2016

Optimization and cost analysis of lignocellulosic biomass feedstocks supply chains for biorefineries

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Optimization and cost analysis of lignocellulosic biomass feedstocks supply chains for biorefineries

by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural and Biosystems Engineering

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Iowa State University

Ames, Iowa

2016

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ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my major professor Dr. Stuart Birrell for his guidance and support throughout the research. I really want to thank him for his intellectual as well as moral support during my ISU stay. I would also like to thank my committee members, Dr. Brumm, Dr. Darr, Dr. Duffy, Dr. Raman, and Dr. Steward for their invaluable time and intellectual suggestions.

In addition, I would like to thank the department faculty, staff and many colleagues for the help and making my time at Iowa State University a wonderful experience.

Last but not the least, I would like to thank my sisters and brothers, family and friends for their encouragement and support. I would like to express sincere thanks to my mother for her unconditional love, support, trust and encouragement. I would like to thank my husband for his support and patience.

My special thanks goes to my adorable son Aaroh who keeps me going no matter what.

ABSTRACT

This study estimated the biomass harvest and transport cost considering single pass biomass harvest with bulk and bale collections of biomass. Lignocellulosic biomass feedstocks costs were estimated using both corn stover and switchgrass as part of the feedstock supply chain. Harvest and transport cost for multi-pass biomass harvest operations using multiple feedstocks were analyzed and the optimal number of machines for all unit operations were estimated for each supply chain.

This dissertation calculated and compared the biomass harvest and transport cost for single pass biomass harvest with bulk and bale collections of biomass. The objective of the research was to find the optimal number of machines, and least cost biomass harvest and transportation costs based on the harvest window, machine capacity, farm sizes and yield of the biomass. The least cost model was developed using the mixed integer non-linear programming model developed in General Algebraic Modeling System. The cost of harvest and transport using the bulk stover collection method was estimated about \$25 Mg^{-1} (\$23 ton^{-1}) considering a transport distance of 3.2 km (2 miles) for primary storage from the field with the harvestable stover yield of 4.4 Mg ha^{-1} (2 ton ac^{-1}) for the farm size of 2,000 ha. (5,000 ac.)

Biomass feedstocks cost at the gate of biorefinery was estimated for multi-pass harvest systems with multi-feedstocks. Corn stover was considered a by-product of grain production and switchgrass as a single product. Planting and establishment cost was also considered along with harvest and transport cost for switchgrass. The cost of switchgrass varied from \$75 Mg^{-1} to \$97 Mg^{-1} (\$68 ton^{-1} to \$88 ton^{-1}) and cost of corn stover varied from \$75 Mg^{-1} to \$97 Mg^{-1} (\$20 ton^{-1} to \$25 ton^{-1}) respectively with the farm sizes variation from 400 ha to 2,000 ha (1,000 ac to 5,000 ac).

CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

Biomass is an important and promising renewable energy resource to meet the increased energy needs of the world and to reduce the United States dependence on fossil fuel. Due to adverse environmental impacts of fossil fuels, energy from biomass has become a more accepted form of energy. Biofuel production is a more sustainable way to meet the raising global demands of energy for the 21st century. United States has a long term goal of replacing 30 percent of the fossil energy used with the use of a 1 billion tons of biomass feedstocks (Sharma et al., 2013). First generation biofuels such as bio-diesel, corn-ethanol are produced using soybeans, palm oil, corn grain, sugar can and other crop products, whereas, biofuel’s produced from non-food lignocellulosic feedstocks, are referred to as second generation biofuels (Naik et al., 2010). First generation biofuels; produced from grains and sugarcane have limitations for the fossil fuel substitution, mainly due to the consequences related to the competition between food and energy. Therefore second generation biofuels produced from lignocellulosic biomass have to play a major role in the development of a future bioenergy industry. Production and consumption of biofuels have increased rapidly in the past two decades, but it has not been free of controversy because of the food versus fuel issue (Carricuiry et al., 2011). Therefore, to overcome the negative consequences related to the competition between food and energy, there is an increasing focus on biofuel production from lignocellulosic feedstocks.

Lignocellulosic biomass includes agricultural residues, forest residues and energy crops, which can be inexpensive and abundant in nature compared to non-lignocellulosic biomass. Lignocellulosic biomass can be classified into three main components: cellulose (30-50%), hemicellulose (15-35%) and lignin (10-20%) (Limayem et al., 2012). For this research, corn stover and switchgrass were considered as main lignocellulosic biomass feedstocks. Corn stover is the non-grain part of corn plant, consisting of the cob, leaf, stalk and husk components. Compared to other biomass feedstock, corn stover has considerable advantages because it comes with the high-value co-product and corn stover is abundant in North America (Shinners et al., 2007). Multi-biomass supply chains can reduce biofuel production costs significantly, by spreading capital costs and reducing warehouse requirements (Rentizelas et al., 2009). This research analyzed the costs associated with corn stover and switchgrass as a dual-feedstock biomass supply. Switchgrass is a high potential yield warm season perennial energy crop native to North America. Due to the high biomass yield and low input parameters needed for switchgrass production, there is significant amount of research being conducted on the use of switchgrass and other perennial herbaceous crops for ethanol and other advanced biofuel production through thermochemical conversion processes (Virgilio et al., 2007). An analysis of machinery optimization and cost analysis of switchgrass production, harvest and transport to biorefinery is included in this dissertation.

Biomass harvest methods can significantly affect both feedstock costs and feedstock quality. In general, biomass harvest methods can categorized into two groups, 1) single pass harvest, and 2) multi-pass harvest systems. In a single pass stover harvest system, the crop stover and grain is harvested in a single operation, and both corn and stover are harvested and transported off the field at the same time. In a multi-pass harvest system, the first operations are the grain harvest and transportation from the field, and the biomass is harvested and transported from the field in subsequent operations. In the single pass harvest system the harvest and field logistics for grain and stover are coupled, whereas, in a multi-pass harvest system the harvest and field logistics for grain and stover are de-coupled. Multi-pass harvest systems can include several different field operations such as conditioning and windrowing, raking, and baling. Both single pass and multi-pass harvest systems require transportation of the biomass from the field to on-farm storage or other specified storage locations, and transportation from the storage location to the biorefinery. The dissertation includes analysis of machinery optimization and harvest costs associated with 1) the single pass harvest systems based on bulk collection of stover (i.e. forage wagons) and baled collection of stover (single pass baler system) for single feedstock supply chain (corn stover) and, 2) multi-pass harvest systems (large square balers) for a multi-feedstock supply chain (corn stover and switchgrass).

1.2 Thesis Organization

This dissertation includes work on biomass harvest and logistics systems model development, optimization and cost analysis of lignocellulosic biomass feedstocks and supply chains. This dissertation is comprised with two manuscripts for refereed journal publications.

The first manuscript entitled "Optimization and Machinery Cost Analysis of Crop Residue Harvest Systems" is submitted to the journal, Transactions of the American Society of Agricultural and Biological Engineers. The author and the primary researcher of this manuscript is Ambika Karkee, graduate student, Department of Agricultural and Biosystems Engineering, Iowa State University, Stuart J. Birrell, Associate Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, who provided intellectual guidance in the research and the preparation of this manuscript and is the corresponding author. The co-authors would also like to acknowledge and recognize the advice and intellectual contributions from the graduate committee consisting of Dr. Thomas Brumm, Dr. Matthew Darr, Dr. Raj Raman, and Dr. Brian Steward.

The second manuscript entitled "Multi-feedstocks Biomass Harvest and Logistics System Model Development" is prepared to submit on the journal, Transactions of the American Society of Agricultural and Biological Engineers. The author and the primary researcher of this manuscript is Ambika Karkee, graduate student, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa. Stuart J. Birrell, Associate Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, provided intellectual guidance in the research and the preparation of this manuscript and is the corresponding author. Again the contributions from the graduate committee consisting of Dr. Thomas Brumm, Dr. Matthew Darr, Dr. Raj Raman, and Dr. Brian Steward, must be acknowledged.

1.3 Literature Review

Energy production from biomass consists of several different operations including planting, harvest, storage, transportation, and processing. Each operation has an effect on the overall cost of fuel produced from biomass, with biomass harvest storage and transportation costs representing a significant amount of the total cost.

Biomass feedstock costs represent almost about 35-50% of the ethanol production cost and the costs are dependent on biomass types, location, yield, weather, harvesting systems, collection methods, storage, and transportation (Sokhansanj et al., 2006). In addition, feedstock quality is an important factor affecting conversion efficiency, and moisture content plays important role in determining the storage losses and biomass quality. Harvesting at the proper stage of plant development is the most effective way of managing moisture content. When dry storage is used, harvesting biomass at too high a moisture contents results in higher storage dry matter losses, whereas if a wet storage (silage) model is used if the moisture content is too dry, significant storage losses and reduction in quality can occur (Mueller et al., 2001). Daily effective field capacity of field machinery, available working days for field operations, probability of a working day, and harvest window all affect the costs of machinery operations and feedstock costs (De Toro, 2005).

The numerous studies on machinery requirements and costs associated with field operations, can be separated into three broad categories; 1) Spreadsheet based cost models, 2) linear programming optimization models, and 3) high level continuous and discreet event simulation modelling.

Salassi et al., (1998) developed a spread-sheet based cost model to estimate the machinery requirements and cost associated with two different harvesting and hauling systems of sugarcane. Gunnarsson et al., (2004) studied the optimization of field machinery for converting the arable land to organic farming and demonstrated that the optimal field machinery system when a field was converted to organic production. Ferrer et al., (2008) used mixed integer linear programming for optimization of grape harvesting, including operational costs and quality. Sogaard et al., (2004) optimized machinery sizes for a machinery system using the non-linear programming model developed for a particular size farm and conventional crop plan, but did not consider biomass harvest. Nilsson (1999a, 1999b) developed a Straw Handling Model (SHAM) to optimize energy and costs in straw production which included an empirical drying model and machine optimization (Nilsson et al., 2001).

Sokhansanj et al., (2006, 2008) developed the IBSAL model, using an object oriented high level discrete event simulation language (EXTENDSim), to simulate biomass supply chains consisting of operational modules connected into a complete supply chain. The IBSAL model calculates cost and energy of each module individually, as well as the integrated cost and energy requirements for the complete supply chain. However, machinery optimization and the impact of field size in overall cost estimation of biomass harvest and transport, can only be achieve through running the program through multiple simulations. Perlack et al., (2002) estimated the cost of corn stover harvest, storage, and transportation using a conventional multi-pass baling system for biorefineries of different sizes. The total estimated stover collection, storage and transport costs were \$47.5 to \$56.9 Mg^{-1} (\$43.1 to \$51.6/ton) (dry weight basis), for refinery sizes of 450 to 3600 dry Mg/day (500 to 4000 dry tons/day).

Switchgrass has been identified as a potential lignocellulosic biomass feedstocks for the production of biofuels. Sokhansanj et al., (2009) estimated that the current cost of switchgrass production excluding the establishment cost to be \$45.7 Mg^{-1} (\$41.5 ton^{-1}) with the yield consideration of 9.07 Mg ha^{-1} (4.05 ton ac^{-1}). The estimated cost using current baling technology was \$23.72 Mg^{-1} (\$21.52 ton^{-1}), with a possible reduction to \$16.01 Mg^{-1} (\$14.52 ton^{-1}) in the future.

However, establishment costs are a significant factor since switchgrass attains only about two thirds of its maximum production capacity in the first two years reaching maximum capacity at the end of third year of planting (Mclaughlin et al., 2005). Epplin et al., (1996) estimated the cost of production and transporting switchgrass to ethanol conversion facility. Estimated cost to lease a hectare of cropland and plant it to switchgrass was about \$297.48 ha^{-1} (\$120.19 ac^{-1}). The calculations estimated a cost of \$46.35 ha^{-1} (\$18.83 ac^{-1}) for establishment amortized over 10 years, \$59.13 ha^{-1} (\$23.93 ac^{-1}) for fertilizer and other operating inputs, \$74.00 ha^{-1} (\$29.95 ac^{-1}) for land rent and \$37.48 ha^{-1} (\$15.16 ac^{-1}) for machinery fixed cost (Epplin et al., 1996).

Cobuloglu et al., (2014) developed an optimized model for the analysis of switchgrass production at the farm level, which incorporated the environmental impacts of biomass production including soil erosion, carbon emission, bird population and carbon sequestration in the optimization model, and stated that switchgrass production was highly profitable assuming a market price of \$132 Mg^{-1} (\$120 ton^{-1}). Haque et al., (2012) estimated the necessary ethanol price for a biorefinery as a breakeven point considering switchgrass as a single feedstocks. The studied included a range of refinery sizes 95, 190, and 380 million liters yr^{-1} (25, 50 and 100 million gals yr^{-1}), conversion rates 250, 330, and 417 liters Mg^{-1} (60, 80, 100 gal ton^{-1}), and determined that the nominal breakeven price was \$0.58 per liter (\$2.21 per gallon) of ethanol.

The studies which are mentioned earlier have evaluated the switchgrass production cost, However, most have ignored the effect of machinery optimization for the production, harvest and transport of biomass, and the interaction between yield, producer size and feedstock costs. In addition all the studies are based on a single feedstock supply chain and did not consider multi-feedstock supply chains.

Lignocellulosic biomass can be considered as a potential feedstock for gasification to produce syngas which can be used to generate heat and electricity or can be used to produce fuel such as ethanol or hydrogen (Balat et al., 2009).

1.4 Research Objectives

Several studies have analyzed the feedstock supply chain costs and biorefinery conversion costs. However, in most of the previous research the feedstock supply chain costs were estimated without optimization of the harvest machinery at different scales, or the machinery costs were optimized without considering the biorefinery size.

The overall objective of the research was to develop the optimized number for machinery of crop residue harvest and transportation systems, and the cost analysis of liquid fuel production from biomass feedstock and their interaction at different scale of operation. The specific objectives were as follows:

1. Evaluate harvest and transport cost for two different biomass collection methods
2. Evaluate harvest and transport costs of multi-feedstocks for multi-pass biomass harvest and transport

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CHAPTER 2: OPTIMIZATION AND COST ANALYSIS OF CROP-RESIDUE HARVESTING SYSTEMS

A paper to be submitted to *Transactions of the ASABE*

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2.1 Abstract

The fundamental goal of this research was to provide answers on viable configuration of machinery for crop and biomass harvest and feedstock supply systems. The paper reports on model development to estimate the biomass harvest costs for single pass, bulk and bale biomass collection systems. The objective was to optimize machinery selection for biomass harvest and provide cost estimates for all operations. Harvest systems were analyzed to find out the least cost option for harvest and hauling of crop grain and stover based on harvest windows, biomass machine capacity, yield, and farm size. The optimization analysis estimated the number, type and cost of machinery systems required to achieve the specified harvest operations. A mixed integer non-linear programming model was developed in General Algebraic Modeling System (GAMS) to carry out the performance analysis of the machinery and operations. Result from the optimized model for the bulk stover collection system is presented in this paper.

2.2 Introduction

Biomass has great potential to provide renewable energy for the future of United States, and in 2005 was the largest domestic source of renewable energy, providing 3% of total energy consumption in the country, and is especially attractive because it one of the few renewable sources of liquid transportation fuel currently available (Perlack et al 2005).

Biofuels can be produced directly from food crops such as corn, soybean, wheat, sugarcane, or from the agricultural residues produced as by/co-product of the grain and dedicated lignocellulosic energy crops as switchgrass, miscanthus, energy sorghum and other herbaceous crops. Due to the fuel versus food debate when food crops are used from biofuel production, there is greater focus of biofuel production from cellulosic agricultural residues and energy crops, which have lower carbon emission and require less fertilizer (Cobuloglu et al., 2014). Substitution of petroleum and fossil fuel with the biomass derived fuels to achieve national energy independence and sustainable economic growth has resulted in increased interest in the production of lignocellulosic biofuels and bioproducts (Zhu et al 2012).

Corn stover is the residue remaining on the surface after the grain collection, and is the largest underutilized crop residue in the United States. Removal of excess corn stover from the field after meeting soil carbon and erosion needs, can provide over 100 million dry tons for the production of biofuels and chemicals (Kadam et al., 2003; Atchison et al., 2004). The amount of excess stover available for collection in the field depends on topography, soil type, crop rotation and tillage practice (Kadam et al., 2003).

Cost and availability of feedstock for biofuel production are the critical parameters for the success and growth of the bio-economy. A significant cost of production of biofuels are the biomass harvesting, storage and transportation costs. Feedstock supply chains from field to the bio-refinery consists of different processes such as harvesting, field densification/processing, storage and transportation. Rentizelas et al (2009) have stated that a significant limitation in the increased use of biomass as an energy supply is the biomass supply chain costs. Biomass feedstock costs represent almost about 35-50% of the ethanol production cost and the costs are dependent on biomass types, location, yield, weather, harvesting systems, collection methods, storage, and transportation distances (Sokhansanj et al., 2006). Sorensen (2003) estimated harvest costs account for over 30% of the total cost of the machinery cost for field operations.

The numerous studies on machinery requirements and costs associated with field operations, can be separated into three broad categories; 1) Spreadsheet based cost models, 2) linear programming optimization models, and 3) high level continuous and discreet event simulation modelling.

Salassi et al., (1998) developed a spread-sheet based cost model to estimate the machinery requirements and cost associated with two different harvesting and hauling systems of sugarcane, given a particular farm size. Gunnarsson et al., (2004) studied the optimization of field machinery for converting the arable land to organic farming, including the effects of timeliness costs and product prices on the optimal machinery system. Ferrer et al., (2008) developed a mixed integer liner programming model to optimally schedule wine grape harvest operations considering both the machinery cost and grape quality. Their results showed that the routing of the harvest operations was important, due to the costs incurred and the impact time and hauling of harvested products had on grape quality; based on this finding, they proposed a compromise harvesting schedule that considered both operation costs and grape quality. Arjona et al., (2001) developed an activity simulation model for machinery cost analysis of the harvest and transportation systems on a sugarcane plantation. Sogaard et al., (2004) optimized machinery sizes for a machinery system using the non-linear programming model developed for a particular size farm and conventional crop plan, but did not consider biomass harvest. De Mol et al., (1997) developed a simulation model and an optimization model was developed to analyze the cost of the logistics of different potential biomass feedstocks in the Netherlands.

Nilsson (1999a, 1999b) developed a Straw Handling Model (SHAM) which included three sub models; 1) harvesting and handling, 2) weather and field drying, and 3) field/storage locations, to optimize energy and costs in straw production. Nilsson et al., (2001) used the SHAM simulation model to find optimal machinery combinations, and analyze the effects of geographical and climatic factors in the performance and cost for collection of the fuel straw. They found that moisture content, relative humidity, frequency and duration of precipitation, field size, fraction of land area utilized, and transportation distance from field to storage were all critical parameters for designing cost effective handling systems.

Perlack et al., (2003) analyzed feedstock collection costs for corn stover, in a multi-pass baling system after grain harvest. The analysis assumed that the windrow was created by the combine, and the bales were collected using a self-loading bale wagon. Availability of corn stover residue in a particular area is based on the field level and landscape level. For the biomass baling systems, large round or large square balers were considered. Stover collection methods using silage/forage wagons were considered, but believed to be an expensive method for feedstock collection. The preferred method for stover collection was using the combine for windowing stover and collection with a tractor, large round baler with mega-tooth pickup head and crop processor, and self-loading bale wagons. The delivered feedstock cost at the refinery gate were estimated to range from $47.53 to $56.88 a dry Mg^{-1} ($43.10 to $51.60 a dry ton), assuming a farmer payment of $11 Mg^{-1} ($10 ton^{-1}).

Sokhansanj et al., (2006, 2008) developed an Integrated biomass supply analysis and logistics model (IBSAL) using the object oriented high level discrete event simulation language EXTEND, to simulate different field operations such as combining, windrowing, swathing, baling, loading, stacking, and field transportation as independent modules connected together into an integrated supply chain model. However, machinery optimization and the impact of field size in overall cost estimation of biomass harvest and transport, can only be achieved by running the program through multiple simulations.

The objective of this study was to optimize the machinery for single pass corn stover harvest, and find out the least cost harvest systems and harvest machinery based on crop area, yield, biomass collection methods, storage distances and harvest window. The specific objectives were:

1) Determine price and performance data for all unit operations for single pass biomass harvest for a range of operational capacities.
2) Develop a generalized method to estimate machinery performance for different machine configurations, including the effect of the individual unit operational performance on the overall performance of the system.
3) Develop an optimization model to determine the least cost set of machinery for all unit operations across a range of operation scales.

The optimization biomass harvest optimization model considers two stover collection methods (bulk collection, and large square bale collection), different scales of farm operations, and transportation distances to the storage locations. The optimization model determines both the size and number of machines required for all unit operations, given the scale of operations, available and optimal harvest period, and available field working days. The optimization model included a spreadsheet database for machinery data and a non-linear programming optimization model developed using the General Algebraic Modeling System (GAMS) software (GAMS, 2008).

2.3 Model Development

2.3.1 Overview

The objective of this work was to develop a generalized method that could be used for optimization of many different machinery unit operations in any feedstock supply chain. The overall process flow for single pass harvesting is shown in figure 1, for two different harvesting scenario's, a bulk harvesting method based on forage wagons, or the direct single pass baling method.

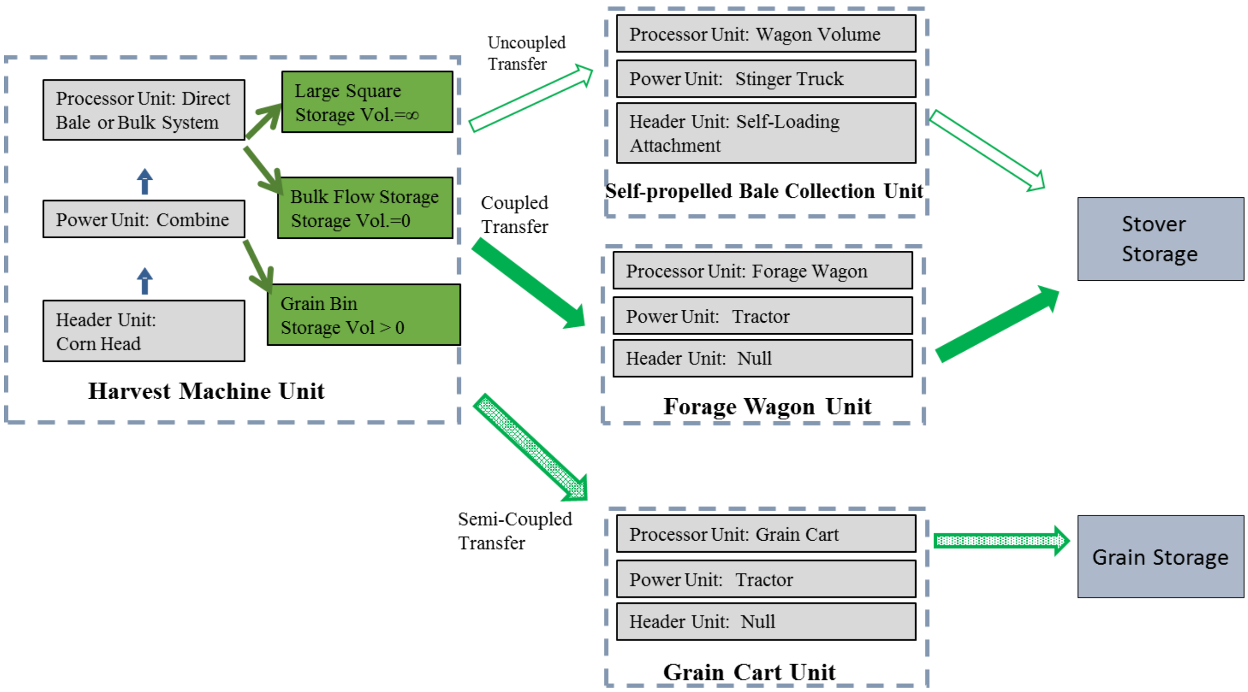


Figure 2. 1: Overall process flow diagram for single pass harvesting of grain and corn stover.

All unit operations, were considered as a combination of three sub-units, a Power Unit, a Header Unit, and a Processor Unit. The header, power unit and processor are considered as a single unit operation and effective capacity of overall unit is obtained by multiplication of performance efficiency of individual sub-units. For those operations, which do need all 3 sub-units, the sub-units not required are assigned with a null value and have no influence on the unit operation performance or cost. Constraints can be utilized to ensure that the power unit, header unit and processor unit are compatible, and sized correctly. This provides a framework capable of modelling a number of different unit operations; from a grain combine harvester, to a conventional square baling operation, self-propelled or tractor pulled bale collection unit, semi-truck or wagon transportation unit, or pre-processing unit such as a grinder.

In the case shown in Figure 1, the Harvest Machine Unit considers the corn or corn/stover head as header unit, the combine as power unit, and the direct bale or bulk system as the processor unit. In this case the nominal performance of the unit is determined by the combine capacity and field efficiency, multiplied by the performance efficiency of the header and processor unit. Therefore, if a standard corn head is used for grain only harvest, the combine performance efficiency would be assigned a value equal to the normal field efficiency of a grain combine, the efficiency of the header unit (standard corn head) would be approximately 100%, and since there is no processor the processor efficiency would be a null value and have no effect. If a combine is modified for single pass stover harvest, with a stover collection head, and a direct square baler attached to the combine, then the combine efficiency would remain the nominal combine field, but the header unit (corn/stover header) efficiency and the processor unit (direct baler) efficiency would be less than 100%, depending on how much each sub-unit decreased the performance of the operation.

A self-propelled Stinger Bale Collection unit, would consist of the Stinger truck as the power unit, the bale pickup unit as the header unit, and the storage on the rear of the stinger as the process unit. The nominal field performance of the unit would be based on field speed of the power unit, while the header unit efficiency would account for the reduction in capacity when individual bales are picked up.

The performance of any unit operation can be influenced by both prior and subsequent operations, depending on the method of transfer (Uncoupled Transfer, Semi-Coupled Transfer, and Coupled Transfer) between the different unit operations. When Harvest Unit with a Large Square Direct Baler is used and the Transport Unit is a tractor drawn bale collection unit the machine operations are Uncoupled, since the operation of the Harvest Unit and Transportation Unit are effectively independent of each other, in terms of the cycle time of both machines. In this case the effective storage volume of the Direct Baler (Harvest Machine Processor Unit) is infinite since all the bales can be left on the field until collected. When the stover is harvested in bulk, the operation of Harvest Unit and Transportation Unit (Bulk Forage Wagon) are Coupled, since their operation is completely dependent on the cycle time of the transport unit, and a Transport Unit must be available beside the Harvest Unit for harvesting to continue, and vice versa. However, the transfer of the grain from the Harvester Unit is Semi-Coupled, since the Harvester Unit has a limited storage capacity (Grain Bin Capacity) and can continue to harvest for a limited time without the grain cart beside the combine. If the travel and unload cycle time of the grain cart is less than the time to fill the grain bin harvest operations the Harvest Unit until does not need to stop.

Different harvest systems based on biomass collection methods were analyzed to find the least cost option of harvest and hauling stover and grain, based on crop area, yield, biomass collection methods, storage distances and harvest window. Standard cost analysis methods were used to determine the fixed and variable costs including capital costs, operating cost and timeliness costs for all operations. Machinery prices, capacity and salvage value were collected from the past 20 years, and the salvage value of the different machinery units calculated for the relevant annual use based a regression mode of the historical prices for used machines.

Harvest of agricultural residues from crops such as corn, wheat, and soybean can be done either by single pass system or multi-pass harvest systems. This research focused on single pass stover harvest methods, but could be utilized for multi-pass harvest operations as well as for multi crop systems.

2.3.2 GAMS model

General Algebraic Modeling System (GAMS Development Corp, Washington, DC) provides a high level language for non-linear programming optimization (GAMS @2008). This study was focused on optimization and cost analysis of single pass stover harvest based on two different methods of residue collection, in the first method, stover was collected as a bulk in forage wagons, and the second was a large square baler attached to the combine and large square transported using a biomass hauler. The optimization models developed accounted for machines of different sizes, and the influence of prior and subsequent unit operations, on the performance of any particular unit operation. The constraints ensured that all operations were completed within the harvest period and accounted for timeliness costs related to harvest delayed past the optimum harvest period.

For the optimization model, the maximum harvest period, optimum harvest period and timeliness co-efficient were all based on the values for the state of Iowa. The machinery cost and performance database harvest, transportation and processing unit operations were determined from prior literature and/or OEM manufacturers. Parameters such as repair factors, economic life and fuel consumption was taken from ASAE standards, D 497.4. The salvage value was estimated based on the used machinery prices of last 20 years, and in most cases was approximately 35% original purchase price. Each unit operation could select from a number of different sizes of machinery in the database.

2.3.3 Model parameters

The primary model parameters included are; the area harvested per year, grain and stover yields, harvested fraction of the stover, distance to storage, probability of a working day, maximum harvest period, and machinery operational parameters such as price, machine life, power requirements, nominal operational capacity and efficiency.

2.3.4 Decision variables and constraints

The primary decision variables size and number of machines required for each unit operation. The primary constraint is that all unit operations have sufficient capacity to complete the area to be harvested within the maximum harvest period. Additional constraints ensure that the type of machines used are compatible and account for any cycle time delays within and between unit operations.

2.3.5 Objective function

The objective function was to minimized overall costs, which included fixed and variable costs and timeliness costs. The capital costs is treated as fixed cost includes; purchase cost, installation cost (when applicable), housing and property tax cost. The direct cost includes labor, fuel and lubrication costs, average yearly repair and maintenance costs.

2.3.6 Machinery and timeliness costs

The brake specific fuel consumption (B_{SFC}) for a specific operation and machine size is expressed in gal/hp.hr based on the following equation (ASAE, D 497.4, 2003), as shown in the equation (1).

$$B_{SFC(ji)} = 0.52X + 0.77 - 0.44(738X_{ji} + 173)^{1/2} \quad (1)$$

Where, X_{ji} is the ratio of equivalent PTO power required to Rated PTO power (default value = 0.856), for a machine of size (i) for unit operation (j).

The total annual fuel consumption cost (f_c) per unit for each operation is expressed in the equation (2).

$$f_{c(ji)} = B_{SFC(ji)} * r * t_{ij} * X_i * p_{m(ji)} \quad (2)$$

Where, $f_{c(ji)}$ is the fuel consumption cost ($/yr.), r is the fuel cost ($/gal), t_{ij} is the total operating hour (hr./yr.), $p_{m(ji)}$ is the rated PTO power of machines (Hp), for a machine of size (i) for unit operation (j).

Lubrication cost ($L_{c\ (ji)}$) are considered as the 15% of fuel consumption cost and is expressed in the equation (3).

$$L_{c(ji)} = 0.15 * f_{c(ji)} \quad (3)$$

Repair and maintenance cost of machines is expressed through the equation (4).

$$r_{m(ji)} = \frac{l_{p(ji)} \times r_{f1(ji)} \times (t_{ij} * l_{m(jj)}/1000)^{r_{f2(ji)}}}{l_{m(ji)}} \qquad (4)$$

Where, r_m is the repair and maintenance cost ($/yr.), $l_{p\,(ji)}$ and $l_{m\,(ji)}$ are list price ($) and economic life of machines (years), respectively. Repair factors $r_{f1\,(ji)}$ and $r_{f2\,(ji)}$ are taken from (ASAE, D497.4, 2003) corresponding to size (i) of machines which are used unit operation j.

Timeliness cost is considered as zero when the harvest is completed within the optimum harvest window. If the total area cannot be harvested within the optimum window, timeliness cost is expressed through the equation (5).

$$t_c = \sum_i \frac{1}{N_i * C_{a(i)}} * \frac{k * y * (A - A_o)^2 \times v}{l * h * P_{wd}} \qquad \text{if, } A_o \le A \qquad (5)$$

Where, Tc is the timeliness cost ($/yr.), $C_{a\,(i)}$ is the capacity of the harvest machines (ha h^{-1}) which is calculated based on the equation (6), and N_i is the number of harvest machines of size (i) selected. K is the timeliness coefficient, y is the yield (Mg ha^{-1}), A is the total area (ha yr^{-1}), A_o is the area covered during the optimum harvest window (ha yr^{-1}), v is the value of yield ($ Mg^{-1}), h hours per day, P_{wd} is the probability of a working day, and l is equivalent to either 2 or 4 based whether the operation centered around the optimum period, or begins(ends) at the start(end) of the optimum period.

The machine capacity ($C_{a\,(i)}$) in ha h^{-1} or machine capacity ($C_{m\,(i)}$) in (ton h^{-1}), is shown below.

$$C_{a(i)} = \sum_i v_s * w * e_{ff} * Y * X_u \quad \text{or} \quad C_{m(i)} = \sum_i v_s * w * e_{ff} * Y * X_u \qquad (6)$$

Where, $v_{s(i)}$ is the travel speed (km hr^{-1}), $w_{(i)}$ is the width (m) of machine, $e_{ff(i)}$ is the efficiency of machine, Y is the yield (Mg ha^{-1}) and X_u is the relevant required unit conversion factor. Note: The timeliness cost is calculated for the harvest unit operation only, assuming that only grain yield timeliness costs are considered.

The area covered within optimum harvest window, A_o is shown below.

$$A_o = \sum_i h \times C_a \times P_{wd} \times (T_{oe} - T_{os}) \quad (7)$$

Where, T_{oe} and T_{os} are optimum end and optimum start date of harvest. P_{wd} is the probability of working day.

The total capital cost per year ($C_{c\,(ji)}$) for any specific machine is given by Equation (8).

$$C_{c(ji)} = P_{(ji)} * \left[\frac{(1 - s_{(ji)}) \times i_r \times (1 + i_r)^{n_{(ji)}}}{(1 + i_r)^{n_{(ji)}} - 1} + tis \right] \quad (8)$$

Where $C_{c\,(ji)}$ is the capital cost ($/yr.). $P_{(ji)}$, $s_{(ji)}$, i_r, $n_{(ji)}$, tis are purchase price ($), salvage value (decimal percent), real interest rate (decimal percent), life of machine (year), and tax, insurance and shelter (decimal percent), respectively.

Using equation (1) through equation (8), the total annual cost of any unit operation ($Z_{(j)}$), (excluding labor costs and timeliness costs) is calculated as shown in equation (9),

$$Z_j = \sum_i N_{ji} * (C_{c(ji)} + f_{c(ji)} + l_{c(ji)} + r_{m(ji)}) \quad (9)$$

Where, Z_j is the annual machinery cost ($/yr.) for unit operation (j), where N_{ji} is the number of machines of size (i) for the unit operation, and the other terms are described in above equations.

The labor costs $l_{a\,(ji)}$ were based on the total operation hours for season, as shown in the equation (10).

$$l_{a(ji)} = 10 * t * N_{ji} \quad (10)$$

Where, N_{ji} is the number of machines of size (i) for the unit operation (j). This calculations assumes that all seasonal labor would be hired for the full duration of the harvest.

2.3.7 Optimization constraints

There are number of constraints that must be satisfied to ensure that all unit operations are completed within the harvest window. The constraints for the model are described using equation (11) through equation (13).

The capacity of the harvest operations must guarantee that harvest for the given area is completed within the harvesting window period, which is true if the constraint shown in Equation (11) is satisfied.

$$\sum_{i} \mathrm{N_i} \times \mathrm{c_{a(i)}} \times \mathrm{t} \geq \mathrm{A} \qquad (11)$$

Where, $C_{a\,(i)}$, is the harvest machine capacity in (ha hr^{-1}), and Ni is the number of harvest machines of size (i) selected.

The number of machines should be integer and greater than 1 for all unit operations (j), as shown in equation (12).

$$\sum_{i} \mathrm{N_{ij}} \geq 0 \qquad (12)$$

There is time limit for machinery operations, and it is assumed that all unit operations must be completed with the maximum harvest period. The total annual operational hours per season (t) cannot exceed the total available hours within the harvest window, which is true if the constraint shown in equation (13) is satisfied.

$$t \leq h \times d \qquad (13)$$

The objective is to minimize the overall harvest and transportation costs including fixed and variable costs and timeliness costs, as shown below in equation (14).

$$\mathrm{O_{bj}} = \sum_{j} \sum_{\mathrm{i}} \mathrm{N_{ji}} (\mathrm{C_{(ji)}} + \mathrm{f_{c(ji)}} + \mathrm{l_{c(ji)}} + \mathrm{r_{m(ji)}} + \mathrm{l_{a(ji)}}) \quad + \quad t_c \qquad (14$$

Where, O_{bj} is the objective function, C (ji) is the capital cost ($/yr.), f_c (ji) is the fuel cost ($/yr.), $l_{c\,(ji)}$ is the lubricating cost ($/yr.), $r_{m\,(ji)}$ is the repair and maintenance cost ($/yr.), $l_{a\,(ji)}$ is the lubricating cost ($/yr.), and t_c is the timeliness cost ($/yr.).

2.3.9 Optimization for single pass harvest-baling as a residue collection method

For this harvesting option, baler is considered as a processor unit attached to the grain combine and self-propelled bale wagons as field collection unit. On-Farm stover storage locations at different distances from the field were considered. Grain carts and grain truck were used for hauling grain from the combine to local grain storage bins. To find the optimum number of each machine, the objective function as shown in the equation (14) was used with the additional constraints to account for the interaction between different unit operations.

The additional constraints used in GAMS model are shown through equation (15) to equation (21).

The total number of calendar working days for each operation was given by equation (15).

$$d \le t_e - t_s \qquad (15)$$

Where, d is total number of calendar working days per season, t_e and t_s are harvesting maximum end date and minimum harvesting start date, respectively.

The total number of working hours per season (hr. yr^{-1}) is shown in the equation (16).

$$t = h \times d \times p_{wd} \qquad (16)$$

Where, h is the number of working hours (day^{-1}), d is the total number of calendar working days, and P_{wd} is the probability of working day during this period.

Balers are used as processors with combines, therefore, numbers of balers are equal to the numbers of combines, given by equation (17).

$$N_C = N_{SB} \qquad (17)$$

Where, N_C and N_{SB} are number of combines and number of balers respectively.

The number of grain carts are equal to the number of grain cart tractors (18).

$$N_G = N_{TG} \tag{18}$$

Where, N_G and N_{TG} are number of grain carts and number of grain cart tractors, respectively.

The number of tractor drawn bale collection wagons are equal to number of tractors as shown in the equation (19), self-propelled biomass hauler also can be used for field transport and in that condition, equation (19) is not needed.

$$N_W = N_{WT} \tag{19}$$

Where, N_W and N_{WT} are number of bale collection wagons and tractors respectively.

The capacity of the balers must be sufficient to for the balers for baling operations to be completed with total number of working hours per season as shown in equation (20).

$$\sum_i N_{SB(i)} \times C_{SB(i)} \times t \geq A \tag{20}$$

Where $N_{SB\,(i)}$ and $C_{SB\,(i)}$ are number, and capacities of the square balers, respectively.

The self-propelled bale collection wagons must have sufficient time and capacity to be able to remove all the bales for all of the harvested hectares within the harvest period is shown in equation (21).

$$= \sum_i \frac{1}{\frac{1 \times d_s}{s_{hf}(i)} + \frac{1 \times d_s}{s_{rf}(i)} + \frac{C_b(i)}{C_a(i) \times s \times h_s \times (1 - f_s)}} \times \frac{C_b(i)}{s \times h_s \times (1 - f_s)} \times t_w \times w_i \quad = \quad A \tag{21}$$

Where,

t_w = working hour of self-propelled bale wagons (h yr^{-1})

A = area harvested (ha yr^{-1})

s = total stover yield (Mg ha^{-1})

h_s = harvestable stover in fraction of total stover

f = fraction of weight loss in bales formation

$C_{b(i)}$ = capacity of self-propelled bale collection wagons (Mg load^{-1})

W_i = number of bale wagons

d_s = storage distance (km)

$S_{h(i)}$ = hauling speed of bales for self-propelled bale wagons (km h^{-1})

$s_{r(i)}$ = return speed for self-propelled bale wagons (km h^{-1})

$t_{l(i)}$ = loading time of bales (h^{-1})

$t_{i(i)}$ = idle time in field per load (h^{-1})

2.3.10 Optimization for single pass harvest-bulk stover as a residue collection method

For this harvesting option, a standard grain combine was the harvest power unit, a modified biomass collection head as the header unit, and a modified chopper and forage blower as the harvest processor unit. The capacity harvester unit processor was adjusted based on the relative performance of the header and processors units, compared to a standard combine. In this situation, there are two simultaneous field transport systems; 1) grain carts and related tractors to remove grain from the combine (Semi-Coupled Transfer Process), and 2) forage wagons and related tractors to remove bulk stover from the combine to the storage location. For the optimal selection of machinery, an adjustment for the capacity selection within the sets of machines was done was further constrained. If a larger combine was selected the system automatically selected a larger units for other operations. The objective function of equation (14) was applied for this module, with the additional constraints to account for the interaction between different unit operations.

The forage wagons must have sufficient time and capacity to be able to remove all the bulk stover for all of the harvested hectares within the harvest period as shown in equation (22).

$$\frac{1}{\frac{1\times d_s}{s_{hf}(i)}+\frac{1\times d_s}{s_{rf}(i)}+\frac{C_w(i)}{C_a(i)\times s\times h_s\times(1-f_s)}}\times\frac{C_w(i)}{s\times h_s\times(1-f_s)}\times t_w\times w_i=A \quad (22)$$

Where,

t_w = working hours of forage wagons (h yr^{-1})

A = area harvested (ha yr^{-1})

s = total stover yield (Mg ha^{-1})

h_s = harvestable stover in fraction of total stover

f_s = fraction of weight loss in stover collection

$C_{w(i)}$ = capacity of forage wagons (Mg $load^{-1}$)

w_f = number of wagons

d_s = storage distance (km)

C_{ac} = average capacity of combines (ha h^{-1})

t_w = working hour of wagons (h)

To prevent any down time for combine operations due to the unavailability of grain carts and grain trucks in the field, it is considered that there are plenty of grain carts and tractors to collect the grain from combine

Average combine capacity (C_{ac}) is calculated using equation (23)

$$C_{ac}=\frac{N_{c1}\times C_{c1}+N_{c2}\times C_{c2}+N_{c3}\times C_{c3}}{N_{c1}+N_{c2}+N_{c3}} \quad (23)$$

Where; C_{c1}, C_{c2} and C_{c3} are capacities of combine size 1, 2 and 3 respectively.

Average cycle time for grain cart (T_{ac}) to return to a combine after unloading, is calculated through equation (24).

$$T_{ac} = \frac{N_{g1} \times T_{g1} + N_{g2} \times T_{g2} + N_{g3} \times T_{g3}}{N_{g1} + N_{g2} + N_{g3}} \tag{24}$$

Where N_{g1}, N_{g2}, N_{g3} are number of grain carts for types 1, 2 and 3 respectively. T_{g1}, T_{g2} and T_{g3} are cycle times for grain cart and tractor set up 1, 2 and 3 respectively.

The average time for the combine to fill the combine bin without unloading bin time, and the associated grain cart cycle time constraint is shown in equation (25).

$$T_{ab} = \frac{\frac{N_{c1} \times V_{b1}}{C_{c1}} + \frac{N_{c2} \times V_{b2}}{C_{c2}} + \frac{N_{c3} \times V_{b3}}{C_{c3}}}{N_{c1} + N_{c2} + N_{c3}} \geq T_{ac} \tag{25}$$

Where V_{b1}, V_{b2}, V_{b3} is volume of combine grain bins for combines types 1, 2 and 3 respectively. The constraint that the average grain cart cycle time must be equal or less than average bin fill time, to ensure that the combines will not have to stop and wait for a grain cart to unload.

Average cycle time (T_c) for forage wagon is calculated using equation (26).

$$T_c = d_s \times \left(\frac{1}{s_{hf}} + \frac{1}{s_{rf}} \right) + \frac{V_w}{U_w} \tag{26}$$

where, d_s is the storage distance from the field**.** s_{hf} and s_{rf} are hauling speed and return speed of forage wagons (km h^{-1}) respectively. V_w is the volume of wagon in cubic meters and U_w is the unloading rate of the forage wagons.

Average fill volume (V_w) of forage wagon is given by equation (27).

$$V_w = \frac{N_{w1} \times V_{w1} + N_{w2} \times V_{w2} + N_{w3} \times V_{w3}}{N_{c1} + N_{c2} + N_{c3}} \tag{27}$$

Average fill time of wagon (T_w) is calculated using equation 28.

$$T_w = \frac{V_w}{C_c} \tag{28}$$

Where, V_w and C_c are average fill volume of wagon and average combine capacity respectively.

If the combines are to continue harvesting without interruption, there must be at least one forage wagon beside each combine and one having wagon completed the transportation and unload cycle. If the wagon cycle time (T_{cw}) is greater than wagon fill time (T_w) then additional wagons are needed to ensure harvest is not delayed. The minimum number of additional wagons (E_w) needed can be determined using equation (29).

$$E_w = Int\left(\frac{T_{cw}}{T_w}\right) + 1 \qquad (29)$$

Where T_{cw} is the average cycle time for wagons.

To make sure that combine operation was never stopped, total number of wagons must equal or greater than number of combines as shown in equation (30).

$$N_{w1} + N_{w2} + N_{w3} + E_w \geq N_{c1} + N_{c2} + N_{c3} \qquad (30)$$

A necessary constraint is that the number of machines must greater than 0 for all unit operations (j), as shown in equation (31).

$$\sum_i N_{ij} \geq 0 \qquad (31)$$

2.4 Results and Discussion

In this study, it is assumed that the stover feedstock is a by-product of the grain production. Therefore, the marginal cost of biomass harvest is the difference in cost between single-pass biomass harvest of grain and stover, and the grain only harvest. In some cases, the marginal biomass cost of a particular unit operation can be negative. The result for different cases are not consistent all the time because of the variation with the assumptions.

The model was optimized using mixed integer nonlinear programming solver in General Algebraic Modeling System. Fundamental input parameters for base case is shown in table (2.1). Biomass harvest and transportation cost was determined by subtracting grain only harvest cost from grain and biomass harvest and transport cost model.

Table 2. 1: Input parameters in GAMS for base case

Corn field, ha (ac)	2,024 (5,000)
Yield of corn, Mg ha^{-1} (bu ac^{-1})	11 (175)
Total harvestable stover, Mg ha^{-1} (ton ac^{-1})	4.93 (2.2)
Amount of stover required to stay in the field	30%
Probability of working day	0.64
Timeliness coefficient	0.003
Optimum harvest end (Calendar days)	300
Optimum harvest start (Calendar days)	280
Harvesting start (Calendar days)	255
Harvesting end (Calendar days)	325
Operation time (hr. day^{-1})	10
Value of fuel ($ gal^{-1})	4

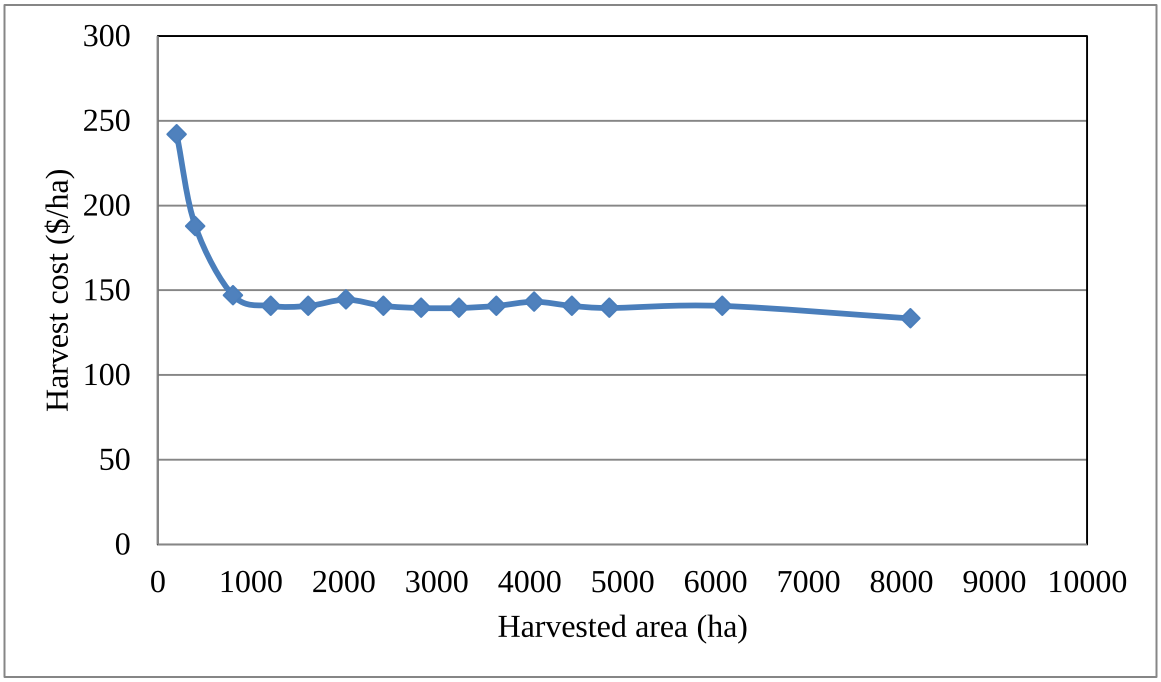
Results for base case for grain only harvest and hauling are shown in the table (2.2). The total cost per year was based on the total grain harvest and hauling cost. Harvest days as Calendar days, harvest time (h), total cost ($ $year^{-1}$), total timeliness cost ($ $year^{-1}$), number of machines for each unit operation and overall cost ($ ha^{-1}) is shown in the table (2.2). Owning all machinery, total harvest and hauling cost of corn grain for almost 2,000 ha of production field is estimated about $132 ha^{-1} ($53.5 ac^{-1}). The total cost including grain and biomass harvest and hauling cost considering biomass as a co-product with crop is shown in the table (2.3). Optimum number and size of combine is 2 with the power requirement of 360 HP size. Distance to grain hopper was considered 2 mile from the field and the yield of grain was 175 (bu ac^{-1}).

Table 2. 2: Results for base case, grain only harvest

Corn field, ha (ac)	2,024 (5,000)
Harvest days (calendars days)	32
Harvest time (hr.)	205
Total cost ($)	267,811
Cost, $ ha^{-1} ($ ac^{-1})	132.2 (53.5)

No. Combine	2 x(360Hp Combine)
No. Grain carts and Tractors	1x(1050 bu. cart), 1x(1200 bu. cart)

Effect of farm size on grain harvest cost was determined as shown in the Figure 2.2. Harvest cost was decreased significantly with the increased sizes of the harvested field. Grain harvest and hauling cost for about 200 ha (500 acre), production field is almost about \$240 ha^{-1} (\$97 ac^{-1}) and it goes down almost to \$185 ha^{-1} (\$75 ac^{-1}) for 405 hectare (1,000 ac) production



farm.

Figure 2. 2: Effect of farm size on grain harvest cost

Beyond almost 1,200 hectare (3,000 acre) production field, cost doesn't decrease significantly. These field sizes variation were done considering the constant yield of 11 Mg ha^{-1} 175 (bu ac^{-1}) and 3.22 km (2 mile) of grain hopper distance from the field. Effect of farm size on grain harvest cost with yield variation was studied. With different sizes of field and grain yield variation, harvest cost variation was shown in figure 2.3, considering 3.22 km (2 mile) of grain hopper distance from the field.

Results for base case for grain and biomass harvest and hauling costs considering bulk stover collection method are shown in the table (2.3). The total cost per year was based on the total grain and biomass harvest and hauling cost. Harvest days as Calendar days, harvest time (h), total cost ($ year^{-1}), total timeliness cost ($ year^{-1}), number of machines for each unit operation and overall cost ($ ton^{-1}) is shown in the table (2.3). Owning all equipment, total harvest and hauling cost of grain and biomass for 2,000 ha (5,000 acre) of production area is almost about $ 250 ha $^{-1}$ ($101 ac^{-1}). Optimum number and size of combine is 2 of type 3.

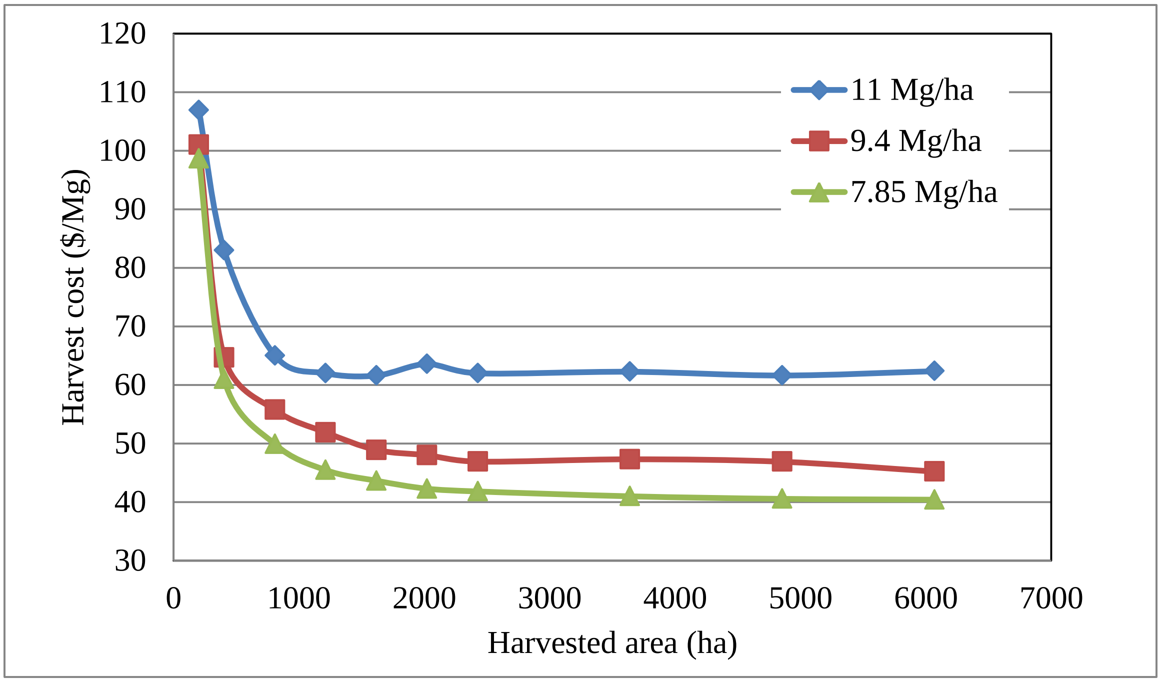


Figure 2. 3: Effect of farm size on grain harvest cost with yield variation

Table 2. 3: Results for base case, grain and biomass harvest cost

Corn field, ha (ac)	2,024 (5,000)
Total cost ($ year^{-1})	504,000
Cost $ ha^{-1} ($ ac^{-1})	249.08 (100.8)
No. Combine	2 (type 3)
No. Grain carts and Tractors	3 (type 3)
No. Forage wagons and Tractors	4 (type 1) 8 (EW)

Effect of farm size on grain and biomass harvest cost is shown in the figure 2.4. Harvest cost decreases with a higher rate with the increased sizes of the fields in the beginning and slope decreases after a certain size of field as shown in the figure 2.4. 3.22 km (2 mile) of grain hopper distance from the field was considered for the cost analysis. Stover yield was assumed 4.48 Mg ha^{-1} (2 ton ac^{-1}) and on-farm storage distance from the field was considered 1 mile to get a result as shown in figure 2.4. Grain yield of 11 Mg ha^{-1} (175 bu ac^{-1}) was taken for all farm sizes in the calculation.

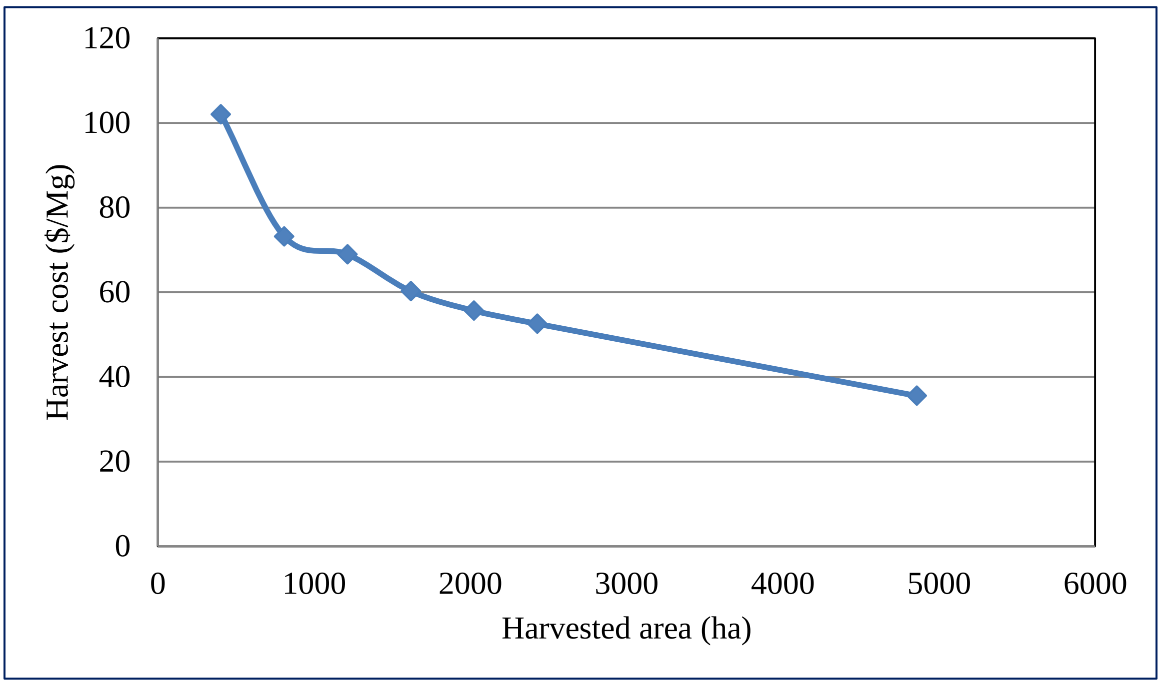


Figure 2. 4 : Effect of farm size on grain and biomass harvest cost for bulk stover collection

Grain only model and grain and biomass model were developed separately. The difference of the cost of these two models is considered as the cost of biomass harvest and hauling as shown in the table (2.4) for the bulk collection method of biomass. The size of harvested field was 2,024 ha (5,000 ac) with the grain yield of 11 Mg ha^{-1} (175 bu ac^{-1}) and harvested stover yield of 4.48 Mg ha^{-1} (2 ton ac^{-1}). The hauling distance of grain cart was taken 3.22 km (2 mile) and on-farm storage location for biomass was considered 1.61km (1 mile) from the field.

The harvest and transportations costs for the optimal selection of the machinery for different harvest scenarios are shown in the table 2.4.

Table 2. 4: Grain and biomass harvest and hauling cost

Machinery and cost types	Grain only $/ha ($/ac)	Grain and biomass $/ha ($/ac)	Biomass only $/ha ($/ac)	Biomass only $/Mg ($/ton)
Combines	85.92 (34.77)	117.72 (47.64)	31.80 (12.87)	7.09 (6.44)
Capital cost	31.85 (12.89)	50.90 (20.6)	19.05 (7.71)	4.25 (3.86)
Repair & M cost	24.32 (9.84)	24.54 (9.93)	0.22 (0.09)	0.05 (0.05)
Fuel & Lub. cost	27.70 (11.21)	39.54 (16)	11.84 (4.79)	2.64 (2.395)
Labor cost	2.03 (0.82)	2.47 (1.001)	0.45 (0.18)	0.10 (0.091)
Grain carts and tractors	74.50 (30.15)	59.68 (24.15)	-14.83 (-6.00)	-3.31 (-3.00)
Capital cost	42.23 (17.09)	25.6 (10.36)	-16.63 (-6.73)	-3.71 (-3.37)
Repair & M cost	0.91 (0.37)	8.57 (3.47)	7.66 (3.10)	1.71 (1.55)
Fuel & Lub. cost	28.29 (11.45)	25.5 (10.32)	-2.79 (-1.13)	-0.63 (-0.57)
Labor cost	3.04 (1.23)	2.47 (1.00)	-0.57 (-0.23)	-0.13 (-0.12)
Forage wagons and tractors		137 (55.33)	136.72 (55.33)	30.49 (27.67)
Capital cost		69.14 (27.98)	69.14 (27.98)	15.42 (13.99)
Repair & M cost		10.21 (4.13)	10.2 (4.13)	2.27 (2.07)
Fuel & Lub. cost		51.55 (20.86)	51.55 (20.86)	11.49 (10.43)
Labor cost		5.78 (2.34)	5.78 (2.34)	1.28 (1.17)
Timeliness cost	0.00	0.00	0.00	0.00
Total	160.42 (64.92)	314.12 (127.12)	154 (62.20)	34.28 (31.10)

The optimal selection of the machinery number and type for grain only harvest and grain transportation are shown in the table 2.5. The optimal selection of the machinery number and type for grain and biomass harvest and grain and biomass transportation are shown in the table 2.6. Field efficiency was used as 0.65 to obtain the result as shown in the above table. Yield of 11 Mg ha^{-1} (175bu ac^{-1}) and grain hopper distance of 3.22km (2 mile) was used in the calculation. Harvest cost very slightly went up with the use of bigger machine each time even with the increased farm sizes. Type of each machinery is shown in the appendix A.

Table 2. 5: Optimal number of machinery for grain harvest and hauling cost

Farm size, ha (ac)	Harvest cost, $/ha ($/ac)	No. Of Combine (type)	No. Of Grain cart (type)
202 (500)	240 (97)	1(1)	1(1)
404 (1,000)	185.3 (75)	1(1)	1(1)
809 (2,000)	145.79 (59)	1(2)	1(3)
1,214 (3,000)	138.4 (56)	1(2)	1(3)
1,619 (4,000)	136 (55)	1(2)	2(3)
2,024 (5,000)	143.3 (58)	2(2)	2(3)
2,428 (6,000)	138.4 (56)	2(2)	2(3)
4,047 (10,000)	140.85 (57)	4(2)	1(1) 1(3)

Table 2. 6: Optimal number of machinery for grain and biomass harvest and hauling cost

Field size ha (ac)	Harvest cost $/Mg ($/ton)	No. of Combine (type)	No. of Grain cart (type)	No. of Forage wagon (type)
202 (500)	240.3 (218)	1(2)	1(1)	2(1) 3(EW)
404 (1,000)	101.4 (92)	1(3)	1(2)	2(1) 3(EW)
809 (2,000)	72.75 (66)	1(2)	2(1)	3(1) 5(EW)
1,214 (3,000)	68.34 (62)	1(2)	2(1)	2(1) 7(EW)
1,619 (4,000)	59.52 (54)	2(3)	3(3)	5(1) 7(EW)
2,024 (5,000)	55.11 (50)	2(3)	3(3)	4(1) 8(EW)
2,428 (6,000)	51.81 (47)	2(3)	3(3)	5(1) 7(EW)
4,046 (10,000)	65.04 (59)	4(3)	4(2),1(3)	7(1) 9(EW)

Storage distance from the field has a significant impact on the transport cost component. Grain and biomass harvest and transport cost variation with storage distances for bulk stover collection is shown in the figure 2.5. Grain hopper distance of 1.6km (1 mile) was considered in the cost analysis with the stover yield consideration of 4.48 Mg ha (2 ton ac^{-1})

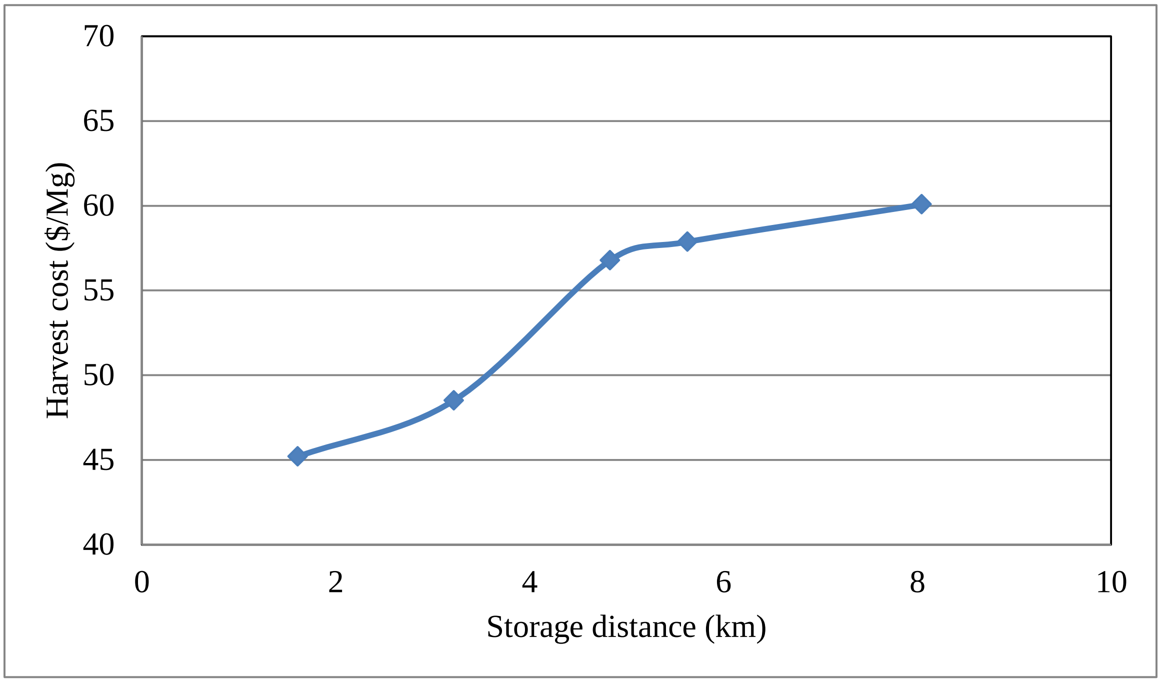


Figure 2. 5: Effect of storage distance on harvest and transport cost for bulk stover collection

Effect of farm size and yield on grain and biomass harvest and transport cost was analyzed from the model, and harvest and transport cost with varying sizes of harvested field is shown in the figure 2.6. Biomass yield of 4.48 Mg ha^{-1} (2 ton ac^{-1}) and on-farm storage distance of 1.6km (1 mile) were considered for the analysis.

Effect of farm size on only biomass harvest and transport cost was found using two models as shown in the figure (2.7). For the cost calculation, a mile of grain hopper distance from the field and a mile of on-farm storage distance for biomass was assumed. For small production farm of 202 ha (500 ac), biomass harvest and transport to on-farm storage was found \$58.4 Mg^{-1} (\$53 ton^{-1}) and for large production farm of 2,024 ha (5,000 ac), biomass harvest and transport cost decreases to \$24.25 (\$22 ton^{-1})

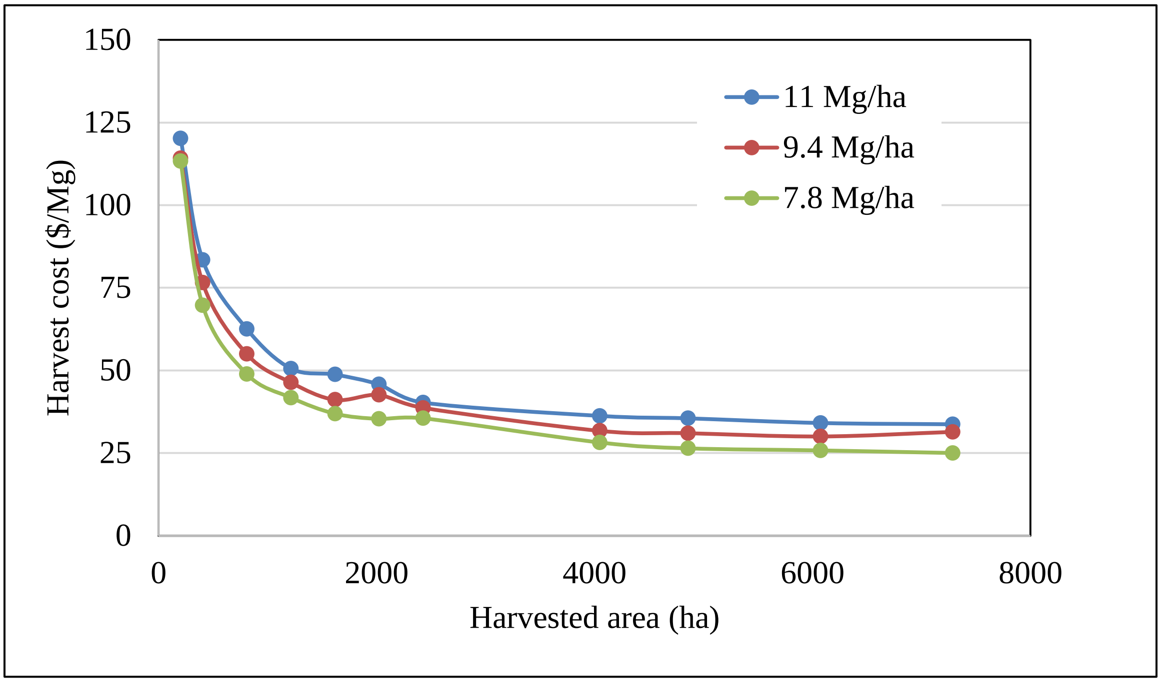


Figure 2. 6: Effect of farm size and yield on grain and biomass harvest and transport cost

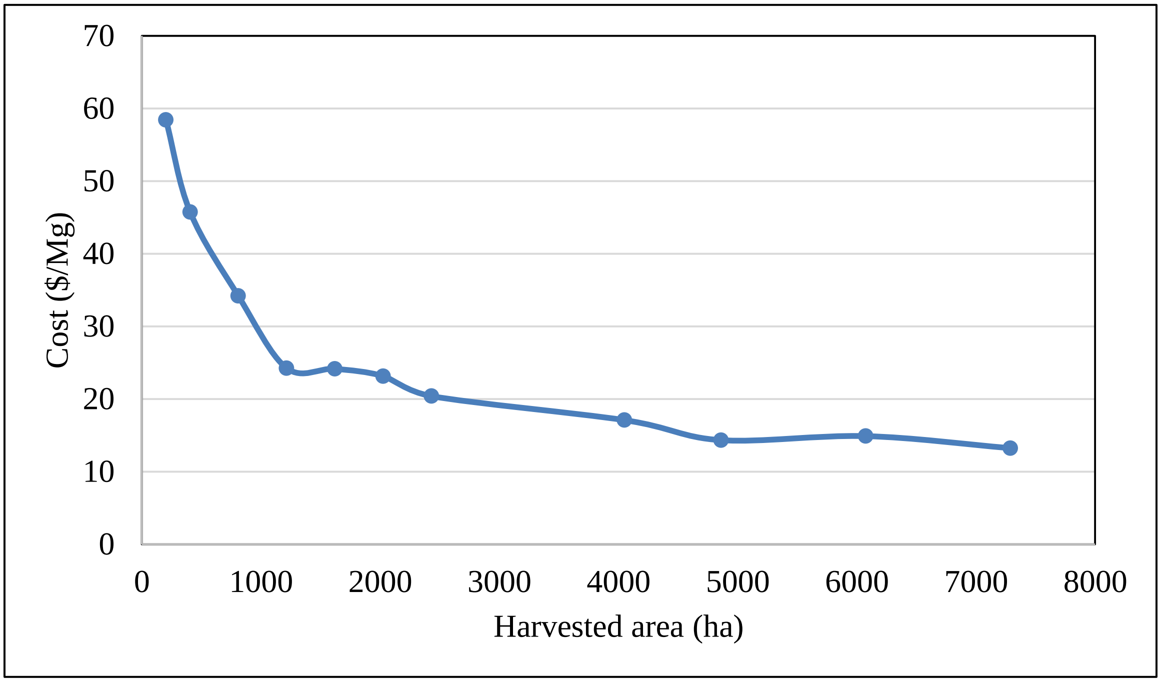


Figure 2. 7: Effect of farm size on biomass harvest and transport cost for bulk stover collection

Cost analysis of grain and biomass harvest for single pass baling was also done with the help of the mixed integer programming model developed in General algebraic modeling system. Effect of farm size on grain and biomass harvest cost for bale stover collection is shown in the figure (2.8). Effect of storage distance on grain and biomass harvest and transport cost for bale collection, biomass harvest and transport cost with farm size variation for biomass collection methods of bulk and baling, biomass harvest and transport cost variation with storage distances for bulk collection and bale collection are estimated as shown in figure 2.9, 2.10 and 2.11 respectively. The types of machines used in the analysis as mentioned above were not as same as the type of machines used to obtain the result shown in figure 2.9, 2.10, 2.11 and 2.12, but the machine types used for the comparison of bulk collection and bale collection methods to obtain the result shown in figure 2.9, 2.10, 2.11, 2.12 were same for common operation.

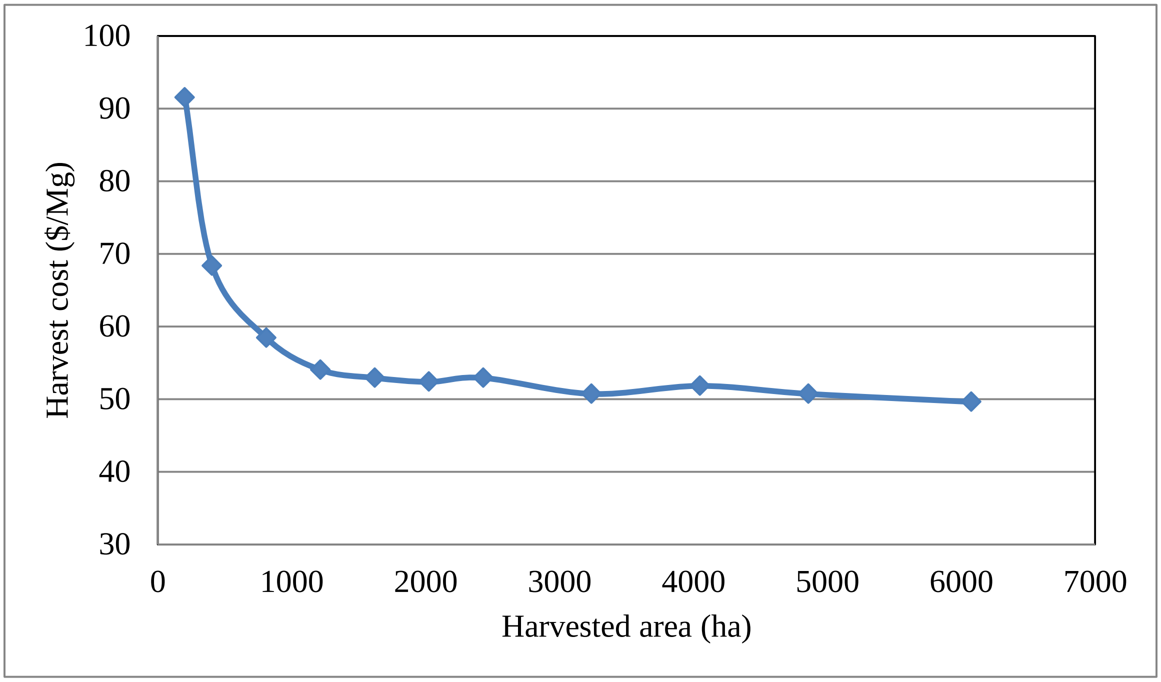


Figure 2. 8: Effect of farm size on grain and biomass harvest cost for bale stover collection

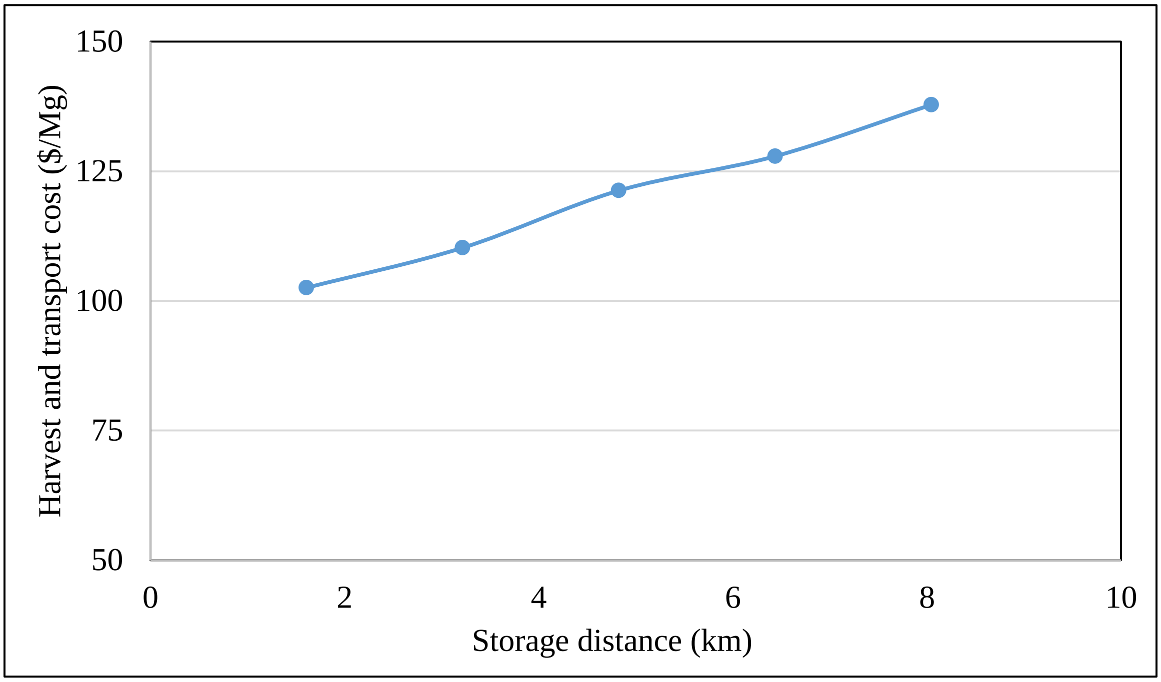


Figure 2. 9: Effect of storage distance on grain and biomass harvest cost for bale stover collection

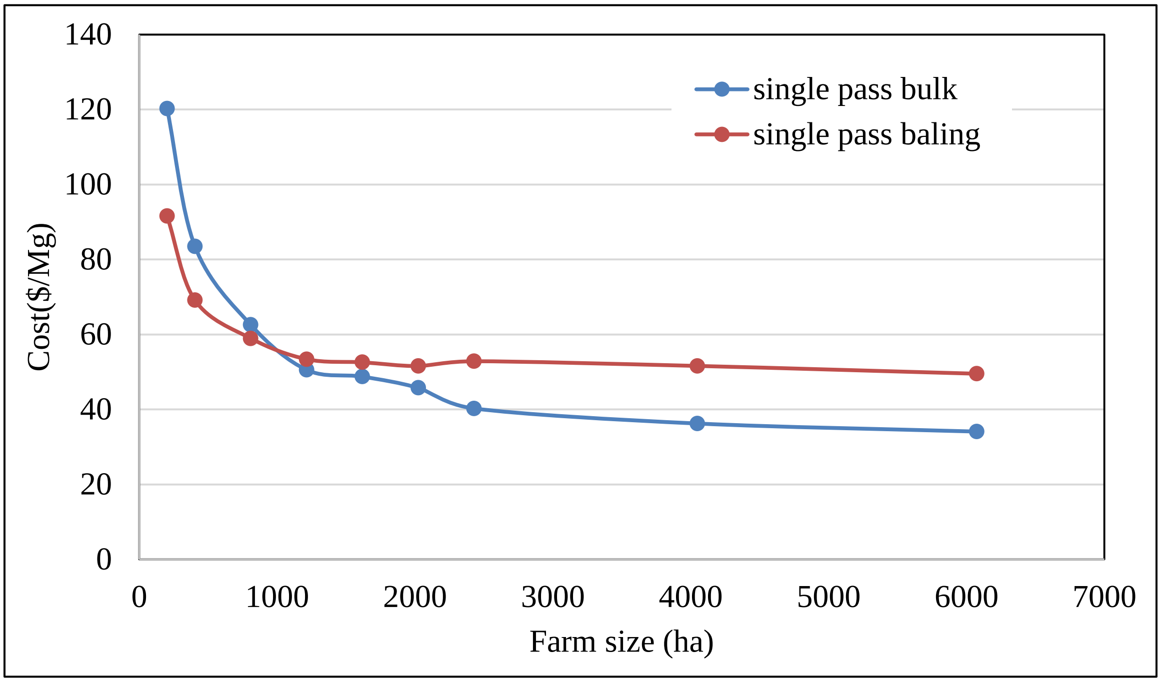


Figure 2. 10: Harvest and transport cost variation with farm size for bulk and baling

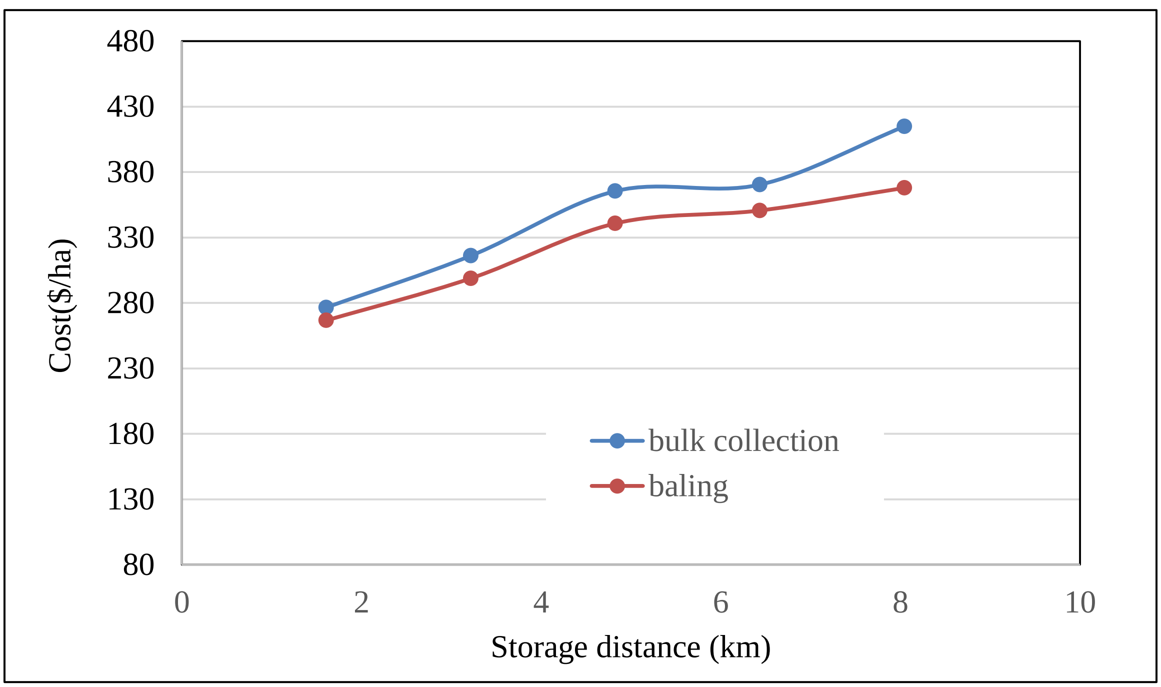


Figure 2. 11: Harvest and transport cost variation for 810 ha farm for bulk and baling

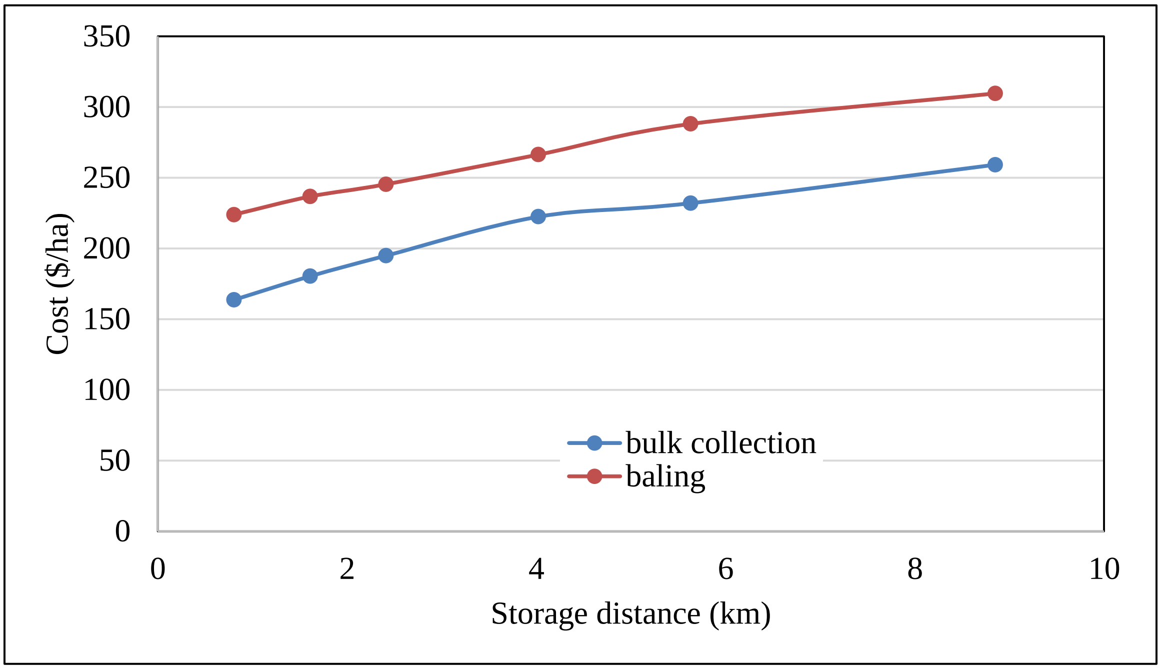


Figure 2. 12: Harvest and transport cost variation for 2,025 ha farm for bulk and baling

2.5 Model Validation

The Optimization Model was manually validated by comparing the output from an optimization scenario with the given inputs, and then manually calculating the costs in a spreadsheet and comparing the estimated costs and operational times. The results showed the optimization model estimates were the same as the manual calculations. A simple example of manual model validation is included in appendix B.

2.6 Sensitivity Analysis

It was analyzed that the change in the objective function value using discrete values of the parameters at the nominal plus or minus given percentage changes (-40%, -30%, -20%, -10%, 10%, 20%, 30%, 40%) for the optimized least cost design as followed (Kim et. al 2011).

One parameter at a time is varied keeping other parameters constant with the base case value. Changes of yield and farm size affect the harvest cost the most and other dominant parameters are harvest window and optimum harvest window as shown in figure 2.14.

Sensitivity analysis has been carried out to find the effect of harvest window to the cost of biomass harvest and transport which was changed within a range of 20% to -20% from the base value of 60 days. Optimum harvest window was also varied from 30% to -30% from the base value of 20 days. To see the impact of farm size on harvest cost, it was varied from 50% to -50% of farm size which was used to calculate the base value, 809 ha (2,000 ac). To find the yield impact on the crop harvest, yield is varied from 16% to -16% from the base value yield of 9.41 Mg ha^{-1} (150 bu ac^{-1}). Parameters were not varied within the same range for all parameters because of their non-realistic values.

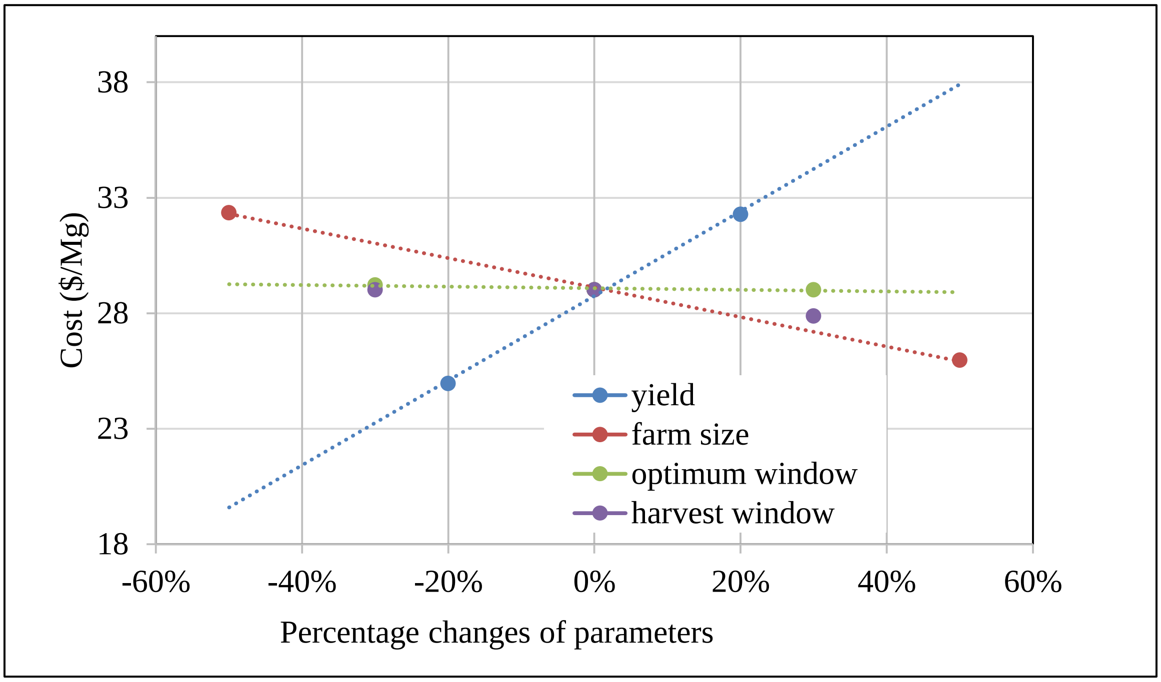


Figure 2. 13: Sensitivity analysis of crop residue harvesting and transportation costs

2.7 Conclusion

The analysis presented in this paper provides the harvest and transport cost of corn and corn stover as a by-product using single pass harvest methods with the direct bulk stover collection methods of biomass. Production farm sizes were varied from 202 to 6070 ha (500 to 15,000 ac) considering single pass harvest operation in the cost analysis. The result was obtained running the Mixed Integer non-Linear Programming Model developed in General Algebraic Modeling System for bulk stover collection method.

For the farm size of 202 ha (500 ac), biomass harvest and transport to on-farm storage was estimated about \$59.52 Mg^{-1} (\$54 ton^{-1}) and for large production field of 2,023 ha (5,000 ac), biomass harvest and transport cost decreases to \$24.25 Mg^{-1} (\$22 ton^{-1}) for bulk collection of biomass. Cost of the only biomass harvest and transport does not include the storage cost and cost of hauling to bio-refinery.

From the optimization model, the cost of harvesting and transport using the bulk stover collection method for biomass ranges from \$24.25 Mg^{-1} to \$58.42 Mg^{-1} (\$22 ton^{-1} to \$53 ton^{-1}) from bigger size to smaller size farm. The cost of harvesting and transport using the bale collection method changes from \$30.86 Mg^{-1} to \$37.47 Mg^{-1} (\$28 ton^{-1} to \$34 ton^{-1}) with the field size variation from bigger to smaller size of 2,024 ha to 202 ha (5,000 ac to 500 ac), considering an on-farm storage distance of 3.22 km (2 miles) for primary storage from the field and the harvestable stover yield of 4.48 Mg ha^{-1} (2 ton ac^{-1}). Harvesting and transportation cost variation was from \$247 ha^{-1} to \$93.9 ha^{-1} (\$100 ac^{-1} to \$38 ac^{-1}) for grain only harvest with the farm size variation from 202 ha to 2,428 ha (500 ac to 6,000 ac) for the same transport distance of 3.22 km (2 miles) from the field to the primary storage locations.

The model developed in this analysis, the mixed integer nonlinear programming model is not compared with the actual machinery sets on the farm, and however the model considers constraints and non-linearity among complex parameters of harvesting including optimum harvest window.

The result presented in this research very much dependent on the assumptions of prices of machines, which may vary significantly with another set of assumptions. Finding the optimum number of machines based on the farm size to determine the least cost of biomass harvest and transport according to the model formulation mentioned in the above section was the objective of the research.

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CHAPTER 3: MULTI-FEEDSTOCKS BIOMASS HARVEST AND LOGISTICS MODEL DEVELOPMENT

A paper to be submitted to *Transactions of the ASABE*

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3.1 Abstract

Multi-feedstocks biomass harvest and logistics system model development is a study to analyze multi-feedstocks biomass harvest and logistic systems. The model includes the analysis of available feedstock supply, harvest and transportation systems costs of multi-feedstocks biomass types. The input parameters considered are scheduling and time of harvest. The objective of the research was to estimate least cost feedstock harvest and supply model and to find the optimum price of mixed feedstock at the gate of the biorefinery with the variation of the sizes of the biorefineries. The analysis includes evaluation of feedstock supply from the producer's fields to on-farm storage locations and final transportation to the bio-refinery gates. The mixed integer non-linear model developed on the GAMS uses yield of biomass, capacity, scheduling of the yearly harvesting, bio-refinery locations and the configurations among logistics means. The objective of this work is to provide information and evaluation methods to assist in identifying cost components for the development of cost effective, efficient and reliable multi-biomass feedstocks supply chains.

3.2 Introduction

The overall system efficiency ratio of energy output to energy input for ethanol production using corn as a feedstock is less than one. Energy input for the production, transportation and processing of corn for bio-fuel production is greater than the lignocellulosic biomass feedstocks (Khanna et. al 2008). Fuel production from cellulosic biomass is the promising as well as unavoidable technology acceptance to meet the increased demand of fuels of this era. All available biomass feedstocks should be considered to establish the biorefinery at a particular location for the sustainable operation and production of the fuel. Secure and reliable biomass supply chain is an important factor for the successful commercialization of cellulosic ethanol (Zhang et. al 2013). The harvesting and transportation model developed in this research considers corn stover and switchgrass, the multi-feedstocks input to the biorefinery. At the gate of the biorefinery, the cost of feedstocks is considered as the combined cost of individual feedstocks. The mathematical optimization model as a mixed integer non-linear programming model using General Algebraic Modeling System (GAMS) is used to minimize the harvesting cost and supply cost of individual feedstocks in two different individual model. Switchgrass is identified as a leading dedicated energy crop by US Department of Energy because it tolerates a wide range of environmental conditions and provides high biomass yield, compared to many other perennial grasses and conventional crop plants (Huang et. al 2009). There are two varieties of switchgrass which are lowland type favorable to the southern and middle latitudes and upland type favorable to the middle and northern latitudes of US. Lowland type switchgrass grow taller and has higher yield than upland types. Producers' willingness to grow switchgrass highly depends on the profitability relative to existing alternative land uses (Duffy et. al 2006). Seed variety, length of the growing season, quality of the land, time of stand, availability of nutrients are the prime factors that affect in switchgrass yields. Northern range switchgrass yields vary from 8.96 Mg ha^{-1} to 17.92 Mg ha^{-1} (4 to 8 ton ac^{-1}) and southern range yields vary from 13.45 Mg ha^{-1} to 22.42 Mg ha^{-1} (6 to 10 ton ac^{-1}) in drier areas and up to 33.62 Mg ha^{-1} (15 ton ac^{-1}) or more in areas where are long growing seasons with the larger sources of water (Huang et. al 2009).

Requirement of a large amount of corn for the large scale production of ethanol occupy huge cropland which is suitable for the food production but cellulosic energy crops like switchgrass can be grown on different types of land and it still has opportunities to reduce the production cost causing the lower feedstock purchase cost (Aklesso et. al 2011). If farmers want to switch to the production of cellulosic crops, they may need to cover the opportunity cost of the crops that are displaced by the biomass production activities (Ebadian et. al 2012).

In this study only land use cost is considered and it is assumed that producers' participation is 100%. Harvesting and transportation cost are calculated from the perspective of owning the machineries needed for each operation. Roadside storage is an ideal storage system for farmers where they can assign a piece of land to store the produced biomass (Zhang et. al 2013), distances for the roadside on-farm storage is considered based on the areas of the production fields. The major logistics activities for switchgrass based bioethanol supply chain are cultivation, harvesting, storage, biomass transportation, bioethanol conversion, bioethanol transportation and bioethanol consumption (Kumar et. al 2007). In the mid-west of US, growing season of switchgrass is April or May and the maximum yield is about 10.1 Mg ha^{-1} to 12.33 Mg ha^{-1} (4.5-5.5 ton ac^{-1}) in mid to late august for locations Nebraska and Iowa (Haque et. al 2012).

The existing forage harvest systems are small bales, large square bales, large rectangular bales, loosely chopped materials and chopped wet material for ensilage systems (Nelson et. al 2006).

There are research about the yield variation with planting date and seeding methods. To our best knowledge, there are no reports on least cost multi-feedstocks cost analysis considering switchgrass planting, harvest and transport and corn stover.

3.3 Materials and Methods

3.3.1 Overview of scenario

Many agricultural crops are efficient to produce the biomass feedstock than corn grain. Ethanol conversion technology is more suitable for the plants containing high amount of cellulose such as grasses (Khanna et. al 2008). Corn stover and switchgrass are considered as the biomass feedstocks for this research. For the analysis of harvesting and supply cost of multi-feedstocks biomass, corn stover is considered as by product with grain. Switchgrass, which is an herbaceous biofuel crop is considered as the single product. For the feedstocks which is considered as by-product, planting cost is not associated in the analysis and for the feedstock which is considered as a single product, harvesting as well as planting cost is considered in the model. For both feedstocks types, multi-pass harvesting options is considered in the analysis. For the corn stover harvesting; combining, windrowing, baling, hauling to the on-farm storage and transportation to the biorefinery is considered as five units operations in the development of the model. For each operation, a machine is assumed as an integrated set of header, power and processor units. Three sets of machines are used for selection in each operation such as combining, windrowing, baling, on-farm hauling, and hauling to the biorefinery to optimize the model. For the switchgrass feedstocks cost analysis; land cost, materials cost, planting cost, harvesting cost, and transportation cost is included. Time of year for seeding, type of seeding method, land use affect the production costs because of the seed used and the success rate of the seeding and the probability of reseeding (Duffy et. al 2006). To analyze the planting cost of switchgrass, two unit operations standard grain drill and spraying are taken in considerations and for the harvesting operations, mower-conditioner, rakes and large squared bales are considered. Spring seeding on grass land with a drill method is taken for cost analysis. Mowing, drilling seed, spraying fertilizer, use of roundup, atrazine, and 2,4D is needed for the land preparation and planting. Transportation cost of switchgrass includes field transportation as a self-propelled hauler and transportation to biorefinery gates as semi-trucks.

Dry storage of biomass is needed for the applications where dry feedstocks are preferred such as combustion and gasification. These economic model do not include the on farm storage cost of the biomass. There was a previous study (Petrolia et. al 2008) to determine the break-even price for switchgrass at which farmers will be indifferent to produce switchgrass in place of other cropping rotations, however for the independent feedstock cost analysis, the available cropland is used considering the participation of producer as 100% in this study.

3.3.2 Optimization and cost analysis of model

Many processes in nature and in society are associated with nonlinearity. Nonlinear types of descriptive models are relevant in many areas of sciences and engineering (Pinter 2008). Mixed integer nonlinear programming is the optimization problems with the continuous and discrete variable and nonlinear functions in the objective function or there could be constraints with nonlinearity. These types of optimization can be used in wide variety of field such as manufacturing, finance, agricultural engineering, and chemical engineering.

A mixed integer non-linear programming model is developed to find the harvesting and transportation cost of biomass feedstocks for the biorefinery. Linearity, non-linearity, equalities, and correlations among different parameters are considered in the development of the model. Considering the integer as well as non-integer variables of the model and non-linearity present in the equations, solver for mixed integer non-linear programming was used. Optimal number of machineries for each unit operations based on the least cost option is determined. Selection of the types of equipment are done independently. Harvesting is a complex field operation which is consisted up off different sets of machines, different sets of operations and different orders of activities. Operations on optimum harvesting windows and start and end of harvesting period further make the system more complicated adding uncertain parameters in the model. Linear and non-linear equations are developed to assign land cost, material cost and operating cost for each operations. Optimal number of machineries for each operations are associated with earlier developed (chapter 2) cost equations to develop the objective function. Minimization of objective function provides the least cost option of planting, harvesting and transportation cost. Consideration of constraints of harvesting, on-farm hauling and transportation to final destination, overall cost is minimized using mixed integer non-linear programming model developed in the GAMS. General description about GAMS is provided in the chapter 2.

3.3.3 Switchgrass cost model

Land use types is one of the major issue for switchgrass planting. Switching from food crops to biofuel crops is an important option to meet the growing need of biomass feedstocks for biofuel production. Land use change for biomass production may impact the carbon balance of ecosystem (Haque et. al 2012). In this paper, grassland is considered for the switchgrass production and land preparation cost is not included.

Switchgrass yield vary with seeding rate, soil types, precipitation, fertility, location, planting methods, land use types and other factors. Switchgrass is significantly affected by soil variety and actual production is far lower than theoretical potential yield (Qin et. al 2007). Planting date has a significant effect on dry matter yield. The early planting dates on summer, April 23 and May 7 had produced lower yields as compared to late planting of May 21 and June 4 during initial harvest years of switchgrass. Seeding rate of almost 4 lb. ac^{-1} pure live seed was enough to maximize switchgrass production over its life time (Virgilio et. al 2007).

Planting systems could vary with seasons and planter types. Previous research has shown that, cost of growing switchgrass in different specific regions of US as compared to other herbaceous grass is low. Switchgrass can be planted with different planting options and methods.

Some of the switchgrass planting methods are described in the following paragraph (Duffy, 2006).

There is frost seeding with airflow planter where airflow planter is used for seeding and spreading fertilizers either on grassland or cropland and atrazine, 2,4D can be used as chemicals. Spring seeding with airflow planter is also a common practice where seeding rate is different from the frost seeding and 2,4D can be used as chemicals. Spring seeding with a drill and spring seeding with a no-till drill are other switchgrass planting practices. Seeding rate is different in no-till drill spring seeding than spring seeding with a drill and it could be done both in cropland and grassland (Duffy, 2006).

Maximizing the yield is one of the main concern of switchgrass harvest. It can be harvested and baled with self-propelled harvesters with a disc mowers for high yielding switchgrass fields [West et. al 2011]. Round bales and square bales has their own advantages and disadvantages during and after harvest. Round bales may have low storage losses but difficult to handle with during trucking as compared to square bales. In order for the use of round bales to biorefinery ‘over-the-road’ hauling technology must be developed (Cundiff et al 2008). Square bales systems are used for the analysis in this research.

3.3.4 Parameters of model

Parameters and decision variables used in the cost analysis model for the cost calculation of switchgrass are as shown as follows:

A_1 =area of pasture land to be planted (ha)
r =cost of fuel (\$ gal^{-1})
h_1 =operation time (hour day^{-1})
v_1 =value of yield (\$ Mg^{-1})

p =probability of working day
p_1 =probability of reseeding
I =amortization of production cost
N_l =life span of switchgrass
s_1 =yield of switchgrass (Mg ha^{-1})
p_{s1} =planting start date (Calendar)
p_{e1} =planting end date (Calendar)
t_{s1} =harvesting start date (Calendar)
t_{e1} =harvesting end date (Calendar)
s_{11} =seed cost (\$ kg^{-1})
q_1 =seed quantity (kg ha^{-1})
s_2 =potassium cost (\$ kg^{-1})
q_2 =potassium quantity (kg ha^{-1})
s_3 =phosphorus cost (\$ kg^{-1})
q_3 =phosphorus quantity (kg ha^{-1})
s_4 =atrazine cost (\$ ha^{-1})
s_5 =24D cost (\$ ha^{-1})
s_6 =roundup cost (\$ ha^{-1})
l_c =price of land (\$ ha^{-1})

For the consideration of a single product switchgrass planting, harvesting and transportation cost analysis, three different time spans are being considered for each section.

Spring seeding with a drill is the planting method included in the model development. Switchgrass could be drilled on the smooth surface where drilling involves planting in rows. A standard grain drill with small seed attachment is the best option of planting (Huang et. al 2009). The favorable time to plant switchgrass is the spring season. Switchgrass starts to germinate when the soil temperature is 10^0C and best condition for growth is the soil temperature of 18^0C with air temperatures 24^0C to 29^0C (Huang et. al 2009). There is no consideration of timeliness coefficient in the cost analysis. List prices, capacity, economic life, power requirement of machineries of planting, harvesting and transportation were prepared as a spreadsheet model from the brochure of manufacturing companies and literatures. Fuel consumption for machineries was estimated using ASAE standard and repair and maintenance cost of equipment was calculated using the repair factors of ASAE standard. Salvage value for almost all machineries was taken as 30% considering the list price of last 15 years.

Fuel consumption for a specific operation is expressed in gal/hp.hr based on the equation as taken from (ASAE, D 497.4, 2003) as shown in the equation 1 from chapter 2. Total fuel consumption cost, lubrication cost and repair and maintenance cost is expressed as same as shown in the equation 2, 3 and 4 respectively from the chapter 2.

To calculate the materials cost for the stand of switchgrass, equations (31) to (38) are used.

- Total land cost $lc \times A_1$ (31)
- Total seed cost $S_1 \times A_1 \times q1$ (32)
- Total reseed cost $(1+p_1) \times S_1 \times A_1 \times q_1$ (33)
- Total potassium cost $S_2 \times A_1 \times q_2$ (34)
- Total phosphorus cost $S_3 \times A_1 \times q_3$ (35)
- Total atrazine cost $S_4 \times A_1$ (36)
- Total 24D cost $S_5 \times A_1$ (37)
- Total Roundup cost $S_6 \times A_1$ (38)

Area covered for the planting of switchgrass is shown in the equation (39), where eff, cat, oeff are field efficiency, capacity of machine, overall operational efficiency respectively, h1 and p are operational hours per day and probability of working day respectively.

$$\sum_i e_{ff\,i} \times c_{at\,i} \times o_{eff\,i} \times h1 \times p \times (p_{e1} - p_{s1}) \times Np_i \quad (39)$$

Working day available for planting, harvesting and transportation are shown in the equation (40), (41) and (42) respectively.

$$t_1 \le h_1 \times (p_{e1} - p_{s1}) \times p \quad (40)$$

$$t_2 \le h_1 \times (t_{e1} - t_{s1}) \times p \quad (41)$$

$$t_3 \le h_1 \times (t_{e1} - t_{s1}) \times p \quad (42)$$

Planting, harvesting and transportation constraint of the model are shown from the equation (43) to (45)

$$\sum_i eff_i \times \mathrm{cat}_i \times t_1 \times N_{p_i} \ \ge A_1 \quad (43)$$

$$\sum_i eff_i \times \mathrm{cat}_i \times t_2 \times N_{p_i} \ \ge A_1 \quad (44)$$

$$\sum_i N_{pi} \times \left(\mathrm{den1} \times c_{at\,p_i} / (\mathrm{s1} \times 2000 \times (\mathrm{dt/hst1} + \mathrm{dt/rst1} + \mathrm{ft}))\right) \times eff_i \times t_3 \ \ge A_1 \quad (45)$$

3.3.5 Corn stover cost model

Cost estimation for corn stover which is considered as a by-product with grain provides the harvest and transport cost of corn stover. Total cost of harvest and transport including corn grain and biomass harvest is determined and combine cost is excluded from the total cost to find the corn stover feedstock cost. Parameters and decision variables used in the development of the optimization model for the cost calculation of corn stover feedstocks are as shown as follows:

A_2 =area of corn field, ha

h_2 =operation time (hour day^{-1})

k =timeliness coefficient

y_2 =yield (Mg ha^{-1})

v_2 =value of yield (\$ kg^{-1})

p =probability of working day

l = 2 or 4 depends whether the operation ends at optimum time or not

r_{2f1} =repair factor 1

r_{2f2} =repair factor 2

t_{oe2} =optimum harvest end (Calendar days)

t_{os2} =optimum harvest start (Calendar days)

t_{s2} =harvesting start (Calendar days)

t_{e2} =harvesting end (Calendar days)

d_t =distance of bio-refinery from on-farm storage

HI =harvest index

h_s =harvestable stover in fraction of total stover

d_h =on-farm hauling distance (mile)

Fuel cost, repair and maintenance cost, capital cost for corn stover harvesting and transportation are estimated using equations 2, 4, 8 respectively and timeliness cost is calculated using the equation (46) and terms of equation (46) are described in the previous chapter.

$$t_c = \sum_i \frac{k \times y_2 \times (A_2 - A_o)^2 \times v_2}{l \times h_2 \times C_a \times p} \text{ if, } A_{o2} \le A_2 \tag{46}$$

$$t_c = \sum_i \frac{k \times y_2 \times (A_2 - A_o)^2 \times v_2}{l \times h_2 \times C_a \times p} \text{ if, } A_{o2} \le A_2$$

To consider the minimum grain loss, timeliness cost is considered as zero when the harvesting is completed within the optimum harvesting window. Where C_a is the capacity of machinery of unit 0. Objective function for the model is described through equations (47 to 52). In the equation (47); z_0, i, c_c, c_f, c_r are cost of machinery for unit 0, 1 to 3 of number of machineries of unit 0, capital cost, fuel cost and repair and maintenance cost respectively.

$$z_o = \sum_{i0} N_i \times \left(c_{ci} + c_{f_i} + c_{ri}\right) \tag{47}$$

In the equation (48), $z_{1,}$ i, c_{c1}, c_{f1}, c_{r1} are cost of machinery for unit 1, 1 to 3 number of machineries of unit 1, capital cost, fuel cost and repair and maintenance cost respectively.

$$z_1 = \sum_{i1} N_{i1} \times \left(c_{ci1} + c_{f\,i1} + c_{ri1}\right) \tag{48}$$

In the equation (49), z_2, i, c_{c2}, c_{f2}, c_{r2}, and are cost of machinery for unit 2, 1 to 3 number of machineries of unit 2, capital cost, fuel cost and repair and maintenance cost respectively.

$$z_2 = \sum_{i2} N_{i2} \times \left(c_{ci2} + c_{f\,i2} + c_{ri2}\right) \tag{49}$$

In the equation (50), $z_{3,}$ i, c_{c3}, c_{f3}, c_{r3} and I are cost of machinery for unit 3, 1 to 3 number of machineries of unit 3, capital cost, fuel cost and repair and maintenance cost respectively.

$$z_3 = \sum_{i3} N_{i3} \times \left(c_{ci3} + c_{f\,i3} + c_{ri3}\right) \tag{50}$$

In the equation (51), $z_{4,}$ i, c_{c4}, c_{f4}, c_{r4} and are cost of machinery for unit 4, 1 to 3 number of machineries of unit 4, capital cost, fuel cost and repair and maintenance cost respectively.

$$z_4 = \sum_{i4} N_{i4} \times \left(c_{ci4} + c_{f\,i4} + c_{ri4}\right) \tag{51}$$

The overall objective function as shown in the equation (52) was minimized to obtain the least cost machineries combination for the required area of production field. In the equation (52), z is the harvesting and transport cost of biomass.

$$z = z_0 + z_1 + z_2 + z_3 + z_4 + \sum_{j} c_t \tag{52}$$

Where, i = sizes of machines, N=number of machines, j =operation units, c_t is timeliness cost

Constraints of the model are described through the equations 53 to 58

Area covered at harvesting window is given by equation (53).

$$A_{02} = \sum_{i} N_i \times e_{ff\,i} \times c_{ai} \times o_{eff\,i} \times h_2 \times p \times \left(t_{oe} - t_{os}\right) \tag{53}$$

Number of machines should be integer which is given by equation (54).

$$N_m = \sum_i N_i \geq 0 \tag{54}$$

Availability of machinery should guarantee the harvesting of given area of field within the harvesting window

$$\sum_i N_i \times e_{ff\,i} \times c_{ai} \times o_{eff\,i} \times t \geq A_2 \tag{55}$$

Maximum working calendar day available for operations

$$d_2 \leq t_{e2} - t_{s2}, d_2 \succ 1 \tag{56}$$

Total working hour depends on availability of working day, working hour per day and probability of working day.

$$t_2 = h_2 \times d_2 \times p \tag{57}$$

Hauling operation should guarantee the collecting of available materials from the field which is described by the equation (58) where s, d_{en}, dh, h_{sh1}, r_{sh1}, ft, e_{ff} and o_{eff} are stover available in the field to be removed in Mg per hectare, density of material kg per cubic meter, field hauling distance in km, hauling speed in kilometer per hour, return hauling speed in kilometers per hour, field time in hour, efficiency and overall efficiency of the machineries respectively.

$$\sum_i N_i \times \left(\frac{d_{en} \times c_{ati}}{s \times 2000 \times \left(\frac{dh}{h_{sh1}} + \frac{dh}{r_{sh1}} + ft \right)} \right) \times e_{ff\,i} \times o_{effi} \times t \geq A \tag{58}$$

3.4 Results and Discussion

The cost and optimal number of machineries were estimated with different cases with the variation in the farm size, storage distances, harvesting and planting windows, probability of working day and yield. Assumptions were not considered constant for all cases, therefore the reported result might differ slightly in each case. However for sensitivity analysis, the assumptions were made constant. Parameters which are used in the calculation and the result for few cases are shown in the table 3.1 and table 3.2.

Table 3. 1: Parameters for the base case cost estimation for switchgrass

Area of pasture land, ha (ac)	2,024 (5,000)
Probability of working day	0.64
Probability of reseeding	0.4
Yield of switchgrass, Mg ha^{-1} (ton ac^{-1})	13.45 (6)
Planting start (Calendar days)	90
Planting end (Calendar days)	135
Harvesting start (Calendar days)	240
Harvesting end (Calendar days)	301
Operation time (hr. day^{-1})	10
On-farm hauling distance, km (mile)	1.6 (1)
Transportation distance to bio-refinery, km (mile)	11.21 (5)
Density of bales, kg m^{-3} (lb. $feet^{-3}$)	12
Price of fuel (\$ gal^{-1})	4

Table 3. 2: Results from the base case cost estimation for switchgrass.

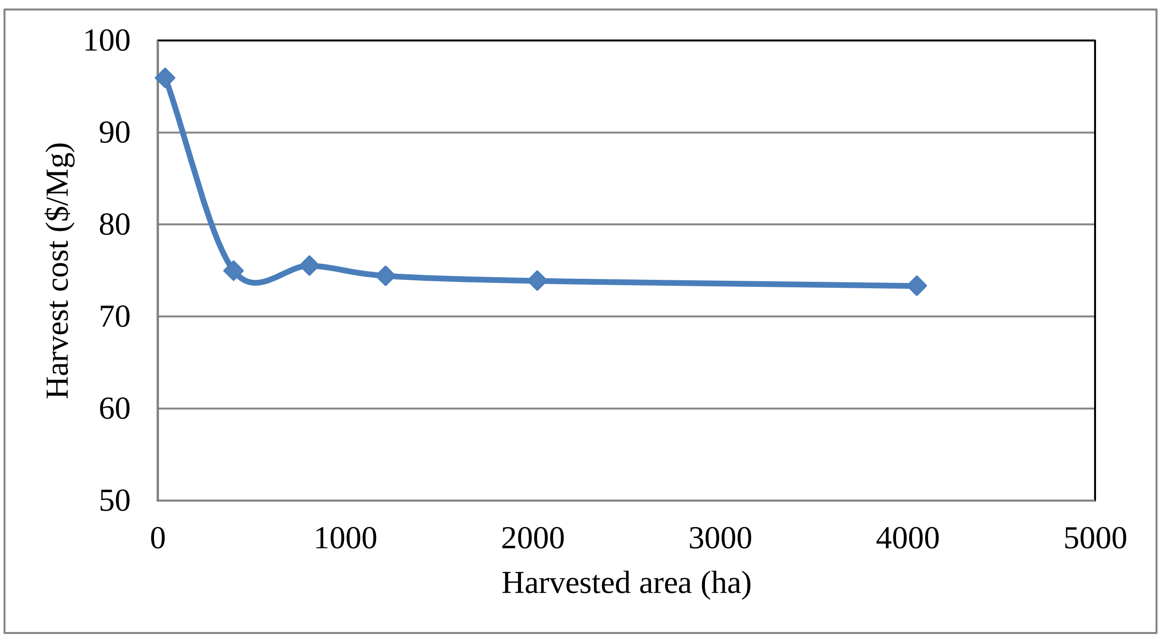
Area of pasture land, ha (ac)	2,024 (5,000)
Total establishment cost (\$)	2,032,522
Harvesting and transportation cost (\$)	607,956
Cost, \$ ha^{-1} (\$ ac^{-1})	1,305 (528)
Cost, \$ Mg^{-1} (\$ ton^{-1})	88

Cost of feedstock at the gate of biorefinery was based on the harvesting and transportation cost as well as establishment cost.

Table 3. 3: Results for the cost estimation of 405 ha farm for switchgrass.

Area of pasture land, ha (ac)	405 (1000)
Total establishment cost ($)	407,405
Harvesting and transportation cost ($)	150,258
Cost, $ ha^{-1} ($ ac^{-1})	1,376 (557)
Cost, $ Mg^{-1} ($ ton^{-1})	93

Switchgrass establishment cost was determined with the consideration of 40% reseeding and attaining maturity within the third year of initial planting. Establishment cost is shown in the figure 3.1. It was very high almost about $97 Mg^{-1} ($88 ton^{-1}) for 40.47 ha (100 ac) field and almost about $74.96 Mg^{-1} ($68 ton^{-1}) for a 809 ha (2,000 ac) field. The yield of switchgrass was taken as 13.45 Mg ha^{-1} (6 ton ac^{-1}) for this analysis. Establishment cost variation was reported



almost constant after certain size of production field as shown in the figure 3.1.

Figure 3. 1: Establishment cost of switchgrass with variation of production field

Switchgrass harvest and transport cost variation with the variation of size of field is shown in the figure 3.2. Harvest and transport cost was estimated almost about \$27.56 Mg^{-1} (\$25 ton^{-1}) for 405 ha (1,000 ac) field and \$22.05 Mg^{-1} (\$20 ton^{-1}) for 810 ha (2,000 ac) field. Yield of switchgrass was assumed 13.45 Mg ha^{-1} (6 ton ac^{-1}) and farm storage distance and biorefinery distances of 1.6km (1 mile) and 16km (10 mile) respectively. Sudden increase in cost after certain farm size might be due to the requirement of bigger size machine.

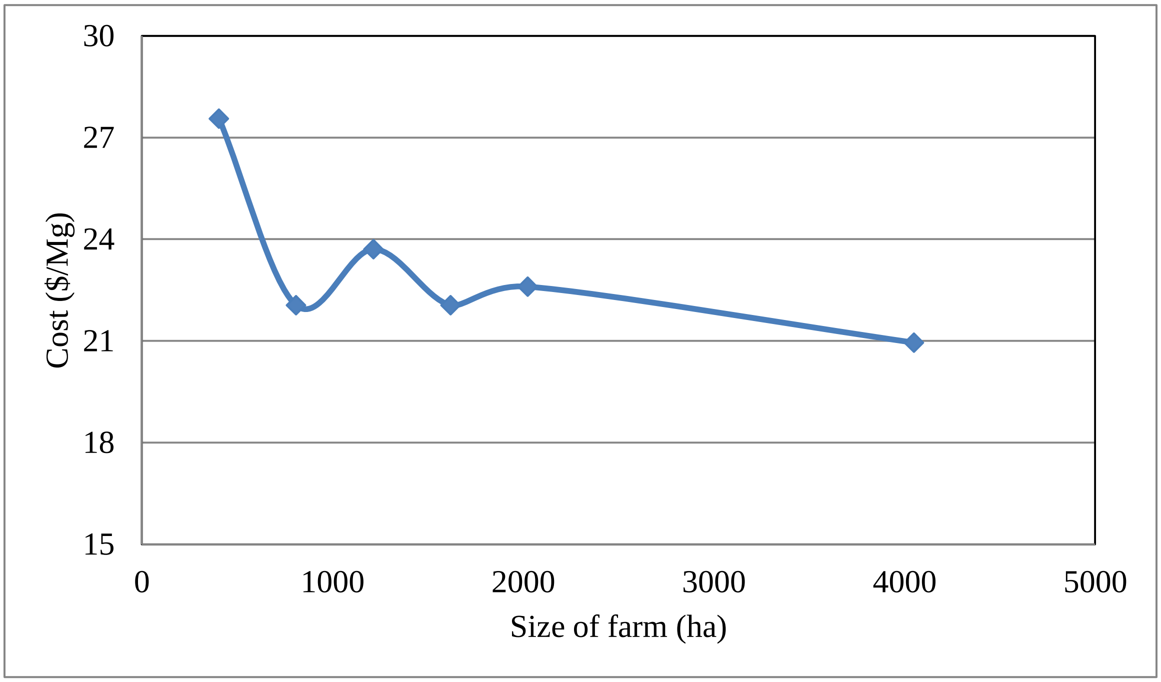


Figure 3. 2: Switchgrass harvest and transport cost variation with the size of field

Effect of yield on switchgrass harvest and transport cost is shown in the figure 3.3. The size of production field was considered 2,024 ha (5,000 ac) and on-farm storage distance of 1.6km (1 mile) and biorefinery location was assumed within a distance of 16km (10 miles).

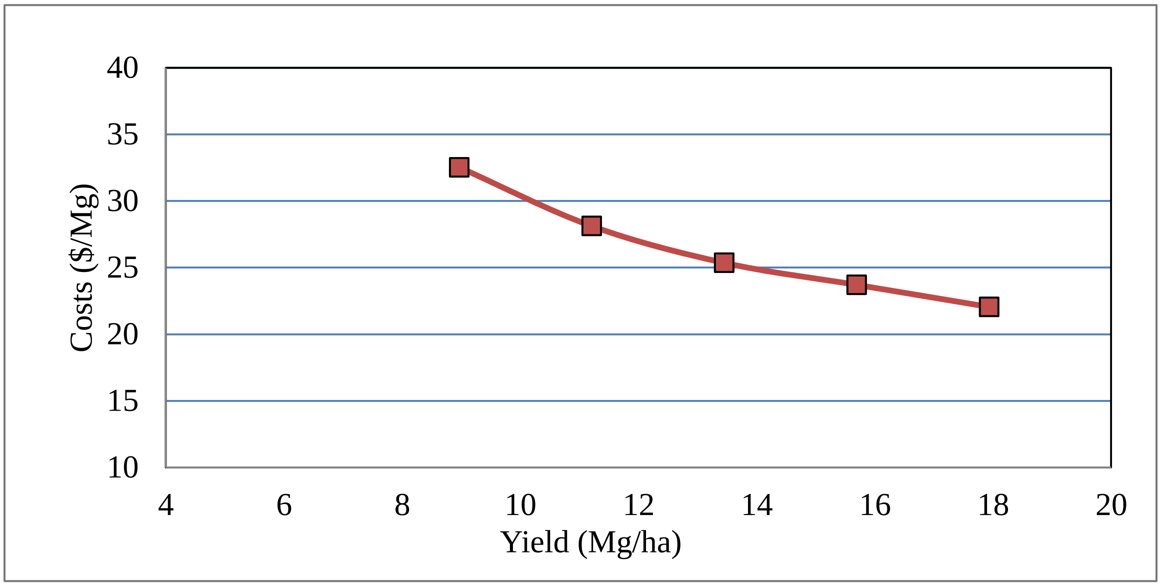


Figure 3. 3: Effect of yield on switchgrass harvest and transport cost

3.5 Sensitivity Analysis

Change in the objective function value using discrete values of the parameters at the nominal plus and minus given percentage changes (-40%, -30%, -20%, -10%, 10%, 20%, 30%, 40%) for the optimized least cost of biomass harvest and transport was estimated. One parameter at a time is changed keeping other parameters constant with the base case value. Changes of the probability of working day affects the least cost of feedstock the most and another dominant parameter is yield. Field storage distance and biorefinery distance has least impact on feedstocks cost as shown in figure 3.4.

Base cost of biomass harvest and transport for multi-pass corn stover harvest was estimated with farm size of 2,024 ha (5,000 ac). Sensitivity analysis was carried out to find the effect of probability of working day to the cost of biomass harvest and transport. Probability of working day is varied from 50% to -50% of base value which was taken 0.64. To find the storage distance impact on the cost of biomass harvest and transport, on-field storage distance is varied within 50% to -50 % of 1.6km (1 mile) of base value. Bio-refinery distance was taken as 16km (10 mile) for base value of objective function and its contribution to changes in base value was estimated varying within 50% to -50% as shown in figure 3.4.

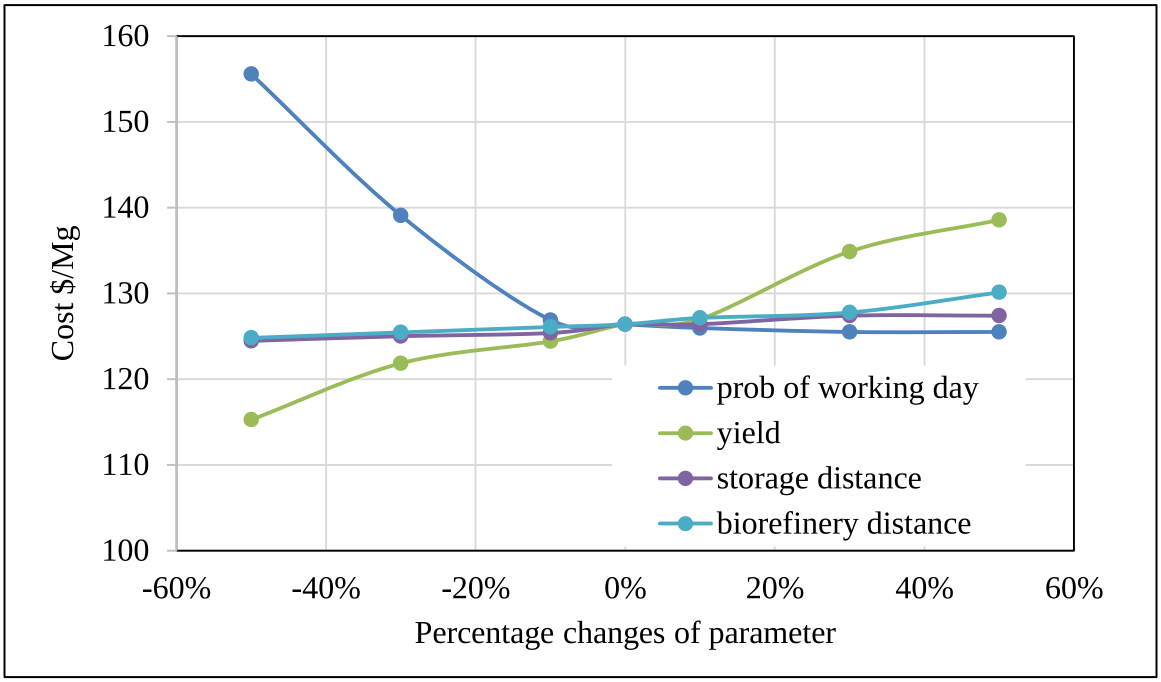


Figure 3. 4: Sensitivity analysis of biomass harvest and transport cost

To find the least cost of mixed-type feedstocks, corn stover cost model was run for different cases. To estimate the cost of feedstock of corn stover, the optimization model was run with the input parameters as shown in the table 3.4.

Table 3. 4 Input to GAMS model for corn stover

Corn field, ha (ac)	809 (2,000)
Probability of working day	0.64
Timeliness coefficient	0.003
Optimum harvest end (Julian day)	305
Optimum harvest start (Julian day)	280
Harvesting start (Julian day)	260
Harvesting end (Julian day)	320
Operation time (hr. day^{-1})	10
Price of fuel ($ gal^{-1})	4
Residue available, Mg ha^{-1} (ton ac^{-1})	4.48 (2)
Radius, km (miles)	17.22 (10.7)

Table 3. 5: Cost estimation for 1,200 ha farm for corn stover

Corn field, ha (ac)	1,214 (3,000)
Cost, \$ ha^{-1} (\$ ac^{-1})	296.53 (120)
Cost, \$ Mg^{-1} (\$ ton^{-1})	66.14 (60)

Total cost of the table 3.5, includes the combine cost as well. Detailed cost structures of different harvest operations and transport for corn stover feedstock is shown in the figure 3.5.

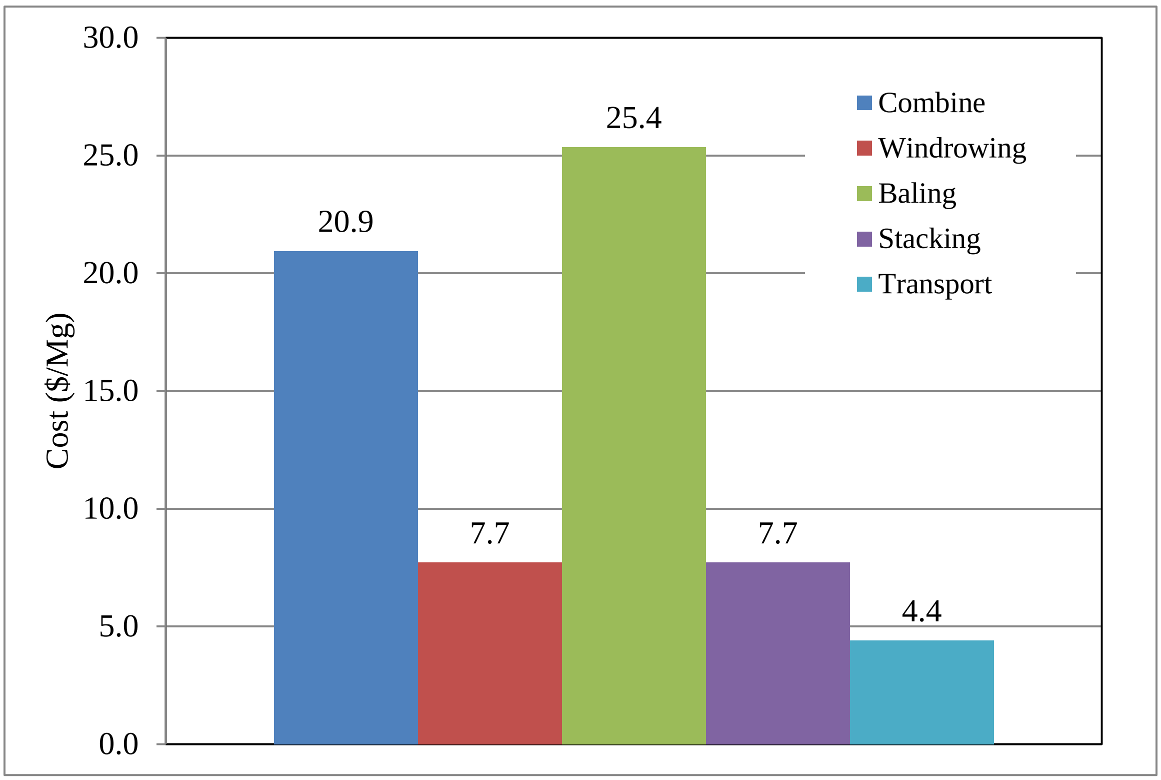


Figure 3. 5: Biomass harvest cost for 1,200 ha, farm for corn stover

The biomass only harvest and transport cost considering corn stover as a by-product with the corn production is about \$45.19 Mg^{-1} (\$41 ton^{-1}) excluding combine cost. Production farm size of 1,214 ha (3,000 ac) was considered for this analysis. On-farm storage distances of 1.6km (1 miles) and final feedstock transport distance was 17.22 km (10.7 miles). Available yield of biomass was assumed as 4.48 Mg ha^{-1} (2 ton ac^{-1}).

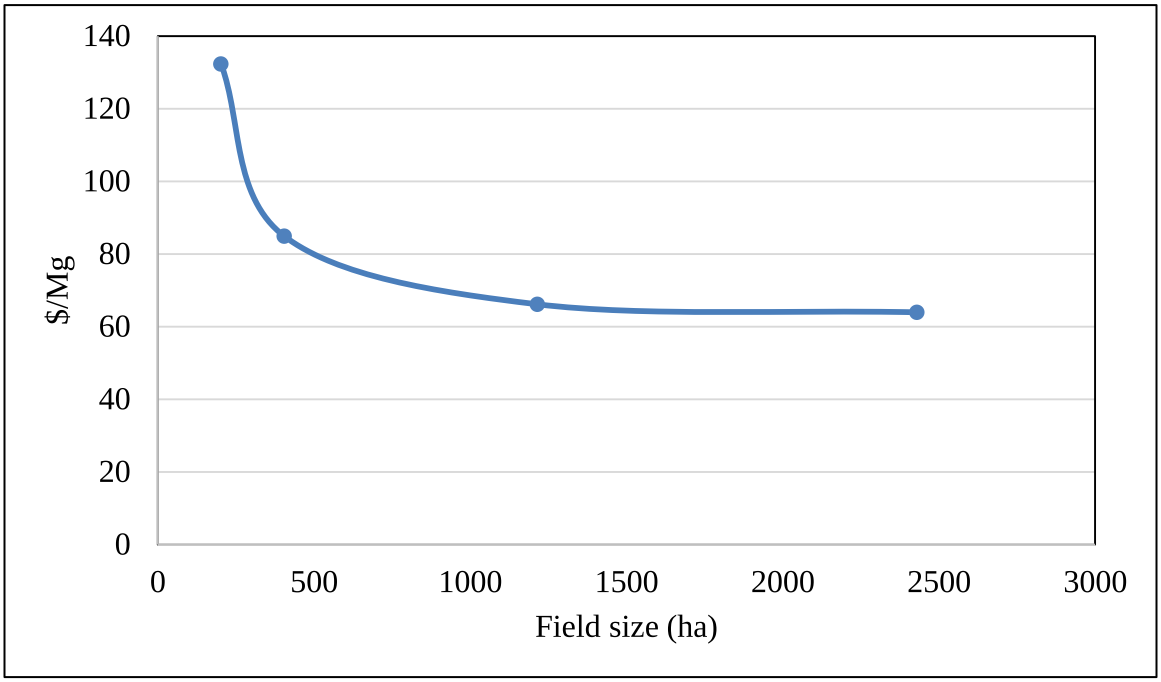


Figure 3. 6: Corn stover cost variation with the size of field

Corn stover harvest and transport cost variation with the size of field was estimated as shown in the figure 3.6. The data used for this analysis were as same as above. Only the farm sizes were varied for the same transportation distances to biorefinery. The feedstock cost varies significantly from almost about \$132.27 Mg^{-1} (\$120 ton^{-1}) for a 202 ha (500 ac) farm size to almost about \$66.13 Mg^{-1} (\$60 ton^{-1}) for a 1,214 ha (3,000) ac farm size.

Corn stover feedstock cost at the gate of the biorefinery is shown in the figure 3.7. Harvesting and transport cost varies with the tonnage required, i. e, with the sizes of the biorefinery within \$50.71 Mg^{-1} (\$46 ton^{-1}) to \$57.32 Mg^{-1} (\$52 ton^{-1}) as shown in the figure 3.7. As the sizes of the biorefinery increases, the radius of the collecting material increases causing increment to the harvesting and transport cost accordingly. In the model; Ames, Iowa was considered assuming 100% producers participation. From the figure 3.7, it can be concluded that, feedstock prices increases from almost \$50.71 Mg^{-1} (\$46 ton^{-1}) to \$57.32 Mg^{-1} (\$52 ton^{-1}) with the increment of the sizes of the biorefinery from 0.05M ton to 1M ton annually.

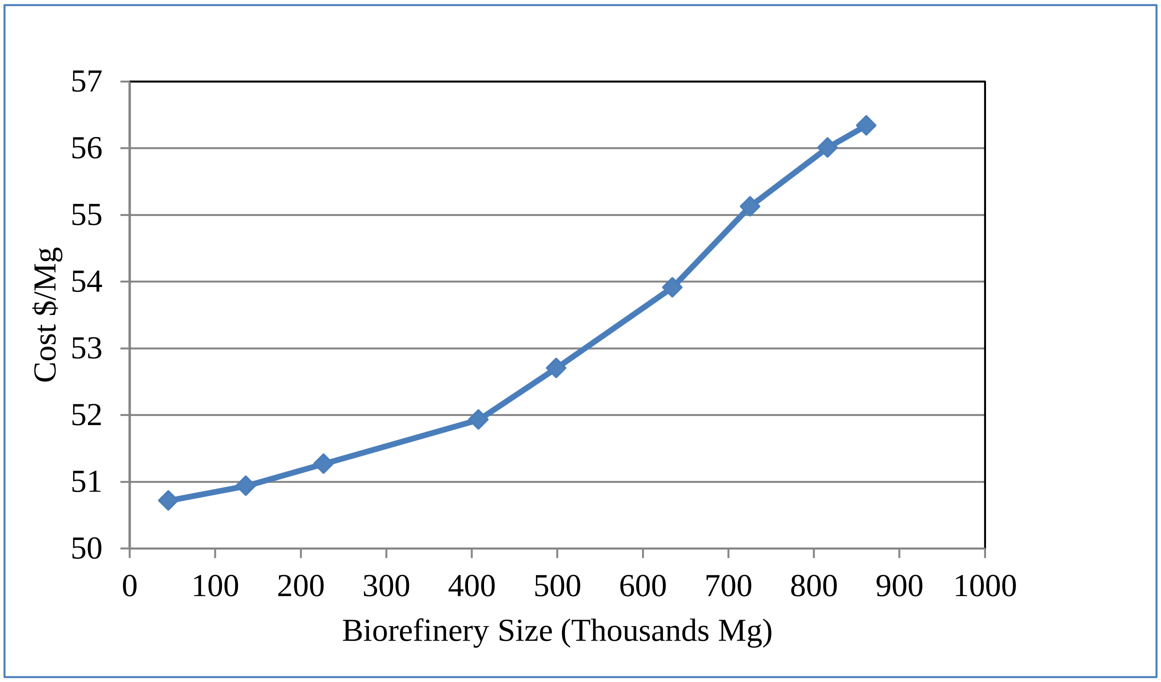


Figure 3. 7: Harvesting and transport cost variation of corn stover

From two independent optimization model, cost of feedstock at the gate of biorefinery, feedstock prices for corn stover and switchgrass were estimated. Corn stover price varies from \$27.55 Mg^{-1} (\$25 ton^{-1}) to \$22.05 Mg^{-1} (\$20 ton^{-1}) based on the sizes of farm for the same tonnage required. The average price of corn stover at the gate of the biorefinery considering 1,214 ha (3,000 ac) production area with the tonnage required of 0.45MMg (0.5M ton), is \$45.2 Mg^{-1} (\$41 ton^{-1}). Similarly, cost of switchgrass is \$97 Mg^{-1} (\$88 ton^{-1}). Considering the average price of both feedstocks at the gate of the biorefinery, with the proportion of 1:1 of switchgrass and corn-stover, average price of feedstocks will be \$71.65 Mg^{-1} (\$65 ton^{-1}) for the biorefinery sizes of 0.45MMg (0.5M ton) per year. (It was based on Ames, Iowa). Considering field size of 80.94 ha (200 ac), average multi-feedstock cost at the gate of biorefinery for the same tonnage required was estimated almost about \$176.37 Mg^{-1} (\$160 ton^{-1})

3.6 Conclusions

Mixed types biomass feedstocks cost at biorefinery gate were estimated. Switchgrass as a single product and corn stover as a by-product with corn were considered as multi-feedstocks. For switchgrass, planting and establishment cost was also estimated along with harvest and transport cost. Storage cost is excluded for both feedstocks types.

Switchgrass harvest and transport cost was estimated almost about \$27.56 Mg^{-1} (\$25ton^{-1}) for 405 ha (1,000 ac) farm and \$22 Mg^{-1} (\$20 ton^{-1}) for 1618 ha (4,000 ac) farm with the assumption of switchgrass yield of 13.45 Mg ha^{-1} (6 ton ac^{-1}), with the on-farm storage distance of 1.6km (1 mile) and distances to biorefinery of 16km (10 mile). Effect of yield on switchgrass harvest and transport cost was estimated. The analysis was done for the bigger size farm of 2,024 ha (5,000 ac), switchgrass harvest and transport cost changes from almost \$33.1 Mg^{-1} (\$30 ton^{-1}) to \$22.05 Mg^{-1} (\$20 ton^{-1}) with the yield variation from 4 ton ac^{-1} to 8 ton ac^{-1} with on-farm storage distance of 1.6km (1 mile) and biorefinery distance of 16km (10 mile).

The biomass harvest and transport cost considering corn stover as a by-product with the corn production was estimated almost about \$45.19 Mg^{-1} (\$41 ton^{-1}) excluding combine cost with the production farm size of 1,214ha (3,000 ac) and on-farm storage distance of 1.6km (1 mile) and final feedstock transport distance of 17.22km (10.7 miles), with the yield of biomass as 4.48 Mg ha^{-1} (2 ton ac^{-1}). For multi-pass corn stover harvest, cost of combine, windrowing, baling, stacking and transport were estimated as \$20.94 Mg^{-1} (\$19 ton^{-1}), \$7.72 Mg^{-1} (\$7 ton^{-1}), \$25.35 Mg^{-1} (\$23 ton^{-1}), \$7.72 Mg^{-1} (\$7 ton^{-1}) and \$4.41 Mg^{-1} (\$4 ton^{-1}) respectively, even though; combine cost is not included in the feedstock cost.

Switchgrass feedstock cost varied almost from \$123.46 Mg^{-1} (\$112 ton^{-1}) to \$94.8 Mg^{-1} (\$86 ton^{-1}) with the farm size variation from 405 ha (1,000 ac) to 2024 ha (5,000 ac). Corn stover biomass cost of harvest and transport varies from almost about \$27.56 Mg^{-1} (\$25 ton^{-1}) to \$22.05 Mg^{-1} (\$20 ton^{-1}). Averaging the farm sizes, estimated cost of multi-feedstock at the gate of biorefinery of size 0.5M ton annually is about \$67.24 Mg^{-1} (\$61 ton^{-1}). It does not include the storage cost.

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CHAPTER 4: GENERAL CONCLUSIONS

An optimization model for single pass biomass harvest for two different biomass collection methods (Bulk Collection, Large Square Bale Collection) was developed , and extended for multi-pass biomass harvest for multi-feedstocks (Corn Stover and Switchgrass). The tentative feedstocks harvest and field transportation costs to the storage location were estimated based on different farm sizes.

Biomass harvest and transport costs for single pass bulk stover collection method was estimated to be \$23.15 Mg^{-1} (\$21 ton^{-1}), for transport distance of 3.22km (2 miles) to storage, assuming a yield of 4.48 Mg ha^{-1} (2 ton ac^{-1}) for farm sizes of over 2,428 ha (6,000 ac). For the farm size of 405 ha (1,000 ac), biomass harvest and transport to on-farm storage was estimated about \$59.52 Mg^{-1} (\$54 ton^{-1}) and a farm size of 2,024 ha (5,000 ac), the biomass harvest and transport costs decreased to \$25.35 Mg^{-1} (\$23 ton^{-1}). Cost models for single pass biomass harvest and transport does not include the storage cost and transportation costs to the biorefinery.

The total harvest and transport for multi-pass corn stover harvest was approximately \$45.2 Mg^{-1} (\$41 ton^{-1}), with \$7.72 Mg^{-1} (\$7 ton^{-1}) windrowing cost, \$25.35 Mg^{-1} (\$23 ton^{-1}) baling cost, \$7.72 Mg^{-1} (\$7 ton^{-1}) stacking cost and \$2.2 Mg^{-1} (\$2 ton^{-1}) road transport cost.

Conventional Switchgrass harvest and transport costs decreased from \$33.1 Mg^{-1} (\$30 ton^{-1}) to \$22 Mg^{-1} (\$20 ton^{-1}) with the yield increment from 8.97 Mg ha^{-1} (4 ton ac^{-1}) to 17.94 Mg ha^{-1} (8 ton ac^{-1}), showing the importance of yield on feedstock cost. Establishment cost of switchgrass varied from \$97 Mg^{-1} (\$88 ton^{-1}) to \$74.95 Mg^{-1} (\$68 ton^{-1}) for 40.5 ha (100 ac) to 2,024 ha (5,000 ac), farm sizes respectively. The aggregated feedstock costs for an integrated switchgrass and corn stover supply chain (excluding storage) was estimated to be \$67.24 Mg^{-1} (\$61 ton^{-1}).

The result varies significantly with the assumptions and case studies as well as with the prices of machine that have been used in the analysis and result are not consistent throughout the chapter 2 and chapter 3 because of the variation in the assumptions e.g. the price of the same type of machine might have different assumptions depending on the type of case analysis. The major factor for inconsistent result was due to the assumptions of new machine for some categories and considering used machine price for the same categories in different case analysis.

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APPENDIX A – BIOMASS PLANTING, HARVEST AND TRANSPORT ASSUMPTIONS

Symbols	Name	Value
A	Area of field	5000 (vary)
r	Price of fuel	4
h	Operation hours per day	10
k	timeliness coefficient	0.003
y	yield on bushel per acre	175 (vary)
v	value of yield on dollars per bushel	3
p	probability of working day	0.64 (vary)
l	whether the operation ends at optimum time or not	4
rf1	repair factor 1	0.12 (vary)
rf2	repair factor 2	2.3 (vary)
toe	optimum harvest end	300 (vary)
tos	optimum harvest start	280 (vary)
ts	harvesting start	255 (vary)
te	harvesting end	325 (vary)
sh11	hauling speed of grain tractor for type 1	5
sr11	return speed of grain tractor for type 1	10
sh12	hauling speed of grain tractor k for type 2	10
sr12	return speed of grain tractor k for type 2	20
sh13	hauling speed of grain tractor k for type 3	10
sr13	return speed of grain tractor k for type 3	20
HI	harvest index '	0.5
s	total stover tons per acre	4.2
dh	hauling distance on-farm storage	2 (vary)
catc01	cap of combine type 1, ac/hr.	6.06 (vary)
catc02	cap of combine type 2, ac/hr.	16.26 (vary)
catc03	cap of combine type 3, ac/hr.	20.47 (vary)
eff01	eff of unit zero 1	0.75
eff02	eff of unit zero 2	0.75

Symbols	Name	Value
eff03	eff of unit zero 3	0.75
oeffc01	overall eff of unit zero for set 1	1
oeffc02	overall eff of unit zero for set 2	1
oeffc03	overall eff of unit zero for set 3	1
pc01	power of combine type 1	185
pc02	power of combine type 2	360
pc03	power of combine type 3	543
pt21	power of tractor type 1	225
pt22	power of tractor type 2	245
pt23	power of tractor type 3	270
lpc01	list price of combine type 1	109,180
lpc02	list price of combine type 2	300,000
lpc03	list price of combine type 3	359,260
lph01	list price of header type 1	24,287
lph02	list price of header type 2	37,089
lph03	list price of header type 3	43,845
lpt21	list price of tractor type 1	172,000
lpt22	list price of tractor type 2	186,000
lpt23	list price of tractor type 3	200,000
ppc01	purchase price of combine type 1	91,782
ppc02	purchase price of combine type 2	270,000
ppc03	purchase price of combine type 3	323,334
pph01	purchase price of header type 1	21,858
pph02	purchase price of header type 2	33,380
pph03	purchase price of header type 3	39,460
ppt21	purchase price of tractor type 1	154,800
ppt22	purchase price of tractor type 2	167,400
ppt23	purchase price of tractor type 3	180,000
lpp21	list price of processor for tractor 1, grain wagon type 1	120,000
lpp22	list price of processor for tractor 1, grain wagon type 2	144,000

Symbols	Name	Value
lpp23	list price of processor for tractor 1, grain wagon type 3	165,000
ppp21	purchase price of processor for tractor 1, grain wagon type 1	108,000
ppp22	purchase price of processor for tractor 1, grain wagon type 2	129,600
ppp23	purchase price of processor for tractor 1, grain wagon type 3	148,500
dgh	distance to grain hopper	1 (vary)
den	density of bales, lb./ft3	12
dy	density of bulk materials, lb./ft3	3
sh1	hauling speed of forage wagon 1	10
sr1	return speed of forage wagon 1	20
sh2	hauling speed of forage wagon 2	10
sr2	return speed of forage wagon 2	20
sh3	hauling speed of forage wagon 3	10
sr3	return speed of forage wagon 3	20
lpfw1	list price of forage wagon 1	25,000
lpfw2	list price of forage wagon 2	32,000
lpfw3	list price of forage wagon 3	39,000
lpft1	list price of forage tractor 1	74,000
lpft2	list price of forage tractor 2	186,000
lpft3	list price of forage tractor 3	200,000
ppfw1	purchase price of forage wagon 1	22,500
ppfw2	purchase price of forage wagon 2	28,800
ppfw3	purchase price of forage wagon 3	35,100
ppfw1	purchase price of forage tractor 1	66,600
ppfw2	purchase price of forage tractor 2	167,400
ppfw3	purchase price of forage tractor 3	180,000
pft1	power of forage tractor type 1	100
pft2	power of forage tractor type 2	245
pft3	power of forage tractor type 3	270
caft1	cap of forage wagon 1 cubic feet	1,040
caft2	cap of forage wagon 2 cubic feet	1,142

Symbols	Name	Value
caft3	cap of forage wagon 3 cubic feet	1,243
lpb1	list price of baler type 1	62,700
lpb2	list price of baler type 2	76,200
lpb3	list price of baler type 3	82,100
ppb1	purchase price of baler type 1	56,430
ppb2	purchase price of baler type 2	68,580
ppb3	purchase price of baler type 3	73,890
shh1	hauling speed of biomass hauler type 1	10
srh1	return speed of biomass hauler type 1	20
shh2	hauling speed of biomass hauler type 2	10
srh2	return speed of biomass hauler type 2	20
shh3	hauling speed of biomass hauler type 3	10
srh3	return speed of biomass hauler type 3	20
lpha31	list price of biomass hauler type1	129,000
lpha32	list price of biomass hauler type 2	139,000
lpha33	list price of biomass hauler type 3	168,450
ppha31	purchase price of biomass hauler type 1	116,100
ppha32	purchase price of biomass hauler type 2	125,100
ppha33	purchase price of biomass hauler type 3	151,605
lpw11	list price of windrower type 1	112,717
lpw12	list price of windrower type 2	119,830
lpw13	list price of windrower type 3	151,651
ppw11	purchase price of windrower type 1	101,445
ppw12	purchase price of windrower type 2	107,847
ppw13	purchase price of windrower type 3	136,485
pw11	power of windrower type 1	110
pw12	power of windrower type 2	148
pw13	power of windrower type 3	235
lpst41	list price of semi-truck and trailer	82,053
lpst42	list price of semi-truck and trailer	100,850

Symbols	Name	Value
lpst43	list price of semi-truck and trailer	100,850
ppst41	purchase price of semi-truck and trailer	73,847
ppst42	purchase price of semi-truck and trailer	90,765
ppst43	purchase price of semi-truck and trailer	90,765
catst41	capacity of semi-truck and trailer, ton	3,500
catst42	capacity of semi-truck and trailer, ton	4,000
catst43	capacity of semi-truck and trailer, ton	4,000
cap11	capacity of planting machine type 1, ac/hr.	4.5
cap12	capacity of planting machine type 2, ac/hr.	6
cap13	capacity of planting machine type 3, ac/hr.	8
lpp101	list price of planting machine type 1	83,080
lpp102	list price of planting machine type 2	101,980
lpp103	list price of planting machine type 3	139,088
ppp101	purchase price of planting machine type 1	74,700
ppp102	purchase price of planting machine type 2	91,782
ppp103	purchase price of planting machine type 3	125,179
lpp1	list price of rake type 1	96,000
lpp2	list price of rake type 2	96,000
lpp3	list price of rake type 3	96,000
ppp1	purchase price of rake type 1	86,400
ppp2	purchase price of rake type 2	86,400
ppp3	purchase price of rake type 3	86,400
hst1	hauling speed of semi-truck and trailer type 1	40
rst1	return speed of semi-truck and trailer type 1	50
hst2	hauling speed of semi-truck and trailer type 2	50
rst2	return speed of semi-truck and trailer type 2	55
hst3	hauling speed of semi-truck and trailer type 3	55
rst3	return speed of semi-truck and trailer type 3	60
p1	probability of reseeding	0.4
s1	yield of switchgrass tons per acre	6 (vary)

Symbols	Name	Value
ps1	planting start	90 (vary)
pe1	planting end	135 (vary)
ts1	harvesting start	240 (vary)
te1	harvesting end	301 (vary)
s11	seed cost dollar per pound	5
q1	seed quantity pound per acre	7
s2	potassium cost dollar per pound	2
q2	potassium quantity pound per acre	45
s3	phosphorus cost dollar per pound	3
q3	phosphorus quantity pound per acre	35
s4	atrazine cost dollar per acre	3
s5	24D cost dollar per acre	4
s6	roundup cost dollar per acre	15
lc	price of land dollar per acre	90

APPENDIX B – AN EXAMPLE OF MANUAL VALIDATION

No of combines for 5,000 ac, type 2	2
Capacity of size 2 combine, ac/hr	16.26
days available	44.8
optimal hour	205.002
field efficiency	0.75
hour per day	10
probability of working day	0.64
area covered, ac	5,000