL QUALITY CHANGE

4.1 Introduction

Due to the increase of energy demand and the need of reducing greenhouse emissions, there is a strong necessity to decrease the dependence on fossil-based fuels (Zanchi et al., 2011; REN21, 2012). Biomass materials such as trees, grasses and agricultural crops have thus become imperative alternative energy resources (DOE, 2004). Among all these materials, woody biomass is one of the most feasible choices because of its relatively low cost and high availability (DOE, 2004).

In most regions in North America, green biomass is directly processed into small chips by mills or other wood-using facilities. This introduces many problems and concerns, such as a the risk of self-ignition, health issues caused by the release of high concentrations of allergenic microspores, and most important, dry matter loss followed by the decrease of the biomass quality (Fredholm and Jirjis 1988, Jirjis 1995). Previous studies showed that the dry matter loss in a large green chip pile was approximately 12 percent during a 7-month storage period (Hornqvist and Jirjis 1999). A dry matter loss of 26 percent was also found in large bark piles throughout a 6-month storage period (Fredholm and Jirjis 1988). In addition, the dry matter loss in the large bark pile resulted in a 20 percent reduction in energy content (Fredholm and Jirjis 1988), thus lowering the energy yield and the value of woody biomass feedstock.

Due to the above concerns, the duration of the wood chips storage is normally suggested to be less than 6 months. Kofman and Spinelli (1997) suggested that willow from short rotation coppice (SRC) be preferred to deliver immediately to heating plants after harvested to avoid difficulty in storage; if the biomass has to be stored as wood chips, the storage time should not exceed 2 months. In Michigan, according to experienced forest products manager, the typical storage period of biomass chip pile is around 60-70 days (Scott Robbins, personal contact, October 15th, 2013). However, there has been no study available to prove the validity of these suggestions for wood chip storage in Michigan. In addition, a key yet unresolved issue is how to predict the moisture content in a biomass pile without frequently measurement (Erber et al., 2012). This is also the problem for biomass HHV estimate, because all existing models to predict the HHV of woody biomass use independent variables such as fixed carbon content, volatile matter content and ash content, which all require additional testing (Parikh et al, 2005; Grover et al, 2002; Channiwala and Parikh, 2002).

Several studies highlighted that the storage of logging residue in bundles can produce high-quality biomass feedstock with low moisture content (MC), increased higher heating value (HHV), and low ash content (Lehtikangas 2001, Pettersson and Nordfjell 2007, Afzal et al. 2010). Patterson et al. (2008) reported that the MC of biomass bundles decreased by 10 to 25 percent within 1 month after piling. Meanwhile, Karha and Vartiamaki (2006) found that the reduction of MCs resulted in a 12 to 28 percent increase in energy content per unit volume. The major problems in producing biomass bundles with a slash bundler is the low productivity and the high hourly cost due to delays caused by saw binding, materials handling, twine spool collapse, and slow movement at the site (Leinonen 2004, Rummer et al. 2004, Patterson et al. 2008, Harrill 2010). This makes the economic feasibility of using the savings from transporting low MC and highly compacted biomass to pay for the cost of bundling operations questionable.

This study was designed and conducted in five different regions in Michigan. The objectives of this study are: 1) to monitor the change of moisture content (MC) and higher heating value (HHV) in logging residue pile and wood chips pile during a 4 months field storage; 2) to examine the effect of storage locations, positions within a biomass pile on wood MC and HHVs in logging residue pile and wood chips pile.

4.2 Methodology

4.2.1 Site conditions

4.2.1.1 Logging residues storage study sites

The two study sites were both located in Escanaba, Upper Peninsula of Michigan. The first study site (Site 1) was a mixed-species forest stand containing various hardwood and softwood species, including sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), and white spruce (*Picea glauca*). The second study site (Site 2) was located in a red pine (*Pinus resinosa*) stand, 45.4 miles away from Site 1. The monthly precipitation at both sites averaged from 0.5 to 4.1 inches from June to November 2011, and the monthly maximum temperature varied from 53.4°F to 84.2°F.

A mechanized cut-to-length harvesting system was used to harvest the trees at the two study sites from June 1 to 25, 2011. At Site 1, logging residues, including limbs, tops, and broken logs, were shuttled to the roadside and piled by a Ponsse Buffalo forwarder with 15 tons of loading capacity. The resulting residue piles averaged 86 feet long, about 34 feet wide, and 15 feet high (sample size, n = 18). At Site 2, the forwarder piled the logging residues into two different sizes. Small, cone-shaped piles were made with a geometric dimension of 9 to 10 feet in diameter and 2 to 3 feet in height, while the large piles were piled into a shape and size similar with those at Site 1. A total of 60 small piles were established in three rows under partial shade of the residual stands after the thinning treatment, while three large piles were piled without touching any of the residual stand crown shade.

4.2.1.2 Wood chips storage study sites

The first study site (Site 1) was located at Michigan State University (MSU) Forest Biomass Innovation Center, Escanaba, Michigan (45.75° N, 87.06° W). The wood chips pile at Site 1 was established on July 14th, 2013 using 33.14 green tons of Jack Pine (*Pinus banksiana*) hog fuel generated from a Cut-to-length (CTL) harvesting and grinding operation. The dimension of the pile was measured to be around 15 feet in length and 7 feet in height.

The second study site (Site 2) was at MSU Tree Research Center in East Lansing, Michigan (42.74° N, 84.48° W). The wood chips pile at Site 2 was set up on July 19th 2013, consisting of 25.87 green tons of Pitch pine (*Pinus rigida*) wood chips resulted from a Whole-tree (WT) harvesting and chipping operation. The pile had a dimension of 12 feet in length and 6 feet in height.

The third study site (Site 3) was at MSU Kellogg Biological Station in Augusta, Michigan (42.34° N, 85.35° W), and the wood chips pile was established on July 31st, 2013, with around 20 green tons of Larch (*Larix decidua*) chips harvested using a WT harvesting plus chipping operation. The size of the pile was 10 feet in length and 6 feet in height.

4.2.2 Biomass moisture content and HHV

The MC of the sample wood chips was measured at the Michigan State University (MSU) lab following ASTM E 871-82 (ASTM International 2003a). The

HHV of the sampled wood chips was tested at MSU using an oxygen bomb calorimeter according to the standard described by ASTM E 711-87 (ASTM International 2003b).

4.3 Results

4.3.1.1 Biomass moisture content change of wood residue piles

The initial wet-basis biomass MCs at Site 1 ranged from 25.0 to 47.0 percent and averaged 34.0 percent (n = 78). ANOVA indicated that after 5 months of field storage, the average biomass MCs were significantly decreased to around 26.3 percent ($P < 0.05$). During field storage, biomass MC continuously decreased from late June to September. The monthly MC (Figure 5) decreased 9.6 percent from June to July, 2.1 percent from July to August, and 5.1 percent from August to September. The lowest average biomass MC of 17.2 percent was recorded in September, and a statistically insignificant regain of biomass MC ($P = 0.27$) was detected from September to October. The increase of biomass MC became significant from October to November ($P < 0.05$), when the field-stored biomass MC returned to 26.3 percent. The overall pattern of biomass MC change implied that field storage and air-drying of unprocessed logging residues can effectively reduce the biomass MC, especially if residues are collected before October.

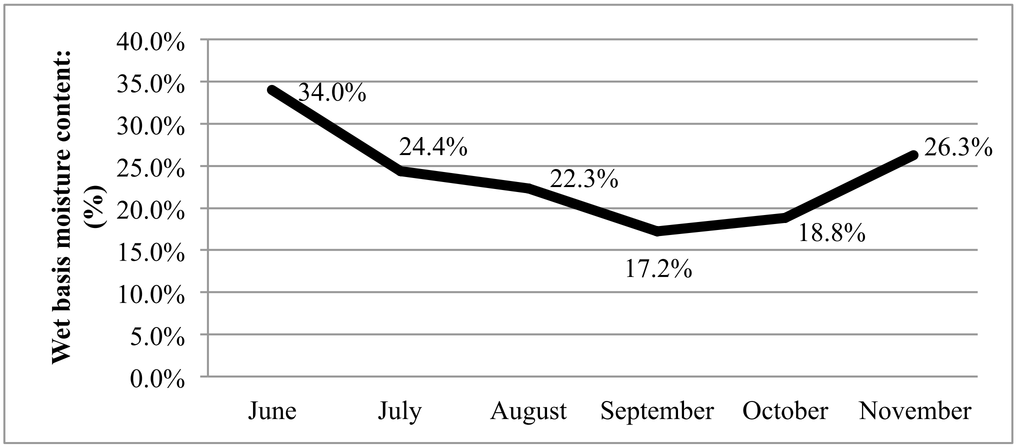


Figure 5. Biomass moisture content (wet basis, %) changes in logging residues piles in site 1 throughout field storage period.

At Site 2, MC change followed the same pattern as Site 1 (Figure 6) because of the similar harvesting time and weather conditions. The Wilcoxon signed-rank test (Higgins 2004) indicated a significant difference in biomass MC change between the large and small biomass piles ($P < 0.05$). The initial average MC of small piles was tested to be 48.2 percent, and the large piles' average MC was lower at 42.8 percent. However, MCs of small piles decreased noticeably faster compared with larger piles from June to the end of August. In September, the average MCs of both large and small piles reached the lowest point at around 16.0 percent. Starting in September, the biomass MCs in both large and small piles began to rise, with a faster increase shown in small piles (**Fig. 6**). At the end of the field storage, the small piles resulted in a higher average MC of 43.8 percent compared with large piles at 38.7 percent. This result suggested that a smaller pile could be used for short-term storage of woody biomass, while larger piles are more suitable for long-term storage because biomass MC in larger piles is less sensitive to weather conditions.

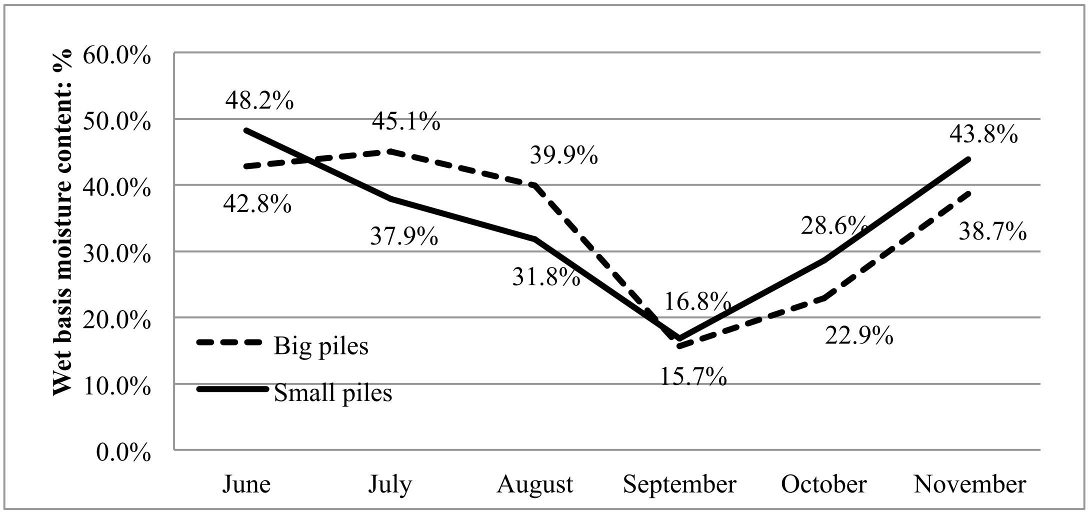


Figure 6. Wood moisture content changes affected by pile sizes in logging residue piles in Site 2.

4.3.1.2 Biomass moisture content change of wood chips piles

The initial wet basis biomass MCs were 29.4% at Site 1, 27.8% at Site 2, and 52.9% at Site 3 (sample size n= 6 at each study site). After 4 months of field storage, the biomass MC at Site 1, Site 2, and Site 3 increased to 39.3%, 28.2% and 63.6%, respectively. Compared with the initial values, MC increases percentage at the three study sites were 33.4%, 1.6% and 20.2%, respectively.

The biomass MC change at the three study sites during storage was illustrated in Figure 7. At Site 1, the biomass MC increased from 29.4% to 31.6% on September 9th, and then decreased to the lowest value of 19.0% on October 21st. The highest MC of 39.3% was reached on December 2nd. Biomass MC at Site 2 has the minimum fluctuation range compared with the other two study sites. The lowest biomass MC of 25.9% was reached around the middle of the August and the highest MC of 31.8% appeared in the middle of November. The biomass MC at Site 3 first climbed up to 56.4%

on August 12th and followed by a decline to its lowest point of 51.0% on October 7th. The highest biomass MC of 63.6% was reached on December 2nd.

During storage, the overall patterns of biomass MC change at the three study sites did not show a clear declining trend, but kept stable within a certain range and even increased towards the winter. This indicated that storing woody biomass in the form of chips pile might not effectively reduce the biomass MC.

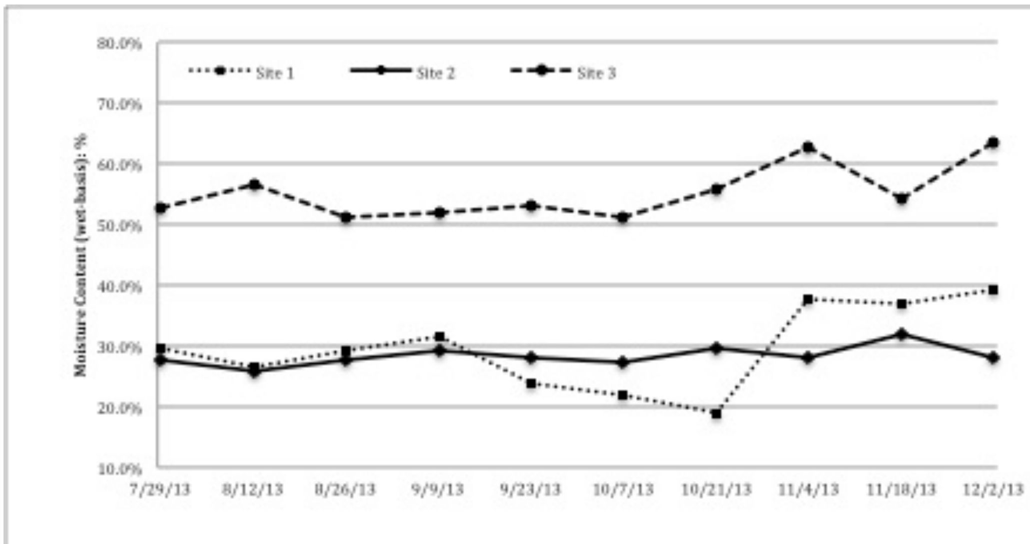


Figure 7. Biomass moisture content (wet basis, %) changes in wood chips piles throughout field storage period

4.3.1.3 Biomass HHV change in logging residue piles

In wood logging residues piles storage study, the average HHV for each randomly selected residue pile ranged from 7,610 to 8,344 BTUs per dry pound from June to November (Figure 8). A statistically higher average HHV was detected by multiple comparisons in July compared to the other five months (*p-value* < 0.05); while the HHVs in the other five months were statistically similar (*p-value* = 0.26). Since the biomass HHV in July (8,344 BTUs/lb) and the average HHV of the other five months (7,811 BTUs/lb) only bears a difference of about 6.4%, the HHVs throughout the storage period were considered to generally be the same. Over the time course of the study, piling unprocessed, loose logging residue did not significantly alter biomass HHV on a dry basis.

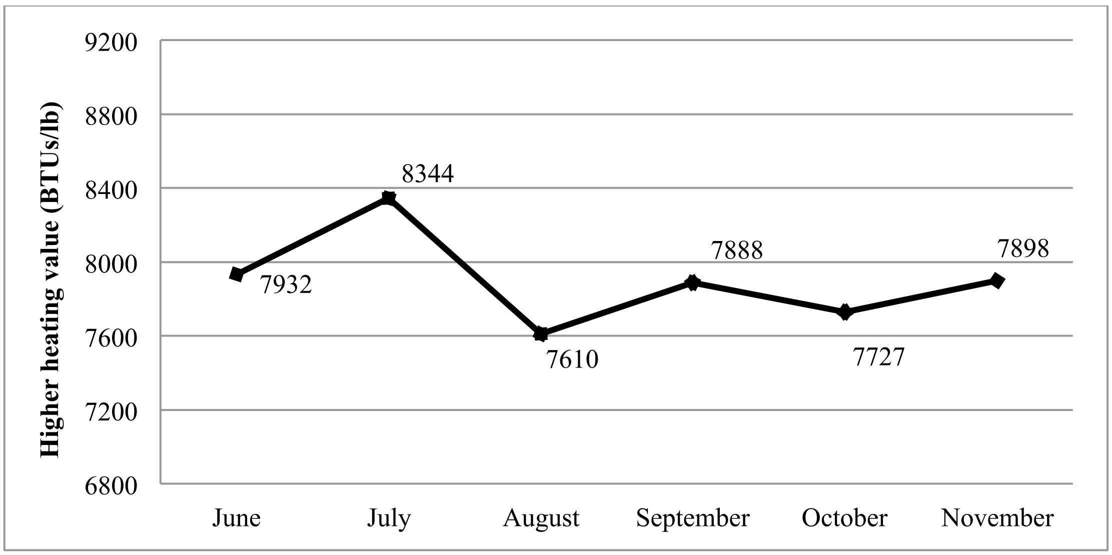
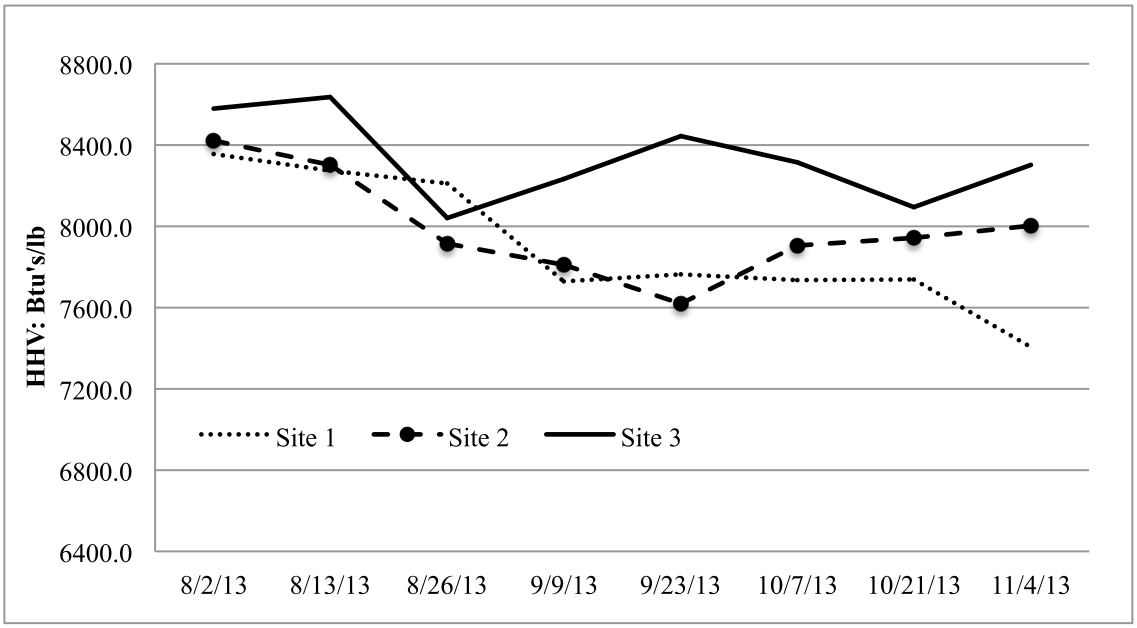


Figure 8. Biomass HHV changes in logging residues piles throughout field storage period.

4.3.1.4 Biomass HHV change in wood chips piles

Compared to logging residues piles, wood chip HHVs at the three study sites all decreased from the initial values during field storage (Figure 9). At Site 1, wood chip HHVs decreased from 8,355.5 ± 352.1 to 7,404.6 ± 340.2 BTUs per dry pound, with a continuous declining trend. At Site 2, the wood chip HHVs constantly deceased from their original value of 8,422.0 ± 438.2 BTUs per dry pound to the lowest point of 7,618.2 ± 699.9 BTUs per dry pound in late September, and then slightly increased to 8,001.9 ± 132.0 BTUs per dry pound in early November. At Site 3, wood chip HHVs started at 8,579.5 ± 189.4 BTUs per dry pound and ended at 8,300.9 ± 436.7 BTUs per dry pound accompanied by the larger variations. The highest value of Site 3 wood chip

HHVs of 8,634.2 ± 157.6 BTUs per dry pound was found in the middle of August, and the lowest value of 8,039.3 ± 272.3 BTUs per dry pound was detected at the end of August (Figure 9). The decrease in biomass HHV caused by the field storage method in this study suggested that storing woody biomass in chip form could not necessarily



ensure a high energy content of biomass.

Figure 9. Biomass HHV changes in wood chips piles throughout field storage period.

4.4 Discussions

4.4.1 Wood logging residues piles

The air-dried method tested in this study resulted in a significant reduction in piled biomass MC during a 5-month storage time. The MCs of piled biomass rapidly decreased after harvesting with the lowest MC detected around the end of August at both study sites, due to the relatively low air humidity and rainfall. Biomass MC started to increase in September and kept rising until November when low temperature limited water transfer between wood and air (Gigler et al., 2000). The resulting biomass MC change during the 5-month field storage is comparable with the findings from other studies (Nellist, 1997; Gigler et al., 2000; Nurmi, 1995). Millet (1953) and Gautam et al. (2012) also found that the MC of field-stored biomass would further decrease with longer storage time and become significantly lower in the second storage season. Because of the shorter field storage time and limited data quantity, data from this study cannot support their findings. Evaluating biomass MC change over a longer field storage period is necessary to determine whether biomass MC cumulatively decreases on an annual basis.

Many studies found that HHV of biomass can only be maintained during the first four months of field storage and will decrease after 18 months, due to the changes in the chemical composition resulting from biodegradation processes (Nurmi, 1995; Brand et al., 2011). Although data from this study is limited in determining the pattern of piled biomass HHV over a longer storage period, it is sufficient to ascertain that maintaining biomass HHVs stable over 5 months in the field is feasible. The fast decrease of biomass MC towards winter can effectively restrict microbial activities and decay in wood can be minimized (Gautam et al., 2012; Hudson, 1992).

4.4.2 Wood chips piles storage

Based on the research results, the chipped biomass MC increased after 4 months of field storage at all the study sites. This finding was consistent with the results provided by Afzal et al. (2010), who observed a biomass MC increase of around double the initial value. This observed wood chip MC change pattern is different from the findings in the previous study using unchipped biomass, which showed a continuously declining trend in biomass MC during a similar storage period (Lin and Pan 2013). The main reasons for the difference are the smaller particle size and higher degree of compaction in the wood chip pile, compared with an unchipped biomass pile (Afzal et al. 2010). The small chip size and high compaction resulted in less space for air movement and therefore lower drying rate within the chip piles, thus causing irregular and increasing MC during the field storage (Jirjis 1995, 2001; Garstang et al. 2002).

In this study, decreases in biomass HHVs were observed at all study sites, which was consistent with many other studies (Jirjis and Theander 1990, Jirjis et al. 2005 Afzal et al. 2010). The reason for biomass HHV decline was the high MC remaining in the piles, which enhanced the microbial activity and resulted in lower HHVs (Hudson 1992, Gautam et al. 2012). Microbes, such as mold fungi, wood-decaying fungi, and blue stain fungi, will start to consume the wood biomass by aerobic degradation and then produce heat, carbon dioxide, and water (Eriksson 2011). Most of the time the microbes attack cellulose and hemicellulose; they degrade lignin as well (Eriksson 2011). Noticeable variations in biomass HHVs were observed at Sites 2 and 3 (Figure 9). The wood chips at these two study sites were all produced from whole trees and consisted of branches, barks, and chunk wood. In this mixture of wood chips produced from different parts, the content and types of lignin and the extractives are expected to be substantially diverse, which can directly lead to the diversity in biomass HHV (White 1987, Melin 2008, Telmo and Lousada 2011, Burkhardt et al. 2013). Meanwhile, the decomposition rates are also found to be faster in the branches and barks compared with the chunk wood part (Slaven et al. 2011). The variations found in biomass HHV decline, therefore, can be committed to the different chemical compound contents and varying decomposition rates of the wood chips. This finding implies that the biomass HHVs of whole tree wood chips are more erratic and difficult to predict during the field storage.

4.5 Conclusion

Storage is a key component within the woody biomass supply chain, especially when year-round harvesting is impossible. In order to better understand the field storage of woody biomass, 5 wood storage studies have been conducted to monitor the biomass quality (biomass MC and biomass HHV) change under different storage forms, wood logging residues piles and wood chips piles. In wood logging residues piles, biomass MCs were significantly reduced during the storage period. As an important fuel quality property, biomass HHV was determined to be generally stable during the 5-month storage period. In comparison, because of the small particle size and high degree of compaction in the wood chip pile, increases in biomass MCs were observed at all wood chips piles. In addition, decreasing trends of biomass HHV were detected during the storage time, at all wood chips piles, as a result of energy loss caused by the high MC and microbial activity in the wood chip pile.

Further monitoring of biomass MC and HHV over a longer field storage period will reveal whether biomass MC will cumulatively decrease on an annual basis and whether HHV of field-stored biomass is stable for more than 5 months. In addition, future research will be conducted to develop a biomass field drying model to quantify the relationship between biomass MC change and weather factors and thus to better understand the mass and energy flow in field-stored biomass pile.

CHAPTER 5 COST MINIMIZATION OF WOODY BIOMASS LOGISTICS INTEGRATING INFIELD DRYING AS A COST-SAVING PREPROCESS IN MICHIGAN

5.1 Introduction

With the development of computational tools, mathematical models for optimization have been widely used to implement cost-effective bioenergy production (Macmillan 2001, Mentzer 2001, Rönnqvist 2003, Gunnarsson et al. 2004, Bredström et al. 2004). As woody biomass transportation cost accounts for the largest part of the total cost and energy consumption (Eriksson and Björheden 1989, Allen et al. 1998, Alam et al. 2012), the developed optimization tools focus primarily on two categories: location selection and woody biomass collection. The location selection models have emphasized mainly on finding the best location for single or multiple processing facilities over the large-scale biomass supply chain (Zhang et al. 2011). The optimization models for woody biomass collection have aimed generally to estimate the feedstock availability and reduce cost for biomass procurement (Ranta 2002, 2005; Panichelli and Gnansounou 2008). For instance, Lautala et al. (2012a) have published a cost minimization model to minimize the cost of woody biomass transportation using railroads in Michigan and Wisconsin. However, as a critical phase in woody biomass supply chain logistics, optimization of woody biomass storage has rarely been studied (Rentizelas et al. 2009).

Storage is complicated because of the changing seasonal availability of woody biomass and the varied demand of energy plants throughout the year (Sokhansanj et al. 2006, Lin and Pan 2013). Meanwhile, different storage methods will produce biomass at various quality levels, which can significantly affect the transportation and energy conversion efficiency (Jirjis 2005, Casal et al. 2010). The most common way in the northern United States to store green biomass is to directly process wood into chips and store these in piles before being used (Lin and Pan 2013). This storage method poses several problems, such as dry matter loss, moisture content (MC) increase, and energy content reduction (Fredholm and Jirjis 1988, Thörnqvist and Jirjis 1999, Jirjis 2001, Garstang et al. 2002, Afzal et al. 2010). Storing forest harvesting residues in bundles, as the second option, can produce high-quality biomass feedstock with low biomass MC, higher energy content, and low ash content (Lehtikangas and Jiris 1998, Pettersson and Nordfjell 2007, Afzal et al. 2010). Yet the bundling technology is associated with several problems, such as high capital investment and low productivity caused by saw binding, materials handling, twine spool collapse, and slow movement at the harvesting site (Leinonen 2004, Rummer et al. 2004, Harrill 2010). Compared with piling wood chips and bundling residues, leaving unchipped or unbundled harvesting residues on-site in piles can avoid high processing costs and effectively reduce biomass MC, thus increasing transportation and conversion efficiency (Amos 1998, Lin and Pan 2015).

In Michigan, there are 11 biomass-based power plants with a total of 210 MW of energy generated annually, which is about 2.8 percent of the total production in the United States (Biomass Power Association 2014, Biomass Magazine 2015). During the winter in Michigan, from October to March, the average high temperature is about 41°F, and the average low temperature is about 26°F. With more than 51 inches of annual snowfall, forest harvesting operations are not always possible in the winter months. To ensure a cost-effective and reliable supply of high-quality biomass feedstock to the power plants, a computer-aided improved operations system was developed. The objectives of this research were (1) to develop an improved operations system that can increase biomass feedstock quality and minimize the total cost, including processing, storage, and transportation, and (2) to test the effects of transportation distance and biomass MC on the total cost of processing, storage, and transportation. In this article, the objective function is set to be the total cost (in dollars). The unit cost of the biomass feedstock (dollars per green ton; short ton) is also reported.

5.2 Problem Description

5.2.1 Feedstock storage and transportation operations

Because the quantitative relationships between local weather factors and biomass MC during storage are developed based on two previous studies conducted in Michigan from August to November, the woody biomass is assumed to be harvested at the beginning of August and stored in the field from August to November (Lin and Pan 2013, 2015). The selected harvest site is a natural forest stand with mixed hardwood and softwood species 40 miles away from the feedstock end user, Cadillac Renewable Energy LLC. A part of the logging residues are in-woods chipped and then transported to and stored in the end user's facility to meet its first-month demand. The remaining unprocessed residues are allowed to be piled at the harvest site for a certain time. The unprocessed residues are chipped and hauled to the end user based on its continued monthly demand.

5.2.2 Feedstock end user and demand

The feedstock end user, Cadillac Renewable Energy LLC, is located in Cadillac, Michigan. It is one of the largest biomass-based power plants in Michigan and is exclusively designed to use recycled wood waste as its primary fuel source. This power plant has a 38-MW energy production capability, and the average monthly use of woody material (~45% MC) is about 35,000 green tons in the wintertime and about 25,000 green tons in other months. These feedstocks are constantly supplied by 40 logging companies delivering around 1,000 green tons (equivalent to 550 dry tons if assuming 45% MC) per month. Although the hauling distance varies for each logging company, the average feedstock supply radius is around 20 to 40 miles.

5.2.3 Traditional operations system and improved operations system

In this case simulation, a traditional operations system refers to the traditional way of handling harvested biomass, where logging residues are directly processed into wood chips and immediately delivered to the feedstock end user and then stored in the facility as a wood chip pile. In an improved operations system (Figure 10), a linear programming model is used to determine the weight of the logging residue that will be chipped right away and delivered to the feedstock end user to meet its immediate demand; the remaining unprocessed portion will be stored as a large logging residues pile at the roadside. After several months of air-drying, unprocessed logging residues will be chipped by a mobile chipper and delivered to the feedstock end user monthly.

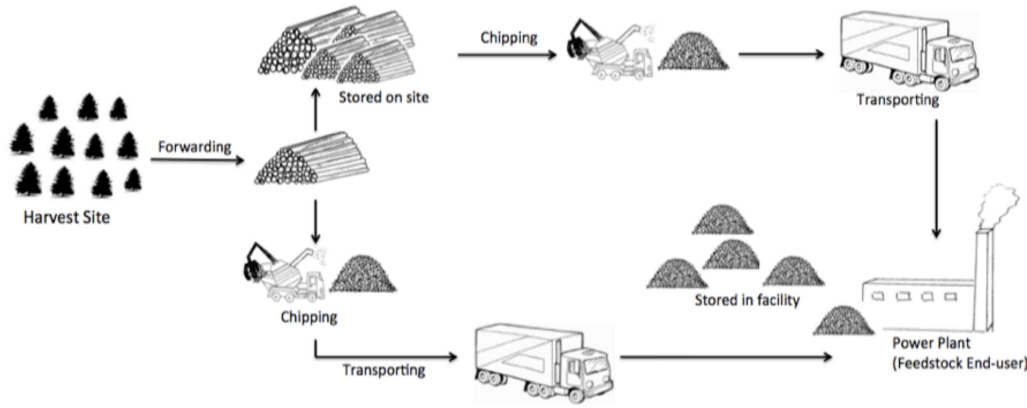


Figure 10. An illustration of the improved operations system includes biomass chipping, storage, and transportation

5.2.4 Biomass storage

In the improved operations system, chipping, storage, and transportation costs are closely related to the woody biomass MC, which is significantly affected by storage form. Two previous studies (Lin and Pan 2013, 2015) showed that piling unprocessed logging residues can effectively reduce biomass MC but that piling wood chips cannot. Several predictive equations were developed in these two previous studies to reveal the quantitative relationship between certain weather conditions and the MC of the logging residues pile (Table 11). Because biomass MC is critical for deciding the selling price of woody biomass in this model, we use the previously developed predictive model and the local weather conditions from August to November 2013 to predict the monthly MC of piled logging residues. The biomass MCs of the wood chip pile are cited values from the study published by Lin and Pan (2015).

Table 11. August-to-November woody biomass moisture content in Michigan (Lin and Pan, 2013; Lin and Pan, 2015)

Biomass MC (%)	Wood Chips Pile (WCP)	Logging Residues Pile (LCP)
August	40.3%	23.8%
September	39.3%	18.1%
October	40.7%	26.1%
November	45.5%	25.9%

5.2.5 Transportation costs

The one-way transportation distance is set to be 40 miles in this case simulation. The transportation cost in dollars per green ton is estimated based on the equation developed for the Lower Peninsula of Michigan (Lautala et al. 2012b; Table 12).

Table 12. Transportation costs at different transportation distances in Michigan

One-way transportation distance (mi)	Transportation cost ($/green ton)
20	5.88
30	6.42
40	6.97
50	7.52
60	8.07

5.2.6 Holding cost and additional profit

In the improved operations system, part of the fresh biomass will be stored as residue piles at the harvest site for air-drying. This will delay the feedstock suppliers' cash flow and lead to future operation costs, such as those for machine mobilization. The delay in cash flow in this model is defined as the holding cost, which accounts for the interest lost from the revenue of all the piled logging residues. The equation used to calculate the holding cost (HC) is

$$\mathrm{HC} = R_R \cdot \left[1 + r \cdot t + (1 + r \cdot t)^2 + \cdots + (1 + r \cdot t)^j\right] \qquad (1)$$

$$R_R = WR_n \cdot PR_0 \qquad (2)$$

where j is the total time of biomass storage (j = 3 months); R_R is the total revenue for selling all the biomass stored in logging residue pile form; WR_n is the green weight of biomass harvested in August, stored as piled logging residue for n months; PR_0 is the purchasing price ($/green ton) of logging residues that were harvested in August; r is the yearly interest rate (0.03); and t = 1 month (0.08 yr).

It is beneficial for feedstock end users to use feedstock with higher energy content and lower MC to increase energy conversion efficiency. To offer an incentive and profit for feedstock suppliers to store biomass in residue piles, it is assumed that the feedstock purchase price is based on their lower heating value (LHV), which will increase with the decrease of biomass MC. Therefore, drier biomass has higher purchasing prices (Roise et al. 2013). The Michigan-based prevailing purchase price for wood chips is assumed to be $23.00 per green ton for biomass with 45 percent MC (L. Heibel, personal communication, June 11, 2014; N. Verhanovitz, personal communication, June 25, 2014). The LHV of the 45 percent MC wood chips can be estimated using the following equation (Maker 2004):

$$\text{LHV} = \text{HHV} \times (1 - \text{MC}/100) \qquad (3)$$

where HHV is the higher heating value of the oven dried biomass and MC is the wet-basis MC of the received biomass.

For instance, if the HHV of the woody biomass is assumed to be 8,400 BTUs/lb (Maker 2004), the LHV of 45 percent MC woody biomass is calculated to be 4,620.00 BTUs/lb. When the Michigan-based prevailing purchase price is $23.00/green ton, then the energy cost is determined to be $2.49 per million BTUs ($2.49/MM BTUs). The calculated feedstock purchase prices for woody biomass at various MC levels are summarized in Table 13.

Table 13. Calculated feedstock purchased prices based on the LHV and the energy cost of \$2.49/MM Btus.[a]

Biomass MC (%)	HHV (BTUs/lb)	LHV (BTUs/lb)	Calculated purchase price (\$/green ton)
60	8,400	3,360.00	16.73
55	8,400	3,780.00	18.82
50	8,400	4,200.00	20.91
45	8,400	4,620.00	23.00
40	8,400	5,040.00	25.09
35	8,400	5,460.00	27.18
30	8,400	5,880.00	29.27
25	8,400	6,300.00	31.36
20	8,400	6,720.00	33.45

[a] LHV = lower heating value; MC = moisture content; HHV = higher heating value.

5.2.7 Mathematical model

5.2.7.1 Indices

n: biomass storage time (*n* = 0, 1, 2, 3 months).

Variables-

WC_n: green weight of biomass harvested in August, stored as piled wood chips for *n* months (Figure 11);

WR_n: green weight of biomass harvested in August, stored as piled logging residue for *n* months (Figure 11).

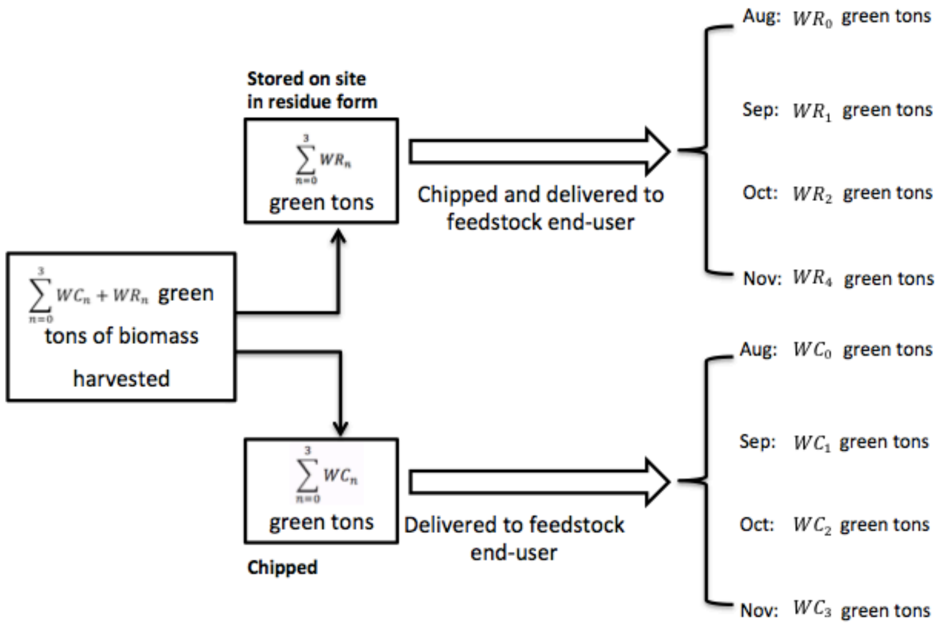


Figure 11. The weight of woody biomass feedstock delivered to the end-user

5.2.7.2 Parameters

db: monthly feedstock demand of 1,000 green tons (45% MC in wet basis; equivalent to 550 dry tons) for the energy plant;

Z: total cost of preprocessing, storing, and delivering feedstock;

KC: total chipping cost ($) for processing all the biomass;

KP: total piling cost ($) for shaping the logging residues into biomass piles;

KMG: machine mobilization cost ($) of moving a mobile grinder to the harvest site;

KML: machine mobilization cost ($) of moving a loader to the harvest site;

KT: transportation cost ($) of delivering chipped biomass to the end user;

AP: additional profit ($) earned by selling higher-quality biomass;

mc_{Cn}: MC of biomass harvested in August and stored as wood chips for n month(s);

mc_{Rn}: MC of biomass harvested in August and stored as logging residue for n month(s);

hhv: higher heating value (BTUs/lb); LHV_{Cn}: net energy content of wood chips (BTUs/lb);

LHV_{Rn}: net energy content of logging residue (BTUs/lb);

PC_n: purchasing price ($/green ton) of wood chips that were harvested in August and stored for n month(s);

PR_n: purchasing price ($/green ton) of logging residues that were harvested in August and stored for n month(s);

p_s: standard purchasing price ($23/green ton) for energy plant to purchase biomass (45% wet basis);

ec_s: energy cost ($/BTU);

HC: costs ($) incurred while holding the biomass stored as logging residues piles;

r: yearly interest rate.

5.2.7.3 Constraints

Satisfy the monthly demand (dry weight) of the energy plant:

$$[(1-mc_{Cn})\cdot WC_n + (1-mc_{Rn})\cdot WR_n] - (1-45\%)\, db \geq 0$$

where

n = 0, 1, 2, 3 months;

mc_{Cn} = MC of biomass harvested in August and stored as wood chips for n month(s);

mc_{Rn} = MC of biomass harvested in August and stored as logging residue for n month(s);

WC_n = the green weight of biomass harvested in August and stored as wood chip pile for n month(s);

WR_n = the green weight of biomass harvested in August and stored as piled logging residue for n month(s);

db = 1,000 green tons (MC = 45%, or 550 dry tons).

5.2.7.4 Objective function

The total cost can be expressed as

$$Z = KC + KP + KMG + KML + KT - AP + HC \qquad (4)$$

where

$$KC = 5.00 \sum_{n=0}^{3}(WC_n + WR_n) \qquad (5)$$

$$KP = 4.59\sum_{n=0}^{3} WR_n \qquad (6)$$

$$KMG = 2.52\sum_{n=0}^{3}(WC_n + WR_n) \qquad (7)$$

$$KML = 2.52\sum_{n=0}^{3} WR_n \qquad (8)$$

$$KT = 6.97\sum_{n=0}^{3}(WC_n + WR_n) \qquad (9)$$

$$AP = \sum_{n=0}^{3}(PC_n \cdot WC_n + PR_n \cdot WR_n) - PC_0 \cdot \sum_{n=0}^{3}\left(WC_n + WR_n\right) \quad (10)$$

$$PC_n = LHV_{Cn} \cdot \frac{2{,}000 \text{ lb}}{\text{green ton}} \cdot ec_s \quad (11)$$

$$LHV_{Cn} = \sum_{n=0}^{3} hhv\left(1 - mc_{Cn}\right) \qquad (12)$$

$$PR_n = LHV_{Rn} \cdot \frac{2,000 \text{ lb}}{\text{green ton}} \cdot ec_s \quad (13)$$

$$LHV_{Rn} = \sum_{n=0}^{3} hhv\left(1 - mc_{Rn}\right) \quad (14)$$

$$\text{HC} = WR_n \cdot PR_0 \cdot r \cdot t \cdot \left[1 + \left(1 + r \cdot t\right) + \left(1 + r \cdot t\right)^2 + \left(1 + r \cdot t\right)^3\right] \quad (15)$$

where n = 0, 1, 2, 3 months;

r = 0.03 (yearly interest rate);

t = 1 month (0.08 yr);

WC_n = green weight of biomass harvested in August and stored as wood chips for n month(s); WR_n = green weight of biomass harvested in August and stored as piled logging residue for n month(s);

PC_n = purchasing price ($/green ton) of wood chips that were harvested in August and stored for n month(s);

PR_n = purchasing price ($/green ton) of logging residues that were harvested in August and stored for n month(s);

hhv = higher heating value (BTUs/lb);

LHV_{Cn} = net energy content of wood chips (BTUs/lb);

LHV_{Rn} = net energy content of logging residue (BTUs/lb);

ec_s = energy cost ($/BTU);

mc_{Cn} = MC of biomass harvested in August and stored as wood chips for n month(s); and mc_{Rn} = MC of biomass harvested in August and stored in logging residue for for n month(s). Other parameter values are listed in Table 14**.**

This linear programming optimization model is analyzed by Solver (Frontline Systems, Inc. 1990–2009) and can also be solved by other software, such as the General

Algebraic Modeling System (GAMS Development Corporation 2013), LINDO API 9.0 (LINDO Systems, Inc. 2015a), or LINGO 15.0 (LINDO Systems, Inc. 2015b).

Table 14. Parameter values used in the case simulation

Site conditions		
Feedstock user	Cadillac Renewable Energy	
Transportation distance (miles)	40	
Parameters	**Wood Chips Pile (WCP)**	**Logging Residues Pile (LCP)**
Chipping cost ($/green ton)	5.00[1]	5.00[1]
Piling cost ($/green ton) [4]	0	4.59[2]
Machine mobilization cost ($/green ton) [5]	2.52[3]	2.52[3]
Total Processing cost ($/green ton)	7.52	12.11
Transportation cost ($/ green ton) [6]	6.97[1]	6.97[1]

(1) Lautala et al., 2012
(2) Harrial, 2010
(3) Zamora, 2013
(4) Assume the chipper has an attached loader; the wood chips are blown to a chip van and hauled away immediately after the chipping operations.
(5) The mobilization cost includes cost for moving chipper and loader.
(6) The transportation cost is 9.75 $/green ton with additional $0.15/green ton per mile after 20 miles (Barnes, 2010).

5.2.8 Results and Discussion

5.2.8.1 The improved operations system A

The details of using the improved operations system to continuously supply the end user with high-quality biomass feedstock for 4 months is summarized in Table 15. The improved operations system favors a shift from piling wood chips toward piling logging residues for achieving lower MC.

Table 15. The costs of using an improved operations system to sell biomass feedstock to the end user in improved system A[a]

Month	Storage form		Split cost ($)				Holding cost ($)	Total cost ($)
	Wood chip pile	Logging residues pile	Chipping	Piling	Machine mobilization	Transportation		
Aug.	$\sum_{n=0}^{3} WC_n$ = 921.69[b]	$\sum_{n=0}^{3} WR_n$ = 2,157.99[c]	4,608.45	9,905.16	7,760.78	6,424.18	164.96	28,863.54
Sep.	WC_1 = 0.00	WR_1 = 671.51	3,357.53	0.00	1,692.19	4,680.39	165.36	9,895.48
Oct.	WC_2 = 0.00	WR_2 = 744.49	3,722.45	0.00	1,876.12	5,189.10	165.76	10,953.44
Nov.	WC_3 = 0.00	WR_3 = 741.99	3,709.95	0.00	1,869.81	5,171.67	166.15	10,917.60
Total	921.69	2,157.99	15,398.38	9,905.16	13,198.91	21,465.34	662.24	60,630.06
							Total biomass harvested (green tons)	3,079.68
							Additional profit ($)	22,204.90
							Total cost after additional profit ($)	38,425.16
							Production cost ($/green ton)	12.48

[a] Definitions of the abbreviations used in the equations are provided in the text.
[b] Total weight of green biomass stored as wood chip pile.
[c] Total weight of green biomass stored as logging residues pile.

At the beginning of August, a total of 3,079.68 green tons of biomass will be harvested to meet the end user's demand until November. An amount of 921.69 green tons of biomass will be immediately processed into wood chips and delivered to the end user to meet its August demand. The remaining 2,157.99 green tons of biomass will be stored as piled logging residues at the harvest site. At the end of August, a mobile grinder needs to be moved to the harvest site to process 671.51 green tons of 1-month air-dried logging residue into wood chips. The wood chips will then be delivered to the end user to meet its September demand. During October and November, a similar process will take place. The chipper will produce 744.49 green tons of 2-month field-stored biomass and 741.99 green tons of 3-month field-stored biomass to meet the end user's October and November demands, respectively.

The highest total operations cost of $28,863.54 occurs in August. The chipping cost, piling cost, machine mobilization cost, and transportation cost account for 15.96, 34.31, 26.89, and 22.26 percent of the total cost, respectively. The lowest total cost of $9,895.48 is in September. This includes the chipping cost, machine mobilization cost, and transportation cost for selling 671.51 green tons of biomass stored as logging residue pile. The monthly total costs for October and November are $10,953.44 and $10,917.60, which depend mainly on the weight of biomass processed and delivered in each month. The total cost for the 4 months of operations sums up to $60,630.19, and the unit production cost is $19.68/green ton. The largest component of the total cost is the transportation cost, which represents 35.40 percent of the total cost. The holding cost of $662.24 accounts for only 1.09 percent of the total cost owing to the relatively small amount of held biomass.

5.2.8.2 Comparison between improved operations system A and the traditional operations system

The total cost of the improved operations system A is $60,630.19, which costs the feedstock supplier $6,089.70 more compared with the traditional operations system because of the extra machine mobilization cost and the piling cost associated with establishing logging residue piles (Table 16). However, the higher cost of the improved operations system can be offset by the additional profit of $22,204.90 from selling higher-quality feedstock (Table 15). As a result, the feedstock suppliers can expect a net cost (total cost minus the additional profit) of \$38,425.29 by adopting the improved operations system.

Table 16. The costs of using a traditional operation system to sell biomass feedstock to the end user[a]

Month	Storage form		Split cost (\$)				Holding cost (\$)	Total cost (\$)
	Wood chip pile	**Logging residues pile**	**Chipping**	**Piling**	**Machine mobilization**	**Transportation**		
Aug.	$\sum_{n=0}^{3} WC_n =$ 3764.00[b]	$\sum_{n=0}^{3} WR_n =$ 0.00[c]	18,820.02	0.00	9,485.29	26,235.08		54,540.36
Sep.	$WC_1 =$ 906.64	$WR_1 =$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oct.	$WC_2 =$ 927.32	$WR_2 =$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov.	$WC_3 =$ 1,008.35	$WR_3 =$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	3,764.00	0.00	18,820.02	0.00	9,485.29	26,235.08	0.00	54,540.36
							Total biomass harvested (green tons)	3,764.00
							Additional profit (\$)	0.00
							Total cost after additional profit (\$)	54,540.36
							Production cost (\$/green ton)	14.49

[a] Definitions of the abbreviations used in the equations are provided in the text.
[b] Total weight of green biomass stored as wood chip pile.
[c] Total weight of green biomass stored as logging residues pile.

In improved operations system A, the total amount of biomass required to meet the end user's 4-month demand is 3,079.68 green tons, while in the traditional operations system, a total of 3,764.00 green tons of biomass is required to meet the 4-month demand. The 684.32 green tons of reduction in green biomass delivered to the end user is caused by the drier biomass using the logging residues pile as the storage method suggested by the improved operations system.

5.2.8.3 Improved operations system with two feedstock end users (system B)

To further test the model, a second feedstock end user (end user 2) is introduced to the operations system. End user 2 is assumed to be located 20 miles away from the harvest site, with a monthly demand of 2,000 green tons of woody biomass (1,100 dry tons assuming 45% wet-basis MC). All the parameters remain the same as those in the improved operations system A with one feedstock end user. The corresponding objective function becomes the summed net cost of supplying woody biomass to two end users. The constraints for the improved operations system B are to meet the 1,000 green tons of monthly demand for end user 1 (550 dry tons assuming 45% wet-basis MC) and 2,000 green tons of monthly demand for end user 2 (1,100 dry tons assuming 45% wet-basis MC). The decision variables are the monthly delivered biomass weight in green tons to the two end users.

Table 17 presents the optimized solution with the monthly delivered biomass weight for end user 1 and end user 2. Since the unit cost (dollars per green ton) for chipping, piling, and machine mobilization is the same for the two end users, the total chipping, piling, and machine mobilization costs for end user 2 are doubled compared with end user 1 owing to its doubled biomass monthly demand. For the transportation cost, the unit transportation cost for end user 2 is reduced because of the shorter transportation distance; therefore, the transportation cost will not increase proportionally to the biomass weight increase (Figure 12). The simulation showed that the total cost to supply biomass feedstock to the two end users is $123,100.57 with a unit cost of $13.32/green ton.

The results indicate that the logging residue pile is the recommended storage form in operations system B because it can produce drier woody biomass. However, there is a small chance that the biomass from one harvest site can support two feedstock end users at the same time because 1 MW of electrical production requires 3,987 acres of typical pine plantation (National Association of Conservation Districts 2015).

Table 17. The costs of using an improved operations system to sell biomass feedstock to the two end users in improved system B[a]

Month	End user 1[b]		End user 2[c]		Split cost ($)				Holding cost ($)	Total cost ($)
	Wood chip pile	Logging residues pile	Wood chip pile	Logging residues pile	Chipping	Piling	Machine mobilization	Transportation		
Aug.	$\sum_{n=0}^{3} WC_n$ = 921.69[d]	$\sum_{n=0}^{3} WR_n$ = 2,157.99[e]	$\sum_{n=0}^{3} WC_n$ = 1,843.38[f]	$\sum_{n=0}^{3} WR_n$ = 4,315.97[g]	13,825.35	29,715.47	23,282.35	31,802.1	494.89	99,120.16
Sep.	0	671.51	0	1,343.01	10,072.58	0	5,076.58	12,577.3	496.08	28,222.54
Oct.	0	744.49	0	1,488.98	11,167.36	0	5,628.35	13,944.31	497.27	31,237.29
Nov.	0	741.99	0	1,483.98	11,129.85	0	5,609.44	13,897.47	498.46	31,135.23
Total	921.69	2,157.99	1,843.38	4,315.97	46,195.14	29,715.47	39,596.73	72,221.18	1,986.7	189,715.23
									Total biomass harvested (green tons)	9,239.03
									Additional profit ($)	66,614.65
									Total cost after additional profit ($)	123,100.57
									Production cost ($/green ton)	13.32

[a] Definitions of the abbreviations used in the equations are provided in the text.
[b] End user 1 refers to Cadillac Renewable Energy.
[c] End user 2 refers to the simulated second feedstock end user, which is added to test the model.
[d] Total weight of green biomass stored as wood chip pile for end user 1.
[e] Total weight of green biomass stored as logging residues pile for end user 1.
[f] Total weight of green biomass stored as wood chip pile for end user 2.
[g] Total weight of green biomass stored as logging residues pile for end user 2.

5.2.8.4 Sensitivity analysis—Effects of transportation distance on the total cost and the improved operations system

In this simulation, the transportation distance from the harvest site to the end user was set at 40 miles. In the sensitivity analysis, the range of the transportation distance considered is from 20 to 60 miles. The transportation distance has no impact on the biomass storage and transportation strategy but affects the total cost through changing the transportation cost. When the distance increases from 20 to 60 miles, the total cost after deducting the additional profit rises linearly from $35,056.08 to $41,806.73 (Figure 12). The sensitivity analysis indicates that every 1 mile of transportation distance increase will raise the total cost by $168.77. The additional profit earned from selling higher-quality feedstock is $22,204.90. This additional profit can cover the increased transportation cost caused by a one-way distance increase for up of 171 miles. This result suggests that the negative impact of longer transportation distance in the woody biomass supply chain can be mitigated by the higher feedstock quality.

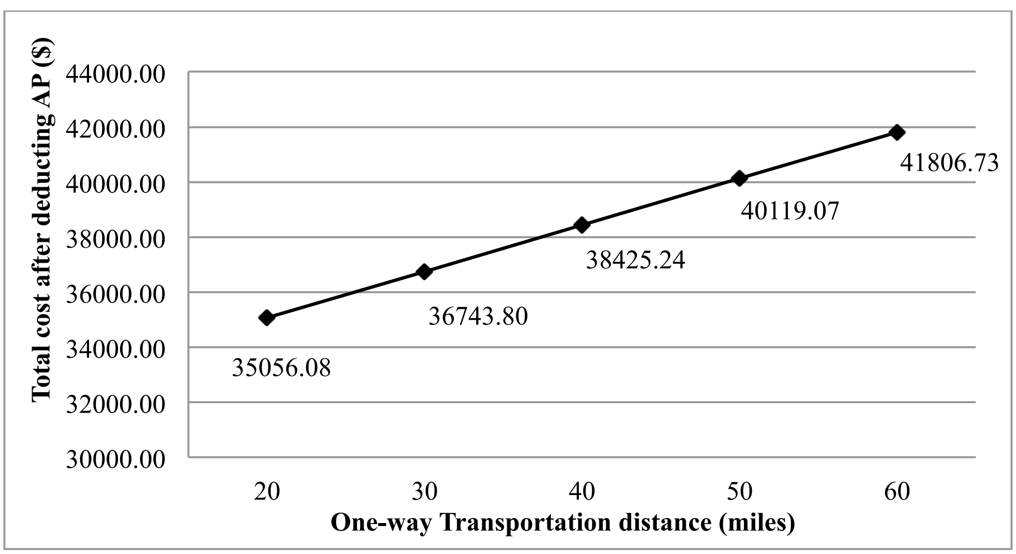


Figure 12. Total cost after deducting AP associated with different one-way transportation distances

5.2.8.5 Sensitivity analysis—Effect of biomass MC on the total cost and the improved operations system

The effect of biomass MC on the total cost was determined by changing the MC at a 5 percent increment (Figure 13). On average, every 1 percent increase in biomass MC can result in a $760.68 increase in the total cost after deducting additional profit. With every 5 percent decrease in biomass MC, the total cost after deducting additional profit is reduced by $2,976.29. On the other hand, when the biomass MC increases by 5, 10, and 15 percent, respectively, the total cost after deducting additional profit will increase to $3,439.78, $4,023.11, and $4,772.51, respectively. In addition, this cost increase owing to feedstock MC increment presents an ascending curve instead of being linear, indicating that a large increase in MC will have a more significant impact on the total cost. The harvesting operations, therefore, are suggested to take place in the late spring or summer, when initial biomass MC tends to be lower, to reduce the total cost.

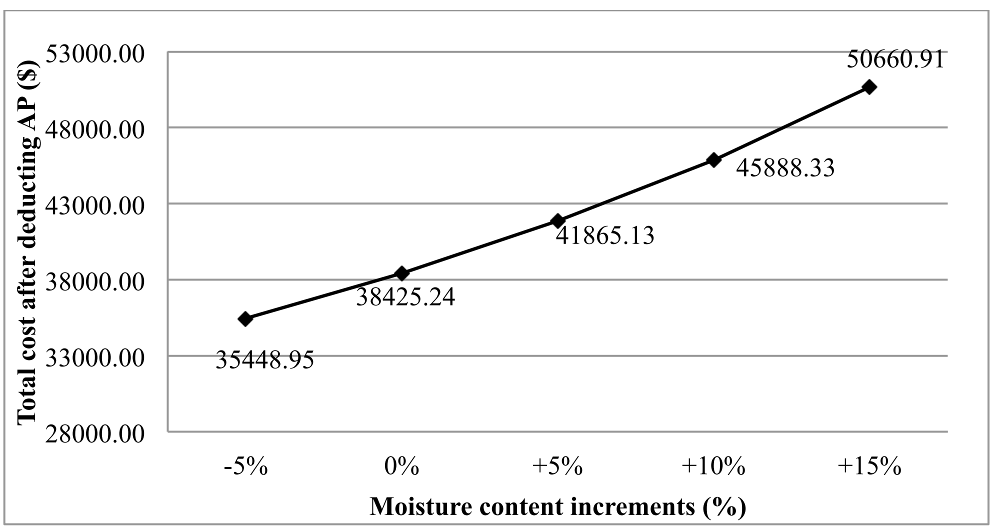


Figure 13. Total cost after deducting AP associated with different biomass MC

Although the effect of biomass MC on the total cost is nonlinear (Figure 13), the sensitivity analysis indicates that every 1 percent decrease in biomass MC will reduce the total delivered biomass green weight by 52.10 green tons on average. This means that using the improved operations system can prevent 52.10 tons of water from being transported to the end user, thus increasing the transportation efficiency. For different biomass MC, piling unprocessed logging residue is always the preferred way to store biomass mainly because this storage method can produce drier biomass feedstock through air-drying.

5.2.8.6 Model limitations

The improved operations system simulated by the linear programming model has many limitations in real operations. For example, real operations cannot process field-stored biomass at the accurate amount as the computer-aided improved operations system suggests. However, this improved operations system can serve as a guideline for real-world operations. The scheduling of real-world operations can be adjusted toward what the improved operations system indicates; thus, improved feedstock supply chain cost-effectiveness can be realized.

The calculated feedstock purchase price in this simulation is based on a feedstock purchase price provided by a personal research contact (L. Heibel, personal communication, June 11, 2014) because currently the increased economic value of higher-quality feedstock is justifiable only by increased recoverable energy content. In reality, a feedstock conversion and upgrading facility may only partially return its profit from using higher-quality feedstock to the feedstock suppliers. The current US market does not have any mechanism for pricing the higher-quality woody biomass or allocating the increased profit between feedstock suppliers and end users. Using drier biomass is a more profitable way for both feedstock suppliers and end users, as transporting drier biomass (having higher energy content) results in lower energy cost and using drier biomass increases boiler efficiency.

The additional profit from selling higher-quality feedstock discussed in this article is based on using direct combustion as the conversion option. The additional profits from the increased efficiency using different biomass conversion and upgrading options will vary. In addition to direct combustion, other conversion and upgrading options include palletization, fast pyrolysis, torrefaction, and fermentation. In future research, more conversion and upgrading scenarios will be considered.

5.2.8.7 Conclusion

An improved operations system for biomass storage and transportation is proposed using a computer-based linear programming technique. The case simulation results indicate that when using logging residue pile as the major storage form, the extra cost of $6,089.70 owing to piling operations and machine mobilizations can be offset by the additional profits of $22,204.90 from selling higher-quality feedstock. In addition, because of the drier biomass achieved in the improved operations system, the delivered biomass green weight to satisfy the 4-month energy demand is reduced by 684.32 green tons compared with the traditional operations system. By introducing end user 2 in the additional testing of the operations system, the simulation results confirm that logging residue pile is still the preferred storage method.

CHAPTER 6 LIFE CYCLE ASSESSMENT OF MIXED-SPECIES FOREST AND SHORT ROTATION WOODY CROP PLANTATION IN MICHIGAN

6.1 Introduction

Woody biomass is the third largest renewable energy source and contributes about 10% of the global primary energy consumption (EIA, 2017; Lauri et al., 2014). Historically, it was assumed that the carbon emitted into the air from biomass combustion is sequestrated by future tree growth. Under this regeneration assumption, woody biomass has been recognized as "carbon neutral" and "environmentally friendly" and recommended as a carbon sources to replace fossil fuels (Lippke et al., 2011). However, immediate carbon dioxide emissions can cause near-term increases in atmospheric carbon, which may require a long time to be resequestered (Cherubini et al., 2011; Sedjo, 2011; Sedjo, 2013). The total annual greenhouse gas (GHG) emissions from the global woody biomass supply chain are estimated to be 890 million tonnes, with more than half of the carbon released from energy consumption (FAO, 2007; Asikainen et al., 2010). The global warming effect caused by this large carbon flux should not be underestimated. To completely assess the environmental performance of woody biomass, it is necessary to study cradle-to-grave GHG emissions in the woody biomass supply chain (Sedjo, 2013; England et al., 2013).

Many life cycle assessment (LCA) studies have been carried out globally to quantify the environmental impacts of short rotation woody crop (SRWC) production systems (Mann and Spath, 1997; Keoleian and Volk, 2005; Adler et al., 2007; González-Garcìa et al., 2010; Di Nassi o Nasso et al., 2010; Gabrielle et al., 2013; Vasquez Sandoval, 2015). These LCAs have suggested crucial areas need to be improved to further reduce GHG emissions and improve sustainability. However, these LCAs rarely include combustion or biomass utilization, which normally contributes the largest amount of GHG emissions in the woody biomass supply chain. Klein et al. (2015) reported that only 14% of the 28 reviewed LCAs of forest production systems used a cradle-to-grave scope, and over 54% did not mention any methodical approach besides the Intergovernmental Panel on Climate Change (IPCC) (2006) guidelines. The energy ratios reported by previous cradle-to-farm gate LCAs vary from 13 to 79, and from 3 to 16 in the cradle-to-grave LCAs. The GHG emissions reported ranged from 39 to 2,953 g CO_2-eq/kWh. These large variations were due to different scope definition, project goals, system boundaries, raw materials, and research locations in each study.

A similar problem is also found in the LCAs for forest production systems that are not SRWC. In 29 reviewed LCAs conducted from 2000 to 2017, there are 18 LCAs that define the scope from forest to plant gate, 7 from forest to forest road, and 4 from cradle-to-grave. In addition, 12 different functional units such 1 m^3 over bark, 1 acre, 1 year, 1 oven dry ton, and 1 MJ were used in these LCAs. These differences in the previous studies have made comparisons between studies difficult and biased (Klein et al., 2015).

Besides the incomplete scope and the different functional units chosen, a critical but often-neglected component in previous LCAs is the soil organic carbon (C) sequestration, which determines the net environmental benefit of biomass energy production (Anderson-Teixeira et al., 2009; Russell et al., 2015). Soil organic C stock is one of the major benefits of growing woody biomass and can play an important role in offsetting GHG emissions (Liski et al., 2006; Goglio et al., 2015). However, soil organic carbon has been excluded from previous LCA approaches (Helin et al., 2013).

Another important environmental aspect, typically ignored in woody biomass supply chain analyses, is the nutrient pool. Excessive removal of forest debris from harvesting sites can cause significant negative impacts to nutrients cycles, soil, and site productivity (Martin et al., 2000; Watmough and Dillon, 2003; Walker et al., 2010). For instance, Achat et al. (2015) concluded that whole-tree harvesting (WTH) caused a 3-7% reduction in tree growth up to 33 years after harvesting. Mason et al. (2011) reported that WTH caused 5-9% height and diameter reduction at two medium fertility sites, with 9% height reduction and 19% diameter reduction at the poor fertility site. In order to maintain a nutrient balance and utilize forest resources sustainably, it is important to estimate the nutrient loss caused by forest harvesting.

GHG emissions in woody biomass production systems in Michigan and the Lake States have rarely been studied. So far, only Handler et al. (2014) published an LCA that analyzed GHG emissions and energy inputs in the harvesting and transportation stages (truck and railway transport) for the round wood supply chain in MI. This study was based on previous published peer-reviewed literature, national databases, and a Michigan loggers' survey.

By 2015, there are over 20 million acres of forested land in Michigan, and 19.3 million acres are timberland (Pugh et al., 2016). In order to provide a clearer picture of the energy and mass flow in woody biomass production systems, a comprehensive LCA that includes all life cycle stages is necessary. With the help of LCA, better decisions can be made in promoting woody biomass utilization, and in improving the system performance in terms of minimizing environmental impacts (Puettmann, 2006).

6.2 Goal, Scope and Functional Unit for Life Cycle Assessment

This LCA followed the standard approach suggested by ISO 14040 series, Environmental Management-Life Cycle Assessment. The goal of this LCA study is to analyze and compare the environmental impacts, including soil carbon sequestration, GHG emissions, nutrient depletion and Energy Return on Investment (EROI) in five woody biomass production systems in Michigan. The site location, stand type, harvesting system, and cut type for the five studied systems are summarized in Table 18. Life cycle stages considered are: forest cultivation, management (fertilization and herbicide application), harvesting, forest residues extraction, pre-processing, transportation, storage, and combustion (Figure 14). In the hybrid poplar (Site 3) and hybrid willow (Site 4) plantations, the harvesting, extraction, and pre-processing stage were combined into one stage because a reconfigured harvester was employed. The functional unit (FU), forming the basis of comparison between systems for this LCA, was selected to be 1 kWh of electricity produced by co-firing wood pellets.

Table 18. Information of studied woody biomass production systems

Site	Location	Stand type	Tree species	Harvesting system	Area (acres)
1	Augusta, MI	Mixed-species (average age 10-year)	85% Douglas-fir, 5% Norway spruce, 5% white spruce and 5% hardwoods	Whole-tree harvesting system	23.31
2	East Lansing, MI	Mixed-species (average age 15-year)	55% poplar, 25% Engelmann spruce, 10% larch and 5% pine.)	Whole-tree harvesting system	28.55
3	Escanaba, MI	Hybrid poplar plantation (7-year old)	Hybrid poplar	Whole-tree harvesting system	7.80
4	Albion, MI	Hybrid willow plantation (3-year old)	Hybrid willow	Harvest-and-chip harvesting system	1.10
5	Gwinn, MI	29-year-old Jack pine plantation	Jack pine	Cut-to-length harvesting system	66.00

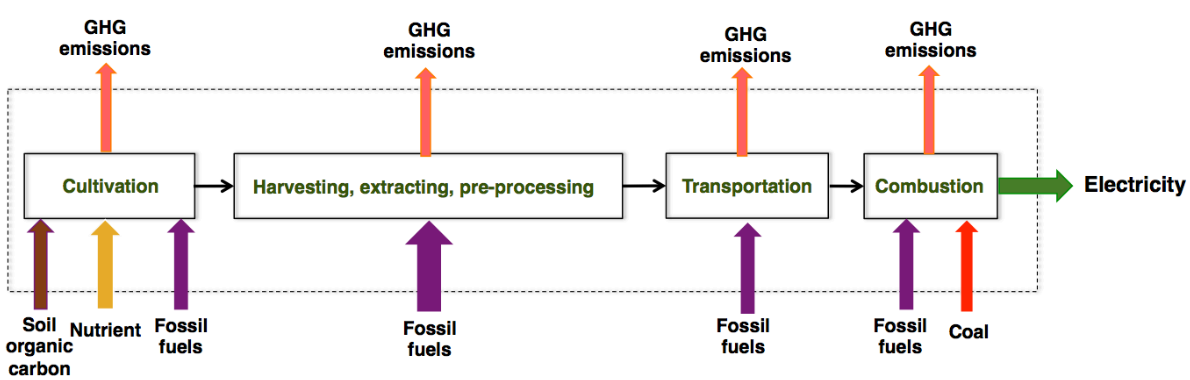


Figure 14. System boundary of woody biomass production systems in this LCA study

6.3 Life cycle inventory (LCI)

A life cycle inventory was tabulated in MS Excel for each woody biomass production system regarding fertilizer, herbicide, energy, and fossil fuel use during the whole life cycle. The life cycle inventory for each site is summarized in **Tables 19-23**. In the harvesting, extraction, and pre-processing stages, fossil fuel consumption for each machine was calculated by multiplying their total operation time (hours) to the diesel consumption rates (gals/hour), which were based on their horsepower provided by the manufacturing company. Total operation time (hours) was calculated by dividing the harvested biomass dry weight (BDT) by the predicted productivity (BDT/Productive Machine Hour (PMH)) obtained upon multiple linear regression of time and motion study date for each site. The total diesel consumption of each machine, in gallons, was converted into equivalent GHG emissions. For combustion, an overall boiler capacity of 21 MWh and a combustion efficiency of 35% were assumed based on conventional power plant practice in the U.S.

Table 19. Life cycle inventroy of site 1

Site 1	
Process/activity	**Value**
Cultivation	
Herbicide application (Glyphosate)	16.6 lbs
Herbicide application (Simazine)	32.12 lbs
Fertilizer (Ammonium Sulfate)	0 lb
Harvesting operation	
Feller-buncher (Diesel)	80.37 gal
Skidder (Diesel)	50.23 gal
Loader (Diesel)	18.42 gal
Chipper (Diesel)	125.23 gal
Transportation (Chip-van)	318.64 gal
One way distance (miles)	74.3 miles
Total green weight	223.56 green tons
Combustion (T.B. Simon Power Plant)	
Higher heating values	9173 Btus/lb (21.34 MJ/kg)
Recoverable Heating Value	2970 Btus/lb (6.91 MJ/kg)
Boiler capacity	21 MWh
Plant efficiency	35%
CO_2 emissions	232.21 metric tons
CH_4 emissions	0.08 metric tons
NO_2 emissions	0.01 metric tons

Table 20. Life cycle inventory of site 2

Site 2	
Process/activity	**Value**
Cultivation	
Herbicide application (Glyphosate)	16.6 lbs
Herbicide application (Simazine)	32.12 lbs
Fertilizer (Ammonium Sulfate)	0 lb
Harvesting operation	
Feller-buncher (Diesel)	45.88 gal
Skidder (Diesel)	41.40 gal
Loader (Diesel)	22.32 gal
Chipper (Diesel)	151.73 gal
Transportation (Chip-van)	163.53 gal
One way distance	4.4 miles
Total green weight	344.29 green tons
Combustion (T.B. Simon Power Plant)	
Higher heating values	7179 Btus/lb (16.70 MJ/kg)
Recoverable Heating Value	2025 Btus/lb (4.71 MJ/kg)
Boiler capacity	21 MWh
Plant efficiency	35%
CO_2 emissions	238.82 metric tons
CH_4 emissions	0.08 metric tons
NO_2 emissions	0.01 metric tons

Table 21. Life cycle inventory of site 3

Site 3	
Process/activity	**Value**
Cultivation	
Tilling/spading	15.4 gal diesel
Herbicide application:	6.16 gal diesel
-Scepter 70 DG (tractor)	0.34 gal
-Pendulum (Tractor)	5.85 gal
-Glyphosate (manual)	0.25 gal
Sapling Planting	2.94 gal diesel
Coppice Cut	5.46 gal diesel
Insecticide application: -BT Insecticide (manual)	0.26 gal
Herbicide application: -Glyphosate spot app (manual)	0.26 gal
Harvesting operation	
Feller-buncher (Diesel)	103.9 gal
Skidder (Diesel)	23.8 gal
Loader (Diesel)	20.8 gal
Grinder (Diesel)	82.3 gal
Transportation (Chip-van)	318.23 gal
One way distance	50 miles
Total green weight	265 green tons
Combustion (T.B. Simon Power Plant)	
Higher heating values	8518 Btus/lb (19.81 MJ/kg)
Recoverable Heating Value	2902 Btus/lb (6.75 MJ/kg)
Boiler capacity	21 MWh
Plant efficiency	35%
CO_2 emissions	224.48 metric tons
CH_4 emissions	0.08 metric tons
NO_2 emissions	0.01 metric tons

Table 22. Life cycle inventory of site 4

Site 4	
Process/activity	**Value**
Cultivation	
Tilling/spading	5.6 gal diesel
Herbicide application	2.31 gal
-Simazine	0.91 lb
-Goal	0.46 gal
-Glyphosate	1.82 lb
Sapling Planting	4.52 gal diesel
Coppice Cut	0.77 gal diesel
Herbicide application (glyphosate, manual)	1.82 lb
Harvesting operation	
Harvesting Unit	3.89 gal diesel
Chip Collector	3.89 gal diesel
Chip Loader	0.57 gal diesel
Transportation (Chip-van)	7.40 gal diesel
One way distance	50 miles
Total green weight	12.71 green tons
Combustion (T.B. Simon Power Plant)	
Higher heating values	8014 Btus/lb (18.64 MJ/kg)
Recoverable Heating Value	2903 Btus/lb (6.75 MJ/kg)
Boiler capacity	21 MWh
Plant efficiency	35%
CO_2 emissions	10.80 metric tons
CH_4 emissions	0.004 metric tons
NO_2 emissions	0.0005 metric tons

Table 23. Life cycle inventory of site 5

Site 5	
Process/activity	**Value**
Cultivation	
Herbicide application (Glyphosate)	16.6 lbs
Herbicide application (Simazine)	32.12 lbs
Fertilizer (Ammonium Sulfate)	0 lb
Harvesting operation	
Forwarder (Diesel) 1	90.53 gal
Loader (Diesel)	8.38 gal
Chipper (Diesel)	56.98 gal
Transportation (Chip-van)	175.09 gal
One way distance (miles)	49 miles
Total green weight	146.21 green tons
Combustion (T.B. Simon Power Plant)	
Higher heating values	8689 Btus/lb (20.21 MJ/kg)
Recoverable Heating Value	3548 Btus/lb (8.25 MJ/kg)
Boiler capacity	21 MWh
Plant efficiency	35%
CO_2 emissions	142.99 metric tons
CH_4 emissions	0.05 metric tons
NO_2 emissions	0.01 metric tons

6.4 Life Cycle Impact Assessment (LCIA)

In this LCA, three life cycle impact categories were considered: 1) net GWP, which is the total GWP minus soil carbon sequestration; 2) macro nutrient (N, P, K) removal, which is presented as Abiotic Depletion Potential; 3) energy return on investment (EROI), defined as the renewable energy returned on fossil energy invested. GHG emissions are converted into Global Warming Potential (GWP) using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 database. Detailed approaches to account for soil carbon sequestration, nutrient removal, and EROI are described in subsequent sections.

6.4.1 Soil carbon sequestration estimation

Soil carbon sequestration rates (kg C/acre/yr) are compiled from previous published studies that have similar soil properties or forest types with the studied sites (Table 24). To avoid using a single averaged value from previous studies, Crystal Ball software was used to perform Monte-Carlo simulation for the generation of the probability distributions at each study site. Uniform probability distributions were selected with range from R to S, where R was the lowest value and S was the highest value referenced from previous published studies (Table 24). The 95-percentile values for each distribution from Site 1 to 5 were 509.10, 667.35, 777.64, 155.63 and 582.65 kg C/acre/yr, respectively. These values were used to estimate the total soil carbon sequestration (kg C) during the cultivation period. The soil C sequestration value for sites 1, 2, and 5 are similar in magnitude, while the value of site 3 is higher and the value at site 4 is much lower. The highest soil C sequestration value for site 3 was included as per Arevalo et al. (2011), which was a study conducted at Alberta, CA, to investigate soil C changes in 2-4 and 9-11 years after land conversion from agricultural land to hybrid poplar plantations. In their study, site preparation (tillage operations and mechanical activities) and negligible soil biomass due to saplings being small, contribute to soil C loss during the first two years, then, after four years the soil C starts to increase, and in year seven, the soil C content reaches the pre-plantation level. This explains the lower soil C changes found in newly established hybrid willow plantation sites, and why the soil C value at site 4 (a 3-year old hybrid willow plantation) is much lower compared to other study sites.

Table 24. Referenced studies in soil carbon sequestration rates estimation

Site	Referenced study	Wood species/Forest type	Region, Country	Soil series	Sampling depth	Soil organic C sequestration rat (kg of C/acre/yr)
1	Vesterdal et al, 2006.	Norway Spruce	Tsjh, SE	Sandy	Forest floor + 0-25 cm	299.47
		Norway Spruce	Gejlvang, DK	Poor sandy	Forest floor + 0-25 cm	411.11
		Oak and Norway Spruce	Sellingen, NL	Poor sandy	Forest floor + 0-25 cm	598.94
	Gough et al., 2008.	Aspen-dominated mixed northern hardwood forest	Michigan, US	Sandy	0-20 cm	619.17
	Schulp et al., 2008.	Douglas Fir	Veluwe, NL	Loamy cover sands	Forest floor + Humus layer + 0-20 cm	598.94
	Rytter. 2012.	Poplar plantation	Uppsala, SE	Clay	0-30 cm	210.44
2	Rothstein et al., 2004.	Jack pine	Michigan, US	Sandy	0-100 cm	647.50
	Vesterdal et al, 2006.	Norway Spruce	Tsjh, SE	Sandy	Forest floor + 0-25 cm	299.47
		Oak and Norway Spruce	Sellingen, NL	Poor sandy	Forest floor + 0-25 cm	598.94
	Schulp et al., 2008.	Scots pine	Veluwe, NL	Loamy cover sands	Forest floor + Humus layer + 0-20 cm	649.93
	Arevalo et al., 2011.	Poplar plantation	Alberta, CA	Silty clay loam	0-30 cm	809.37
	Wang et al., 2012.	Jack pine	Saskatchewan, CA	Sandy	0-40 cm	726.05
	Rytter. 2012.	Poplar plantation	Uppsala, SE	Clay	0-30 cm	210.44
3	Arevalo et al., 2011.	Poplar plantation	Alberta, CA	Silty clay loam	0-30 cm	809.37
	Rytter. 2012.	Poplar plantation	Uppsala, SE	Clay	0-30 cm	210.44
4	Lockwell et al., 2012.	Willow Plantation	Southern Quebec, CA	Clay - loam	0-40 cm	0.00
	Rytter. 2012.	Willow Plantation	Nyköping, SE	Clay - clay loam	0-30 cm	165.92
5	Rothstein et al., 2004.	Jack pine	Michigan, US	Sandy	0-100 cm	647.50
	Wang et al., 2012.	Jack pine	Saskatchewan, CA	Sandy	0-40 cm	726.05

6.4.1.1 Nutrient removal

Nutrient removal in each site was estimated by multiplying nutrient (N, P and K) concentrations in removed biomass with the removed biomass weight. The detail methodology of estimating biomass weight and nutrient concentration are presented in the following sections:

6.4.1.2 Biomass weight estimation

Sites 1-4 are harvested by WT harvesting systems, the total removed biomass weight was estimated based on the recorded tree diameter at breast height (DBH) and the equation provided by Jenkins et al. (2003):

$$bm = Exp(\beta_0 + \beta_1 \ln dbh) \quad [1]$$

where *bm* = total aboveground biomass (kg dry weight) for trees 2.5 cm *dbh* and larger

dbh = diameter at breast height (cm)

Exp = exponential function

ln = log base e (2.718282)

Parameters β_0 and β_1 were cited from Jenkins et al. (2003) and depend on tree species.

Site 5 was harvested by a CTL system and the pulpwood was shipped to a paper mill. The branch biomass was milled on site and sent to an end-user for co-firing combustion. The total weight of harvested branch biomass is the total recorded biomass weight sent to the feedstock end-user.

6.4.1.3 Macronutrient (N, P, K) concentrations

Monte-Carlo simulations were performed to provide the 95-percentile value of the nutrient concentration probability distribution. The maximum and minimum nutrient concentration ($\mu g/g$) values were cited from two databases: one compiled by Pardo et al. (2004), which includes foliar nutrient data from 218 articles and publications in the Northeastern United States, and another compiled by Paré et al. (2013) in Canada that has 12,800 nutrient concentration values for different components of the 30 most common Canadian tree species.

Table 25. Nitrogen concentration allocation in stem, foliage, branch, and bark

Common name	Scientific name	Component							
		Stem (%)	SE	Foliage (%)	SE	Branch (%)	SE	Bark (%)	SE
Balsam fir	*Abies balsamea*	0.089	0.041	1.351	0.186	0.370	0.138	0.449	0.176
Paper birch	*Betula papyrifera*	0.096	0.028	2.063	0.346	0.394	0.107	0.364	0.124
White spruce	*Picea glauca*	0.058	0.011	1.175	0.169	0.363	0.127	0.303	0.066
Black spruce	*Picea mariana*	0.076	0.041	0.951	0.186	0.284	0.072	0.240	0.036
Jack pine	*Pinus banksiana*	0.067	0.019	1.176	0.180	0.296	0.074	0.246	0.052
Lodgepole pine	*Pinus contorta*	0.045	0.021	1.070	0.168	-	-	0.273	0.033
Quaking aspen	*Populus tremuloides*	0.130	0.058	2.179	0.558	0.498	0.144	0.450	0.263
Douglas fir	*Pseudotsuga menziesii*	0.133	0.020	2.197	0.387	0.370	0.066	0.396	0.060
Softwoods		0.075	0.003	1.289	0.012	0.318	0.011	0.314	0.009
Hardwoods		0.129	0.007	2.124	0.093	0.379	0.013	0.436	0.014

Table 26. Phosphorus concentration allocation in stem, foliage, branch, and bark

Common name	Scientific name	Component							
		Stem (%)	SE	Foliage (%)	SE	Branch (%)	SE	Bark(%)	SE
Balsam fir	*Abies balsamea*	0.008	0.005	0.155	0.035	0.085	0.049	0.052	0.014
Paper birch	*Betula papyrifera*	0.013	0.009	0.211	0.073	0.053	0.021	0.034	0.010
White spruce	*Picea glauca*	0.005	0.002	0.169	0.038	0.050	0.024	0.042	0.014
Black spruce	*Picea mariana*	0.007	0.007	0.130	0.033	0.040	0.013	0.047	0.041
Jack pine	*Pinus banksiana*	0.005	0.002	0.119	0.023	0.029	0.015	0.026	0.008
Lodgepole pine	*Pinus contorta*	0.008	0	0.127	0.019	0.000	0.000	0.049	0.005
Quaking aspen	*Populus tremuloides*	0.014	0.009	0.213	0.07	0.074	0.031	0.054	0.025
Douglas fir	*Pseudotsuga menziesii*	0.007	0.004	0.171	0.034	0.063	0.013	0.023	0.006
Softwoods		0.007	0.001	0.156	0.002	0.055	0.004	0.046	0.002
Hardwoods		0.011	0.001	0.175	0.005	0.069	0.013	0.042	0.003

Table 27. Potassium concentration allocation in stem, foliage, branch, and bark

Common name	Scientific name	Component							
		Stem		Foliage		Branch		Bark	
		(%)	SE	(%)	SE	(%)	SE	(%)	SE
Balsam fir	*Abies balsamea*	0.090	0.036	0.558	0.119	0.241	0.089	0.250	0.109
Paper birch	*Betula papyrifera*	0.053	0.017	0.889	0.219	0.159	0.052	0.120	0.035
White spruce	*Picea glauca*	0.044	0.011	0.579	0.156	0.260	0.184	0.164	0.075
Black spruce	*Picea mariana*	0.043	0.022	0.552	0.117	0.134	0.031	0.154	0.013
Jack pine	*Pinus banksiana*	0.045	0.019	0.409	0.106	0.155	0.052	0.115	0.024
Lodgepole pine	*Pinus contorta*	0.041	0	0.551	0.135	0.000	0.000	0.171	0.052
Quaking aspen	*Populus tremuloides*	0.112	0.045	0.962	0.423	0.277	0.111	0.263	0.062
Douglas fir	*Pseudotsuga menziesii*	0.100	0.029	0.874	0.244	0.252	0.037	0.119	0.033
Softwoods		0.060	0.003	0.653	0.017	0.177	0.012	0.173	0.013
Hardwoods		0.077	0.003	0.854	0.030	0.348	0.061	0.420	0.178

6.4.2 Abiotic Depletion Potential (ADP)

This impact category quantifies the extraction of minerals and fossil fuels needed by each system. In this study, ADP represents biomass nutrient removal that occurs during forest harvesting. The ADP of each study site is calculated following the method provided by Guinée (2001). Based on the ADP extraction rate suggested by Guinée (2001), every 1 kg of N, P and K removal results in 18.70 g, 0.08 g and 0.03 g of antimony equivalent removal.

6.4.3 Energy Return On Investment (EROI)

To evaluate the energy use efficiency of the biomass production system in each studied cite, the total renewable energy gained and the fossil fuel energy input were calculated to determine the ratio of the amount of usable energy delivered from the amount of energy supplied.

The total renewable energy gained was determined by the total recoverable heating values for woody biomass, which were calculated with the formula described by Ince (1979):

$$RHV = HHV \bullet (1 - MC_{wb}) - HL \qquad [2]$$

Where:

RHV= recoverable heating value, BTUs/pound

HHV= higher heating value, BTUs/pound

MC_{wb}= wet-basis moisture content, percent

HL= heat loss, BTUs/pound

At each study site, random wood samples were collected from the harvesting operations. The moisture contents of the wood chips were measured following ASTM E 871-82 (ASTM International 2003a). The biomass HHV was tested using an oxygen bomb calorimeter at MSU based on the standard described by ASTM E 711-87 (ASTM International 2003b).

The fossil fuel consumption of each machine was calculated by multiplying their total operation time (hours) to the diesel consumption rates (gals/hour), which are based on their horsepower provided by the manufacturing company and consumption rates provided by Plummer and Stokes (1983). Fuel consumption was converted to an equivalent heating value so that comparisons could be made with energy output values in the form of British Thermal Units (BTU). As described by Adams (1983), it was assumed that one gallon of diesel fuel was approximately equal to 137,000 BTUs.

6.4.4 Sensitivity analysis

Sensitivity analyses were performed to study the impacts of moisture content, energy demand of the power plant, and transportation distances on the GWP generated by producing 1 kWh of electricity. These three factors are increased or decreased by 10% to reveal their impacts on the GWP.

6.5 Life Cycle Assessment Results and Discussion

6.5.1 Global Warming Potential (GWP)

Fig. 15a-e present the GWP for Site 1-5 itemized for each system component, including biomass cultivation, harvesting, pre-processing, transportation, combustion, and soil C sequestration. Figure 16 presents GWP contributions from all life cycle stages, excluding combustion and soil carbon sequestration. At Site 1, GHG emissions from biomass harvesting (feller-buncher) and collecting (skidder) are 1,320 kg of CO_2-eq (or 9.77 kg CO_2-eq per dry ton). Sonne (2006) reported that the GHG emissions from the harvesting and collecting were 5.9 Mg CO_2-eq per 700 m^3 timber harvested in Douglas-fir plantations located along the coastal regions of the Pacific Northwest, which is equivalent to 15.90 kg CO_2-eq per dry ton assuming a dry wood density of 530 kg per m^3 (Engineering Toolbox, 2004). The lower emissions found in this study can be attributed to Michigan's flatter terrain when compared to the coastal Pacific Northwest, which increases the productivity and decreases diesel fuel consumption.

The total GHG emissions generated in Site 2 were 2.48E+05 kg of CO_2-eq (or 1.94 kg of CO_2-eq/kWh). The largest contributor was biomass combustion, and the second largest contributor was biomass pre-processing (loading and chipping). Many studies have concluded that transportation was the largest contributor to the total GWP in the woody biomass supply chain, starting from cultivation (Berg and Lindholm, 2005; Michelson et al., 2008; Neupane et al., 2011). However for this studied site, while the transportation distance was only five miles, biomass pre-processing was the largest GWP contributor compared to the other system components. This confirms that the impact of transportation highly depends on the hauling distance, which is also concluded by Zhang et al. (2015).

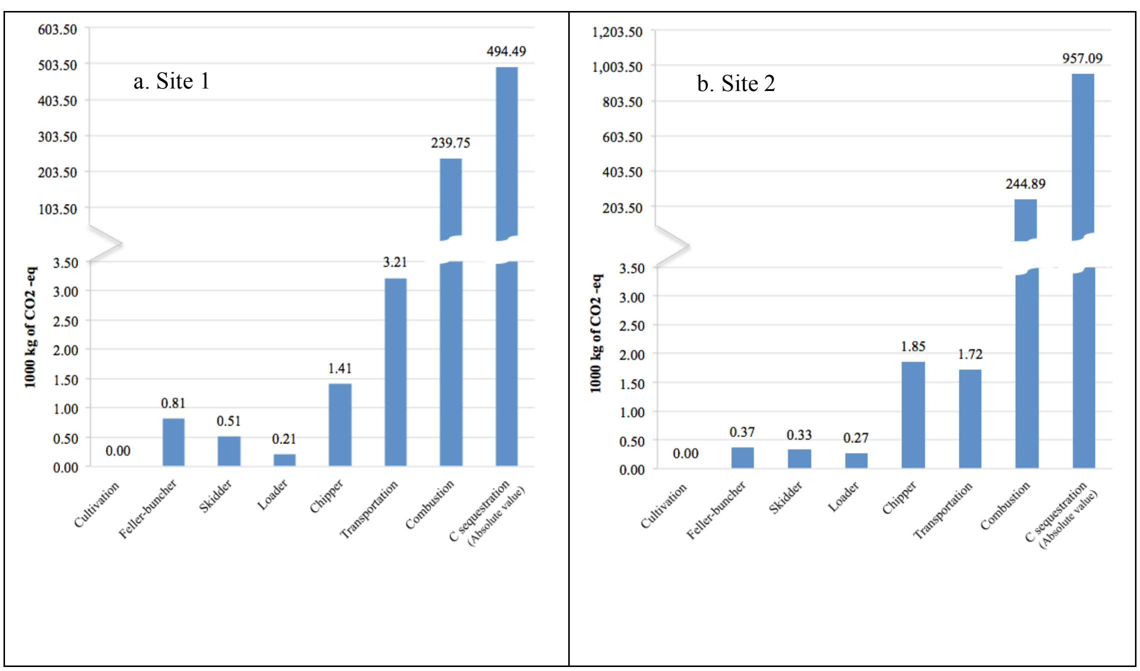
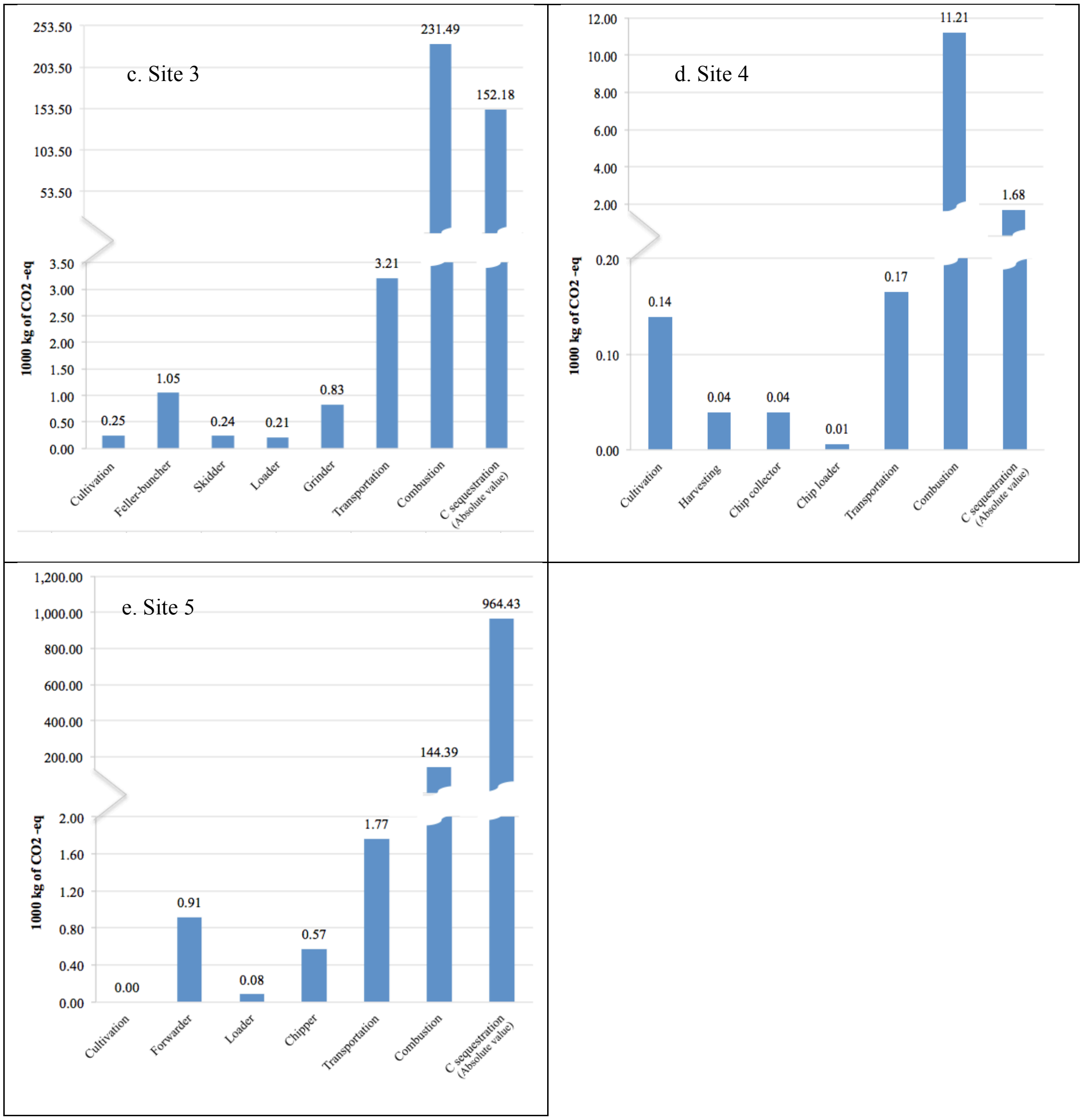
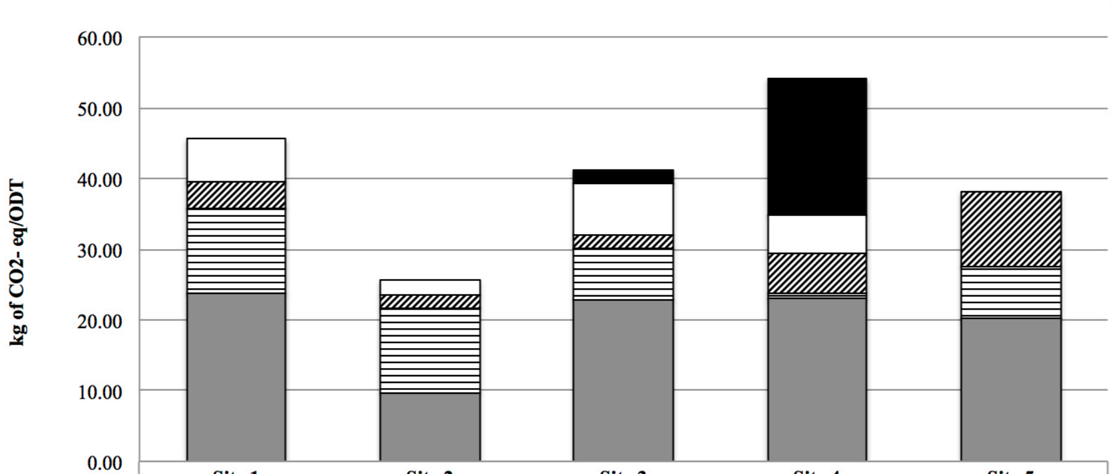


Figure 15 a-e. GHG emissions contribution of Site 1 to Site 5

Figure 15a-e (cont'd)





	Site 1	Site 2	Site 3	Site 4	Site 5
Cultivation	**0.00** (0%)	**0.00** (0%)	**1.76** (4%)	**19.32** (36%)	**0.00** (0%)
Harvesting	**6.02** (13%)	**2.06** (8%)	**7.46** (18%)	**5.47** (10%)	**0.00** (0%)
Collecting	**3.75** (8%)	**1.86** (7%)	**1.71** (4%)	**5.47** (10%)	**10.41** (27%)
Pre-processing	**12.01** (26%)	**12.00** (47%)	**7.40** (18%)	**0.81** (1%)	**7.51** (20%)
Transportation	**23.81** (52%)	**9.73** (38%)	**22.84** (55%)	**23.05** (43%)	**20.13** (53%)

Figure 16. GHG emissions of cultivation, harvesting, collecting, pre-processing (loading + grinding/chipping), and transportation in Site 1 to 5

Fiala and Bacenetti (2011) reported GHG emissions from harvesting 5-6 years old poplar plantations ranging from 15.7 to 18.2 kg CO_2-eq/ODT. These values are comparable with the results we obtained from Site 3, which was 16.57 kg CO_2-eq/ODT. The total GHG emissions from cultivation, harvesting and transportation stages in the Site 3 case were found to be 41.17 kg CO_2-eq/ODT. This was lower than the number reported by Vasquez Sandoval (2015) of 93.1 kg CO_2-eq/ODT. This large difference is mainly due to the higher emissions (34 kg CO_2-eq/ODT) in their cultivation stage, and 13.9 kg CO_2-eq/ODT emissions from a land restoration activity, which was not considered in our study.

Caputo et al. (2014) conducted a LCA to quantify GWP in different short rotation willow biomass production scenarios. In one of the scenarios, the total GWP was about 61.22 kg CO_2-eq per dry ton of woody biomass produced, including cultivation, harvesting (with a Case New Holland forage harvester), and transportation

(transportation distance = 44 miles (or 71 km)). The GHG emissions in Site 4 (54.12 kg CO_2-eq/ODT) were slightly lower but comparable with the number reported by Caputo et al. (2014). The difference may be caused by the higher GHG emissions in the cultivation stage in Caputo et al. (2014). Krzyżaniak et al. (2016) have reported average GHG emissions of 44.54 kg CO_2-eq/ODT and 61.67 CO_2-eq/ODT in hybrid willow plantations when transportation distances were 31 miles (or 50 km) and 62 miles (or 100 km). They also highlighted that N, P, K fertilizer application contributed 74% to the total global warming potential, therefore, the cultivation stage was the largest GHG emissions contributor and should be carefully managed. Overall, the GHG emissions in each study site were in a comparable range with previous studies.

In all study sites, biomass combustion was consistently the largest contributor to the GHG emission (**Fig. 15a-e**). This is consistent with the emission factors reported by EPA (2014). As discussed above, although these emissions could be sequestrated by future biomass growth, the global warming effect caused by this remaining carbon flux should not just be neglected (Cherubini et al., 2011; Helin et al., 2013). As such, it is very important to optimize biomass combustion efficiency and to minimize the GHG emissions in this stage. The second largest GWP contributor was transportation, which contributed 52%, 55%, 43%, and 53% to the total GWP in Site 1, 3, 4, and 5. In Site 2, transportation only contributed 38% because the transportation distance was less than 5 miles. This finding suggested that transportation played an important role in total GWP in addition to combustion, a result confirmed by other cradle-to-gate LCA studies of woody biomass supply chain (Michelsen et al., 2008; Neupane et al., 2011; Handler et al., 2014; Chen et al., 2017).

6.5.2 Soil C sequestration and its uncertainty

Forests sequester CO_2 from the atmosphere by photosynthesis; the sequestered C is either converted into biomass or fixed into soil organic matter pool through litter decomposition (Gru¨ neberg et al., 2014). As the largest carbon pools (about 80%) in Earth's terrestrial ecosystems, soil organic carbon plays an important role in offsetting the carbon emissions in bioenergy production systems (Lal, 2008; Helin et al., 2013; Qin et al., 2016). Qin et al. (2016) suggested that including soil organic carbon (SOC) sequestration in LCA could significantly influence the total GHG footprints of bioenergy production systems, which is corroborated by our findings. In Site 1, 2 and 5, soil C sequestration fully offsets all GHG emissions generated in biomass production and combustion stages (**Fig 15 a, b and e**). However, soil C changes can be highly impacted by vegetation type, stand age, and the time period considered. For instance, soil C loss is observed in sites that are newly converted from forestland or agricultural land to SRWC plantation (Grigal and Berguson, 1998; Arevalo et al., 2011). This is because during site preparation, tillage disrupts soil structure and causes soil organic matter oxidation. In addition, in the first two years, the litter contribution from young trees is lower than agricultural land, which leads to decreased soil microbial activity and soil organic matter input (Arevalo et al., 2011). The total soil C increases after two years of plantation establishment, soil C formation rates were faster after year 4, and the total soil C slowly reached the pre-plantation level at year 7 (Arevalo et al., 2011). Similarly, Qin et al. (2016) reported that soil C level decreased during 0-5 years in cropland to willow, forestland to willow, and grassland to willow sites. Owing to this fact, the soil C sequestration in Site 3 was much lower, and the net GWP at these sites was higher than

Sites 1, 2, and 5. Although soil C increase rate at Site 4 is higher that other study sites, due to the shorter time period of Site 4 (seven years), the total soil C increase is still lower than Site 1, 2, and 5. In conclusion, after subtracting the CO_2-eq sequestration from the total GHG emissions, the net GWP caused by woody biomass production systems could be very low, even negative. However, with such high uncertainties found in soil C sequestration values, future work is required to develop a consistent approach to include soil C in LCA. In addition, more effort is needed to develop a soil C model that includes different soil C sequestration rates under different vegetation types, time horizons, and soil depths.

6.5.3 Sensitivity analysis: impacts of transportation distance, biomass moisture content and biomass HHV on the GHG emissions.

To reveal how changes in transportation distance, biomass moisture content, and biomass HHV affect the GHG emissions in each site, sensitivity analyses were conducted (**Fig. 17a-e**). The biomass moisture content and biomass HHV both have a non-linear effect on the GWP, while the transportation distance has a linear effect. Compared to moisture content and transportation distance, changes in biomass HHV have the largest impact on GHG emissions. The major cause of this observation is the non-linear relationship between biomass HHV and biomass recoverable heating value. Based on Equation [2], a 50% increase in biomass HHV can increase the total recoverable heat by over 50%, reducing the biomass feed rate and combustion emissions by more than 50%. Due to the nonlinearity in HHV's sensitivity, reducing HHV is more problematic than raising HHV is beneficial. This suggests that combusting wood pellets with low HHV raises more concerns in causing high GHG emissions.

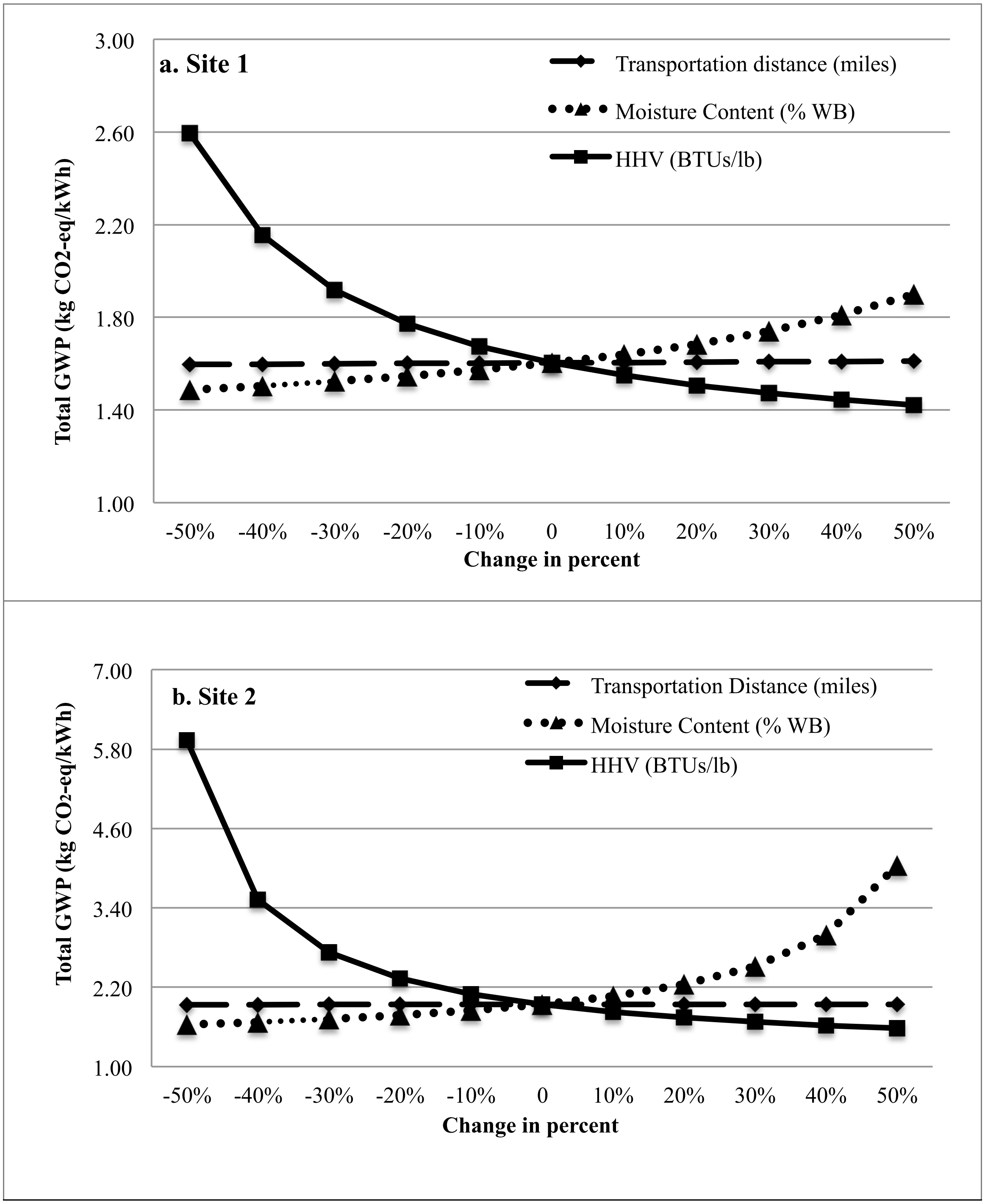
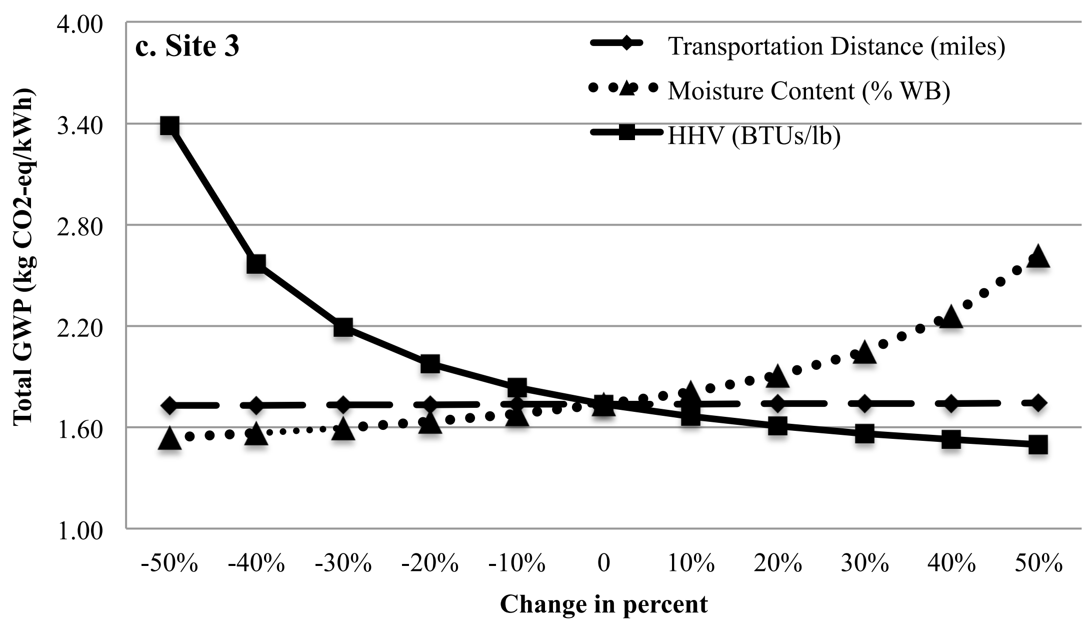


Figure 17 a-e. Sensitivity analysis of Site 1 to 5: impacts of transportation distance, biomass moisture content and biomass HHV on the GWP

Figure 17 a-e (cont'd)



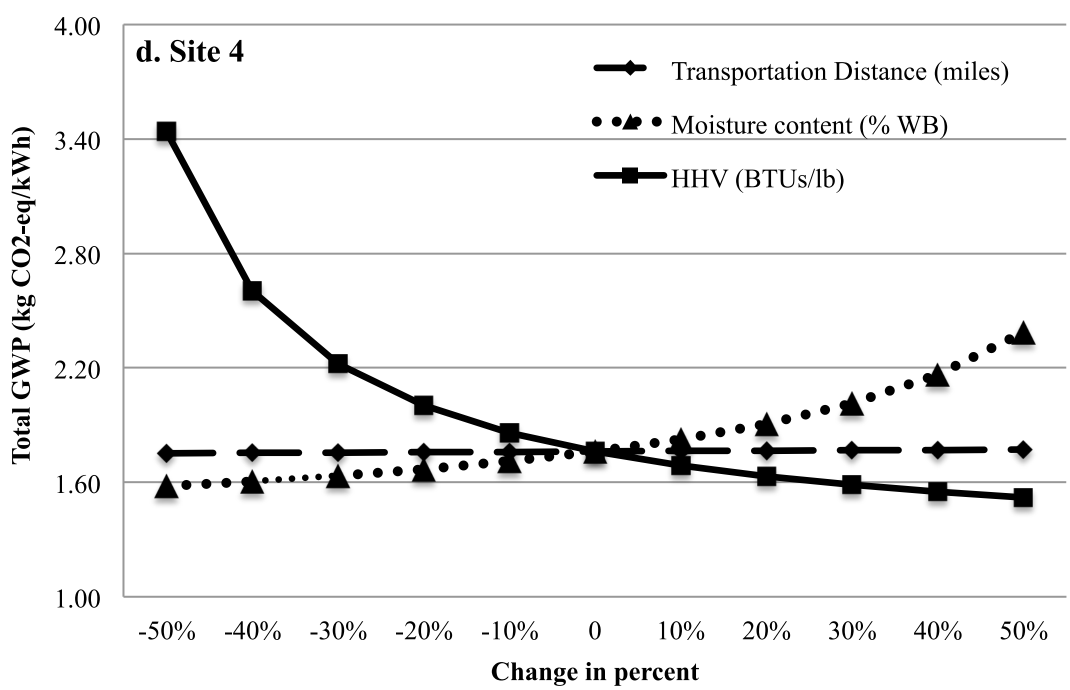
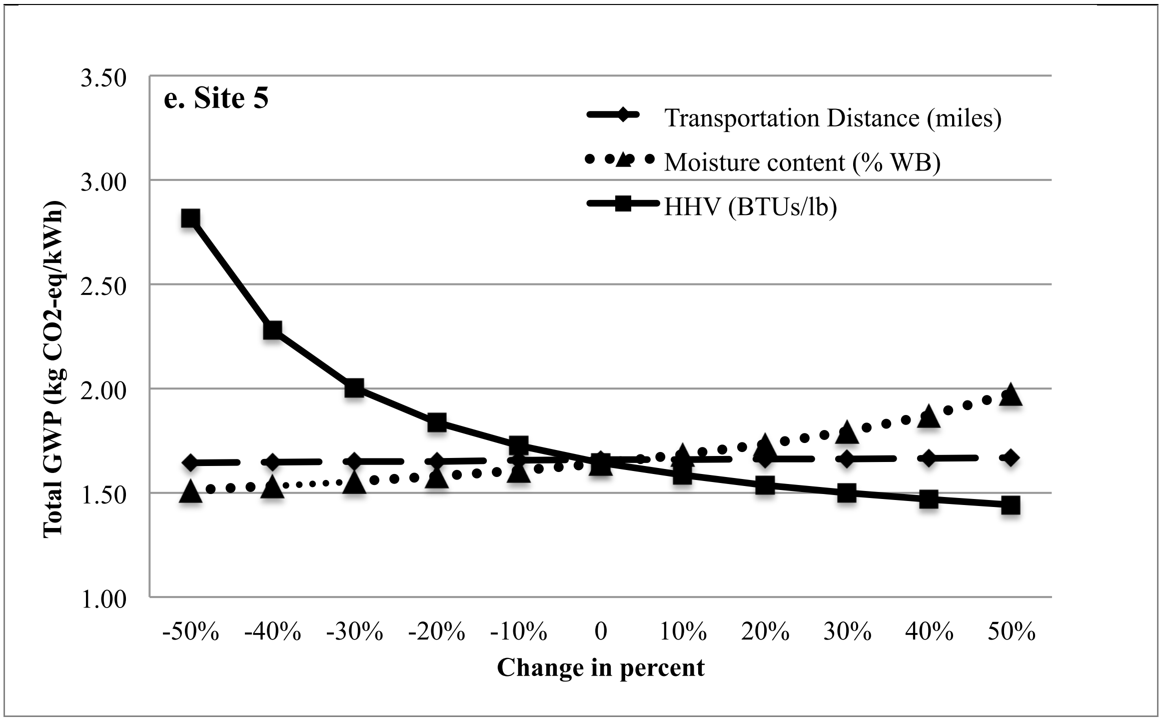


Figure 17 a-e (cont'd)



Variation of biomass moisture can non-linearly affect emissions, as impacts are larger when biomass is wetter. Assuming that green woody biomass has a HHV of 9,173 Btus/lb and a moisture content of 35%, the recoverable heating value is calculated to be 4,250 Btus/lb; if the moisture content rises from 35% to 70%, the recoverable heating value decreases to 1,290 Btus/lb (about 70% decrease). To satisfy the same energy demand, more than twice the amount green biomass will be required. Because wetter biomass has a lower recoverable heating value, more biomass is required for energy generation, resulting in increased emissions.

Woody biomass transportation has been largely studied, with key focuses on location selection and transportation distance minimization (Zhang et al., 2011; Alam et al., 2012). However in this study, transportation distance has small and linear impact on GHG emissions. In all study sites, each 10% decrease or increase in transportation distance only causes 0.04% to 0.11% decrease or increase in the total GWP produced. Therefore, transport distances under 75 miles do not practically contribute to GWP.

6.5.4 Energy Return on Investment (EROI)

To evaluate the energy use efficiency of the biomass production system, the fossil fuel energy input and the total renewable energy gained were calculated and presented in kWh (**Fig. 18a-e**).

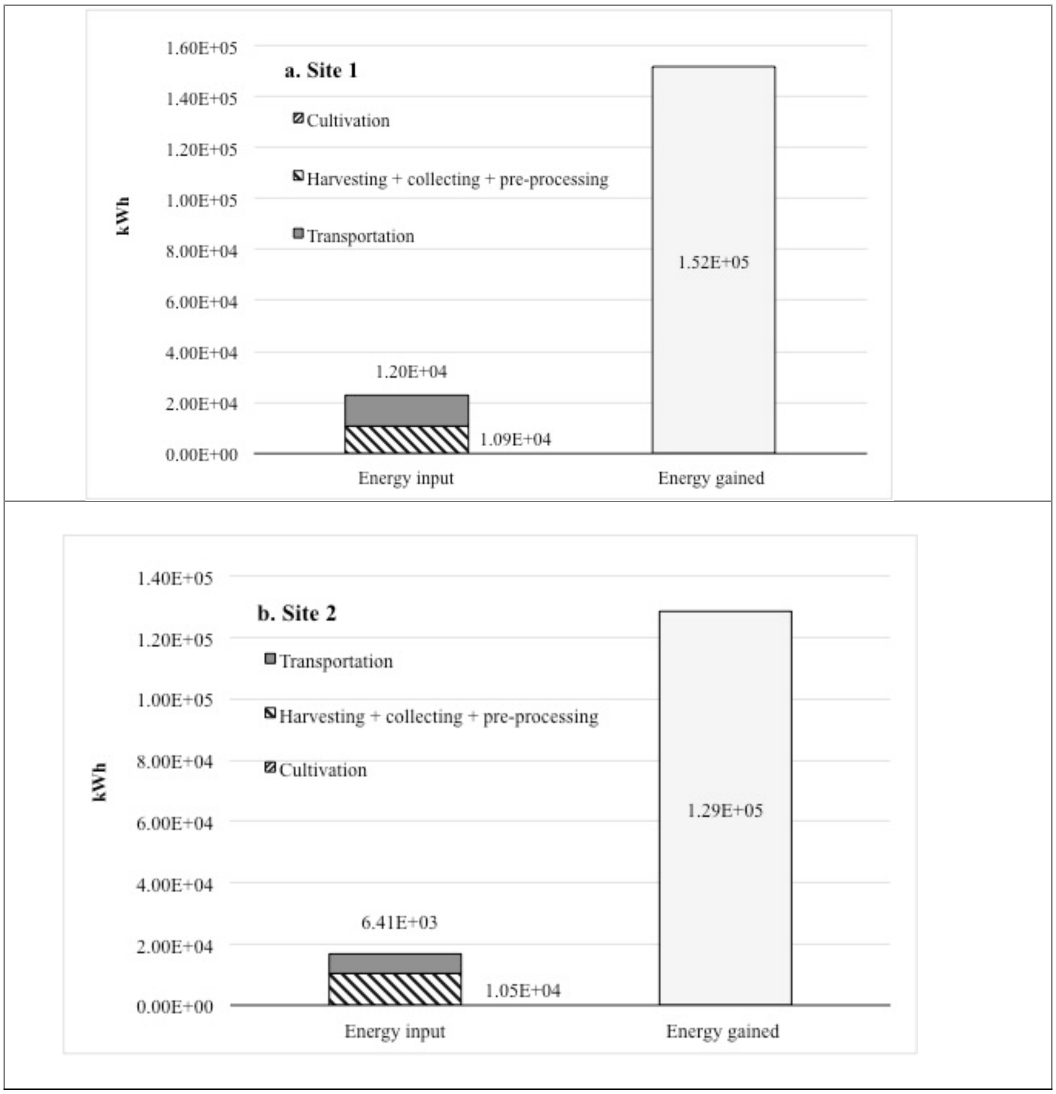
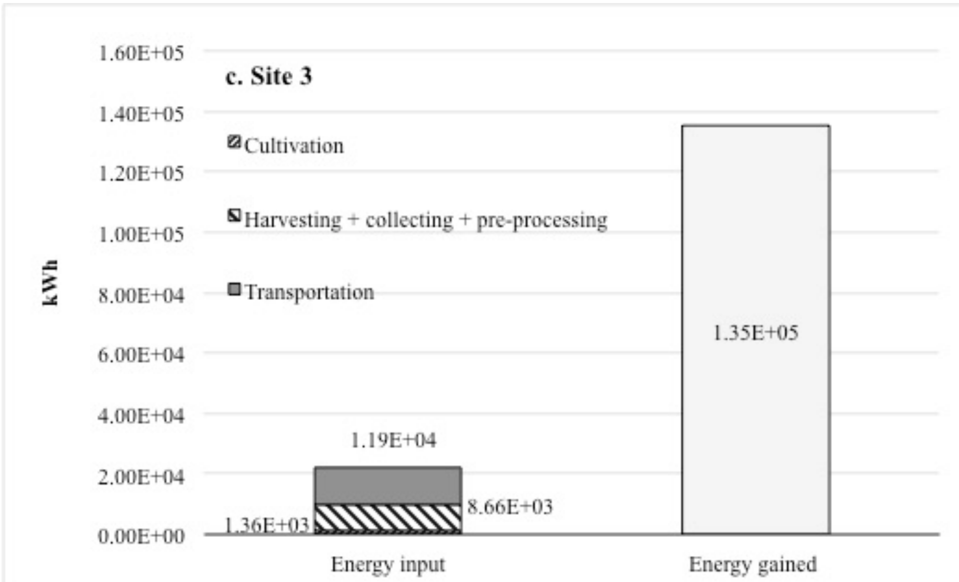


Figure 18 a-e. Energy input and out of Site 1 to 5

Figure 18 a-e (cont'd)



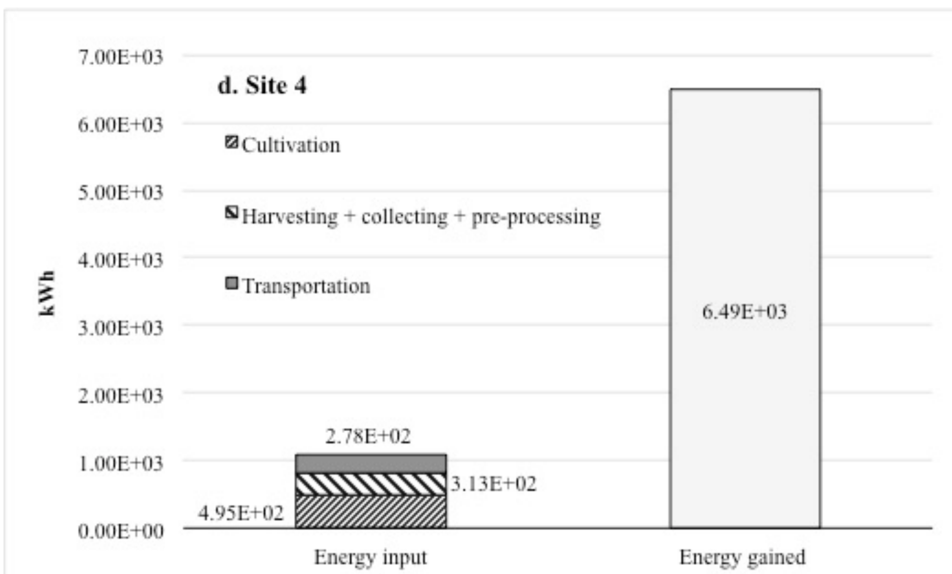
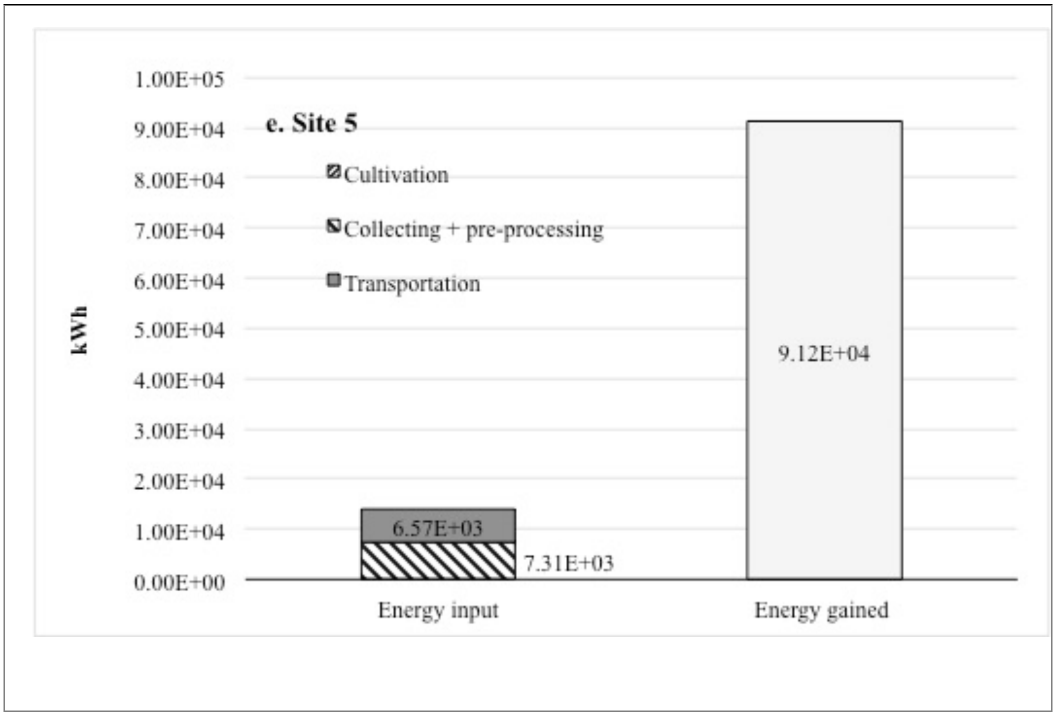


Figure 18 a-e (cont'd)



In Site 1, 2 and 5, the fossil fuel energy inputs in the cultivation stage were 0 because these sites were hand planted and managed manually. The overall EROI in Site 1 to 5 were determined to be 6.63, 7.60, 6.16, 5.97 and 6.57, respectively. The highest EROI was found in Site 2 because the much shorter transportation distance (4.5 miles) and lower fossil fuel consumptions. The lowest EROI of 5.67 observed in Site 4 was mainly due to the relatively larger fossil fuel inputs in the cultivation stage. Statistically, it is not fair to compare the EROI of the five study sites because there is no replication for each production system. In addition, fossil fuel input in each study site heavily depends on the specific management practices (site preparation, fertilization application and herbicide application), harvesting operation productivities, and transportation distances. However, we can still reach some general conclusions. First, in Site 1, 2, 3 and 5, transportation is consistently the largest contributor to the total fossil fuel consumption (54%, 38%, 54% and 53%). The second largest contributor is the biomass loading plus grinding/chipping stage, in Site 1, 2, 3 and 5, it consumed 24%, 41%, 18% and 20% of the total fuel consumption, respectively. These results suggest that in order to improve the EROI of a woody biomass supply chain that is harvested by traditional harvesting system, transportation and biomass handling stages should be the key focuses. Second, in SRWC plantations (Site 3 and Site 4) management practices in the cultivation stage should be carefully planned. In Site 3, fossil fuel input during cultivation only accounts for 7% of the total value because the insecticide and herbicide were manually applied. In Site 4, all management practices were done using machines, and cultivation accounts for 27% of the total fossil fuel consumption. The high capital inputs (machinery use and fertilization) caused by intensive management practices in energy crops production systems have also been reported by Liska et al. (2009), Grassini et al. (2012) and Djomo et al. (2015).

EROI values of bioethanol production systems were reported to be around 3 to 5 based on 31 previous LCAs (Hall et al., 2013). Zaimes et al. (2015) reported EROIs ranged from 1.52 to 2.56 in fast pyrolysis systems using perennial grasses. They concluded that the major reasons for the low EROI were high fossil hydrogen consumption and a high process electricity requirement. Later in 2017, after about 40% reduction in hydrogen use, Zaimes et al. reported EROIs from 1.32 to 3.76 using SRWC in several multistage torrefaction and pyrolysis systems. Compared to liquid biofuels, wood torrefaction, and pyrolysis, producing wood pellets for electricity generation from these five sites appears to achieve a higher EROI.

6.5.5 Nutrient Removal and Abiotic Depletion Potential (ADP)

The 95th percentiles in the N, P, and K simulated distributions were used to quantify the nutrient removal in each study site (Table 28). Nutrient removal caused by forest harvesting has been largely studied due to concerns of nutrient depletion in forest soils (Stark, 1979; Paré and Thiffault, 2016). Among the five studied sites, the least nutrient removal occurred in Site 5 because only the logging residues were collected for energy production. Saunders et al. (2011) have conducted a study to analyze nutrient concentration of logging residues in mixed-wood forests in Maine, U.S. They reported that lower nutrient (N, P, K) concentrations were found in softwood debris compared to hardwood, which is also confirmed by the analysis of tree nutrient content published by Paré et al. (2013). This result suggests that using wood chips generated from softwood species could reduce nutrient removal compare to hardwood species.

Table 28. Nutrient removal in each studied site

	Site 1	Site 2	Site 3	Site 4	Site 5
Biomass harvested (ODT)	134.94	177.31	140.48	7.18	87.73
N concentration (%)	3.26	2.94	3.84	3.15	1.65
P concentration (%)	0.29	0.35	0.43	0.31	0.17
K concentration (%)	1.52	1.56	2.02	1.87	0.68
N removed (kg)	3,990.77	4,729.06	4,893.81	205.24	1,313.13
P removed (kg)	355.01	562.98	548.00	20.20	135.29
K removed (kg)	1,860.73	2,509.30	2,574.35	121.84	541.17

The total ADPs in Site 1 to 5 were calculated as 4.93E-04 kg antimony/kWh (or 0.55 kg antimony/ODT), 6.89E-04 kg antimony/kWh (or 0.50 kg antimony/ODT), 6.77E-04 kg antimony/kWh (or 0.65 kg antimony/ODT), 5.92E-04 kg antimony/kWh (or 0.54 kg antimony/ODT) and 2.69E-04 kg antimony/kWh (or 0.28 kg antimony/ODT), respectively. There are only a few studies that estimated ADP in bioenergy production systems. Krzyżaniak et al. (2015) reported a range of ADP from 0.31 to 0.74 kg antimony/ODT in hybrid willow production systems with different biomass production yield. Luo et al. (2009) and Bai et al. (2010) have reported ADP of producing bioethanol using sugarcane and switchgrass. However, the functional unit in these two studies is defined as power to wheels for 1 km driving of a midsize car, which is very difficult to compare with our functional unit.

6.6 Conclusion

This LCA estimated the environmental impacts generated in five woody biomass production systems in Michigan, U.S., including cultivation, biomass harvesting, collecting, pre-processing, transportation, and combustion stages. The estimated GWP in all study sites were in a comparable range with previous published LCAs. It is important to note that, among all studied life cycle stages, biomass combustion consistently contributes about 95% to 97% of the final GWP. Biomass HHV and biomass moisture content are the two most important factors in biomass combustion efficiency; they highly affect total energy production and resulting GWP emissions. In our cradle-to-plant gate scope, transportation contributed from 35% to 55% of total GWP and was determined to be the largest source of GWP. This finding confirmed with other previous studies and suggested that biomass transportation was a key link to minimize environmental burdens in biomass value chains. Soil C sequestration played a significant role in reducing the net GWP of woody biomass production system, and when included, results in all five sites becoming carbon negative. However, due to the high uncertainties in accounting soil C stocks, future research is required to quantify soil C changes under different scenarios and to develop a consistent and comprehensive approach to include soil C in LCA. In terms of EROI, using woody biomass for electricity production may be a better option compared to other bio-products such as liquid biofuels and wood pellets. The EROI of producing wood chips greatly depends on the transportation efficiency and biomass pre-processing (loading and grinding/chipping) productivities. Also, in SRWC plantation, intensive machinery management should be reduced to improve the EROI. The nutrient removal and ADP were lower when using softwood pellets produced from logging residues from the CTL harvesting system vs. using hardwood pellets produced from WT harvesting system. To reduce the nutrient depletion in forest ecosystems, careful selection should be made in choosing tree species.

In conclusion, considering the large amount of GHG emissions and the long time required to sequester these emissions, biomass combustion should be included in future LCAs of woody biomass supply chains. In order to reduce the GHG emissions from the combustion stage, future research efforts should be aimed to provide biomass with lower moisture content and higher HHV. Utilizing woody biomass for bioenergy production can be carbon neutral while including soil C increase during biomass growth, however future work is needed to reduce the uncertainties of including soil C in LCAs.

CHAPTER 7 MULTI-CRITERIA OPTIMIZATION FOR WOODY BIOMASS SUPPLY CHAIN IN MICHIGAN

7.1 Introduction

Historically, woody biomass has been recognized as a “carbon neutral” energy resource, and has been recommended for large-scale production to mitigate CO_2 emissions and to replace established fossil fuels. Unlike the steady state operation of fossil fuel, the supply chain of woody biomass can be highly complex because of its reliance on several activities such as biomass availability, the demand of consumers, the logistical cost, and various regulations and policies (Soylu, 2006). In the past decades, many studies has been published to predict and to reduce the logistics cost in the woody biomass. Woody biomass transportation cost accounts for the largest part of the total cost and energy consumption (Eriksson and Bjö̈rheden, 1989; Allen et al., 1998; Alam et al., 2012). Thus, optimization models have been developed to identify the optimal location of bio-refinery or power plant in Italy (Freppaz et al., 2004), Austria (Schmidt et al., 2009), Greece (Rentizelas and Tatsiopoulos, 2010), Sweden (Leduc at al., 2010 aandb), Finland (Natarajan et al., 2014), Colombia (Duarte et al., 2014), and U.S. (Kim et al., 2011 aandb). Lautala et al. (2012) have published a cost minimization model to minimize the cost for woody biomass transportation using railroads in Michigan and Wisconsin. However, a woody biomass production system with minimized cost might have high carbon footprints. Therefore, it is critical to include both the economic and environmental criteria when optimizing the biomass production system and understand the trade-off between the two objectives.

Multi-criteria optimization has been commonly used to support decision making with multiple competing criteria in renewable energy systems. Ayoub et al. (2009) proposed a multi-level optimization model to determine the bioenergy generation plan using different energy sources, with optimized energy efficiency, total cost and CO_2 emissions for Japan. Zamboni et al., (2009) have developed a multi-objective environmental optimization model to apply in a corn-based bioethanol system in Italy. You and Wang (2011) presented a county-level optimization model to determine the optimal biomass (agricultural, energy crops, and wood residues) supply chain design under economic and environmental criteria in Iowa. Multi-objective optimization framework has also been used to determine the conversion technologies, facility size, location, and raw material in a global scale (Giarola et al. 2011 and 2013). Santibañ ez et al. (2011, 2015 and 2016) developed three different multi-objective optimization models to address different needs in the bio-refinery supply chain in Mexico using multi-feedstock.

There are only a few studies focus on multi-criteria optimization in woody biomass supply chain. Steubing et al. (2012) developed a strategy to determine the optimal size and location of a bioenergy plant that converts wood to synthetic natural gas in Switzerland. The minimal cost can be achieved when the plant size is around 100-200 MW, however if the environmental performance is considered, the optimal plant size is determined to be 90 MW. Kanzian et al. (2013) have formulated a model to maximize the profit and minimize the CO_2 emissions in a wood-based supply chain in Austria, with decision variables of pre-processing location, transportation mode, volume and terminal. The results suggested that with 4.5% increase in CO_2 emissions, the profit can be increased to more than twice. A strategic multi-objective optimization framework was developed to design the optimal supply chain networks with maximum Net Present Value (NPV) and minimal GHG emissions, for woody biomass supply chain in 20 years horizon (Cambero et al., 2016). This model was applied in a case study in British Columbia, Canada. The results indicated that converting woody biomass to pellet and bio-oil and export to Europe could achieve the highest NPV and lowest GHG emissions. However, optimization model that considers both economic and environmental impacts of woody biomass supply chain in U.S. lacks (Shabani et al., 2013b), which indicates a great need for future study. In order to sustainably utilize woody biomass as a bioenergy source in Michigan and U.S., there is a great need to combine environmental and economic demands and develop a multi-criteria optimization framework. This study aims to 1) provide an optimized logistic strategy, which can minimize the total logistic cost and GHG emissions using multi-criteria optimization method, 2) and to examine the impacts of transportation distance and carbon tax policy on the biomass production strategy.

7.2 Problem description

Figure 19 presents the four decision nodes considered in this optimization model framework: biomass sources (B), harvesting system (H), pre-processing (P), and biomass conversion and utilization (C). In this model, the considered biomass sources include natural forest stand (FS), short rotation hybrid poplar (*Populus spp*.) (SRP) and short rotation hybrid willow (SRW). The natural forest stand is defined as a contiguous community of mixed hardwood and softwood species trees with uniform age and average DBH. The short rotation hybrid poplar is defined as a hybrid poplar plantation with the average tree DBH equal to 5-6 inches; while the short rotation hybrid willow is defined as a hybrid willow plantation with the average tree DBH equal to 2-3 inches.

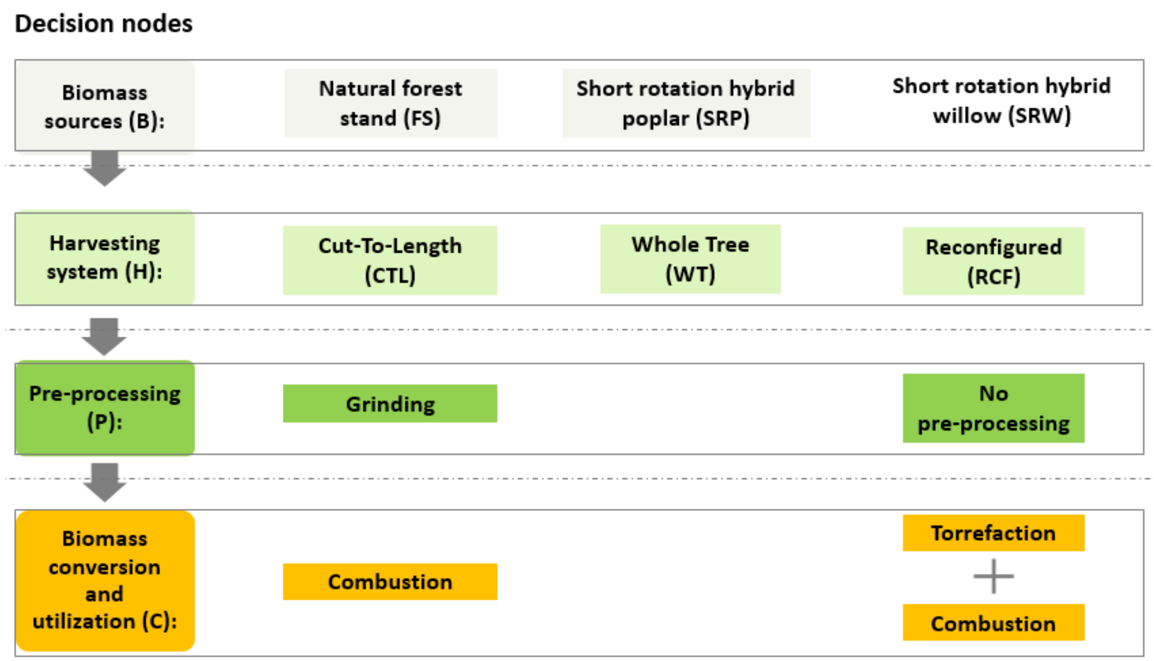


Figure 19. Decision nodes in the multi-criteria optimization model

Harvesting systems included in this model are Whole-Tree (WT) harvesting system, Cut-To-Length (CTL) harvesting system and reconfigured (RCF) harvesting system. It is assumed that biomass from natural forest stand can be harvested by both WT and CTL harvesting system. The selection of harvesting system for different biomass sources are based on below assumptions: 1) FS can be harvested by either WT or CTL harvesting system; 2) SRP can only be harvested by WT harvesting system; 3) SRW can only be harvested by RCF harvesting system. Also assumed is that all of the woody biomass will be harvested under the scenario of WT or RCF harvesting system, but with CTL harvesting system, only logging residues will be collected.

In WT and CTL harvesting system, the harvested biomass is directly pre-processed by a loader and a grinder. In RCF harvesting, biomass is harvested and chipped by the reconfigured harvesting machine, so there is no additional pre-processing associated.

There are two options in the biomass conversion and utilization stage: 1) the woody biomass can be directly delivered from the harvesting cite to the biomass power plant, and be co-fired with coal, or 2) the woody biomass can first be transported to a torrefaction plant, torrefied, and then delivered to the biomass power plant. Based on the above assumptions, a total of 8 routes were defined (Figure 20). The multi-criteria optimization model determines the weight (short green ton) of woody biomass assigned to each route, to meet the yearly total energy demand of a wood-based power plant, with minimal total logistic cost and GHG emissions.

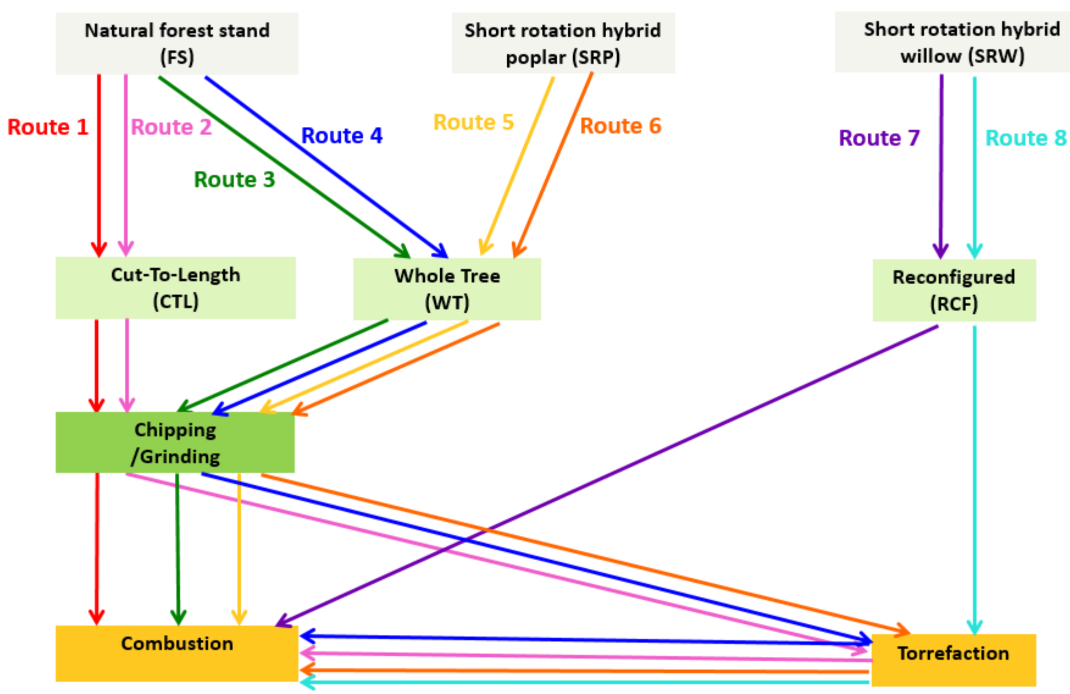


Figure 20. Defined possible routes in the multi-criteria optimization model

7.3 Mathematical model

7.3.1 Indices

a: decision variable (*a* = 1,2,…,8)

i: biomass sources (*i*: 1 = FS; 2 = SRP; 3 = SRW)

j: Harvesting systems (*j*: 1 = Cut-To-Length harvesting system; 2 = Whole-Tree harvesting system; 3 = reconfigured harvesting system)

k: Pre-processing (*k*: 1 = grinding; 2 = no pre-processing)

l: Biomass conversion and utilization (*l*: 1 = direct combustion; 2 = combustion after torrefaction)

m: transportation routes (*m*: 1 = from the harvesting site to biomass power plant; 2 = from the harvesting site to torrefaction depot; 3 = from the torrefaction depot to biomass power plant)

7.3.2 Parameters

EC_i: site establishment cost (pesticide and herbicide cost) of different biomass sources ($/gt),

GC_{ijk}: biomass generation cost, the total cost biomass harvesting, collection and preprocessing ($/gt) of different biomass sources, harvested by different harvesting systems, and pre-processed by different way,

TC_m: biomass transportation cost ($/short ton/mile) of different transportation routes, calculated using (1)

$TC_{lm} =$

$truck\ hourly\ cost\ \left(\frac{\$}{hr}\right) *$

$(predicted\ travel\ time\ (hr) * 2 + truck\ loading\ time) \div$

$biomass\ weight\ per\ truck\ load\ (short\ ton)$ (1)

The truck hourly cost of 70.07 $/hr is cited from previous study,

the predicted travel time is calculated using previous developed equation based on Michigan's road conditions:

$Total\ predicted\ time\ (hrs)\ =\ 1.130 * DR\ (miles)\ +\ 0.050 * GR\ (miles)\ +$

$0.092 * PR\ (miles)\ +\ 0.019\ Hwy\ (miles)\ -\ 0.403,$

the truck loading time of 0.67 hr is cite from previous study,

when m = 1 and 2, the biomass weight per truck load is 33 short tons (for 30-50% moisture content biomass),

when m = 3, the biomass weight per truck load is calculated as 90 short tons (truck volume = 145 yard^3; wood pellets density = 725 kg/m^3 (Adams et al., 2015))

TRC: biomass torrefaction cost ($/gt),

EE$_i$: GHG emissions from site establishment of different biomass sources (kg CO_2 – eq/gt),

GE$_{ijk}$: the total GHG emissions from biomass harvesting, collection and pre-processing stages (kg CO_2 –eq/gt) of different biomass sources, harvested by different harvesting systems, and pre-processed by different way

TE$_l$: GHG emissions from biomass transportation (kg CO_2 –eq/ short ton/mile) of green harvested biomass or wood pellets,

calculated using (2)

$TE =$

$(predicted\ travel\ time\ (hr) * 2 + truck\ loading\ time) *$

$truck\ fuel\ consumption\ \left(\frac{gals}{hr}\right) *$

$GHG\ emissions\ per\ gal\ of\ fossil\ fuels\ (\frac{\text{kg CO2 –eq}}{gal}) \div$

$biomass\ weight\ per\ truck\ load\ (short\ ton)$ (2)

The predicted travel time is calculated using previous developed equation based on Michigan's road conditions:

$Total\ predicted\ time\ (hrs) =$

$1.130 * Dirt\ Road\ (miles) + 0.050 * Gravel\ Road\ (miles) + 0.092 *$

$Paved\ Road\ (miles) + 0.019\ Highway\ (miles) - 0.403,$

the truck loading time of 0.67 hr is cite from previous study,

the truck fuel consumption of 12 gals/hr is cited from the Carter (2017),

GHG emissions from consuming one gallon of fossil fuel is 10.08 kg CO_2 –eq,

the biomass weight per truck load is 33 short tons for 30-50% moisture content biomass, and for wood pellets, the biomass weight per truck load is calculated as 90 short tons (truck volume = 145 $yard^3$; wood pellets density = 725 kg/m^3 (Adams et al., 2015))

TRE: GHG emissions from biomass torrefaction (kg CO_2 –eq/gt),

CBE_a: GHG emissions from the biomass combustion (kg CO_2 –eq/gt) using biomass from different sources, harvested and pre-processed by different methods, utilized and converted by different ways,

calculated by the Electronic Code of Federal Regulations 98.33 (e)(1),

BY_i: biomass yield (odt/acre) of different biomass sources is cited from previous studies,

MC_l: wet-basis moisture content (%) of biomass utilized and converted by different methods,

RHV_a: recoverable heating value (kWh/gt) of biomass from different sources, harvested and pre-processed by different methods, utilized and converted by different ways, calculated by the method provided by Ince (1979),

D_m: transportation distance between different transportation routes,

DB: annual energy demand of the biomass power plant (kWh),

C: daily processing capacity of the torrefaction depot (ODT/day),

N: number of torrefaction depots,

CS_i: carbon sequestration of different biomass sources (MG C/acre),

The values of all the parameters used in this model are presented in Table 29.

Table 29. Parameters used in the multi-criteria optimization model

	Parameters	Value	Unit	Remarks
		Cost parameters		
Establishment cost	EC1	0.79	$/gt	Chapter 3
	EC2	0.28	$/gt	Chapter 3
	EC3	0.8	$/gt	Chapter 3
Generation cost	GC11	17.26	$/gt	Chapter 3
	GC12	8.4	$/gt	Pan and Srivastava, 2013
	GC22	11.27	$/gt	Carter et al., 2016
	GC33	40.5	$/gt	Carter et al., 2016
Transportation cost	TC1	0.19	$/short ton/mile	Calculated
	TC2	0.19	$/short ton/mile	Calculated
	TC3	0.07	$/short ton/mile	Calculated
Torrefaction cost	TRC	69.97	$/gt	Cited
		GHG emissions parameters		
Establishment emissions	EE1	0	kg CO2 –eq/gt	Chapter 3 - TRC site
	EE2	0.93	kg CO2 –eq/gt	Chapter 3 - FBIC site
	EE3	10.47	kg CO2 –eq/gt	Chapter 3 - KBS site

Table 29 (cont'd)

Generation emissions	GE11	10.75	kg CO2 –eq/gt	Chapter 3- Gwinn site
	GE12	8.2	kg CO2 –eq/gt	Chapter 3- TRC site
	GE22	8.78	kg CO2 –eq/gt	Carter et al., 2016
	GE33	6.63	kg CO2 –eq/gt	Carter et al., 2016
Combustion emissions	CBE_1	937.24	kg CO2 –eq/gt	Calculated
	CBE_2	463.4	kg CO2 –eq/gt	Calculated
	CBE_3	942.19	kg CO2 –eq/gt	Calculated
	CBE_4	467.25	kg CO2 –eq/gt	Calculated
	CBE_5	978.96	kg CO2 –eq/gt	Calculated
	CBE_6	477.87	kg CO2 –eq/gt	Calculated
	CBE_7	998.62	kg CO2 –eq/gt	Calculated
	CBE_8	483.18	kg CO2 –eq/gt	Calculated
Transportation emissions	TRE1	0.33	kg CO2 –eq/short ton/mile	Calculated
	TRE2	0.33	kg CO2 –eq/short ton/mile	Calculated
	TRE3	0.12	kg CO2 –eq/short ton/mile	Calculated
Torrefaction emissions	TRE	21.76	kg CO2 –eq/gt	Cited
		Biomass properties		
Biomass yield	BY1	6.21	ODT/acre	Chapter 3- TRC site
	BY2	18.01	ODT/acre	Chapter 3- FBIC site
	BY3	6.53	ODT/acre	Chapter 3- KBS site
Biomass moisture content	MC1	50	% (wet-basis)	Chapter 3
	MC2	50	% (wet-basis)	Chapter 3
	MC3	5	% (wet-basis)	Chapter 3

Table 29 (cont'd)

Biomass lower heating value	RHV_1	689.46	kWh/short ton	Chapter 3
	RHV_2	1423.97	kWh/short ton	Chapter 3
	RHV_3	689.24	kWh/short ton	Chapter 3
	RHV_4	1423.36	kWh/short ton	Chapter 3
	RHV_5	687.60	kWh/short ton	Chapter 3
	RHV_6	1421.68	kWh/short ton	Chapter 3
	RHV_7	686.73	kWh/short ton	Chapter 3
	RHV_8	1420.83	kWh/short ton	Chapter 3
Other parameters				
Transportation distance	D1	20	miles	Assumption
	D2	20	miles	Assumption
	D3	20	miles	Assumption
Power demand	DB	50	MWh	Assumption
Daily capacity of torrefaction depot	C	100	ODT/day	Assumption

7.3.3 Decision Variables

x_a: the green weight (short ton) of woody biomass from *i* biomass source, harvested by *j* harvesting system, pre-processed by *k* method, and converted and utilized using *l* method.

The eight decision variables included in this model are described as below:

x_2: the green weight (short ton) of woody biomass from FS, harvested by CTL harvesting system, grinded, and directly combusted,

x_3: the green weight (short ton) of woody biomass from FS, harvested by CTL harvesting system, grinded, torrified, and combusted,

x_4: the green weight (short ton) of woody biomass from FS, harvested by WT harvesting system, grinded, and directly combusted,

x_5: the green weight (short ton) of woody biomass from FS, harvested by WT harvesting system, grinded, torrified, and combusted,

x_6: the green weight (short ton) of woody biomass from SRP, harvested by WT harvesting system, grinded, and directly combusted,

x_6: the green weight (short ton) of woody biomass from SRP, harvested by WT harvesting system, grinded, torrified, and combusted,

x_7: the green weight (short ton) of woody biomass from SRW, harvested by RCF harvesting system, and directly combusted,

x_8: the green weight (short ton) of woody biomass from SRW, harvested by RCF harvesting system, torrified, and combusted.

7.3.4 Objective functions

The first objective function of this model is to minimize the total biomass production cost (a sum of site establishment cost, biomass generation cost, transportation cost, conversion cost) per kWh electricity generated. The cost minimization function is specified as below:

$$\boldsymbol{Cost}\ (¢/\text{kWh}) =$$

$$\left[\sum_{i=1}^{3}\sum_{a=1}^{8} EC_i\, x_a + \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{2}\sum_{a=1}^{8} GC_{ijk}\, x_a + \sum_{l=1}^{3}\sum_{a=1}^{8} TC_l\, x_a + \sum_{m=1}^{3} TRC \times D_m \times (x_2 + x_4 + x_6 + x_8)\right] * 100 \div \sum_{a=1}^{8} LHV_a\, x_a$$

The second objective function of this mode is to minimize the total GHG emissions (kg CO_2 - eq) per kWh electricity generated. The GHG emissions minimization function is specified as below:

$$GHG(kg\ CO_2 - eq/kWh) =$$

$$\left[\sum_{i=1}^{3}\sum_{a=1}^{8} EE_i\, x_a + \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{2}\sum_{a=1}^{8} GE_{ijk}\, x_a + \sum_{l=1}^{3}\sum_{a=1}^{8} TE_l\, x_a + \sum_{m=1}^{3} TRE \times D_m \times (x_2 + x_4 + x_6 + x_8) - \sum_{i=1}^{3}\sum_{a=1}^{8} CS_i\, x_a\right]$$

$$\div \sum_{a=1}^{8} LHV_a\, x_a$$

7.3.5 Constraints

There constraints in this model are specified as below:

1) The recoverable heating value of the biomass generated needs to satisfy the total annual power demand of the 50 MW biomass power plant;
2) The total woody biomass send to the torrifaction plant(s) do not exceed the total plant(s) capacity.
3) The annual total biomass consumed is less than 650,000 green tons.

7.4 Case scenarios

The developed multi-criteria optimization model is applied for five case scenarios. In case 1 scenario (base scenario), it is assumed that the wood basket has a radius of 20 miles and there is a torrefaction depot located in the center or the wood basket. The wood basket and the torrefaction depot unit are 20 miles away from a biomass power plant. In case 2 to 5, the unit number of the combination of one wood basket with one centralized torrefaction depot is increased from 2 to 5.

7.5 Algorithm

This multi-criteria optimization model was solved in Matlab, using the Non-dominated Sorting Genetic Algorithm II (NSGA- II) method developed by Deb et al. (2002). For each case scenario, a total of 100,000 solutions were produced through 1,000 solutions generations. In the first generation, 100 solutions will be randomly generated. The generated solutions that meet the constraints were ranked based on their associated objective function values. The dominated solutions are eliminated and only the non-dominated solutions were selected to produce 100 solutions in the next generation. After 1000 generations, 100 non-dominated solutions were selected out of the total 100,000 solutions generated and be plotted in the pareto-optimal sets.

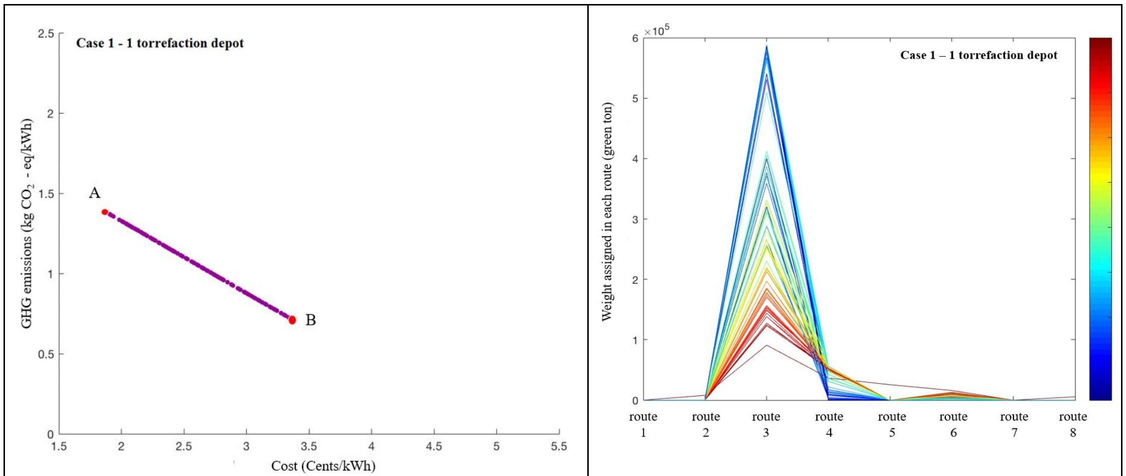
7.6 Results

7.6.1 Pareto-optimal sets analysis

Fig. 21a - 25a present the pareto-optimal sets in the 5 case scenarios, which are the optimized solutions sets generated by the NSGA-II for each case study. The x- and y-axes are the production cost (¢/kWh) and GHG emissions (kg CO_2 - eq/kWh). In each pareto-optimal set figure, 100 points are plotted, and each point represents one optimized solution (**Fig. 21a - Fig. 25a**). The x- and the y-coordinates are the cost and the GHG emissions of that solution.

The pareto-optimal sets of case 1 scenario are presented in **Fig. 21a**. Point A in **Fig. 21a** is the solution with the lowest cost (1.88 ¢/kWh) and the highest GHG emissions (1.38 kg CO_2 – eq/kWh). To achieve this solution, all of the woody biomass will be allocated to route 3. A total of 586,617 green tons of woody biomass will be grown from FS, harvested by WT harvesting system, grinded at the harvesting site into wood chips, and directly delivered to the biomass power plant. The cultivation cost, biomass generation cost, transportation cost and torrefaction cost are 0.115 ¢/kWh (6.08%), 1.219 ¢/kWh (64.67%), 0.551 ¢/kWh (29.25%), and 0.000 ¢/kWh (0.00%), respectively. The GHG emissions from the cultivation, biomass generation, transportation, torrefaction and combustion stages are 0.000 kg CO_2 – eq/kWh (0.00%), 0.012 kg CO_2 – eq/kWh (0.86%), 0.010 kg CO_2 – eq/kWh (0.69%), 0.000 kg CO_2 – eq/kWh (0.00%), and 1.367 kg CO_2 – eq/kWh (98.45%), respectively.

Point B in **Fig. 21a** is the solution with the lowest GHG emissions (0.71 kg CO_2 – eq/kWh) but the highest cost (3.36 ¢/kWh) in case scenario 1. Biomass weight allocated in each route are: 0.00 green tons (route 1), 0.00 green tons (route 2), 123,200.67 green tons (route 3), 52,400.23 green tons (route 4), 0.00 green tons (route 5), 12,965.17 green tons (route 6), 0.00 green tons (route 7), and 0.00 green tons (route 8), respectively. Compared to solution A, the biomass green weight in route 3 in solution B are largely reduced and spread to route 4 and route 6. The cultivation cost, biomass generation cost, transportation cost and torrefaction cost are 0.068 ¢/kWh (2.04%), 0.780 ¢/kWh (23.28%), 0.364 ¢/kWh (10.85%), and 2.138 ¢/kWh (63.82%), respectively. The GHG emissions from the cultivation, biomass generation, transportation, torrefaction and combustion stages are 0.000 kg CO_2 – eq/kWh (0.00%), 0.007 kg CO_2 – eq/kWh (1.05%), 0.006 kg CO_2 – eq/kWh (0.87%), 0.007 kg CO_2 – eq/kWh (0.99%), and 0.691 kg CO_2 – eq/kWh (97.03%), respectively. Switching from solution A to solution B, the GHG emissions can be reduced by 0.66 kg CO_2 – eq/ kWh, yet the cost will climb up by 1.46 ¢/kWh. The trade-off between rising up cost and reducing GHG emissions in case 1 is 2.21 ¢/ kg CO_2 – eq.



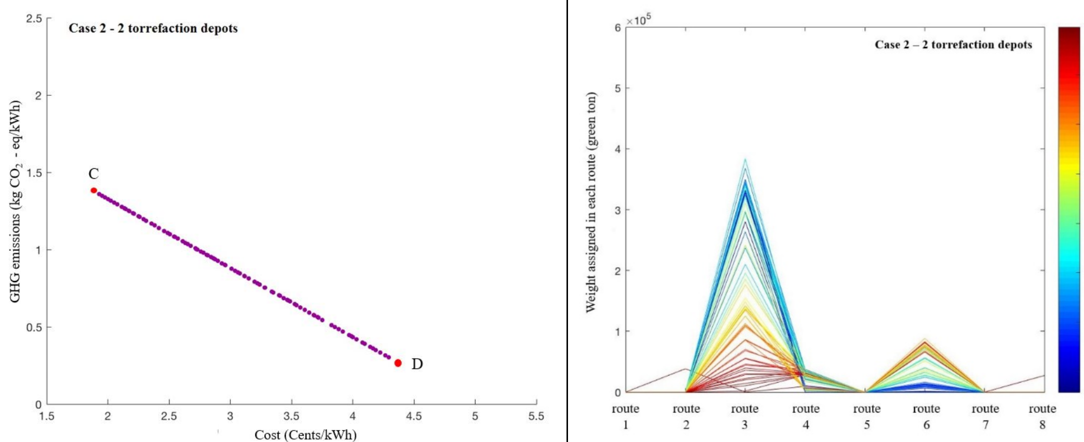
a. The pareto-optimal set of case 1.

b. Decision variable variations of optimal solutions in case 1.

Figure 21a and b. Pareto-optimal sets and decision variable variations in case 1

Fig. 21b shows the variations among the eight decision variables in all pareto-optimal solutions, which is important for the decision makers to execute the optimal solutions. The 8 route options considered in this model are shown in x-axis, and the biomass green weight allocated in each route in a solution is shown in the y-axis. Each line represents one optimal solution, and is colored based on its cost and GHG emissions. The solution colored in deep blue indicates the solution has a low cost but high GHG emission, and deep red indicates the solution has high cost but low GHG emissions. Based on **Fig. 21b,** to achieve the solution with the lowest cost, all the biomass green weight should be allocated to route 3. By shifting the biomass green weight allocated in route 3 to the routes with torrefaction options (route 2, 4 and 6), the GHG emissions can be largely reduced.

In case 2, the number of torrefaction depot increased from 1 to 2, which means the torrefaction capacity is doubled compared to case 1. The optimal solution with the lowest cost and the highest GHG emissions, solution C, is the same solution with solution A in case 1. With all the biomass green weight allocated to route 3, the cost of 1.88 ¢/kWh and the GHG emissions of 1.39 kg CO_2 – eq/kWh can be achieved (**Fig. 22a**). The cost and GHG emissions contributions of each stage in the biomass supply chain in solution C are also the same with solution A. The optimal solution with the lowest GHG emissions and the highest cost in case 2, solution D, has a lower GHG emissions of 0.28 kg CO_2 – eq/kWh and a higher cost of 4.36 ¢/kWh, compared to solution B ($GHG\ emissions\ =\ 0.71\ kg\ CO2 - eq/kWh, cost\ =\ 1.88\ ¢/kWh$) in case 1. In solution D, Biomass weight allocated in each route are: 0.00 green tons (route 1), 25.64 green tons (route 2), 1,691.77 green tons (route 3), 28,329.38 green tons (route 4), 35.30 green tons (route 5), 82,512.60 green tons (route 6), 0.00 green tons (route 7), and 0.00 green tons (route 8), respectively. The cultivation cost, biomass generation cost, transportation cost and torrefaction cost are 0.022 ¢/kWh (0.51%), 0.557 ¢/kWh (12.77%), 0.233 ¢/kWh (5.34%), and 3.552 ¢/kWh (81.39%), respectively. The GHG emissions from the cultivation, biomass generation, transportation, torrefaction and combustion stages are 0.000 kg CO_2 – eq/kWh (0.13%), 0.005 kg CO_2 – eq/kWh (1.66%) , 0.004 kg CO_2 – eq/kWh (1.46%), 0.011 kg CO_2 – eq/kWh (4.12%), and 0.256 kg CO_2 – eq/kWh (92.64%), respectively. By changing from the solution C to solution D, the GHG emissions can be reduced by 1.11 kg CO_2 – eq/kWh, while the cost will be increase by 2.48 ¢/kWh (2.21 ¢/kg CO_2 – eq). **Fig. 22b** shows the variable variations in different optimal solutions in case 2. Compare to case 1, when the torrefaction capacity is doubled, more woody biomass is shifted to route 2, 4 and 6 from route 3, to produce a lower GHG emissions.



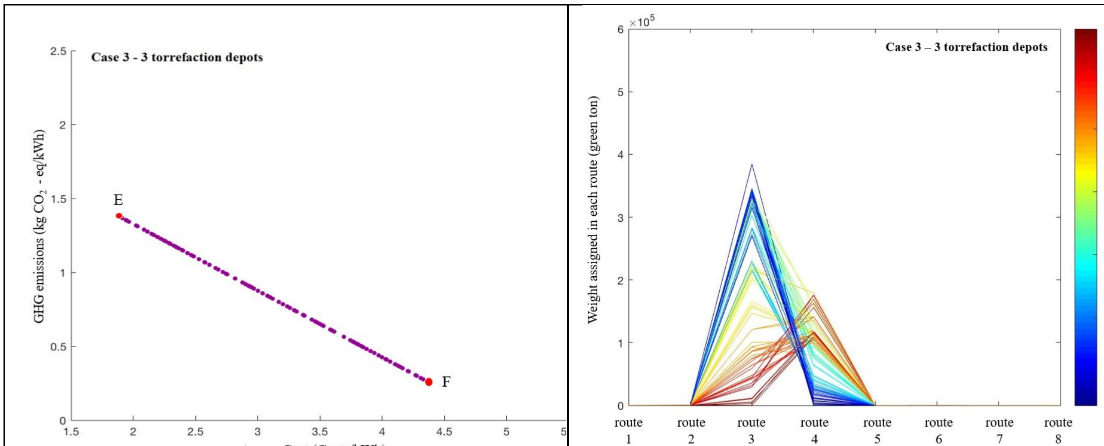
a. The pareto-optimal set of case 2.

b. Decision variable variations of optimal solutions in case 2.

Figure 22a and b. Pareto-optimal sets and decision variable variations in case 2

In case 3, point E and point F (**Fig. 23a and b**) are the solutions with the lowest cost/ the highest GHG emissions and the highest cost/ the lowest GHG emissions. Similar with case 2, solution E is the same solution with solution A and solution C. Solution F has the same cost (4.36 ¢/kWh) but a slightly lower GHG emissions (0.27 kg CO_2 – eq/kWh) compared to solution D (0.28 kg CO_2 – eq/kWh). Biomass weight allocated in each route in solution F are: 0.00 green tons (route 1), 514.40 green tons (route 2), 0.00 green tons (route 3), 109,153.95 green tons (route 4), 30.03 green tons (route 5), 0.00 green tons (route 6), 0.00 green tons (route 7), and 0.00 green tons (route 8), respectively. The cultivation cost, biomass generation cost, transportation cost and torrefaction cost are 0.042 ¢/kWh (0.97%), 0.451 ¢/kWh (10.36%), 0.235 ¢/kWh (5.39%), and 3.630 ¢/kWh (83.30%), respectively. The GHG emissions from the cultivation, biomass generation, transportation, torrefaction and combustion stages are 0.000 kg CO_2 – eq/kWh (0.00%), 0.004 kg CO_2 – eq/kWh (1.63%), 0.004 kg CO_2 –

eq/kWh (1.51%), 0.012 kg CO_2 – eq/kWh (4.31%), and 0.250 kg CO_2 – eq/kWh (92.56%), respectively. The trade-off of reducing the GHG emissions for 1.12 kg CO_2 – eq/kWh is increasing the cost by 2.47 ¢/kWh (2.21 ¢/kg CO_2 – eq). Assigning all the biomass weight to route 3 is still the way to get the lowest cost. With three torrefication depots available, majority of biomass weight will be allocated to route 4 to obtain the lowest GHG emissions (**Fig. 23b**).

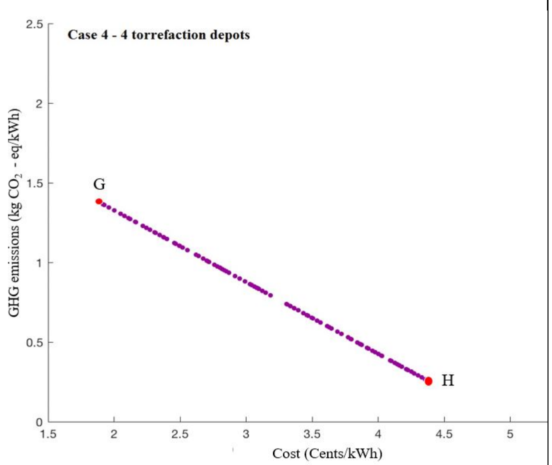


a. The pareto-optimal set of case 3.

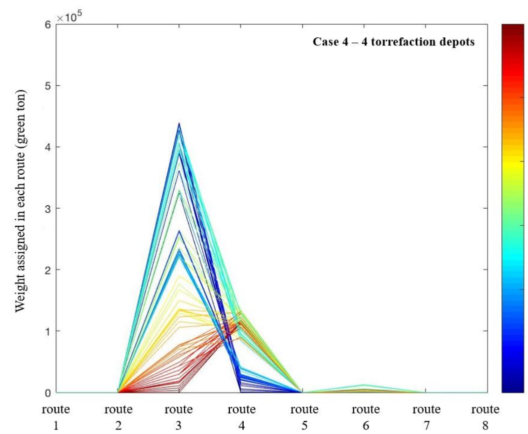
b. Decision variable variations of optimal solutions in case 3.

Figure 23a and b. Pareto-optimal sets and decision variable variations in case 3

In case 4 and case 5, the solutions with the lowest cost and the highest GHG emissions are solution G and solution I (**Fig. 24a** and **Fig. 25a**), which are the same with previous obtained solutions A, C, and E. The solutions with the lowest GHG emissions and the highest cost in case 4 and case 5 are solution H and solution J (**Fig. 24a** and **Fig. 25a**). The economic and environmental performance of solution H and solution J are the same ($cost = 4.36\ ¢/kWh, GHG\ emissions = 0.27\ kg\ CO2 - eq/kWh$). In solution H, the biomass weight allocated in each route are: 0.00 green tons (route 1), 0.00 green tons (route 2), 0.00 green tons (route 3), 114,422.73 green tons (route 4), 0.00 green tons (route 5), 48.60 green tons (route 6), 0.00 green tons (route 7), and 189.76 green tons (route 8), respectively. In solution J, the biomass weight allocated in each route are: 0.00 green tons (route 1), 617.21 green tons (route 2), 0.00 green tons (route 3), 109,309.61 green tons (route 4), 0.00 green tons (route 5), 47.82 green tons (route 6), 0.00 green tons (route 7), and 56.75 green tons (route 8), respectively. When the torrefaction capacity increases from case 4 to case 5, more biomass is allocated to the route 4 with torrefaction option to decrease the GHG emissions (**Fig. 24b** and **Fig. 25b**).

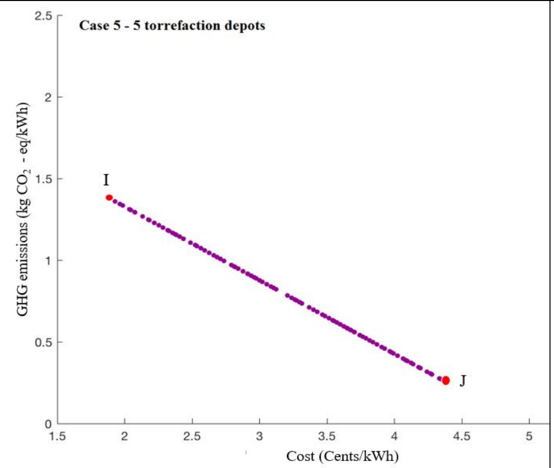


a. The pareto-optimal set of case 4.

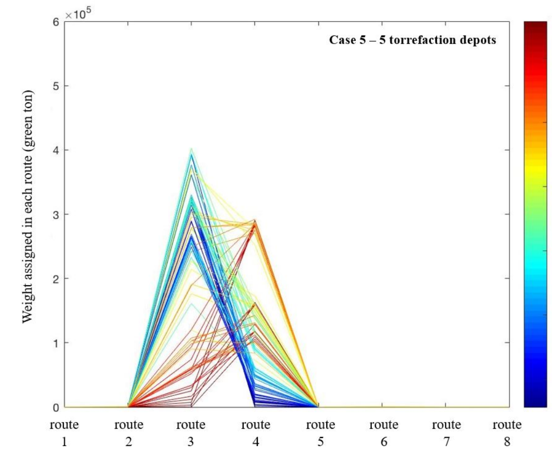


b. Decision variable variations of optimal solutions in case 4.

Figure 24a and b. Pareto-optimal sets and decision variable variations in case 4



a. The pareto-optimal set of case 5.



b. Decision variable variations of optimal solutions in case 5.

Figure 25a and b. Pareto-optimal sets and decision variable variation in case 5

Figure 26 summarizes all of the pareto-optimal sets in the five case scenarios. The solutions with the lowest cost and the highest GHG emissions are the same for the five case scenarios. When the number of available torrefaction depots increases, the trade-off between cost increase and GHG emissions reduction stays at 2.21 ¢/kg CO_2 – eq, but the lowest GHG emissions in each case scenario can be further reduced, from 0.71 kg CO_2 – eq/kWh in case 1 to 0.27 kg CO_2 – eq/kWh incase 5.

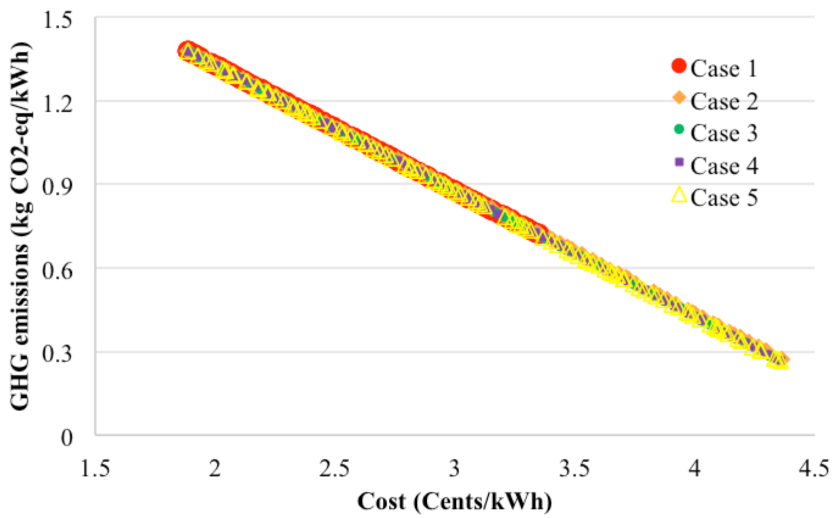
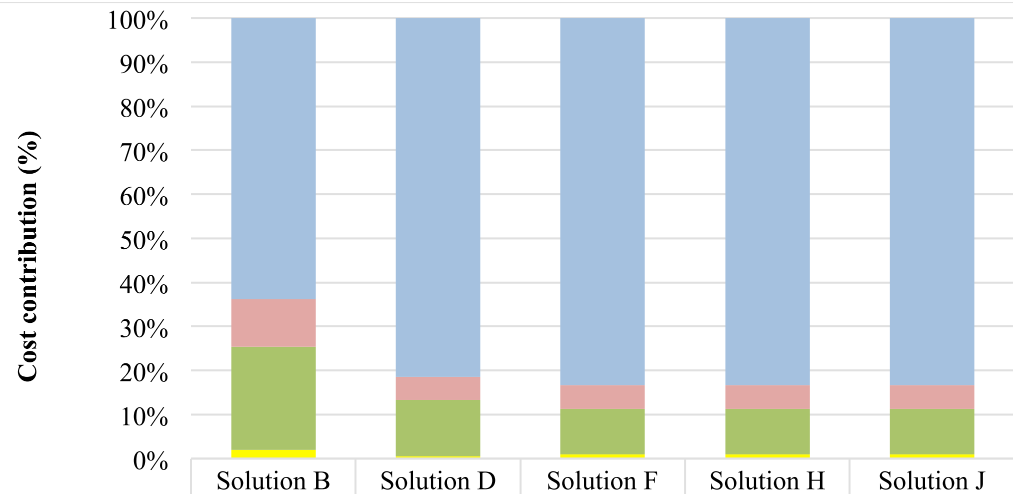


Figure 26. Pareto-optimal sets of the five studied cases

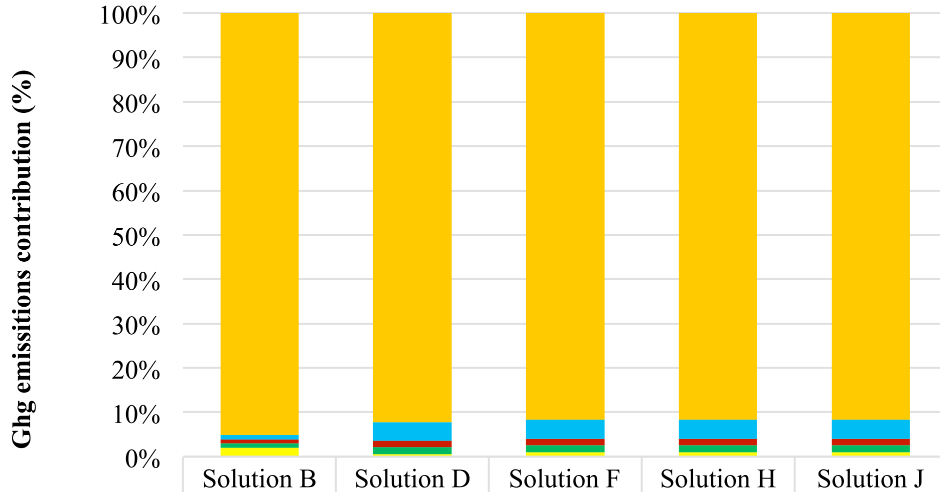
Figure 27 shows the cost contributions of each stage in solution B, D, F, H, and J, which are the solutions with the lowest GHG emissions but highest cost in case 1, 2, 3, 4, and 5. When the torrefaction capacity increases, more biomass are allocated to the route with torrefaction option to further reduce GHG emissions, and the torrefaction cost contributes more to the final cost through case 1 to case 5, from 63.82% to 83.27%. In contrast, the contribution of biomass generation cost and transportation cost are reduced when more biomass are torrified.



	Solution B	Solution D	Solution F	Solution H	Solution J
Torrefaction Cost	63.82%	81.39%	83.30%	83.29%	83.27%
Transportation Cost	10.85%	5.34%	5.39%	5.39%	5.39%
Generation Cost	23.28%	12.77%	10.34%	10.36%	10.37%
Establishment Cost	2.04%	0.51%	0.97%	0.97%	0.97%

Figure 27. Cost contribution of each life stage to the final cost in soultion B, D, F, H and J in base scenario

In Figure 28, the GHG emissions contributions of each stage are shown. In all solutions, GHG emissions from the combustion phase are constantly the largest contributor. However when torrefaction capacity raises, more biomass will be torrified, thus the contribution of combustion stage are lessened and the torrefaction stage becomes the second largest contributor.



	Solution B	Solution D	Solution F	Solution H	Solution J
Combustion Emissions	97.03%	92.64%	92.56%	92.56%	92.56%
Torrefaction Emissions	0.99%	4.12%	4.31%	4.31%	4.31%
Transportation Emissions	0.87%	1.46%	1.51%	1.51%	1.51%
Generation Emissions	1.05%	1.66%	1.63%	1.62%	1.63%
Establishment Emissions	2.04%	0.51%	0.97%	0.97%	0.97%

Figure 28. GHG emissions contribution of each life stage to the final cost in soultion B, D, F, H and J in base scenario

7.6.2 Sensitivity analysis

7.6.2.1 The impact of the transportation distance between torrefaction depot and power plant on the pareto-optimal sets

To evaluate the impact of the transportation distance between the torrefaction depot and the biomass power plant on the pareto-optimal sets and the trade-off between cost and GHG emissions, a sensitivity analysis was conducted using the case 1 scenario. The transportation distance was increased in 20 miles increments, from 10 miles to 90 miles. Figure 29 presents the sensitivity of the model to the transportation distance change. Results suggest that the transportation distance change does not affect the solutions with the lowest cost and the highest GHG emissions ($cost = 1.88$ ¢/kWh; $GHG\ emissions = 1.38\ kg\ CO2 - eq/kWh$) because in those solutions there are no torrefaction options. However, in solution K, L, M, N and O, the solutions with the lowest GHG emissions and the highest cost, as the transportation distance increases from 10 miles to 90 miles, the cost increases from 3.20 ¢/kWh to 3.84 ¢/kWh (Figure 29). The trade-off between cost and GHG emissions for the transportation distance of 10, 30, 50, 70, 90 miles are calculated as 2.14, 2.35, 2.56, 2.75, and 2.97 ¢/kg CO2 – eq, respectively.

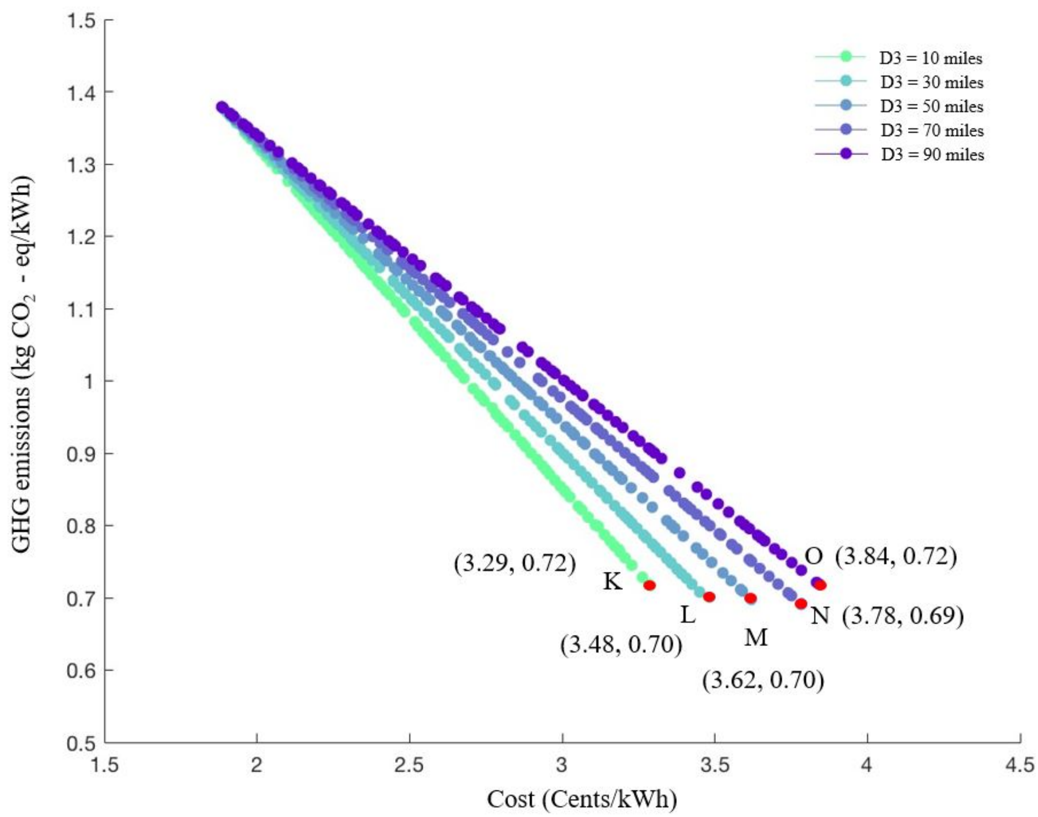


Figure 29. Impacts of distance between the torrefaction depot and the biomass power plant on the pareto-optimal sets in base case

7.6.2.2 The impact of the torrefaction price on the pareto-optimal sets

To examine the impact of torrefaction price on the pareto-optimal sets, the torrefaction price was increased from 54.40 to 80.60 \$/green ton in 6.80 \$/green ton increments. The sensitivity of the pareto-optimal sets to the torrefaction price is presented in Figure 30**.** Changing the torrefaction price does not affect the solutions with the lowest cost and the highest GHG emissions. Point P, Q, R, S, and T represent the solutions that have the lowest GHG emissions and highest cost under different torrefaction prices. When the torrefaction price is equal to 54.40, 61.20, 68.00, 74.80 and 80.6 \$/green ton, the cost are 2.92, 3.18, 3.36, 3.62 and 3.80 ¢/kWh, and the GHG emissions are 0.72, 0.69, 0.71, 0.72, 0.70 kg CO2 – eq/kWh, respectively. The trade-off between cost increase and GHG emissions reduction in solution P, Q, R, S, and T are estimated to be 1.57, 1.88, 2.21, 2.63, and 2.82 ¢/kg CO2 – eq.

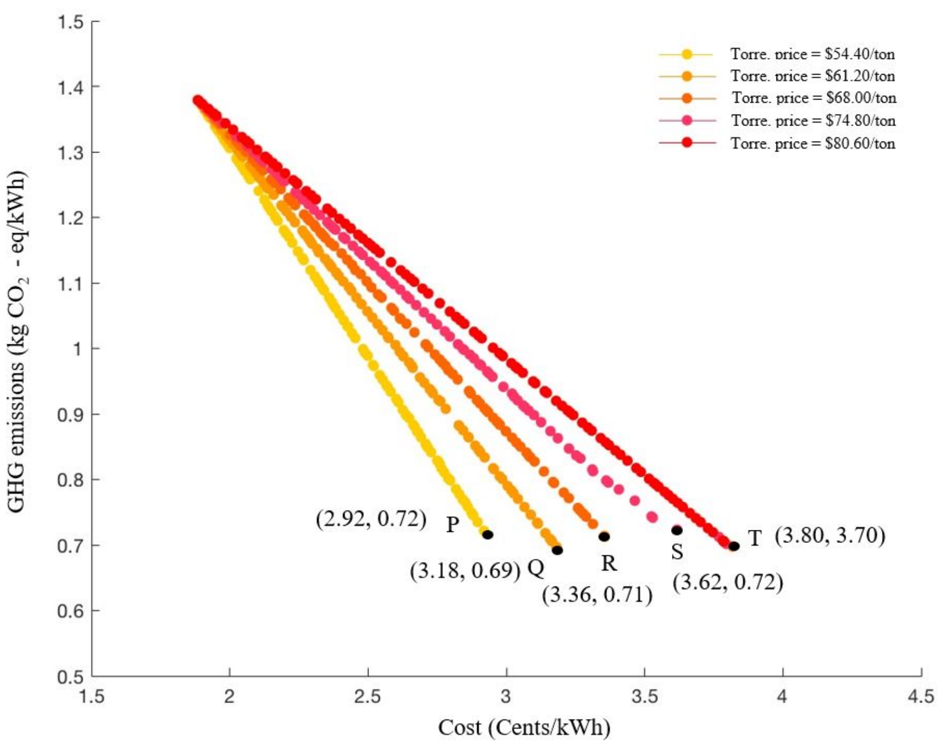


Figure 30. Impacts of torrefaction prices on the pareto-optimal sets in base case

7.7 Discussions

In order to mitigate GHG emissions from burning fossil fuels, using renewable energy sources such as wind, solar and biomass are gaining popularity. However, it is quite challenging to supply woody biomass with low production cost and low GHG emissions at the same time (Basu et al., 2011). Therefore, it is critical to understand the trade-off between decreasing the GHG emissions and increasing the cost.

A typical 50 MW biomass power plant can annually consume 500,000 to 650,000 green tons of woody biomass (Mayhead, 2010; PFPI, 2012). In case 1 scenario solution A, the model assigned a total of 586,617 green tons of woody biomass to route 3 (FS + WT + Grinded + Direct combustion) to achieve the lowest cost at 1.88 ¢/kWh. The biomass feedstock cost in Michigan contributes about 3.50 to 4.60 ¢/kWh to the total electricity production cost of 7.00 to 10.00 ¢/kWh (Mayhead, 2010; EIA, 2015).

Due to the low burning efficiency, producing electricity using woody biomass generally emits more GHG than coal and natural gas. The GHG emissions from burning woody biomass is around 1.36 to 1.42 kg CO_2-eq/kWh, while the GHG emissions from burning coal and natural gas are only around 0.95 kg CO_2-eq/kWh and 0.23 kg CO_2-eq/kWh (PFPI, 2011). In solution A, the total GHG emission is 1.38 kg CO_2-eq/kWh, which is comparable to the normal range. To reduce the GHG emissions by 0.66 kg CO_2-eq/kWh, the model assigned a portion of biomass to torrefaction routes, and thus to reach to the lowest GHG emissions of 0.71 kg CO_2-eq/kWh in solution B. However, the cost of solution B is increased to 3.36 ¢/kWh, which is 1.46 ¢/kWh higher than the cost of solution A. In this case, the trade-off between GHG emissions reduction and cost increase is 2.21 ¢/kg CO_2-eq. EPA has estimated the social cost of carbon from 2015 to

2050, at discount rates of 5%, 3% and 2.5%, to value the social impacts of climate change (EPA, 2016). The social cost of CO_2 on 2020 at 5%, 3% and 2.5% discount rates are \$12, \$42 and \$62 per metric ton CO_2, which are equivalent to 1.2 ¢, 4.2 ¢ and 6.2 ¢/ kg CO_2. At present, the US discount rate is at 1.75%. Assuming on 2020 the discount rate will be at 2.5% and the carbon credit is set at 6.2 ¢/ kg CO_2, then there will be enough incentive for biomass supplier and end-user to adopt solution B instead of solution A.

In case 2 to case 5, while the torrefaction capacity increases, more biomass is assigned to torrefaction routes, and the GHG emissions can be further reduced. Woody biomass has been historically recognized as a renewable energy sources because it is sustainable and widely available. However, the cost and quality of woody biomass can be largely impacted by many factors such as harvesting season, transportation distance, storage form and handling method (Nunes et al., 2014). Torrefaction can be an efficient and a favorable biomass thermal conversion technique to avoid the issues discussed above (Uslu et al., 2008; Ciolkosz and Wallace, 2011). It has been claimed by several studies that torrefaction can increase the energy density of woody biomass by more than 3 times (Samy and Sunita, 2009; Chen and Kuo, 2010; Nunes et al., 2014). With higher energy density and lower moisture content, the transportation efficiency can be largely increased. More important, the moisture content of torrefied wood is around 7-10%, which can largely improve the boiler efficiency compared to wood chips with moisture content of 30-50%. Since over 95% of GHG emissions in woody biomass supply chain are generated in the biomass combustion stage, the improvement in boiler efficiency plays a very important role in GHG emissions reduction.

In woody biomass supply chain, transportation planning has always been a big research focus (Gunnarsson et al., 2004; Gronalt and Rauch, 2007; Kanzian et al., 2009). To figure out the impact of the torrefaction depot location on the pareto-optimal sets, a sensitivity analysis was conducted. When the distance between the torrefaction depot and the biomass power plant increased from 10 miles to 90 miles, the GHG emissions stays in a narrow range, but the cost increased from 3.29 to 3.94 ¢/kWh, by 16.72%. The resulted raise in cost is mainly owing to the longer transportation cost with longer transportation distance. Nevertheless, because of the high energy density of torrified wood pellets, the impact of the increases in transportation distance is relatively small. With 8 times longer transportation distance, the total cost will only be increased by 16.72%.

The price of torrefcation process is an important factor to promote the usage of forest-derived fuels, which can be affected by many factors such as biomass availability, feedstock generation method, biomass quality, drying technology and torrefaction yield (Svanberg et al., 2013; Shah et al., 2012; Pirraglia et al., 2013). Many studies have been conducted to model and minimize the torrefaction cost using different technologies (Svanberg et al., 2013; Gårdbro et al., 2014; Chai and Saffron, 2016). Our study also confirmed that torrefaction price can largely impact the total biomass production cost and the trade-off between GHG emissions reduction and cost increase. For instance, when the torrefaction price is increased in a 10% increment from 54.40 \$/ton to 80.60 \$/ton, the rises in the cost are 8.90%, 15.07%, 23.97% and 30.14%. In addition, as the torrefaction price increases from 54.40 \$/ton to 80.60 \$/ton, to decrease 1 kg of kg CO_2-eq, the trade-off increases from 1.58 ¢ to 2.82 ¢, which is about 79.19% increase.

7.8 Conclusion

A multi-criteria optimization model was developed to provide an optimized woody biomass utilization route and to analyze the trade-off between GWP and cost. The results suggested that in the base scenario, by increasing the cost by 1.46 ¢/kWh (55.54% increase), the total GHG emissions can be reduced by 0.66 kg CO_2-eq/kWh (52.17% decrease). In addition, as an efficient and a favorable biomass thermal conversion technique, torrefaction can be a way to further reduce the GHG emissions of utilizing woody biomass. The sensitivity analysis indicated that biomass HHV and biomass moisture content have larger impacts on the optimized solutions and the trade-offs, compared to the transportation distance. This again, confirmed that in order to largely improve the efficiency and sustainability of the woody biomass supply chain, future research efforts should be spent on improving the HHV and decreasing the moisture content of woody biomass.

CHAPTER 8 CONCLUSION

In this Ph.D. study, five woody biomass production systems were monitored to predict the productivity and production cost of utilizing woody biomass in the State of Michigan. Effective cycle time estimators were illustrated in predictive regression equations for the studied machines. The predicted cycle time for each machine was used with the machine hourly rate to calculate the machine productivity and hourly production cost. The obtained results suggested that due to the higher hourly productivity, WT harvesting systems generally achieved lower production cost (15.57 $/ODT ~ 33.25 $/ODT) than CTL harvesting systems (39.16 $/ODT). Among the five evaluated studied sites, Site 5, the 3-year-old hybrid willow plantation harvested by a reconfigured harvesting system resulted in the highest production cost of 95.92 $/ODT, owing to the low biomass yield per acre and the additional hourly cost from the chips collector. Overall, it can be concluded that producing woody biomass from natural forest stands with the WT harvesting system was the most economical way of utilizing woody biomass as it has the highest productivity and lowest cost.

Storage is a key component within the woody biomass supply chain, especially when year-round harvesting is impossible. In order to better understand the field storage of woody biomass, two studies have been conducted to monitor the biomass quality (biomass MC and biomass HHV) change under different storage forms, wood logging residues piles and wood chips piles. In wood logging residues piles, biomass MCs were significantly reduced during the storage period. As an important fuel quality property, biomass HHVs were determined to be generally stable during the 5-month storage period. In comparison, because of the small particle size and high degree of compaction in the wood chip pile, increases in biomass MCs were observed at all wood chips piles. In addition, decreasing trends of biomass HHV were detected during the storage time, at all wood chips piles, as a result of energy loss caused by the high MC and microbial activity in the wood chip pile.

Five LCAs were conducted to estimate the environmental impacts generated in woody biomass production systems in Michigan, U.S., including cultivation, biomass harvesting, collecting, pre-processing, transportation, and combustion stages. The estimated GWP in all study sites were in a comparable range with previous published LCAs. It is important to note that, among all studied life cycle stages, biomass combustion consistently contributes about 95% to 97% of the final GWP. Considering the large amount of GHG emissions and the long time required to sequester these emissions, biomass combustion should be included in future LCAs of woody biomass supply chains. In order to reduce the GHG emissions from the combustion stage, future research efforts should be aimed to provide biomass with lower moisture content and higher HHV. Utilizing woody biomass for bioenergy production can be carbon neutral while including soil C increase during biomass growth, however future work is needed to reduce the uncertainties of including soil C in LCAs.

Based on the estimated production cost and evaluated GWP, a multi-criteria optimization model was developed to suggest an optimized woody biomass utilization route and to analyze the trade-off between GWP and cost. The results suggested that by increasing the cost by 1.46 ¢/kWh (55.54% increase), the total GHG emissions can be reduced by 0.66 kg CO_2-eq/kWh (52.17% decrease). In addition, as an efficient and a favorable biomass thermal conversion technique, torrefaction has been shown as a way to further reduce the GHG emissions of utilizing woody biomass. The sensitivity analysis indicated that biomass HHV and biomass moisture content have much larger impacts on the optimized solutions and the trade-offs, compared to the transportation distance. This again, confirmed that in order to largely improve the efficiency and sustainability of the woody biomass supply chain, more attention should be spent on improving the energy content and decreasing the moisture content of woody biomass.

APPENDICES

Appendix 1. User guide for the cost prediction spreadsheet model

Introduction

As a state with high availability of forest resources, Michigan has a high potential to develop woody biomass as renewable energy source. Previously, many cost analysis models such as BioSum 3.0, Auburn Harvest Analyzer (AHA) and FRCS-North have been developed to provide logistic cost predictions. The predicting equations in these models were mostly obtained from harvesting operations studies conducted in Northwestern or Southeastern United States, which have the different site and terrain conditions, forest type, and tree size compare to MI. Since woody biomass production cost can be heavily affected by factors such as tree size, spacing, ground slope and roughness, and road type (Wright et al., 2010; Ghaffariyan et al., 2012; Harril and Han, 2012), directly using these models to make cost prediction for MI forest harvesting project may cause inaccurate estimation. Dalia et al. (2014) have published a survey analysis of MI wood-based production (include harvesting and transportation) based on logger's survey, which reported the harvesting productivities of different harvesting systems in different forest types. Although this survey analysis provided a good understanding of logging industry in MI, a cost and productivity prediction model that is developed from MI-based timber harvesting operations is in great need.

In order to provide a better tool to predict the entire supply chain cost (harvesting, biomass collecting, handling, and transportation) of producing wood pellets for energy generation purpose in MI, this spreadsheet model was designed. This model was developed using VBA programming language in Excel, based on multiple regression cost prediction equations that were developed from 5 forest harvesting projects in Michigan. This model can be used to estimate production cost of woody biomass resulting from harvesting operation including whole-tree (WT) harvesting, logging residue extraction in cut-to-length (CTL) harvesting and reconfigured forage harvesting. The target users of this spreadsheet model include contractors and logging companies, researchers and nonprofit organizations. With this model, users can understand the critical cost factors, estimate the harvesting productivity and cost, and design the harvesting project.

Getting started

This spreadsheet model was developed on Excel 2016. It provides estimates of machine hourly rate ($/hr.), harvesting productivity (ODT/hr.), production cost ($/ODT), total cost ($) and cost per acre ($/acre). To get started with this spreadsheet model, Microsoft Office needs to be installed and following information is required:

- Site information such as biomass source, tree species, harvested area (acres), average harvested tree DBH (inches), age of the biomass source (yr.), stand density (trees/acre), and assumed soil carbon sequestration rate (Mg C/ha/yr).
- Herbicide and fertilization application rate during cultivation stage.
- Harvesting prescription, operation method, system type, and pre-processing technologies.
- Transportation method and one-way transportation distance (miles), including transportation distances in dirt road, gravel road, paved road and highway.
- Storage form, moisture content (% wet basis) before storage and after storage.
- Biomass higher heating value (Btus/lb) and boiler combustion efficiency (%).

Using the model

Fig. A-1 shows the model input page of this spreadsheet model. The "Model reset" button in the right upper corner can be used to clear all inputs and output for the model. There are six main sections in the model input page for date entry, including site information, cultivation, harvesting system, transportation system, storage, and combustion system. Detail steps to set up this model will be discussed below.

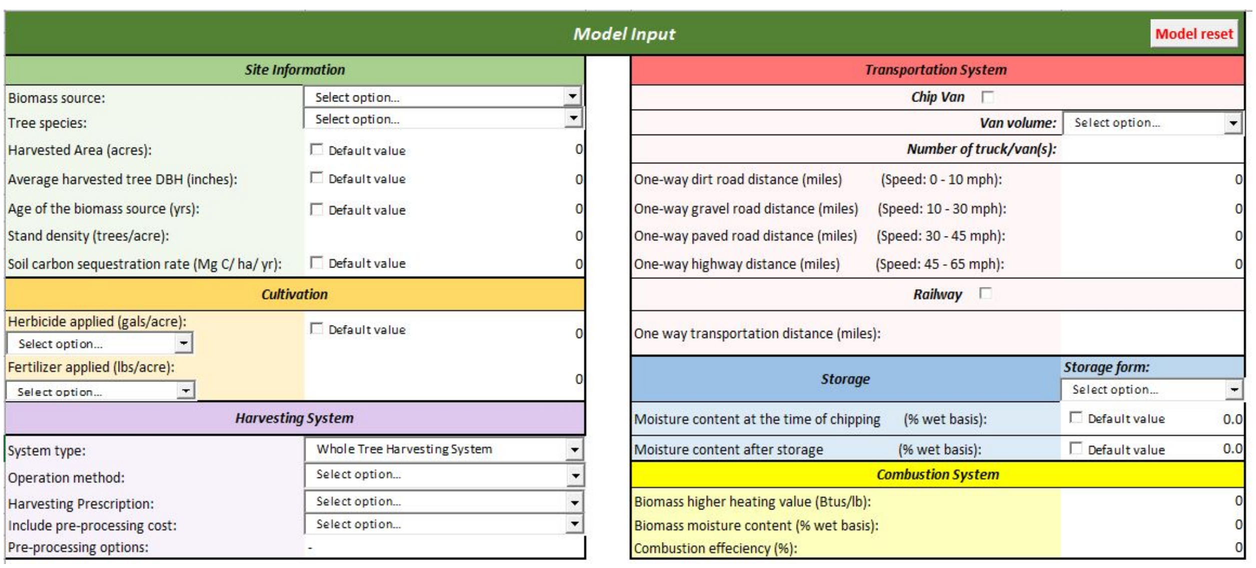


Figure A- 1. Model input page of the cost prediction spreadsheet model

Site information

In this step, users can provide site information inputs such as biomass source, tree species, harvested area, averaged harvested tree DBH and so on. Biomass source options include natural forest and energy wood plantation (**Fig. A-2**). Users can change the selection by clicking "Select option…" and then select another choice in the list. Natural forest in this model refers to secondary forest or timber land that is planted for industrial purpose, while energy wood plantation refers to short rotation hybrid poplar or willow plantations that are grown to be harvested within 2-9 years rotation cycle.

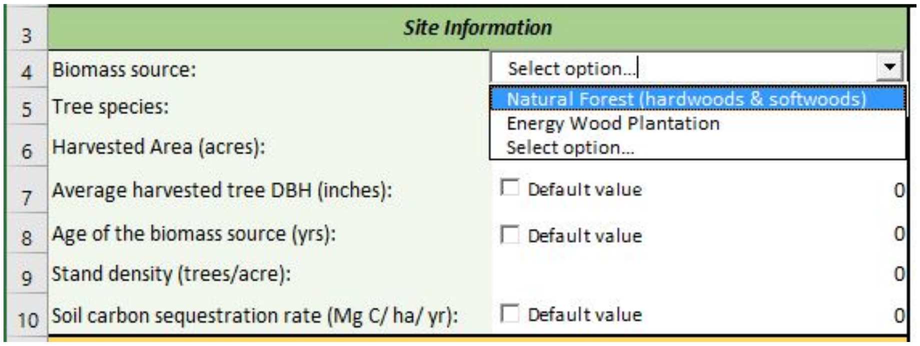


Figure A- 2. Step1: Biomass source selection

Tree species included in this model include hybrid willow, hybrid poplar, Jack pine (*Pinus banksiana*), and mixed hardwood and softwood (**Fig. A-3**). After choosing tree species, users can enter the total number of acres to be harvested, estimated average tree DBH, age of biomass source, stand density and soil C sequestration rate, which should all be numeric characters. User can also click the check-box "Default value" to use values provided by this model. The default values for different tree species are presented in **Table A-1**.

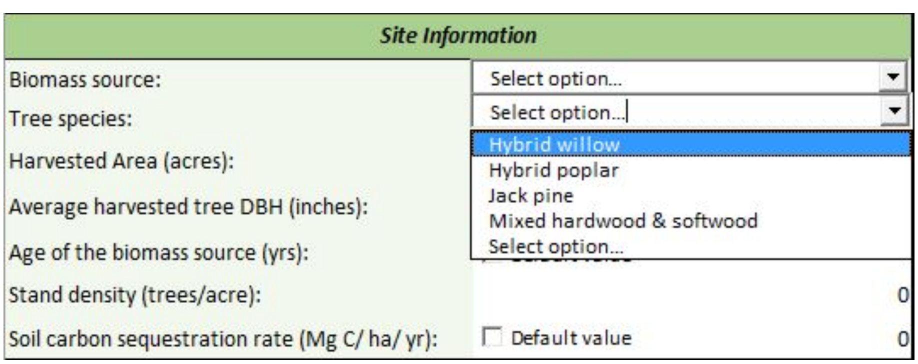


Figure A- 3. Step 1: Tree species selection

Table A- 1. Step 1: Default site information for included tree species

	Harvested area (acres)	Average DBH (inches)	Age (yrs.)	Soil C sequestration rate (Mg C/ha/yr.)
Hybrid willow	1.1	1	3	0.00
Hybrid poplar	7.7	4	7	0.75
Jack pine	56.0	7	29	0.06
Mixed-species	33.0	8	10	0.53

Cultivation

In this step, user can enter fertilization and herbicide application rates (only numeric characters) in biomass cultivation stage (**Fig. A-4**). At current stage, this model only handles one type of herbicide, which is glyphosate. There are many fertilizer choices such as ammonium nitrate, calcium ammonium nitrate and so on. The default value for herbicide rates is 16.6 gals/acre.

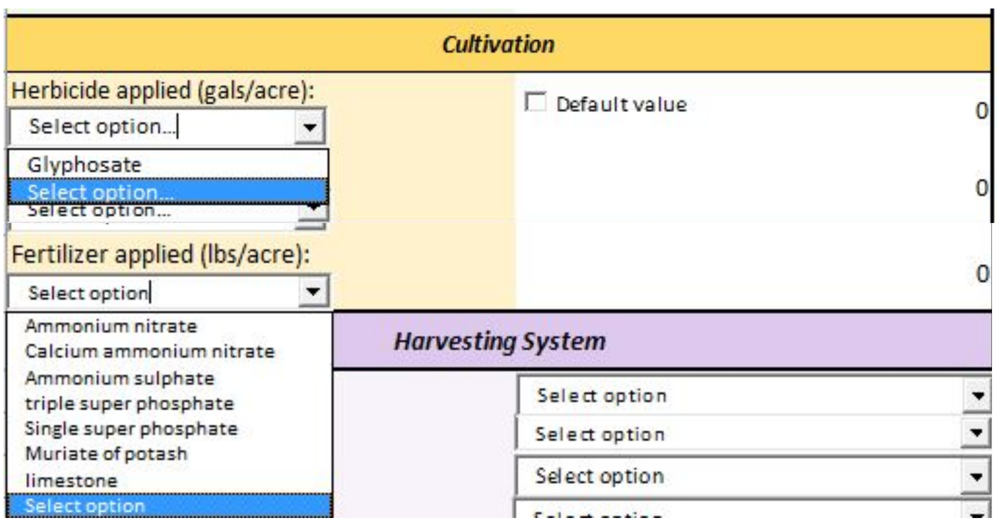


Figure A- 4. Step 2: Herbicide and fertilizer application

Harvesting system

Harvesting prescription and operation method

In this step, user can enter harvesting prescription, operation method, operation system type, and pre-processing technology (**Fig. A-5**). There are two options in harvesting prescription, clear-cut and 70% thinning. If "clear cut" is chosen, it means all trees in the stand will be harvested; if 70% thinning is chosen, it means 70% of the stand will be harvested. For the operation method, this model can only handle cold decking operation at this stage.

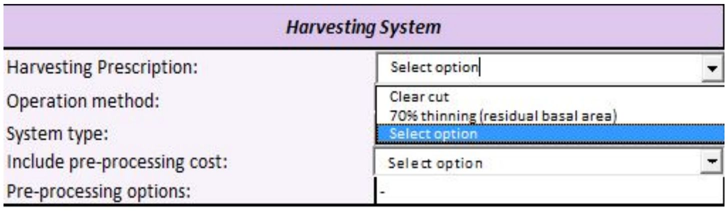


Figure A- 5. Step 3: Choosing harvesting prescription

System type

If user choose whole tree harvesting system, "Whole Tree Harvesting System" window will open for users to input detail information for the harvesting system (**Fig. A-6**). So far this model can only handle medium size rotating saw feller buncher like John Deere 653 G and medium size grapple skidder like John Deere 740 A. The entered number of feller buncher and skidder employed can only be integer number larger than 0.

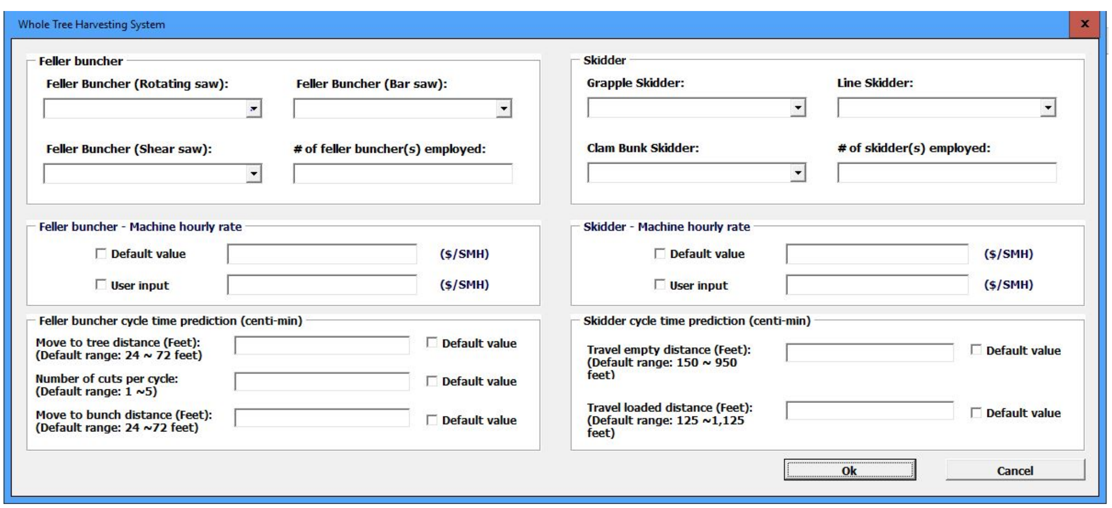


Figure A- 6. Step 3: Whole tree harvesting system information window

In machine hourly rate section for feller buncher and skidder, user can choose to use default value provided by this model or use an estimated value based on user's input. If users choose to input their own machine cost information, machinery cost estimation window (**Fig. A-7**) will open. Machinery cost will be calculated by calculation method developed by Miyata (1980) based on user's input.

In the machine cycle time prediction section, users may use the model default values or input values based on their own projects. The values provided by user have to be non-negative values within the default range listed under each cell. For number of cuts per cycle, please only enter integer values. For feller-buncher, a complete cycle start from 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 per cycle, and move to bunch distance were defined as variables for these elemental activities within a cycle.

For skidder, a complete cycle starts from moving from the landing site to a tree bunch and included subsequent grappling to make a full skid load, return to the landing site, and ended with the placement of loaded trees on the ground near the log loader. Elemental activities within a skidding cycle were defined to be: travel empty distance, positioning distance, number of trees per cycle, and traveling loaded distance.

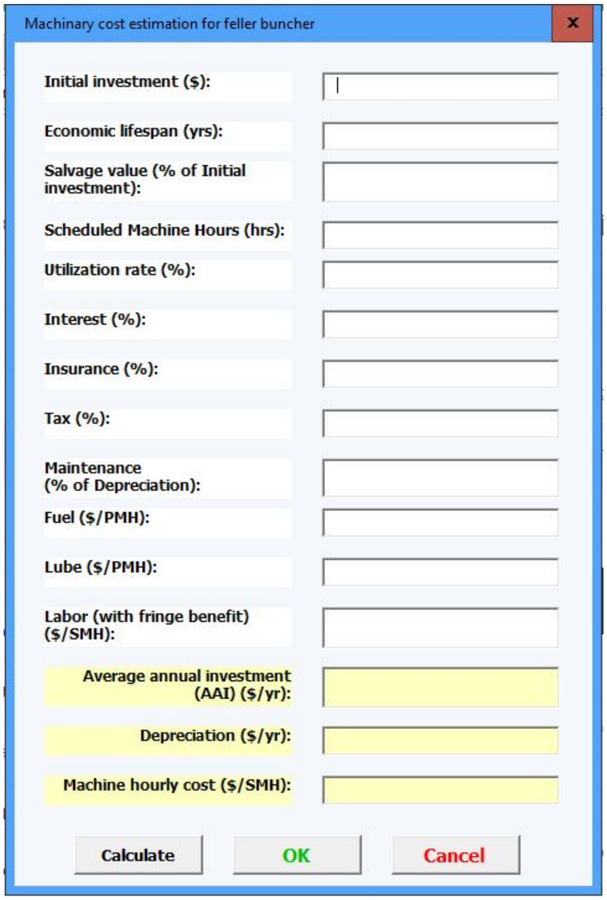


Figure A- 7. Step 3: Harvesting system machinery cost estimation window (feller-buncher)

This model only provides cost and productivity estimates for logging residues collection in the CTL system. If user selected CTL as the desired harvesting system, a window (**Fig. 8**) will open for user to select and enter the specific harvesting system information. This model temporarily can only handle forwarder model such as Ponsse Bison S15. The number of employed forwarder can only be integer that is larger than 0. For the machine hour cost, user can either accept the model default value or use machinery cost estimation tool to obtain a calculated value. In the cycle time prediction section, user can only provide values that are within the valid range of each parameter. A complete cycle for forward starts from the movement from the landing site to a logging residue piles and subsequent grappling to make a full load, travel back to the landing site and unloaded the biomass on the ground near the loader. The included variables in predicting forwarding cycle time are: travel empty distance, intermediate travel distance in feet, number of grapples per cycle, travel loaded distance and number of unloading grapples. For the number of cuts per cycle and number of unloading grapples, please only input integer values.

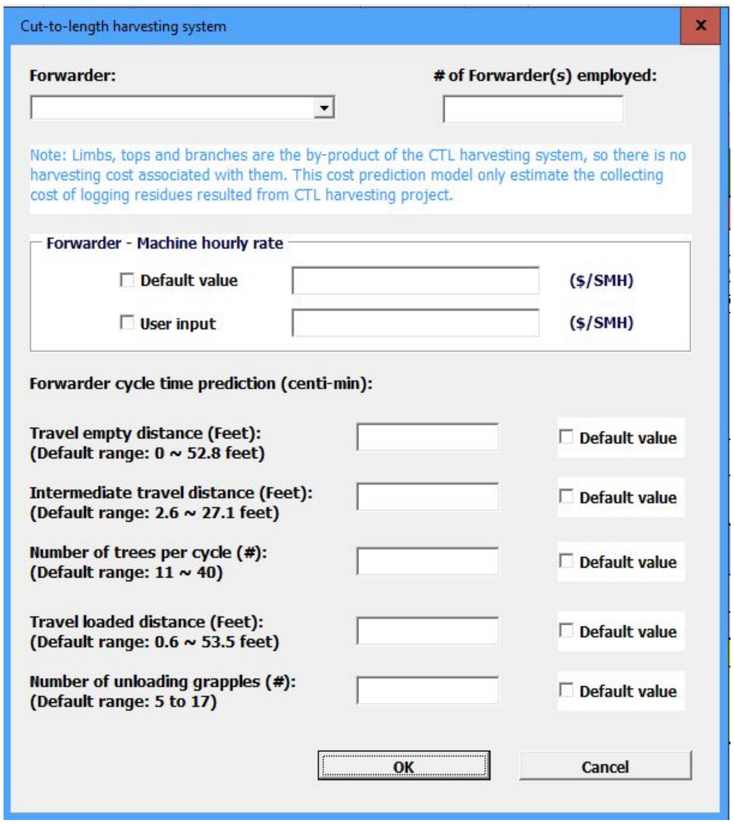


Figure A- 8. Step 3: CTL harvesting system information window

In reconfigured harvesting system information window (**Fig. A-9**), user needs to choose a model for harvester employed and input the unit number of harvester(s) employed. Machinery hourly rate estimation for reconfigured harvesting system can be estimated by user input information or the model default value. In the cycle time prediction section, harvesting speed refers to the driving speed when the reconfigured forage harvester is harvesting the stand, while travel speed refers to the driving speed when the reconfigured forage harvester is not harvesting.

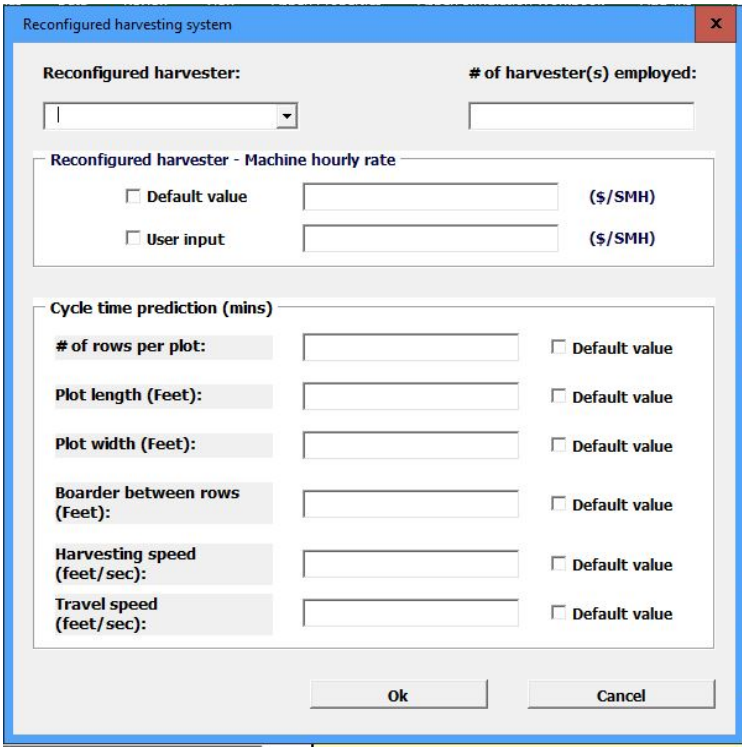


Figure A- 9. Step 3: Reconfigured harvesting system information window

Pre-processing

Pre-processing in this model refers to loading and grinding/chipping operation to process harvested woody biomass into pellets. User can chose if pre-processing will be included in the harvesting system in "Include pre-processing cost" cell (**Fig. A-10**). This model temporary cannot handle chipping operation.

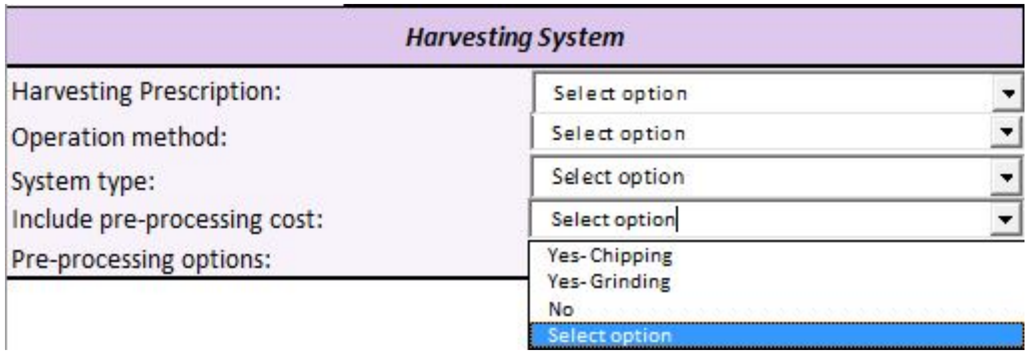


Figure A- 10. Step 3: Include pre-processing in the harvesting system or not

If user chooses to include grinding and loading in the harvesting system, a window (**Fig. A-11**) will show for user to use the model default value or calculate machine hourly rate, and to predict working cycle time prediction in the unit of centi-minute. For the loader-grinder unit, complete cycle was defined as the time required for the loader to supply the grinder with a grapple of trees and process them into wood chips. 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. The input value for number of trees per loading cycle can only be integer that is within the default range of this model.

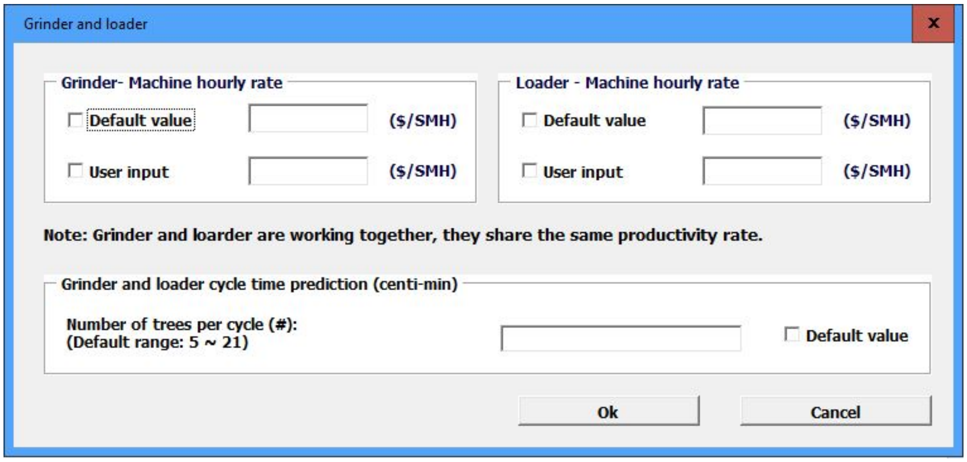


Figure A- 11. Step 3: Grinder and loader information window

Transportation system

In this section, user can set up the transportation system for delivering the biomass (**Fig. A-12**). At this stage, this model can only handle chip van with volume of 148 yd^3. User can enter the travel distance in miles in each road type, which is categorized based on driving speed.

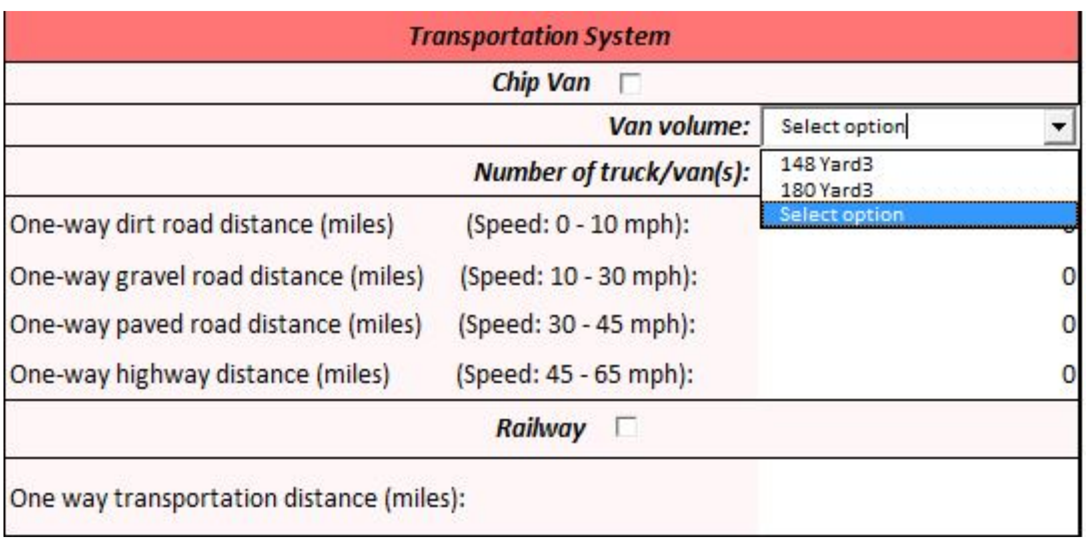


Figure A- 12. Step 4: Transportation system information

Storage

As an important part of the woody biomass supply chain, storage is included in this model (**Fig. A-13**) to estimate the fuel value ($/ton) change caused by storage. The detail method of calculating fuel value can be found in the “Storage” sheet. User can select the storage form of wood chips pile or logging residue pile. For each storage form, different default values of original and resulted moisture contents will be provided by model. Users can also use their own estimates. The input numbers for moisture content at the time of chipping and after storage should be larger than 0 and less than 100. If users do not want to include storage, they may click “None” in the “Storage form” choice list.

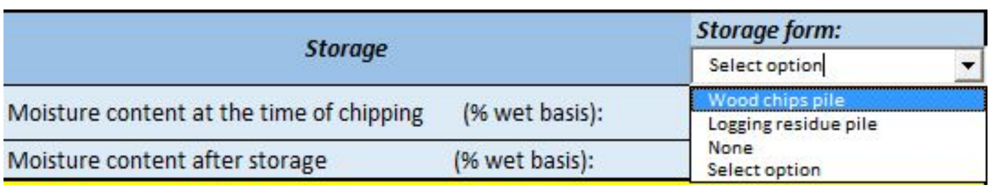


Figure A- 13. Step 5: Storage form and moisture contents during storage

Combustion system

In this section, user can enter the biomass higher heating value (Btus/lb), biomass moisture content (% wet basis) and overall efficiency of combustion system (%) (**Fig. A-14**). This information can be used to estimate the total recoverable heating value of the woody biomass and greenhouse gas emissions produced in combustion stage.

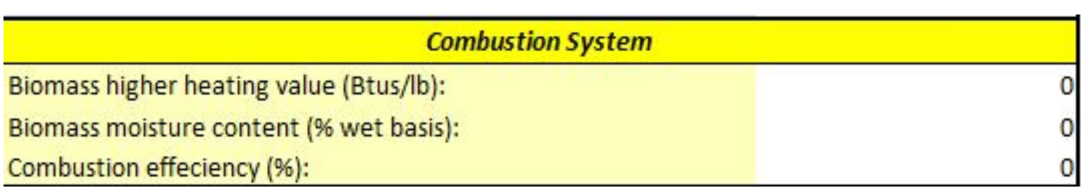


Figure A- 14. Step 6: Combustion system information

Running case and output page

Here we provide an example case for user to get started with the model. The case is describe below:

- The harvested plantation is a 7.7-ac stand of 7-year-old poplar hybrids in Michigan.
- The average DBH of the trees is 4 inches.
- The stand density is 1100 trees/acre.
- It is assumed that the plantation sequesters 2 Mg soil C per ha annually.
- Glyphosate is applied in a rate of 16.6 gallons/acre to remove the weeds.
- No fertilizer is used.
- A whole-tree harvesting system is employed to harvest the site, which includes one unit of feller-buncher (John Deere 653 G), one unit of skidder (John Deere 740A), one unit of grinder (Peterson 4700B) and one unit of loader (Hood S-182).
- The operation method is cold decking operation.
- The harvesting prescription is clear-cut.
- The processed wood chips are delivered by a chip van with volume of 148 yd^3.
- The transportation distance includes 0.2 miles of dirt road, 0.2 miles of gravel road, 0.2 miles of paved road and 60 miles of highway.
- It is assumed that the woody biomass is stored at the biomass power plant, in the wood chips pile. The initial moisture content is assumed to be 29.4% and the resulted moisture content is assumed to be 39.3%.
- The biomass higher heating value of the wood pellets is 8518 Btus/lb. The biomass moisture content is 39.3%. The overall combustion efficiency is 35%.

Once all information about the biomass production system is entered, user can go the "Output" sheet, click the "Calculate" button and all results will be displayed in the "Biomass produced" table and the "Cost prediction" table (**Fig. A-15**). In the "Biomass produced" table, user can read the dry weight and green weight of the total produced biomass. In the "Cost prediction" table, estimated results include machine hourly rate, machine productivity, cost per ODT, cost per green ton, total cost, and cost per acre are listed for each stage of the biomass production system.

Biomass produced	
Oven dry tons:	Green tons:
183.07	259.30

Cost Prediction						
	Machine hourly rate ($/hr)	*Machine productivity (ODT/hr)*	*Cost per ODT ($/ODT)*	*Cost per green ton ($/green ton)*	*Total cost ($)*	*Cost per acre ($/acre)*
Harvesting:	$119.71	14.65	$8.17	$5.77	$1,496.39	$194.34
Skidding/forwarding:	$79.92	36.32	$2.20	$1.55	$402.80	$52.31
Pre-processing:	$201.92	77.88	$2.59	$1.83	$474.66	$61.64
Transportation:	$70.07	6.84	$10.24	$7.23	$1,874.80	$243.48
Include Storage premium :	-	-	-$1.89	-$1.33	-$345.27	-$44.84
Reset Calculate	-	-	$25.09	$17.72	$4,593.93	$596.61

Note: The storage premium reflects the difference of the woody biomass price before storage and after storage. Detailed calculations are included in the worksheet "Storage".

Figure A- 15. Outputs table for the spreadsheet model

Appendix 2. VBA codes for the cost prediction spreadsheet model

Sheet 1. Model input

```
Private Sub A_Change()
Sheet3.Range("B4").Value = A.ListIndex + 1
End Sub

Private Sub B_Change()
Sheet3.Range("B5").Value = B.ListIndex + 1
Dim BS
BS = Sheet3.Range("B4").Value
Dim ts
ts = Sheet3.Range("B5").Value

If (BS = 1 And ts = 1) Then MsgBox "Invalid combination! Hybrid willow can only be
defined as energy woods plantation.", , "Error Msg"
If (BS = 1 And ts = 2) Then MsgBox "Invalid combination! Hybrid poplar can only be
defined as energy woods plantation.", , "Error Msg"
If (BS = 2 And ts = 3) Then MsgBox "Invalid combination! Jack pine can not be defined
as energy woods plantation.", , "Error Msg"
If (BS = 2 And ts = 4) Then MsgBox "Invalid combination! Mixed-species woods can
not be defined as energy woods plantation.", , "Error Msg"

End Sub
Private Sub G_Change()

Sheet3.Range("B15").Value = G.ListIndex + 1

End Sub

Private Sub E_Change()

Sheet3.Range("B17").Value = E.ListIndex + 1

Dim hs
hs = Sheet3.Range("B17").Value
Dim ts
ts = Sheet3.Range("B5").Value
Dim PS
PS = Sheet3.Range("B15").Value

If hs = 1 And ts = 2 Then
WT4_window.Show
Sheet1.Range("f30").Value = "Whole tree harvesting system"
Sheet1.Range("b31").Value = "Feller buncher"
Sheet1.Range("c31").Value = "Unit number:"
```

```
Sheet1.Range("c32").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c34").Value = "Model:"
Sheet1.Range("E31").Value = "Machine productivity (ODT/hr):"
Sheet1.Range("e32").Value = WT4_window.Label12
Sheet1.Range("e33").Value = WT4_window.Label13
Sheet1.Range("e34").Value = WT4_window.Label14
Sheet1.Range("b36").Value = "Skidder"
Sheet1.Range("c36").Value = "Unit number:"
Sheet1.Range("c37").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c39").Value = "Model:"
Sheet1.Range("e36").Value = "Machine productivity (ODT/hr):"
Sheet1.Range("e37").Value = WT4_window.Label16
Sheet1.Range("e38").Value = WT4_window.Label17
Sheet1.Range("e39").Value = WT4_window.Label18
Sheet1.Range("e40").Value = WT4_window.Label18
End If

If hs = 1 And ts = 4 And PS = 1 Then
WT2_window.Show
Sheet1.Range("f30").Value = "Whole tree harvesting system"
Sheet1.Range("b31").Value = "Feller buncher"
Sheet1.Range("c31").Value = "Unit number:"
Sheet1.Range("c32").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c34").Value = "Model:"
Sheet1.Range("E31").Value = "Machine productivity (ODT/hr):"
Sheet1.Range("e32").Value = WT2_window.Label12
Sheet1.Range("e33").Value = WT2_window.Label13
Sheet1.Range("e34").Value = WT2_window.Label14
Sheet1.Range("b36").Value = "Skidder"
Sheet1.Range("c36").Value = "Unit number"
Sheet1.Range("c37").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c39").Value = "Model:"
Sheet1.Range("e36").Value = "Machine productivity (ODT/hr):"
Sheet1.Range("e37").Value = WT2_window.Label15
Sheet1.Range("e38").Value = WT2_window.Label16
End If

If hs = 1 And ts = 4 And PS = 2 Then
WT3_window.Show
Sheet1.Range("f30").Value = "Whole tree harvesting system"
Sheet1.Range("b31").Value = "Feller buncher"
Sheet1.Range("c31").Value = "Unit number:"
Sheet1.Range("c32").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c34").Value = "Model:"
Sheet1.Range("E31").Value = "Machine productivity (ODT/hr):"
Sheet1.Range("e32").Value = WT3_window.Label12
```

```
Sheet1.Range("e33").Value = WT3_window.Label13
Sheet1.Range("e34").Value = WT3_window.Label14
Sheet1.Range("b36").Value = "Skidder"
Sheet1.Range("c36").Value = "Unit number"
Sheet1.Range("c37").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c39").Value = "Model:"
Sheet1.Range("e36").Value = "Machine productivity (ODT/hr):"
Sheet1.Range("e37").Value = WT3_window.Label15
Sheet1.Range("e38").Value = WT3_window.Label16
End If

If hs = 2 Then
CTL_WINDOW.Show
Sheet1.Range("f30").Value = "Cut-to-length harvesting system"
Sheet1.Range("b31").Value = "Fowarder"
Sheet1.Range("c31").Value = "Unit number:"
Sheet1.Range("c32").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("C35").Value = "Machine productivity (ODT/hr):"
Sheet1.Range("c34").Value = "Model:"
Sheet1.Range("e31").Value = CTL_WINDOW.Label14
Sheet1.Range("e32").Value = CTL_WINDOW.Label15
Sheet1.Range("e33").Value = CTL_WINDOW.Label16
Sheet1.Range("e34").Value = CTL_WINDOW.Label22
Sheet1.Range("e35").Value = CTL_WINDOW.Label23
End If

If hs = 3 Then
RCF.Show
Sheet1.Range("f30").Value = "Reconfigured harvesting system"
Sheet3.H.ListIndex = 2
Sheet1.Range("b36:f56").Value = ""
Sheet1.Range("e32:f35").Value = ""
Sheet1.Range("b31").Value = " "
End If

If hs = 4 Then
Sheet6.Range("a65:i84").Interior.ColorIndex = 0
Sheet6.Range("i28:i36").Value = "" 'fb = 0
Sheet6.Range("i42:i52").Value = "" 'sk = 0
Sheet6.Range("i55").Value = "" 'fwd = 0
Sheet6.Range("i66, i74").Value = "" 'rcf = 0
End If

If (ts = 1 And hs = 1) Then MsgBox "Invalid combination! Hybrid willow can only be
harvested by reconfigured harvesting system.", , "Error Msg"
```

```
If (ts = 1 And hs = 2) Then MsgBox "Invalid combination! Hybrid willow can only be harvested by reconfigured harvesting system.", , "Error Msg"
If (ts = 2 And hs = 2) Then MsgBox "Invalid combination! Hybrid poplar cannot be harvested by CTL harvesting system. Please choose other harvesting system.", , "Error Msg"
If (ts = 3 And hs = 3) Then MsgBox "Invalid combination! Jack pine cannot be harvested by reconfigured harvesting system. Please choose other harvesting system.", , "Error Msg"
If (ts = 4 And hs = 3) Then MsgBox "Invalid combination! Mixed-species forest stand cannot be harvested by reconfigured harvesting system. Please choose other harvesting system.", , "Error Msg"

End Sub

Private Sub F_Change()

Sheet3.Range("B16").Value = F.ListIndex + 1

Dim OPM
OPM = Sheet3.Range("B16").Value

If OPM = 1 Then
Sheet3.J.ListIndex = 2
INMC_Df.Value = False
REMC_df.Value = False
Sheet3.Range("e14").Value = 0
Sheet3.Range("e15").Value = 0
End If
'If OPM = 1 Then MsgBox "Invalid Choice! This model temporarily can only handle cold decking operation.", , "Error Msg - Operation method"
End Sub



Private Sub H_Change()
Sheet3.Range("B18").Value = H.ListIndex + 1
Dim PPC_Include
PPC_Include = Sheet3.Range("b18").Value

If Sheet3.Range("b17").Value = 3 And PPC_Include = 1 Then
MsgBox "The reconfigured harvesting system can directly process the woody biomass. It is not necessrary to add a chipper.", , "Error Msg"
End If
```

```
If Sheet3.Range("b17").Value = 3 And PPC_Include = 2 Then MsgBox "The reconfigured harvesting system can directly process the woody biomass. It is not necessrary to add a grinder.", , "Error Msg"
If PPC_Include = 1 And Sheet3.Range("b17").Value = 1 Then
MsgBox "This model can not predict the productivity of chipping operation.", , "Error Msg - chipping"
H.ListIndex = 2
'Sheet3.Range("b19").Value = "Chipping"
'Sheet1.Range("d42").Value = "Chipping"
'CPLD_W.Show
End If

If PPC_Include = 2 And Sheet3.Range("b17").Value = 1 Then
Sheet3.Range("b19").Value = "Grinding"
Sheet1.Range("d42").Value = "Grinding"
Sheet1.Range("b42").Value = "Loader"
Sheet1.Range("c42").Value = "Unit number:"
Sheet1.Range("c43").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c44").Value = "Model:"
Sheet1.Range("c44").Value = "Machine productivity (ODT/PMH):"
Sheet1.Range("b46").Value = "Grinder"
Sheet1.Range("c46").Value = "Unit number:"
Sheet1.Range("c47").Value = "Machine hourly cost ($/SMH):"
Sheet1.Range("c48").Value = "Model:"
Sheet1.Range("c49").Value = "Machine productivity (ODT/PMH):"
GRLD_W.Show
End If

If PPC_Include = 2 And Sheet3.Range("b17").Value = 2 Then
Sheet3.Range("b19").Value = "Grinding"
Sheet1.Range("d42").Value = "Grinding"
GRLD_W.Show
End If

If PPC_Include = 3 Then
Sheet3.Range("b19").Value = "None"
Sheet1.Range("d42,d46").Value = "None"
Sheet6.Range("a46:h47,a45,i46").Interior.ColorIndex = 0 'cell no color
Sheet6.Range("i63").Value = ""
End If

If PPC_Include = 4 Then
Sheet3.Range("b19").Value = "-"
Sheet1.Range("d42").Value = "-"
Sheet6.Range("a46:h47,a45,i46").Interior.ColorIndex = 0 'cell no color
End If
```

```
End Sub
Private Sub I_Change()

Sheet3.Range("E5").Value = I.ListIndex + 1
Dim TC_MD
TC_MD = Sheet3.Range("E5").Value
If TC_MD = 2 Then MsgBox "This model temporarily can only handle truck volume of
148 Yard3.", , "Error Msg - Truck Volume"

End Sub
Private Sub J_Change()

Sheet2.Range("B14").Value = J.ListIndex + 1

End Sub
Private Sub HBSIDE_Click()

If HBSIDE.Value = True Then Sheet3.Range("B12").Value = 16.6
If HBSIDE.Value = False Then Sheet3.Range("B12").Value = 0

End Sub

Private Sub DBH_Click()

Dim ts
ts = Sheet3.Range("B5").Value

If ts = 1 And DBH.Value = True Then Range("B7").Value = 1
If ts = 1 And DBH.Value = False Then Range("B7").Value = 0
If ts = 2 And DBH.Value = True Then Range("B7").Value = 4
If ts = 2 And DBH.Value = False Then Range("B7").Value = 0
If ts = 3 And DBH.Value = True Then Range("B7").Value = 7
If ts = 3 And DBH.Value = False Then Range("B7").Value = 0
If ts = 4 And DBH.Value = True Then Range("B7").Value = 8
If ts = 4 And DBH.Value = False Then Range("B7").Value = 0

End Sub

Private Sub HA_Click()
Dim ts
ts = Sheet3.Range("B5").Value

If ts = 1 And ha.Value = True Then Range("B6").Value = 1.1
If ts = 1 And ha.Value = False Then Range("B6").Value = 0
```

```
If ts = 2 And ha.Value = True Then Range("B6").Value = 7.7
If ts = 2 And ha.Value = False Then Range("B6").Value = 0
If ts = 3 And ha.Value = True Then Range("B6").Value = 56
If ts = 3 And ha.Value = False Then Range("B6").Value = 0
If ts = 4 And ha.Value = True Then Range("B6").Value = 33
If ts = 4 And ha.Value = False Then Range("B6").Value = 0

End Sub

Private Sub AGEde_Click()

Dim ts
ts = Sheet3.Range("B5").Value

If ts = 1 And AGEde.Value = True Then Range("B8").Value = 3
If ts = 1 And AGEde.Value = False Then Range("B8").Value = 0
If ts = 2 And AGEde.Value = True Then Range("B8").Value = 7
If ts = 2 And AGEde.Value = False Then Range("B8").Value = 0
If ts = 3 And AGEde.Value = True Then Range("B8").Value = 29
If ts = 3 And AGEde.Value = False Then Range("B8").Value = 0
If ts = 4 And AGEde.Value = True Then Range("B8").Value = 10
If ts = 4 And AGEde.Value = False Then Range("B8").Value = 0

End Sub
Private Sub CSQ_Click()

Dim ts
ts = Sheet3.Range("B5").Value

If ts = 1 And CSQ.Value = True Then Range("B10").Value = 0.3
If ts = 1 And CSQ.Value = False Then Range("B10").Value = 0
If ts = 2 And CSQ.Value = True Then Range("B10").Value = 0.75
If ts = 2 And CSQ.Value = False Then Range("B10").Value = 0
If ts = 3 And CSQ.Value = True Then Range("B10").Value = 0.06
If ts = 3 And CSQ.Value = False Then Range("B10").Value = 0
If ts = 4 And CSQ.Value = True Then Range("B10").Value = 0.53
If ts = 4 And CSQ.Value = False Then Range("B10").Value = 0

End Sub
Private Sub INMC_Df_Click()

If INMC_Df.Value = True And Sheet2.Range("B14").Value = 1 Then
Sheet3.Range("e14").Value = 29.4 'use the initial mc from the woody chips storage
study
If INMC_Df.Value = True And Sheet2.Range("B14").Value = 2 Then
Sheet3.Range("e14").Value = 34   'use the initial mc from the logging residue study
```

```
If INMC_Df.Value = False Then Sheet3.Range("E14").Value = 0

End Sub
Private Sub REMC_df_Click()

If REMC_df.Value = True And Sheet2.Range("B14").Value = 1 Then Sheet3.Range("e15").Value = 39.3  'use the resulted mc from the woody chips storage study
If REMC_df.Value = True And Sheet2.Range("B14").Value = 2 Then Sheet3.Range("e15").Value = 26.3  'use the resulted mc from the logging residue study
If REMC_df.Value = False Then Sheet3.Range("E15").Value = 0

End Sub
Private Sub Worksheet_Change(ByVal Target As Range)

Dim AGE
AGE = Sheet3.Range("B8").Value

Dim ts
ts = Sheet3.Range("B5").Value

'DBH range
Dim DBH
DBH = Sheet3.Range("B7").Value
If DBH > 10 Then MsgBox "Invalid input, please type in a value lower than 10 inches", , "Error Msg"
If (ts = 1 And AGE > 9) Then MsgBox "Invalid age! The valid age range for hybrid willow is 1~9 year(s).", , "Error Msg"
If (ts = 2 And AGE > 9) Then MsgBox "Invalid age! The valid age range for hybrid poplar is 1~9 year(s).", , "Error Msg"
If (ts = 3 And AGE > 50) Then MsgBox "Invalid age! The valid age range for jack pine is 1~50 year(s).", , "Error Msg"
If (ts = 4 And AGE > 50) Then MsgBox "Invalid age! The valid age range for mixed-species wood is 1~50 year(s).", , "Error Msg"

'Transportation range
Dim DR
DR = Sheet3.Range("E7").Value
If DR > 10 Then MsgBox "Invalid input, please type in a dirt road distance lower than 10 miles.", , "Error Msg"
If DR > 10 Then Sheet3.Range("E7").Value = 0
Dim GR
GR = Sheet3.Range("E8").Value
If GR > 45 Then MsgBox "Invalid input, please type in a gravel road distance lower than 45 miles.", , "Error Msg"
If GR > 45 Then Sheet3.Range("E8").Value = 0
```

```
Dim PR
PR = Sheet3.Range("E9").Value
If PR > 60 Then MsgBox "Invalid input, please type in a paved road distance lower than 60 miles.", , "Error Msg"
If PR > 60 Then Sheet3.Range("E9").Value = 0
Dim Hwy
Hwy = Sheet3.Range("E10").Value
If Hwy > 200 Then MsgBox "Invalid input, please type in a highway distance lower than 200 miles.", , "Error Msg"
If Hwy > 200 Then Sheet3.Range("E10").Value = 0


'Moisture content range
Dim OMC
OMC = Sheet3.Range("E14").Value
'If OMC > 65 Then MsgBox "Invalid input, please type in a moisture content between 25% ~ 65%.", , "Error Msg - Moisture Content."
'If OMC < 25 Then MsgBox "Invalid input, please type in a moisture content between 25% ~ 65%.", , "Error Msg - Moisture Content."
'If OMC > 65 Then Sheet3.Range("E14").Value = 45
'If OMC < 25 Then Sheet3.Range("E14").Value = 45

Dim AMC
AMC = Sheet3.Range("E15").Value
'If AMC > 65 Then MsgBox "Invalid input, please type in a moisture content between 15% ~ 65%.", , "Error Msg - Moisture Content."
'If AMC < 15 Then MsgBox "Invalid input, please type in a moisture content between 15% ~ 65%.", , "Error Msg - Moisture Content."
'If AMC > 65 Then Sheet3.Range("E15").Value = 45
'If AMC < 15 Then Sheet3.Range("E15").Value = 45
End Sub

Private Sub Railway_Click()

If Railway.Value = True Then MsgBox "This model temporarily can not handle railway transportation.", , "Error Msg- Railway"
If Railway.Value = True Then Railway.Value = False

End Sub
```

Sheet2. Model output

```
Private Sub CommandButton1_Click()

'clear the harvesting system info
Sheet1.Range("b31:f56, e30").Value = ""

End Sub

Private Sub SPre_Click()

If SPre.Value = True Then
Sheet1.Range("b13") = 1
End If

If SPre.Value = False Then
Sheet1.Range("b13") = 0
End If

End Sub
```

Forms – WT2 WINDOW

```
'default value click
Private Sub DFFBCOST_Click()
If DFFBCOST.Value = True Then
FBCOST.Text = Sheet6.Range("D20").Value
FBUSDF = "--"
FBDF.Value = False
End If
If DFFBCOST.Value = False Then
FBCOST.Text = "--"
End If
End Sub


Private Sub FBDF_Click()
If FBDF.Value = True Then
FBCOST_W.Show
DFFBCOST.Value = False
End If

If FBDF.Value = False Then
FBUSDF = ""
FBCOST.Text = "--"
End If

End Sub
Private Sub DFSKCOST_Click()

If DFSKCOST.Value = True Then
SKCOST = Format(Sheet6.Range("G20").Value, "0.00")
SKUSDF = "--"
SKDF.Value = False
End If

If DFSKCOST.Value = False Then
SKCOST.Text = "--"
End If

End Sub



Private Sub SKDF_Click()
If SKDF.Value = True Then
SKCOST_W.Show
DFSKCOST.Value = False
```

```
End If

If SKDF.Value = False Then
SKUSDF = ""
SKCOST.Text = "--"
End If

End Sub

Private Sub DFMTD_CLICK()

If DFMTD.Value = True Then FBMTD.Text = Format(Sheet6.Range("E33").Value,
"0")
If DFMTD.Value = False Then FBMTD.Text = "0"

End Sub
Private Sub DFCUTS_Click()


If DFCUTS.Value = True Then FBCUT.Text = Format(Sheet6.Range("E34").Value,
"0")
If DFCUTS.Value = False Then FBCUT.Text = "0"

End Sub
Private Sub DFMBD_Click()

If DFMBD.Value = True Then FBMBD.Text = Format(Sheet6.Range("E35").Value,
"0")
If DFMBD.Value = False Then FBMBD.Text = "0"

End Sub
Private Sub DFx1_Click()
If DFx1.Value = True Then SKX1.Text = Format(Sheet6.Range("E48").Value, "0")
If DFx1.Value = False Then SKX1.Text = "0"
End Sub
Private Sub DFX2_Click()
If DFX2.Value = True Then SKX2.Text = Format(Sheet6.Range("E49").Value, "0")
If DFX2.Value = False Then SKX2.Text = "0"
End Sub


'Value of textbox

Private Sub NofFB_Change()

Dim numberofFB
```

```
numberofFB = Val(NofFB.Text)
If numberofFB <= 0 Then
MsgBox "Please input a string value equal or larger than 1 .", , "Error Msg - Number of feller buncher(s)"
NofFB.Text = "1"
End If

End Sub

'model choice
Private Sub SS_FB_Change()

If MsgBox("This model temporarily can only handle feller buncher with rotating saw.", , "Error Msg - Shear saw feller buncher") = vbOK Then WT2_window.SS_FB.ListIndex = -1

End Sub
Private Sub BS_FB_Change()

If MsgBox("This model temporarily can only handle feller buncher with rotating saw.", , "Error Msg - Bar saw feller buncher") = vbOK Then WT2_window.BS_FB.ListIndex = -1

End Sub

Private Sub LINE_SK_Change()

If MsgBox("This model temporarily can only handle grapple skidder.", , "Error Msg - Line Skidder") = vbOK Then WT2_window.LINE_SK.ListIndex = -1

End Sub
Private Sub CB_SK_Change()

If MsgBox("This model temporarily can only handle grapple skidder.", , "Error Msg - Clam Bunk Skidder") = vbOK Then WT2_window.CB_SK.ListIndex = -1

End Sub
Private Sub NofSK_Change()

Dim numberofSK
numberofSK = Val(NofSK.Text)
If numberofSK <= 0 Then
MsgBox "Please input a string value equal or larger than 1 .", , "Error Msg - Number of skidder(s)"
NofSK.Text = "1"
End If
```

```
End Sub

Private Sub WheelFB_BOX_Change()

Dim FB_VL
FB_VL = WT2_window.WheelFB_BOX.Value
If FB_VL = "Large (with swing-boom and self leveling cab)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"
If FB_VL = "Small (drive-to-tree)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"

End Sub

Private Sub WheelSK_BOX_Change()

Dim SK_VL
SK_VL = WT2_window.WheelSK_BOX.Value
If SK_VL = "Large (300 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.", , "Error Msg - Skidder"
If SK_VL = "Small (237 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.", , "Error Msg - Skidder"
End Sub

Private Sub WT_CANCEL_Click()
Unload WT2_window
'Nofill the productivity estimation equation of the selected machine
Sheet6.Range("a26:I99").Interior.ColorIndex = 0 'every cell
End Sub
Private Sub WT_OK_Click()

Dim FB_VL
FB_VL = WT2_window.WheelFB_BOX.Value
If FB_VL = "Large (with swing-boom and self leveling cab)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.Please change your choice.", , "Error Msg - Feller buncher"
If FB_VL = "Small (drive-to-tree)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.Please change your choice.", , "Error Msg - Feller buncher"

Dim SK_VL
SK_VL = WT2_window.WheelSK_BOX.Value
```

```
If SK_VL = "Large (300 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.Please change your choice.", , "Error Msg - Skidder"
If SK_VL = "Small (237 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.Please change your choice.", , "Error Msg - Skidder"

Sheet1.Range("d31").Value = NofFB
Sheet2.Range("a10").Value = NofFB
Sheet1.Range("d36").Value = NofSK
Sheet2.Range("a11").Value = NofSK

'SK prediction
Dim x1
x1 = Val(SKX1.Text)

Dim x2
x2 = Val(SKX2.Text)

'Highlight the productivity estimation equation of the selected machine
Sheet6.Range("a26,a27:i27").Interior.ColorIndex = 36 ' TITLE
Sheet6.Range("a32:h35").Interior.ColorIndex = 36 'FB3
Sheet6.Range("I32").Interior.ColorIndex = 37 'FB3
Sheet6.Range("a40,a41:i41").Interior.ColorIndex = 36 'SK TITLE
Sheet6.Range("a47:h49").Interior.ColorIndex = 36 'SK3
Sheet6.Range("I47").Interior.ColorIndex = 37 'SK3

'harvesting system info summary
Sheet1.Range("e30").Value = "Whole tree harvesting system" 'system
Sheet1.Range("b31").Value = "Feller buncher:" 'machine
Sheet1.Range("b36").Value = "Skidder:"        'machine
Sheet1.Range("d34").Value = WheelFB_BOX.Text    'model
Sheet1.Range("d39").Value = WheelSK_BOX.Text    'model
If DFFBCOST.Value = True Then
Sheet1.Range("d32").Value = Val(FBCOST.Text) 'default hourly cost
Sheet1.Range("c33").Value = "(Model default value)"
End If
If FBDF.Value = True Then
Sheet1.Range("d32").Value = Val(FBUSDF.Text) 'user defined hourly cost
Sheet1.Range("c33").Value = "(User input value)"
End If
If DFSKCOST.Value = True Then
Sheet1.Range("d37").Value = Val(SKCOST.Text) 'default hourly cost
Sheet1.Range("c38").Value = "(Model default value)"
End If
If SKDF.Value = True Then
```

```
Sheet1.Range("d37").Value = Val(SKUSDF.Text) 'user defined hourly cost
Sheet1.Range("c38").Value = "(User input value)"
End If

'Sheet1.Range("e32").Value = "Move to tree distance (Feet):"
'Sheet1.Range("e33").Value = "Number of cuts per cycle:"
'Sheet1.Range("e34").Value = "Move to bunch distance (Feet):"

Sheet1.Range("f32").Value = Val(FBMTD.Text)
Sheet1.Range("f33").Value = Val(FBCUT.Text)
Sheet1.Range("f34").Value = Val(FBMBD.Text)

'Sheet1.Range("e37").Value = "Travel empty distance (Feet):"
'Sheet1.Range("e38").Value = "Travel loaded distance (Feet):"

Sheet1.Range("f37").Value = Val(SKX1.Text)
Sheet1.Range("f38").Value = Val(SKX2.Text)



'FB prediction
Dim MTD
MTD = Val(FBMTD.Text)

Dim MBD
MBD = Val(FBMBD.Text)

Dim CUT
CUT = Val(FBCUT.Text)

If MTD < 0 Or MTD > 90 Or MBD < 1 Or MBD > 82 Or CUT < 1 Or CUT > 12 Or x1
< 150 Or x1 > 950 Or x2 < 125 Or x2 > 1125 Then
MsgBox "Note: The user input value is beyond the model training range. User should
expect a larger predicting error.", , "Warning - User input is beyond the default range."
End If

Dim FB_PROD
Dim biomasspertree
biomasspertree = Exp(-2.2094 + 2.3867 * Log(2.54 * Sheet3.Range("b7").Value)) 'tree
weight in kg

BPT_ODT = biomasspertree * 2.20462 / 2000

FB_PROD = (CUT * BPT_ODT) / (((11.082 + 0.33 * MTD + 70.098 * CUT + 0.313 *
MBD) * 0.01)) * 60
```

```
Sheet1.Range("f31").Value = FB_PROD
Sheet6.Range("I32").Value = FB_PROD


Dim SK_PROD
SK_PROD = 1.6 * (60 / ((103.343 + 0.102 * x1 + 0.278 * x2) * 0.01))
Sheet1.Range("f36").Value = SK_PROD
Sheet6.Range("I47").Value = SK_PROD

'close the userform if all the condictions are satisfied
If (FB_VL = "Medium (with swing-boom)") And (SK_VL = "Medium") And NofFB >=
1 And NofSK >= 1 Then Unload WT2_window

End Sub
```

WT3 WINDOW

```
'default value click
Private Sub DFFBCOST_Click()
If DFFBCOST.Value = True Then
FBCOST.Text = Sheet6.Range("D20").Value
FBUSDF = "--"
FBDF.Value = False
End If
If DFFBCOST.Value = False Then
FBCOST.Text = "--"
End If
End Sub

Private Sub FBDF_Click()
If FBDF.Value = True Then
FBCOST_W.Show
DFFBCOST.Value = False
End If

If FBDF.Value = False Then
FBUSDF = ""
FBCOST.Text = "--"
End If

End Sub
Private Sub DFSKCOST_Click()

If DFSKCOST.Value = True Then
SKCOST = Format(Sheet6.Range("G20").Value, "0.00")
SKUSDF = "--"
SKDF.Value = False
End If

If DFSKCOST.Value = False Then
SKCOST.Text = "--"
End If

End Sub

Private Sub SKDF_Click()
If SKDF.Value = True Then
SKCOST_W.Show
DFSKCOST.Value = False
End If

If SKDF.Value = False Then
```

```
SKUSDF = ""
SKCOST.Text = "--"
End If

End Sub

Private Sub DFMTD_CLICK()
If DFMTD.Value = True Then FBMTD.Text = Format(Sheet6.Range("E37").Value,
"0")
If DFMTD.Value = False Then FBMTD.Text = "0"
End Sub

Private Sub DFCUTS_Click()

If DFCUTS.Value = True Then FBCUT.Text = Format(Sheet6.Range("E38").Value,
"0")
If DFCUTS.Value = False Then FBCUT.Text = "0"

End Sub
Private Sub DFMBD_Click()
If DFMBD.Value = True Then FBMBD.Text = Format(Sheet6.Range("E39").Value,
"0")
If DFMBD.Value = False Then FBMBD.Text = "0"
End Sub
Private Sub DFx1_Click()
If DFx1.Value = True Then SKX1.Text = Format(Sheet6.Range("E51").Value, "0")
If DFx1.Value = False Then SKX1.Text = "0"
End Sub
Private Sub DFX2_Click()
If DFX2.Value = True Then SKX2.Text = Format(Sheet6.Range("E52").Value, "0")
If DFX2.Value = False Then SKX2.Text = "0"
End Sub
'Value of textbox

Private Sub NofFB_Change()
Dim numberofFB
numberofFB = Val(NofFB.Text)
If numberofFB <= 0 Then
MsgBox "Please input a string value equal or larger than 1 .", , "Error Msg - Number of
feller buncher(s)"
NofFB.Text = "1"
End If

End Sub

'model choice
```

```
Private Sub SS_FB_Change()

If MsgBox("This model temporarily can only handle feller buncher with rotating saw.", , "Error Msg - Shear saw feller buncher") = vbOK Then WT3_window.SS_FB.ListIndex = -1

End Sub

Private Sub BS_FB_Change()
If MsgBox("This model temporarily can only handle feller buncher with rotating saw.", , "Error Msg - Bar saw feller buncher") = vbOK Then WT3_window.BS_FB.ListIndex = -1
End Sub

Private Sub LINE_SK_Change()
If MsgBox("This model temporarily can only handle grapple skidder.", , "Error Msg - Line Skidder") = vbOK Then WT3_window.LINE_SK.ListIndex = -1
End Sub

Private Sub CB_SK_Change()
If MsgBox("This model temporarily can only handle grapple skidder.", , "Error Msg - Clam Bunk Skidder") = vbOK Then WT3_window.CB_SK.ListIndex = -1
End Sub

Private Sub NofSK_Change()
Dim numberofSK
numberofSK = Val(NofSK.Text)
If numberofSK <= 0 Then
MsgBox "Please input a string value equal or larger than 1 .", , "Error Msg - Number of skidder(s)"
NofSK.Text = "1"
End If
End Sub

Private Sub WheelFB_BOX_Change()
Dim FB_VL
FB_VL = WT3_window.WheelFB_BOX.Value
If FB_VL = "Large (with swing-boom and self leveling cab)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"
If FB_VL = "Small (drive-to-tree)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"
End Sub

Private Sub WheelSK_BOX_Change()
```

```
Dim SK_VL
SK_VL = WT3_window.WheelSK_BOX.Value
If SK_VL = "Large (300 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.", , "Error Msg - Skidder"
If SK_VL = "Small (237 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.", , "Error Msg - Skidder"
End Sub

Private Sub WT_CANCEL_Click()
Unload WT3_window
'Nofill the productivity estimation equation of the selected machine
Sheet6.Range("a26:I99").Interior.ColorIndex = 0 'every cell
End Sub

Private Sub WT_OK_Click()
Dim FB_VL
FB_VL = WT3_window.WheelFB_BOX.Value
If FB_VL = "Large (with swing-boom and self leveling cab)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.Please change your choice.", , "Error Msg - Feller buncher"
If FB_VL = "Small (drive-to-tree)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.Please change your choice.", , "Error Msg - Feller buncher"

Dim SK_VL
SK_VL = WT3_window.WheelSK_BOX.Value
If SK_VL = "Large (300 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.Please change your choice.", , "Error Msg - Skidder"
If SK_VL = "Small (237 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.Please change your choice.", , "Error Msg - Skidder"
Sheet1.Range("d31").Value = NofFB
Sheet2.Range("a10").Value = NofFB
Sheet1.Range("d36").Value = NofSK
Sheet2.Range("a11").Value = NofSK

'SK prediction
Dim x1
x1 = Val(SKX1.Text)
Dim x2
x2 = Val(SKX2.Text)
'If x1 < 15 Or x1 > 270 Or x2 <= 0 Or x2 > 3 Or x3 <= 15 Or x3 > 40 Or x4 <= 67.5 Or x4 > 322.5 Then
'MsgBox "Note: The user input value is beyond the model training range. User should expect a larger predicting error.", , "Warning - User input is beyond the default range."
```

```
'End If
'Highlight the productivity estimation equation of the selected machine
Sheet6.Range("a26,a27:i27").Interior.ColorIndex = 36 ' TITLE
Sheet6.Range("a36:h39").Interior.ColorIndex = 36 'FB3
Sheet6.Range("I36").Interior.ColorIndex = 37 'FB3
Sheet6.Range("a40,a41:i41").Interior.ColorIndex = 36 'SK TITLE
Sheet6.Range("a50:h52").Interior.ColorIndex = 36 'SK3
Sheet6.Range("I50").Interior.ColorIndex = 37 'SK3

'harvesting system info summary
Sheet1.Range("e30").Value = "Whole tree harvesting system" 'system
Sheet1.Range("b31").Value = "Feller buncher:" 'machine
Sheet1.Range("b36").Value = "Skidder:"          'machine
Sheet1.Range("d34").Value = WheelFB_BOX.Text    'model
Sheet1.Range("d39").Value = WheelSK_BOX.Text    'model
If DFFBCOST.Value = True Then
Sheet1.Range("d32").Value = Val(FBCOST.Text) 'default hourly cost
Sheet1.Range("c33").Value = "(Model default value)"
End If
If FBDF.Value = True Then
Sheet1.Range("d32").Value = Val(FBUSDF.Text) 'user defined hourly cost
Sheet1.Range("c33").Value = "(User input value)"
End If
If DFSKCOST.Value = True Then
Sheet1.Range("d37").Value = Val(SKCOST.Text) 'default hourly cost
Sheet1.Range("c38").Value = "(Model default value)"
End If
If SKDF.Value = True Then
Sheet1.Range("d37").Value = Val(SKUSDF.Text) 'user defined hourly cost
Sheet1.Range("c38").Value = "(User input value)"
End If

'Sheet1.Range("e32").Value = "Move to tree distance (Feet):"
'Sheet1.Range("e33").Value = "Number of cuts per cycle:"
'Sheet1.Range("e34").Value = "Move to bunch distance (Feet):"

Sheet1.Range("f32").Value = Val(FBMTD.Text)
Sheet1.Range("f33").Value = Val(FBCUT.Text)
Sheet1.Range("f34").Value = Val(FBMBD.Text)

'Sheet1.Range("e37").Value = "Travel empty distance (Feet):"
'Sheet1.Range("e38").Value = "Positioning distance (Feet):"
'Sheet1.Range("e39").Value = "Number of trees per cycle:"
'Sheet1.Range("e40").Value = "Travel loaded distance (Feet):"

Sheet1.Range("f37").Value = Val(SKX1.Text)
```

```
Sheet1.Range("f38").Value = Val(SKX2.Text)

'FB prediction
Dim MTD
MTD = Val(FBMTD.Text)

Dim MBD
MBD = Val(FBMBD.Text)

Dim CUT
CUT = Val(FBCUT.Text)

If MTD < 12 Or MTD > 120 Or MBD < 12 Or MBD > 120 Or CUT < 1 Or CUT > 6 Or
x1 < 75 Or x1 > 800 Or x2 <= 150 Or x2 > 1100 Then
MsgBox "Note: The user input value is beyond the model training range. User should
expect a larger predicting error.", , "Warning - User input is beyond the default range."
End If

Dim FB_PROD
Dim biomasspertree
biomasspertree = Exp(-2.2094 + 2.3867 * Log(2.54 * Sheet3.Range("b7").Value)) 'tree
weight in kg

BPT_ODT = biomasspertree * 2.20462 / 2000
FB_PROD = (CUT * BPT_ODT) / (((25.32 + 0.356 * MTD + 7.179 * CUT + 0.584 *
MBD) * 0.01)) * 60

Sheet1.Range("f31").Value = FB_PROD
Sheet6.Range("I36").Value = FB_PROD

Dim SK_PROD
SK_PROD = 1.1 * (60 / ((103.343 + 0.102 * x1 + 0.278 * x2) * 0.01))
Sheet1.Range("f36").Value = SK_PROD
Sheet6.Range("I50").Value = SK_PROD

'close the userform if all the conditions are satisfied
If (FB_VL = "Medium (with swing-boom)") And (SK_VL = "Medium") And NofFB >=
1 And NofSK >= 1 Then Unload WT3_window

End Sub
```

```
'default value click
Private Sub DFFBCOST_Click()
If DFFBCOST.Value = True Then
FBCOST.Text = Sheet6.Range("D20").Value
FBUSDF = "--"
FBDF.Value = False
End If
If DFFBCOST.Value = False Then
FBCOST.Text = "--"
End If
End Sub

Private Sub FBDF_Click()
If FBDF.Value = True Then
FBCOST_W.Show
DFFBCOST.Value = False
End If

If FBDF.Value = False Then
FBUSDF = ""
FBCOST.Text = "--"
End If

End Sub
Private Sub DFSKCOST_Click()

If DFSKCOST.Value = True Then
SKCOST = Format(Sheet6.Range("G20").Value, "0.00")
SKUSDF = "--"
SKDF.Value = False
End If

If DFSKCOST.Value = False Then
SKCOST.Text = "--"
End If

End Sub



Private Sub SKDF_Click()
If SKDF.Value = True Then
SKCOST_W.Show
DFSKCOST.Value = False
End If
```

```
If SKDF.Value = False Then
SKUSDF = ""
SKCOST.Text = "--"
End If

End Sub

Private Sub DFMTD_CLICK()

If DFMTD.Value = True Then FBMTD.Text = Format(Sheet6.Range("E29").Value,
"0")
If DFMTD.Value = False Then FBMTD.Text = "0"

End Sub
Private Sub DFCUTS_Click()

If DFCUTS.Value = True Then FBCUT.Text = Format(Sheet6.Range("E30").Value,
"0")
If DFCUTS.Value = False Then FBCUT.Text = "0"

End Sub
Private Sub DFMBD_Click()

If DFMBD.Value = True Then FBMBD.Text = Format(Sheet6.Range("E31").Value,
"0")
If DFMBD.Value = False Then FBMBD.Text = "0"

End Sub
Private Sub DFx1_Click()
If DFx1.Value = True Then SKX1.Text = Format(Sheet6.Range("E43").Value, "0")
If DFx1.Value = False Then SKX1.Text = "0"
End Sub
Private Sub DFX2_Click()
If DFX2.Value = True Then SKX2.Text = Format(Sheet6.Range("E44").Value, "0")
If DFX2.Value = False Then SKX2.Text = "0"
End Sub
Private Sub DFX3_Click()
If DFX3.Value = True Then SKX3.Text = Format(Sheet6.Range("E45").Value, "0")
If DFX3.Value = False Then SKX3.Text = "0"
End Sub
Private Sub DFX4_Click()
If DFX4.Value = True Then SKX4.Text = Format(Sheet6.Range("E46").Value, "0")
If DFX4.Value = False Then SKX4.Text = "0"
End Sub

'Value of textbox
```

```
Private Sub NofFB_Change()
Dim numberofFB
numberofFB = Val(NofFB.Text)
If numberofFB <= 0 Then
MsgBox "Please input a string value equal or larger than 1 .", , "Error Msg - Number of
feller buncher(s)"
NofFB.Text = "1"
End If
End Sub
'model choice

Private Sub SS_FB_Change()
If MsgBox("This model temporarily can only handle feller buncher with rotating saw.", ,
"Error Msg - Shear saw feller buncher") = vbOK Then WT4_window.SS_FB.ListIndex
= -1
End Sub

Private Sub BS_FB_Change()
If MsgBox("This model temporarily can only handle feller buncher with rotating saw.", ,
"Error Msg - Bar saw feller buncher") = vbOK Then WT4_window.BS_FB.ListIndex =
-1
End Sub

Private Sub LINE_SK_Change()
If MsgBox("This model temporarily can only handle grapple skidder.", , "Error Msg -
Line Skidder") = vbOK Then WT4_window.LINE_SK.ListIndex = -1
End Sub
Private Sub CB_SK_Change()

If MsgBox("This model temporarily can only handle grapple skidder.", , "Error Msg -
Clam Bunk Skidder") = vbOK Then WT4_window.CB_SK.ListIndex = -1

End Sub
Private Sub NofSK_Change()

Dim numberofSK
numberofSK = Val(NofSK.Text)
If numberofSK <= 0 Then
MsgBox "Please input a string value equal or larger than 1 .", , "Error Msg - Number of
skidder(s)"
NofSK.Text = "1"
End If
End Sub

Private Sub WheelFB_BOX_Change()
```

```
Dim FB_VL
FB_VL = WT4_window.WheelFB_BOX.Value
If FB_VL = "Large (with swing-boom and self leveling cab)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"
If FB_VL = "Small (drive-to-tree)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"
End Sub

Private Sub WheelSK_BOX_Change()
Dim SK_VL
SK_VL = WT4_window.WheelSK_BOX.Value
If SK_VL = "Large (300 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.", , "Error Msg - Skidder"
If SK_VL = "Small (237 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.", , "Error Msg - Skidder"

End Sub

Private Sub WT_CANCEL_Click()
Unload WT4_window
'Nofill the productivity estimation equation of the selected machine
Sheet6.Range("a26:I99").Interior.ColorIndex = 0 'every cell
End Sub

Private Sub WT_OK_Click()
Dim FB_VL
FB_VL = WT4_window.WheelFB_BOX.Value
If FB_VL = "Large (with swing-boom and self leveling cab)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.Please change your choice.", , "Error Msg - Feller buncher"
If FB_VL = "Small (drive-to-tree)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.Please change your choice.", , "Error Msg - Feller buncher"

Dim SK_VL
SK_VL = WT4_window.WheelSK_BOX.Value
If SK_VL = "Large (300 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.Please change your choice.", , "Error Msg - Skidder"
If SK_VL = "Small (237 HP)" Then MsgBox "This model temporarily can only handle medium size skidder such as John Deere 740A.Please change your choice.", , "Error Msg - Skidder"

Sheet1.Range("d31").Value = NofFB
```

```
Sheet2.Range("a10").Value = NofFB
Sheet1.Range("d36").Value = NofSK
Sheet2.Range("a11").Value = NofSK

'SK prediction
Dim x1
x1 = Val(SKX1.Text)

Dim x2
x2 = Val(SKX2.Text)

Dim x3
x3 = Val(SKX3.Text)

Dim x4
x4 = Val(SKX4.Text)

'If x1 < 15 Or x1 > 270 Or x2 <= 0 Or x2 > 3 Or x3 <= 15 Or x3 > 40 Or x4 <= 67.5 Or
x4 > 322.5 Then
'MsgBox "Note: The user input value is beyond the model training range. User should
expect a larger predicting error.", , "Warning - User input is beyond the default range."
'End If

'Highlight the productivity estimation equation of the selected machine
Sheet6.Range("a26,a27:i31").Interior.ColorIndex = 36 ' TITLE
Sheet6.Range("a28:h31").Interior.ColorIndex = 36 'FB1
Sheet6.Range("I28").Interior.ColorIndex = 37 'FB1
Sheet6.Range("a40,a41:i41").Interior.ColorIndex = 36 'SK TITLE
Sheet6.Range("a42:h46").Interior.ColorIndex = 36 'SK1
Sheet6.Range("I42").Interior.ColorIndex = 37 'SK1

'harvesting system info summary
Sheet1.Range("e30").Value = "Whole tree harvesting system" 'system
Sheet1.Range("b31").Value = "Feller buncher:" 'machine
Sheet1.Range("b36").Value = "Skidder:"          'machine
Sheet1.Range("d34").Value = WheelFB_BOX.Text    'model
Sheet1.Range("d39").Value = WheelSK_BOX.Text    'model
If DFFBCOST.Value = True Then
Sheet1.Range("d32").Value = Val(FBCOST.Text) 'default hourly cost
Sheet1.Range("c33").Value = "(Model default value)"
End If
If FBDF.Value = True Then
Sheet1.Range("d32").Value = Val(FBUSDF.Text) 'user defined hourly cost
Sheet1.Range("c33").Value = "(User input value)"
End If
If DFSKCOST.Value = True Then
```

```
Sheet1.Range("d37").Value = Val(SKCOST.Text) 'default hourly cost
Sheet1.Range("c38").Value = "(Model default value)"
End If
If SKDF.Value = True Then
Sheet1.Range("d37").Value = Val(SKUSDF.Text) 'user defined hourly cost
Sheet1.Range("c38").Value = "(User input value)"
End If

'Sheet1.Range("e32").Value = "Move to tree distance (Feet):"
'Sheet1.Range("e33").Value = "Number of cuts per cycle:"
'Sheet1.Range("e34").Value = "Move to bunch distance (Feet):"

Sheet1.Range("f32").Value = Val(FBMTD.Text)
Sheet1.Range("f33").Value = Val(FBCUT.Text)
Sheet1.Range("f34").Value = Val(FBMBD.Text)

'Sheet1.Range("e37").Value = "Travel empty distance (Feet):"
'Sheet1.Range("e38").Value = "Positioning distance (Feet):"
'Sheet1.Range("e39").Value = "Number of trees per cycle:"
'Sheet1.Range("e40").Value = "Travel loaded distance (Feet):"

Sheet1.Range("f37").Value = Val(SKX1.Text)
Sheet1.Range("f38").Value = Val(SKX2.Text)
Sheet1.Range("f39").Value = Val(SKX3.Text)
Sheet1.Range("f40").Value = Val(SKX4.Text)


'FB prediction
Dim MTD
MTD = Val(FBMTD.Text)

Dim MBD
MBD = Val(FBMBD.Text)

Dim CUT
CUT = Val(FBCUT.Text)

If MTD < 0 Or MTD > 90 Or MBD < 1 Or MBD > 82 Or CUT < 1 Or CUT > 12 Or x1
< 120 Or x1 > 432 Or x2 <= 0 Or x2 > 72 Or x3 < 15 Or x3 > 35 Or x4 < 144 Or x4 >
516 Then
MsgBox "Note: The user input value is beyond the model training range. User should
expect a larger predicting error.", , "Warning - User input is beyond the default range."
End If

Dim FB_PROD
Dim biomasspertree
```

```
biomasspertree = Exp(-2.2094 + 2.3867 * Log(2.54 * Sheet3.Range("b7").Value)) 'tree weight in kg

BPT_ODT = biomasspertree * 2.20462 / 2000
FB_PROD = (CUT * BPT_ODT) / (((8.766 + 0.565 * MTD + 8.816 * CUT + 0.325 * MBD) * 0.01)) * 60

Sheet1.Range("f31").Value = FB_PROD
Sheet6.Range("I28").Value = FB_PROD

Dim SK_PROD

SK_PROD = (x3 * BPT_ODT) / ((19.49 + 0.076 * x1 + 0.354 * x2 + 1.778 * x3 + 0.155 * x4) * 0.01) * 60

Sheet1.Range("f36").Value = SK_PROD
Sheet6.Range("I42").Value = SK_PROD
'close the userform if all the condictions are satisfied
If (FB_VL = "Medium (with swing-boom) (John Deere 653G)") And (SK_VL = "Medium (John Deere 740A)") And NofFB >= 1 And NofSK >= 1 Then Unload WT4_window

End Sub
```

Form- CTL window

```
Private Sub CTL_CANCEL_Click()
Unload CTL_WINDOW
Sheet6.Range("a39:h44,A38,I39").Interior.ColorIndex = 0 'CLEAR cell
End Sub

Private Sub DFFWDCOST_Click()
If DFFWDCOST.Value = True Then
FWDCOST.Text = Format(Sheet6.Range("M20").Value, "0.00")
FWDUSDF = "--"
FWDDF.Value = False
End If
If DFFWDCOST.Value = False Then
FWDCOST.Text = "0"
End If
End Sub

Private Sub FORWARDER_BOX_Change()
End Sub

Private Sub fwdDF_Click()
If FWDDF.Value = True Then
FWDCOST_W.Show
DFFWDCOST.Value = False
End If

If FWDDF.Value = False Then FWDUSDF = ""
End Sub

Private Sub FW1_Click()
If FW1.Value = True Then FWX1.Text = Format(Sheet6.Range("E56").Value, "0")
If FW1.Value = False Then FWX1.Text = "0"
End Sub
Private Sub FW2_Click()
If FW2.Value = True Then FWX2.Text = Format(Sheet6.Range("E57").Value, "0")
If FW2.Value = False Then FWX2.Text = "0"
End Sub
Private Sub FW3_Click()
If FW3.Value = True Then FWX3.Text = Format(Sheet6.Range("E58").Value, "0")
If FW3.Value = False Then FWX3.Text = "0"
End Sub
Private Sub FW4_Click()
If FW4.Value = True Then FWX4.Text = Format(Sheet6.Range("E59").Value, "0")
If FW4.Value = False Then FWX4.Text = "0"
End Sub
Private Sub FW5_Click()
```

```
If FW5.Value = True Then FWX5.Text = Format(Sheet6.Range("E60").Value, "0")
If FW5.Value = False Then FWX5.Text = "0"

If FWX1 < 0 Or FWX1 > 52.75 Or FWX2 < 2.6 Or FWX2 > 27.1 Or FWX3 < 11 Or
FWX3 > 40 Or FWX4 < 0.6 Or FWX4 > 53.5 Or FWX5 < 5 Or FWX5 > 17 Then
MsgBox "Note: The user input value is beyond the model training range. User should
expect a larger predicting error.", , "Warning - User input is beyond the default range."
End If
End Sub

'Private Sub FORWARDER_BOX_Change()

'Dim FW_VL
'FW_VL = CTL_WINDOW.FORWARDER_BOX.Value
'If FW_VL = "Large (Load carring capacity: 15 tons)" Then MsgBox "This model
temporarily can only handle forwarder model such as Ponsse Bison S15.", , "Error Msg -
Forwarder"
'If FW_VL = "Medium (Load carring capacity: 13 tons)" Then MsgBox "This model
temporarily can only handle forwarder model such as Ponsse Bison S15.", , "Error Msg -
Forwarder"
'End Sub

Private Sub NofFw_Change()
Dim numberofFW As Integer
numberofFW = Val(NofFw.Text)
Sheet2.Range("A11") = numberofFW
If numberofFW <= 0 Then MsgBox "Please input a integer value equal or larger than 1
.", , "Error Msg - Number of forwarder(s)"
If numberofFW <= 0 Then NofFw.Text = "1"
End Sub

Private Sub CTL_OK_Click()
Dim x1
x1 = Val(FWX1.Text)
Dim x2
x2 = Val(FWX2.Text)
Dim x3
x3 = Val(FWX3.Text)
Dim x4
x4 = Val(FWX4.Text)
Dim x5
x5 = Val(FWX5.Text)
Dim prod
prod = 1.1776 * 60 / ((242.7 + 11.79 * x1 + 14.39 * x2 + 22.32 * x3 + 10.27 * x4 +
27.77 * x5) / 100)
Sheet6.Range("I55").Value = prod
```

```
'Highlight the productivity estimation equation of the selected machine
Sheet6.Range("a54:h60,A53,I54").Interior.ColorIndex = 36 'FW
Sheet6.Range("I55").Interior.ColorIndex = 37 'FW

Dim FW_VL
FW_VL = CTL_WINDOW.FORWARDER_BOX.Value
If FW_VL = "Large (Load carring capacity: 15 tons)" Then MsgBox "This model temporarily can only handle forwarder model such as Ponsse Bison S15. Please change your choice.", , "Error Msg - Forwarder"
If FW_VL = "Medium (Load carring capacity: 13 tons)" Then MsgBox "This model temporarily can only handle forwarder model such as Ponsse Bison S15.Please change your choice.", , "Error Msg - Forwarder"

If FW_VL = "Small (Load carring capacity: 12 tons) (Ponsse Bison S15)" Then Unload CTL_WINDOW
Sheet2.Range("a12").Value = NofFw
End Subwindow
```

Form- RCF window

```
Private Sub RCF_B_Change()
Dim RCF_VL
RCF_VL = RCF.RCF_B.Value
'If RCF_VL = "Large (with swing-boom and self leveling cab)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"
'If RCF_VL = "Small (drive-to-tree)" Then MsgBox "This model temporarily can only handle medium size feller buncher such as John Deere 653G.", , "Error Msg - Feller buncher"
End Sub

Private Sub Nofrcf_Change()
Dim numberofRCF
numberofRCF = Val(NofRCF.Text)
If numberofRCF <= 0 Then
MsgBox "Please input a string value equal or larger than 1 .", , "Error Msg - Number of recofigured harvester(s)"
NofRCF.Text = "1"
End If
Sheet2.Range("a13").Value = NofRCF
End Sub

Private Sub rcf_CANCEL_Click()
Unload RCF
'Nofill the productivity estimation equation of the selected machine
Sheet6.Range("a26:I99").Interior.ColorIndex = 0 'every cell
End Sub

Private Sub rcf_OK_Click()
Dim nU, lE, w, BD, hsP, tsP
nU = Val(n.Text)
Sheet2.Range("a15") = nU
lE = Val(l.Text)
WD = Val(WDI.Text)
BD = Val(B.Text)
hsP = Val(hs.Text)
tsP = Val(ts.Text)

Dim biomasspertree
biomasspertree = Exp(-2.2094 + 2.3867 * Log(2.54 * Sheet3.Range("b7").Value)) 'tree weight in kg
BPT_ODT = biomasspertree * 2.20462 / 2000
Dim PRO

If nU Mod 2 = 0 Then
```

```
TT = nU * lE * hsP + (WD + n * BD) * (nU + 1) * tsP
Sheet6.Range("a65:i65").Interior.ColorIndex = 36 ' TITLE
Sheet6.Range("a66:h73").Interior.ColorIndex = 36 '
Sheet6.Range("I66").Interior.ColorIndex = 37 '
PRO = BPT_ODT * Sheet3.Range("B9").Value / ((TT / 100) / 60)
Sheet6.Range("I66").Value = PRO
Sheet1.Range("f31").Value = Sheet6.Range("i66").Value
Else
TT = nU * lE * hsP + (WD + n * BD) * (nU) * tsP
Sheet6.Range("a65:i65").Interior.ColorIndex = 36 ' TITLE
Sheet6.Range("a74:h81").Interior.ColorIndex = 36 '
Sheet6.Range("I74").Interior.ColorIndex = 37 '
PRO = BPT_ODT * Sheet3.Range("B9").Value / ((TT / 100) / 60)
Sheet6.Range("I74").Value = PRO
Sheet1.Range("f31").Value = Sheet6.Range("i74").Value

End If

Sheet1.Range("e30").Value = "Reconfigured harvesting system"
Sheet1.Range("d31").Value = "Harvester"
Sheet1.Range("d31").Value = Sheet2.Range("a13").Value
If DFRCFCOST.Value = True Then 'use the default info
Sheet1.Range("d32").Value = Sheet6.Range("q20").Value
Sheet1.Range("d34").Value = Sheet6.Range("q5").Value
End If
If DFRCFCOST.Value = False Then
Sheet1.Range("d32").Value = RCFUSDF.Value
Sheet1.Range("d34").Value = RCF_B.Text
End If
Unload RCF
End Sub

Private Sub RCFDF_Click()
If RCFDF.Value = True Then
RCFCOST_W.Show
DFRCFCOST.Value = False
End If

If RCFDF.Value = False Then
RCFUSDF = ""
RCFCOST.Text = "--"
End If
End Sub


Private Sub tsdf_Click()
```

```
If tsdf.Value = True Then ts.Text = Format(Sheet6.Range("D73").Value, "0")
If tsdf.Value = False Then ts.Text = "0"
End Sub

Private Sub wdf_Click()
If wdf.Value = True Then WDI.Text = Format(Sheet6.Range("D69").Value, "0")
If wdf.Value = False Then WDI.Text = "0"
End Sub
```

Form – Preprocessing

```
Private Sub pp_cancel_Click()
Sheet3.Range("b19").Value = "None"
Sheet1.Range("d41").Value = "None"
Unload PP
End Sub

Private Sub PP_OK_Click()
Dim PP_Choice
PP_Choice = PP.PP_Cho.Value
Sheet3.Range("b19").Value = PP_Choice

If PP_Choice = "Chipping" Then
Sheet1.Range("d41").Value = "Chipping"
Sheet1.Range("b42").Value = "Chipper"
End If

If PP_Choice = "Grinding" Then
Sheet1.Range("e41").Value = PP.PP_Cho.Text

Sheet1.Range("b42").Value = "Loader"
Sheet1.Range("D44").Value = "Hood S-182"
Sheet1.Range("D43").Value = Sheet6.Range("N18").Value
Sheet1.Range("D42").Value = "1"
Sheet1.Range("D45").Value = Sheet6.Range("i42").Value

Sheet1.Range("b46").Value = "Grinder"
Sheet1.Range("D48").Value = "Peterson 4700B"
Sheet1.Range("D47").Value = Sheet6.Range("o18").Value
Sheet1.Range("D46").Value = "1"
Sheet1.Range("D49").Value = Sheet6.Range("i42").Value
End If
Unload PP
End Sub
```

Form- grinder loader window

```
Private Sub DFGDCOST_Click()
If DFGDCOST.Value = True Then
GDCOST.Text = Format(Sheet6.Range("O20").Value, "0.00")
GDUSDF = "--"
GDDF.Value = False
End If
If DFGDCOST.Value = False Then
GDCOST.Text = "--"
End If
End Sub

Private Sub DFLDCOST_Click()
If DFLDCOST.Value = True Then
LDCOST.Text = Format(Sheet6.Range("N20").Value, "0.00")
LDUSDF = "--"
LDDF.Value = False
End If

If DFLDCOST.Value = False Then
LDCOST.Text = "--"
End If
End Sub

Private Sub DFx1_Click()
If DFx1.Value = True Then glx1.Text = Format(12, "0")
If DFx1.Value = False Then glx1.Text = "0"
End Sub



Private Sub GDDF_Click()
If GDDF.Value = True Then
GDCOST_W.Show
DFGDCOST.Value = False
End If

If GDDF.Value = False Then
GDUSDF = ""
GDCOST.Text = "--"
End If
End Sub

Private Sub gl_CANCEL_Click()
Unload GRLD_W
Sheet6.Range("a25:i99").Interior.ColorIndex = 0 'CLEAR cell color
```

```
Sheet1.Range("d42:d49").Value = ""
End Sub

Private Sub gl_OK_Click()
Dim x1
If Sheet3.Range("b5").Value = 4 Then
x1 = 6
Else
x1 = Val(glx1.Text)
End If

Dim prod
Dim biomasspertree
biomasspertree = Exp(-2.2094 + 2.3867 * Log(2.54 * Sheet3.Range("b7").Value)) 'tree
weight in kg

BPT_ODT = biomasspertree * 2.20462 / 2000
prod = x1 * BPT_ODT * 6000 / (0.155 * x1 * Sheet3.Range("b7").Value + 20.864)
Sheet6.Range("i63").Value = prod

If glx1 < 5 Or FWX1 > 21 Then
MsgBox "Note: The user input value is beyond the model training range. User should
expect a larger predicting error.", , "Warning - User input is beyond the default range."
End If

'Highlight the productivity estimation equation of the selected machine
Sheet6.Range("a62:h64,A61,I62").Interior.ColorIndex = 36
Sheet6.Range("I63").Interior.ColorIndex = 37

If DFGDCOST.Value = True Then Sheet1.Range("d47").Value = GDCOST.Value
If GDDF.Value = True Then Sheet1.Range("d47").Value = GDUSDF.Value
If DFLDCOST.Value = True Then Sheet1.Range("d43").Value = LDCOST.Value
If LDDF.Value = True Then Sheet1.Range("d43").Value = LDUSDF.Value
Sheet1.Range("d46").Value = 1
Sheet1.Range("d42").Value = 1
Sheet1.Range("d44").Value = Sheet6.Range("n5").Text
Sheet1.Range("d45").Value = prod
Sheet1.Range("d48").Value = Sheet6.Range("o5").Text
Sheet1.Range("d49").Value = prod

If glx1 > 0 Then Unload GRLD_W


End Sub

Private Sub LDDF_Click()
```

```
If LDDF.Value = True Then
LDCOST_W.Show
DFLDCOST.Value = False
End If
If LDDF.Value = False Then
LDUSDF = ""
LDCOST.Text = "--"
End If

End Sub
```

Form –Chipper loader

```
Private Sub DFGDCOST_Click()
If DFGDCOST.Value = True Then
GDCOST.Text = Format(86.59, "0.00")
GDUSDF = "--"
GDDF.Value = False
End If
If DFGDCOST.Value = False Then
GDCOST.Text = "--"
End If
End Sub

Private Sub DFLDCOST_Click()
If DFLDCOST.Value = True Then
LDCOST.Text = Format(59.21, "0.00")
LDUSDF = "--"
LDDF.Value = False
End If

If DFLDCOST.Value = False Then
LDCOST.Text = "--"
End If
End Sub

Private Sub DFx1_Click()
If DFx1.Value = True Then glx1.Text = Format(Sheet6.Range("e68").Value, "0")
If DFx1.Value = False Then glx1.Text = "0"
End Sub



Private Sub GDDF_Click()
If GDDF.Value = True Then
GDCOST_W.Show
DFGDCOST.Value = False
End If

If GDDF.Value = False Then
GDUSDF = ""
GDCOST.Text = "--"
End If
End Sub

Private Sub gl_CANCEL_Click()
Unload CPLD_W
Sheet6.Range("a66:h68,A65,I66").Interior.ColorIndex = 0
```

```
Sheet6.Range("I67").Interior.ColorIndex = 0
Sheet6.Range("I67").Value = ""
Sheet1.Range("d42:d49").Value = ""
End Sub

Private Sub gl_OK_Click()
Dim x1
x1 = Val(glx1.Text)
Dim prod
prod = 0.225 * x1 * Sheet3.Range("b7").Value + 20.864
Sheet6.Range("i67").Value = prod

If glx1 < 2 Or FWX1 > 5 Then
MsgBox "Note: The user input value is beyond the model training range. User should expect a larger predicting error.", , "Warning - User input is beyond the default range."
End If
'Highlight the productivity estimation equation of the selected machine
Sheet6.Range("a66:h68,A65,I66").Interior.ColorIndex = 36
Sheet6.Range("I67").Interior.ColorIndex = 37

If DFGDCOST.Value = True Then Sheet1.Range("d47").Value = GDCOST.Value
If GDDF.Value = True Then Sheet1.Range("d47").Value = GDUSDF.Value
If DFLDCOST.Value = True Then Sheet1.Range("d43").Value = LDCOST.Value
If LDDF.Value = True Then Sheet1.Range("d43").Value = LDUSDF.Value
Sheet1.Range("d46").Value = 1
Sheet1.Range("d42").Value = 1
Sheet1.Range("d44").Value = Sheet6.Range("n5").Text
Sheet1.Range("d45").Value = Sheet6.Range("i67").Value
Sheet1.Range("d48").Value = "Trelan 21 L chipper"
Sheet1.Range("d49").Value = Sheet6.Range("i67").Value
If glx1 > 0 Then Unload CPLD_W
End Sub

Private Sub LDDF_Click()
If LDDF.Value = True Then
LDCOST_W.Show
DFLDCOST.Value = False
End If

If LDDF.Value = False Then
LDUSDF = ""
LDCOST.Text = "--"
End If

End Sub
```

Form – Fbcost

```
Private Sub FB_CAL_Click()

Dim II
II = Val(fbx1.Text)
Dim EL
EL = Val(fbx2.Text)
Dim SV
SV = Val(FBSV.Text) / 100
Dim SMH
SMH = Val(fbx3.Text)
Dim UR
UR = Val(FBUR.Text) / 100

Dim Interest
Interest = Val(fbx5.Text)
Dim Insurance
Insurance = Val(fbx6.Text)
Dim tax
tax = Val(fbx7.Text)
Dim main
main = Val(fbx8.Text)

Dim fuel
fuel = Val(fbx9.Text)

Dim lube
lube = Val(fbx10.Text)

Dim lab
lab = Val(fbx11.Text)

'Calculate AII, depreciation, and final cost
Dim AAI
AAI = II * (1 - SV) * (EL + 1) / (2 * EL) + 0.15 * II
AAI_V.Value = Format(AAI, "0.00")

Dim depre
depre = II * (1 - SV) / EL
fbx4.Value = Format(depre, "0.00")

Dim finalc
finalc = II * (1 - SV) / (EL * SMH) + (Interest / 100 + Insurance / 100 + tax / 100) *
AAI / SMH + (main / 100) * depre / SMH + (fuel * UR) + (lube * UR) + (lab)
fbcost_usdf.Value = Format(finalc, "0.00")
```

```
End Sub

Private Sub FB_CAN_Click()
WT_window.FBUSDF.Text = ""
WT_window.FBDF.Value = False
Unload FBCOST_W
End Sub

Private Sub FB_OK_Click()
Sheet2.Range("c12").Value = fbcost_usdf.Value
WT_window.FBUSDF.Text = fbcost_usdf.Value
WT_window.FBCOST.Text = "--"
Unload FBCOST_W
End Sub
```

Form – Skcost

```
Dim lab
lab = Val(skx11.Text)
'Calculate AII, depreciation, and final cost
Dim AAI
AAI = II * (1 - SV) * (EL + 1) / (2 * EL) + 0.15 * II
AAI_V.Text = Format(AAI, "0.00")
Dim depre
depre = II * (1 - SV) / EL
skx4.Value = Format(depre, "0.00")
Dim finalc
finalc = II * (1 - SV) / (EL * SMH) + (Interest / 100 + Insurance / 100 + tax / 100) *
AAI / SMH + (main / 100) * depre / SMH + (fuel * UR) + (lube * UR) + (lab)
skcost_usdf.Value = Format(finalc, "0.00")
End Sub

Private Sub SK_CAN_Click()
WT_window.SKUSDF.Text = ""
WT_window.SKDF.Value = False
Unload SKCOST_W
End Sub

Private Sub SK_OK_Click()
Sheet2.Range("c13").Value = skcost_usdf.Value
WT_window.SKUSDF.Text = skcost_usdf.Value
WT_window.SKCOST.Text = "--"
Unload SKCOST_W

End Sub
```

Form – LD cost

```
Private Sub ld_CAL_Click()
Dim II
II = Val(LDx1.Text)
Dim EL
EL = Val(LDx2.Text)
Dim SV
SV = Val(LDSV.Text) / 100
Dim SMH
SMH = Val(LDx3.Text)
Dim UR
UR = Val(LDUR.Text) / 100
Dim Interest
Interest = Val(LDx5.Text)
Dim Insurance
Insurance = Val(LDx6.Text)
Dim tax
```

```
tax = Val(LDx7.Text)
Dim main
main = Val(LDx8.Text)
Dim fuel
fuel = Val(LDx9.Text)
Dim lube
lube = Val(LDx10.Text)
Dim lab
lab = Val(LDx11.Text)

'Calculate AII, depreciation, and final cost
Dim AAI
AAI = II * (1 - SV) * (EL + 1) / (2 * EL) + 0.15 * II
AAI_V.Text = AAI
Dim depre
depre = II * (1 - SV) / EL
LDx4.Value = depre
Dim finalc
finalc = II * (1 - SV) / (EL * SMH) + (Interest / 100 + Insurance / 100 + tax / 100) *
AAI / SMH + (main / 100) * depre / SMH + (fuel * UR) + (lube * UR) + (lab)
LDcost_usdf.Value = finalc
End Sub

Private Sub ld_CAN_Click()
GRLD_W.LDUSDF.Text = ""
GRLD_W.LDDF.Value = False
Unload LDCOST_W
End Sub

Private Sub ld_OK_Click()
Sheet2.Range("c12").Value = LDcost_usdf.Value
GRLD_W.LDUSDF.Text = LDcost_usdf.Value
GRLD_W.LDCOST.Text = "--"
Unload LDCOST_W
End Sub
```

Form - Grinder cost

```
Private Sub gd_CAL_Click()
Dim II
II = Val(gdx1.Text)
Dim EL
EL = Val(gdx2.Text)
Dim SV
SV = Val(gdSV.Text) / 100
Dim SMH
SMH = Val(gdx3.Text)
Dim UR
UR = Val(gdUR.Text) / 100
Dim Interest
Interest = Val(gdx5.Text)
Dim Insurance
Insurance = Val(gdx6.Text)
Dim tax
tax = Val(gdx7.Text)
Dim main
main = Val(gdx8.Text)
Dim fuel
fuel = Val(gdx9.Text)
Dim lube
lube = Val(gdx10.Text)
Dim lab
lab = Val(gdx11.Text)
'Calculate AII, depreciation, and final cost
Dim AAI
AAI = II * (1 - SV) * (EL + 1) / (2 * EL) + 0.15 * II
AAI_V.Text = Format(AAI, "0.00")

Dim depre
depre = II * (1 - SV) / EL
gdx4.Value = Format(depre, "0.00")
Dim finalc
finalc = II * (1 - SV) / (EL * SMH) + (Interest / 100 + Insurance / 100 + tax / 100) *
AAI / SMH + (main / 100) * depre / SMH + (fuel * UR) + (lube * UR) + (lab)
gdcost_usdf.Value = Format(finalc, "0.00")
End Sub

Private Sub gd_CAN_Click()
GRLD_W.GDUSDF.Text = ""
GRLD_W.GDDF.Value = False
Unload GDCOST_W
End Sub
```

```
Private Sub gd_OK_Click()
Sheet2.Range("c12").Value = gdcost_usdf.Value
GRLD_W.GDUSDF.Text = gdcost_usdf.Value
GRLD_W.GDCOST.Text = "--"
Unload GDCOST_W
End Sub
```

Forms- Forwarder cost

```
Private Sub fwd_CAL_Click()
Dim II
II = Val(fwdx1.Text)
Dim EL
EL = Val(fwdx2.Text)
Dim SV
SV = Val(FWDSV.Text) / 100
Dim SMH
SMH = Val(fwdx3.Text)
Dim UR
UR = Val(FWDUR.Text) / 100
Dim Interest
Interest = Val(fwdx5.Text)
Dim Insurance
Insurance = Val(fwdx6.Text)
Dim tax
tax = Val(fwdx7.Text)
Dim main
main = Val(fwdx8.Text)
Dim fuel
fuel = Val(fwdx9.Text)
Dim lube
lube = Val(fwdx10.Text)
Dim lab
lab = Val(fwdx11.Text)
'Calculate AII, depreciation, and final cost
Dim AAI
AAI = II * (1 - SV) * (EL + 1) / (2 * EL) + 0.15 * II
AAI_V.Value = Format(AAI, "0.00")
Dim depre
depre = II * (1 - SV) / EL
fwdx4.Value = Format(depre, "0.00")
Dim finalc
finalc = II * (1 - SV) / (EL * SMH) + (Interest / 100 + Insurance / 100 + tax / 100) *
AAI / SMH + (main / 100) * depre / SMH + (fuel * UR) + (lube * UR) + (lab)
fwdcost_usdf.Value = Format(finalc, "0.00")
End Sub

Private Sub fwd_CAN_Click()
CTL_WINDOW.FWDUSDF.Text = ""
CTL_WINDOW.FWDDF.Value = False
Unload FWDCOST_W
End Sub

Private Sub fwd_OK_Click()
```

```
Sheet2.Range("c12").Value = fwdcost_usdf.Value
CTL_WINDOW.FWDUSDF.Text = fwdcost_usdf.Value
CTL_WINDOW.FWDCOST.Text = "--"
Unload FWDCOST_W
End Sub
```

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