

Biomass harvesting cost analysis using field scale testing data

by

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B.S., Kansas State University, 1983
M.B.A., Kansas State University, 2006

AN ABSTRACT OF A DISSERTATION

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Department of Biological and Agricultural Engineering
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Abstract

In 2008 AGCO began a project to develop machinery to harvest biomass for a DOE project called “*Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to supply Crop Residues and A Herbaceous Energy Crops in a Diversified Large Square Bale Format*”. The project considered the harvest of corn stover, wheat straw, switchgrass and energy sorghum. AGCO modified some existing pieces of production hay harvesting equipment and developed a new larger square baler for single pass crop residue harvesting. Field scale tests of the developed equipment occurred in the years 2010, 2011, and 2012. Data collected during these tests included crop harvested, field location, number of hectares harvested, moisture content of harvested biomass, number of bales produced, weight of each bale, time to harvest, model(s) and sizes of machine(s) used, and fuel consumed. Data was collected for different harvesting techniques for crop residues: two-pass vs single-pass harvesting for corn stover and wheat straw. Data was collected for harvesting switchgrass and energy sorghum for comparison purposes. The cropping years were very different over the course of the project due rain fall amounts.

The data was analyzed using American Society of Agricultural and Biological Engineer machinery management standards and accepted Agriculture & Applied Economics Association assumptions. Excel spreadsheets were developed to calculate the harvesting costs on a dry Mg basis for each crop that was harvested. Results from the data analysis was used to modify the Integrated Biomass Supply Analysis and Logistics model to predict harvesting costs for crop residues at different yield levels, harvest conditions, and machine settings for single-pass harvesting.

A number of conclusions can be drawn from this analysis. First, “take rates” for crop residues can have a significant effect on harvest costs. Low “take rates” can make it economically unfeasible to harvest crop residues in some instances. Second, single-pass harvesting of crop residues is less labor and fuel intensive than multi-pass harvesting. Third, the large yields potential of energy sorghum, which requires more operations to harvest than switchgrass, more economically to harvest than switchgrass. Fourth, operational techniques can be used to offset some crop variability to reduce harvest cost of crop residues. Lastly, a decision tool has been developed to aid producers in the decision of whether to harvest corn stover or not based on cost return estimates.

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Approved by:

Major Professor
Dr. Donghai Wang

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Chapter 1 Introduction

1.1 Introduction

Since the oil shocks of the 1970's, compounded by the concerns of global warming and high oil prices of the early 2000's, the search for an alternative energy source to petroleum oil has been underway. Prior to the 19th century, humanity obtained most of its energy from biological sources such as animal fats and oils, wood plants, and other plentiful organic materials. With the adoption of coal and petroleum oil in the late 19th century humanity moved away from its traditional biological energy sources. Coal and petroleum oil are finite, fossil energy sources that will eventual either be used up or become too expensive to be used for energy. With the added concern of global warming due to carbon emissions, humanity has returned to again consider biomass as an energy source.

In 2005 the United States Department of Energy (DOE) published a report called *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (generally referred to as the *Billion Ton Study* or 2005 BTS (Perlack et al., 2005). The goal of this report was to ascertain if enough biomass was available to displace 30% of the United States petroleum consumption. It was estimated that a billion tons of biomass would need to be harvested in order to achieve this goal. The 2005 BTS looked at agriculture and forestry sources to see if that quantity of biomass was even available. The 2005 BTS found that the a billion tons of biomass was potentially available, but some of the feedstocks considered could be too expensive to utilize to feasibly reach the supply goal. The study identified a number of potential biomass feedstocks that did not have established collection methods of their own. These feedstocks, among others, included crop residues (corn stover and wheat straw) and purpose grown energy crops (switchgrass and energy sorghum).

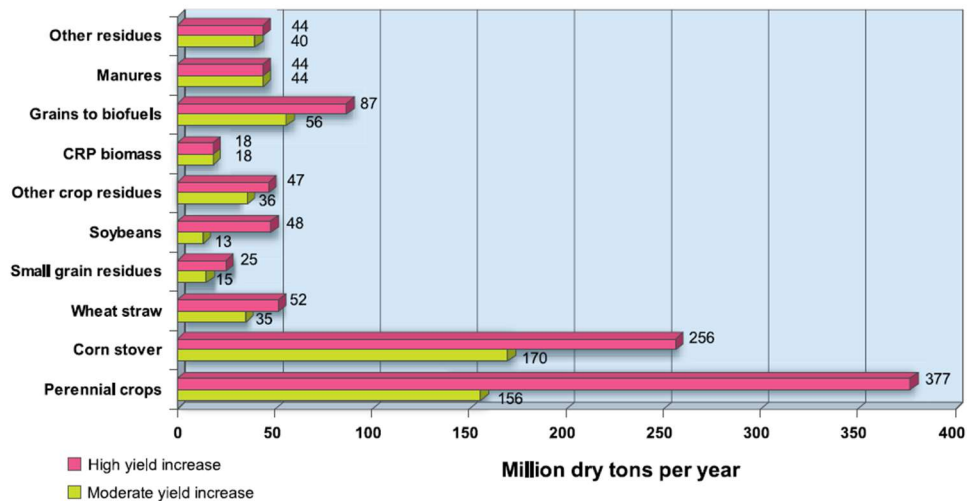


Figure 1.1 Agricultural residue harvest potential assuming crop and harvest technology has been adopted (Image: Perlack et al., 2005)

Crop residues such as wheat straw, corn stover, and energy sorghum biomass were considered to be the more attractive feedstocks in the BTS, because they do not require the conversion of crop land used for food production to the production of energy crops. The normal production of these food crops generate a supply of biomass that, if collected, could be used as a bioenergy feedstock. Essentially, the planting of one crop would generate two different products: grain for food and biomass for energy.

Crops such as switch grass, miscanthus, and energy sorghum were also considered attractive biomass feedstocks that could be grown and harvested from marginal agricultural lands. These crops were considered necessary to provide additional sources of biomass to achieve the billion ton biomass target (Perlack et al., 2005).

The 2005 BTS did not consider the cost or method of harvesting the biomass that was identified as being available. The study only considered the biomass availability. Any costs that were considered used existing harvest cost values available at that time. In addition, the availability of suitable harvesting and handling equipment was not addressed in the report. It

was assumed that any necessary harvest methods necessary to collect the identified sources of biomass would be developed as needed in order to reach the billion ton goal.

For traditional crop residues such as corn stover, harvesting can be accomplished using currently available equipment used to harvest and handle conventional forage crops (Perlack et al., 2002). According to Perlack, the cost of harvesting corn stover using conventional methods was projected to be above \$44/dry Mg. This estimated price was based on conventional equipment used to harvest forage crops, such as alfalfa and prairie hay. It was believed that the price of this biomass could be reduced through the development of advanced equipment specifically designed for the collection of corn stover (Sokhansanj, 2003). The conventional methods of harvesting corn stover use haying tools such as large round balers (LRB's), large square balers (LSB's), rakes, windrowers, stock shredders, bale accumulating devices, conventional transport trucks and tractors. Studies indicate that there are several areas of opportunity to reduce biomass harvesting costs. Some of the identified cost reductions are believed to be through the reduction in harvesting steps, increased bale densities, wider harvest widths, and higher speed harvest methods (Sokhansanj, 2003). An example of the effect to the price of corn stover that one of the identified changes could make was that of the reduction of harvest steps. If the raking step used in the conventional method of harvesting of corn stover was removed, the cost to harvest corn stover could be potentially reduced by nearly \$13.25/dry Mg (Sokhansanj, 2003). Another opportunity to reduce harvest steps that was identified was the development of single pass harvesting equipment. Such equipment would reduce the labor and harvest machinery required to bale crop residues biomass (Sokhansanj, 2003)

It was noted in a study that bioenergy feedstocks are more abrasive, and handled in much larger quantities, than conventional forages (Sokhansanj, 2003). It is believed that these

feedstocks would cause greater year in year out wear on conventional forage harvest equipment compared to normal forage crops. Therefore, it is anticipated that equipment used to harvest and handle bioenergy crops and crop residues would need to be designed to be more durable to handle the rigors of harvesting biomass.

In 2008, the DOE awarded 5 feedstock development grants to develop the feasibility of collecting some of the biomass feedstocks outlined in the 2005 BTS and other studies. AGCO's Hesston, Kansas division was one of the awardees of a development grant. Their project was titled "*Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to supply Crop Residues and A Herbaceous Energy Crops in a Diversified Large Square Bale Format*". This project focused on the harvest and collection of crop residues (corn stover and wheat straw) and purpose grown energy crops (switchgrass and energy sorghum). The project's intent was to answer many of the questions outlined in the BTS and challenges summarized from other published papers written in the early 2000's (Sokhansanj, 2003). One of the AGCO project's intents was to develop and test equipment to harvest crop residues in a single pass. The developed single pass harvesting equipment was to be tested and compared with conventional harvesting techniques on a field scale. The field scale tests would be used to develop actual harvest cost data for the newly developed equipment for use in cost prediction models such as the Integrated Biomass Supply Analysis and Logistics model (IBSAL). The project was also intended to develop large square balers that would achieve higher bale densities and explore the affect the increased bale densities would have on harvest costs. Besides field scale tests on crop residue harvesting, the AGCO project would also conduct field scale production and harvest tests of energy crops such as switch grass and energy sorghum. These

field scale tests provided actual harvest cost data for these crops to verify some of the projected harvesting costs in earlier papers. (Perlack, 2002; Sokhansanj, 2003)

Many studies on crop residue harvesting costs focused on collecting as much biomass as possible from fields without regard to agronomic concerns (soil organic matter, nutrients removed), field erosion (water and wind), and water retention (reduced infiltration due to compaction and evaporation due to soil exposure) (Wilhelm, 2010). The 2005 BTS was concerned that only 70% of above ground crop residues could feasibly be harvested with equipment available. It was believed that if advanced harvesting equipment was developed, crop residue harvest could achieve nearly 100% harvest of above ground crop residues (Sokhansanj, 2002). However, agronomic studies found that residue harvest rates cannot be that large and likely vary depending upon crop, local climate, tillage practices, and residue amounts left in the field from previous crops (Wilhelm, 2010). The 2005 BTS suggested that residue harvest rates could be up to 9 dry Mg/Ha. Agronomic studies indicate that to have sustainably amounts of harvest crop residues, harvest rates may need to be much smaller. A “take-rate” of 0.5 dry Mg/Ha may only be allowable in certain field conditions (Hess, 2010). Calculated biomass harvesting costs were found to be highly sensitive to yield or “take-rates”. High yield crops are much more economical to harvest in \$/dry Mg than low yield crops (Sokhansanj, 2002). The agronomic studies found that fields that might have a large amount of residue may require that a high percentage of the biomass remain on the field to maintain crop productivity. It was found that removal of large amounts of crop residue in certain climates and soil types would reduce soil organic matter, soil nutrient content, increase soil erosion, and reduce the water retention ability of a field. Changes in these factors in turn will reduce the productivity of a field (Hess, 2010).

1.2 Problem Statement

Logistical models, such as the IBSAL model, used to study the biomass supply chain are based on harvest methods and costs used for harvesting conventional forage crops (Perlack, 2002; Sokhansanj, 2003), small research plot data, or estimated costs for proposed harvest equipment and methods (Lanholtz et al., 2016). It is crucial that these models use current and accurate data. Researchers, farmers, and biorefineries are using these models to consider the economic feasibility of bioenergy and bio based products. Logistic models that do not reflect the latest biomass harvest methods and their related costs may result in these stakeholders making significant investments in equipment and business models based on logistic models that may under predict the supply chain cost of biomass. Conversely, these same stakeholders might refrain from investments in the bioeconomy because the predicted costs may be higher than they may actually be. These stakeholders need accurate information to make informed decisions on the large financial investments that are necessary to build the bioeconomy.

This project has developed harvest cost values based on field scale tests that were conducted harvesting biomass crops and residues for energy. The project developed updated costs for the harvesting of corn stover, wheat straw, switchgrass and energy sorghum. This cost analysis included harvest cost data for newly designed and manufactured equipment for single pass harvesting of corn stover and wheat straw as proposed by Sokhansanj (2003). The resulting cost data was then used to update the IBSAL model to reflect the advances of the newly developed harvest equipment. A further step was then taken to evaluate the modified IBSAL model over a range of common biomass harvesting variables to understand the sensitivity of these variables on crop residue cost.

The updated harvest costs were developed for corn stover, wheat straw, switchgrass, and energy sorghum using the AGCO field data, ASABE machinery management standards, Excel spreadsheets, and input costs such as fuel and equipment from appropriate dealers of these items. The results were further analyzed and cost curves and equations that predict harvesting costs over a wide range of variables were developed. Variables considered were crop yield, bale density, biomass moisture content, and harvest rates (“take rates”). The IBSAL model was modified to replicate the harvest costs developed from the collected field data.

1.3 Specific Objectives

The goal of this work was to develop current biomass harvest costs to improve the IBSAL model using field test data collected for purpose built biomass harvesting equipment. The specific research objectives were:

- Analysis of crop residue harvesting costs for two-pass and single pass harvesting systems for wheat straw and corn stover based using field scale test data.
- Analysis of biomass harvesting costs for modified forage harvesting equipment used to harvest switchgrass and energy sorghum energy crops based on field scale test data.
- Modification of the IBSAL model to reflect harvesting costs for purpose built equipment to harvest crop residues and biomass crops based on collected field test data.
- Use the modified IBSAL model, based on collected field test data, to analyze key operational variables and assess their effect on harvest costs. These results were then used to suggest harvesting strategies to reduce crop residue and biomass crop harvest costs.

- Using the modified IBSAL model, a decision tool was developed that a producer can use to determine economic viability of crop residue harvesting for a range of yields and field conditions.

1.4 Related Current and Previous Research

Energy from biomass, in the form of crop residues and purpose grown forage crops, has been considered for many years as a possible alternative to fossil fuels. In 1978 it was estimated that 10% of the United States energy consumption could possibly be supplied from biomass sources (Lipinsky, 1978). Of this biomass supply in 1978, it was estimated that 400 million tons of crop residues were immediately available for collection (Larson et al., 1978). Corn stover and wheat straw were identified as the primary available crop residues. It was estimated at the time that biomass could provide as much as 5% of the United States energy needs (Larson et al., 1978).

In 2005 the Billion Ton Study was released (Perlack et al., 2005). The goal of this study was to ascertain if there was the potential to produce enough biomass yearly to displace 30% of annual U.S. petroleum consumption, which would equate to approximately 1 billion tons of biomass. The 2005 BTS indicated that there is the potential to produce 1.3 billion tons of biomass each year in the United States. Of the 1.3 billion tons, it was believed that agricultural resources could supply 1.1 billion dry Megagram (d. Mg) of biomass per year while still meeting current U.S. food, feed and export demands (Perlack et al., 2005). Of the agricultural resources considered, the study indicated that 471 million d. Mg of crop residues and 415 million d. Mg of perennial crops, such as switchgrass, were available for harvest. The BTS 2005 identified corn stover and wheat straw as the most readily available agricultural residues. It was estimated in 2005 that 83 million d. Mg of corn stover and 12 million d. Mg of wheat straw was readily

available. It is expected that the yearly supply of biomass from these crops could grow, if current yield gains remain constant, to 187 million d. Mg of corn stover and 39 million d. Mg of wheat straw annually. The 2005 BTS did not consider if these materials could or should be harvested, only if the material was available. The study raised a number of concerns regarding the removal of crop residues and nutrients from agricultural lands and yield variabilities at the local level.

The two agricultural residues, wheat straw and corn stover, discussed in the 2005 BTS have been considered for energy use previously. Corn stover has been under consideration for at least the last 30 years. Literature was found showing corn stover being considered for energy as early as 1982 (Richey CB, 1982). Corn stover has been harvested for many years for other uses such as animal fodder and bedding. Equipment used to collect corn stover includes stock shredders, hay rakes, and balers. A typical stover harvesting process is as follows: The combine harvester residue spreader is disengaged during harvesting operations causing residue from the rear of the combine to be windrowed behind the combine; The stocks are then shredded using a stock shredder to loosen additional plants from their roots and added them to the combine windrow; Depending upon the type of shredder used, a raking step may be required to move shredded stocks to the combine windrow; A baler, either a large round baler or a large square baler is the used to bale the stover; The stover bales are then picked up and transported to the field edge or a storage site (Perlack, 2003).

Stover harvesting cost have been regularly estimated based on producer interviews, harvest procedure assumptions and published custom harvesting rates (Sokhansanj, 2002). It is believed that stover harvesting costs could be reduced if equipment was developed specifically for the harvesting of corn stover (Sokhansanj, 2002; Perlack et al., 2005). Several developments

were proposed that would reduce harvesting costs. One proposed piece of equipment would bale stover in a single pass, rather than the multiple passes required in the traditional stover harvesting method. Another development was of an improved large square baler that could produce bales with densities approaching 224 kg/m^3 . Any equipment developed for stover harvest, should be tested and in field scale trials to develop accurate harvest data that can be used to update biomass supply models (Sokhansanj, 2002; Perlack et al., 2005).

The second crop residue considered to be available for biomass harvesting in the 2005 BTS is wheat straw. Wheat straw is considered to be the third largest potential source of biomass for energy after corn stover and grains (Perlack et al., 2005). Equipment often used to harvest wheat straw includes swathers, rakes, and balers. Wheat straw is generally harvested by disengaging the combine harvester straw spreader during the harvest of the grain, which results in a windrow being formed behind the combine. This windrow is then baled with either a large round baler or large square baler. In some cases, wheat straw is swathed after wheat harvest and the resulting windrow is then baled. In rare instances a windrow merging/raking step is added to the harvest process to increase baler productivity. Few studies have been found where wheat straw has been harvested for energy. The studies that were found were focused on soil erosion concerns regarding the harvest of crop residues, not harvesting costs (Nelson, 2002; Larson, 1979).

Two purpose-grown energy crops considered in the 2005 BTS are Switchgrass and Energy Sorghum. Switchgrass is expected to provide a large percentage of biomass for bioenergy (Perlack et al., 2005; Perlack et al., 2011; Langholtz et al., 2016). Switchgrass has been used as animal forage for many years and can be harvested like many other forage crops. Many forage crops are harvested by swathing the crop, using a rake or windrow merger to merge

windrows, and then baled with a large round or large square baler. There have been few large-scale studies of harvesting switchgrass for bioenergy (Mitchell, 2012). Energy sorghum is an annual crop that can be grown as an alternative to switchgrass, a perennial crop. The advantage of sorghum over switchgrass is that it allows producers greater flexibility in the crops they can produce on their land (Perlack et al., 2011; Mitchell, 2016). Sorghum yields can be greater than switchgrass, but require more input costs to grow because the crop must be planted each year. Harvesting costs for both, Switchgrass and Energy Sorghum are based on conventional haying equipment and harvest techniques used for animal forage (Perlack et al., 2011). Improvements in bale density and bale collection equipment could reduce harvest costs for these materials (Perlack., 2002; Perlack et al., 2005).

The volume of biomass that must be harvested to meet energy needs of the billion ton study is much larger than those commonly harvested amounts of corn stover, wheat straw, and forage crops. Harvesting costs for these materials are regularly estimated based on producer interviews, harvest procedure assumptions, test plot data, and published custom harvesting rates (Sokhansanj, 2002). Costs and values used in the 2011 BTS update rely heavily on these costing methods. The most conservative cost estimates were used so as to not understate costs. Test plot data has been singled out as overstating actual yields and are regularly discounted by 20% so as to not overstate yields (Langholtz et al., 2016). The 2005 BTS, among other studies, called for the development of specialized biomass harvest equipment for crop residues and energy crops to better handle the larger volumes of materials that must be harvested (Perlack et al., 2005; Sokhansanj, 2002). Studies also advocate for field scale trials to develop accurate harvest and logistic cost data for use in planning models such as IBSAL (Perlack et al., 2005; Sokhansanj, 2002).

The 2008 AGCO project, funded by the DOE, facilitated the design and development of purpose built biomass harvesting equipment for harvesting corn stover, wheat straw, switchgrass and energy sorghum (USDOE, 2009). The project also funded field scale trials of the newly developed harvest equipment. The five year AGCO project resulted in the development of new pieces of equipment and modifications to existing forage harvesting machines for harvesting crop residues and purpose grown biomass crops. Some of the major advancements resulting from this project were the development of balers designed to be towed by combines, modifications to combines in order that they collect more crop residues for the towed balers, development of high density large square balers, development of high volume biomass swather headers, and self-strapping bale transport trailers (personal communication Maynard Herron Engineering Manager Hay Tools, December 7, 2017). Field scale tests using this equipment were conducted to validate the developed equipment and collect relevant data for harvesting biomass crops. Field scale tests were conducted in 2010, 2011 and 2012 on corn stover and wheat straw using conventional harvesting equipment and methods (two-pass harvesting) and the newly developed equipment (single pass harvesting) for harvesting these residues. Field scale tests were conducted in 2011 and 2012 on the harvest of switchgrass and energy sorghum using the equipment modified for harvesting these crops for energy. Relevant harvesting data (fuel usage, harvesting time, quantities of material harvested, material moisture content, and machines used) was collected for all field scale tests. The field data collected by AGCO during the course of their project was not analyzed nor was the data been published at the completion of the project. AGCO was unable to justify devoting engineering resources to analyze the data at that time (personal communication Maynard Herron, Engineering Manager Hay Tools AGCO, June 2013).

Accurate biomass supply models are necessary for producers and biorefineries to determine prices for biomass feedstocks (Langholtz et al., 2016). The IBSAL model is used by these stakeholders to analyze costs as they build supply chains for the biorefineries that will be needed to supply bioenergy to consumers. The IBSAL model is currently based on published harvesting estimates and test plot data for existing forage harvesting equipment. The IBSAL model, and those stakeholders who use it, would benefit greatly if it was updated using field scale data for equipment specifically designed and built for the harvest of biomass (Sokhansanj, 2011).

There have been two updates to the 2005 BTS: Billion Ton Study Update 2011 (Perlack et al., 2011) and the Billion Ton Report in 2016 (Langholtz et al., 2016). These studies have further outlined the available quantities of different biomass feedstocks, geographic location of the feedstocks and updated the estimated harvest costs of biomass materials. These harvesting costs have been based upon existing price indices for conventional forage harvesting equipment as costs from purpose built biomass harvesting equipment has not been available (Langholtz et al., 2016).

The three different Billion Ton Studies examined different scenarios of biomass availability. All three studies considered scenarios where biomass availability increases. Biomass yield increases are expected to be similar to increases in grain yields (Perlack et al., 2005). Biomass harvest yields are also expected to increase as better collection equipment is developed (Perlack et al., 2005). Conversely, other studies, some dating to the 1970's, raise concerns regarding the amount of biomass that can be sustainably harvested annually (Larson, 1978; Conservations, March 2010). The amount of biomass actually harvested, known as a "take rate", may vary greatly from the estimated amounts of biomass available. Sustainable "take

rates” from agricultural lands may also vary from year to year, field to field and even within fields due to soil nutrient, carbon levels, and erosion concerns (Langholtz et al., 2016). The literature, when taken as a whole, indicates wide variability in annual biomass “take rates”. This variability will affect many aspects of the biomass supply chain. One particular area of concern is harvest costs. As harvesting “take rates” vary so too do the costs of harvesting biomass crops (Perlack et al., 2011). This cost variability may make some harvest “take rates” economically unfeasible and others that may appear unreasonable, feasible. Models, such as IBSAL, can be used to provide producers with guidance for when it is economically reasonable to either harvest or refrain from harvesting biomass.

It is known that the availability of biomass is correlated to the price paid for the biomass (Perlack et al., 2011). The economics of a producer supplying biomass, profits, will also affect the supply of biomass (Wilhelm, 2010). Producers, who are not familiar with their harvesting costs, may collect biomass residues at economically unsustainable rates resulting in financial losses. These losses will ultimately reduce the supply of biomass available to biorefineries. A biorefinery, which represents many million dollars of investment, could potentially lose its supply of biomass as a result of financial losses by their suppliers (producers). Harvesting cost analysis, based on field data and purpose-built biomass harvesting equipment, has been lacking for planners, producers and biorefineries too use (Langholtz et al., 2016). Such information is crucial to producers to as they consider whether or not to harvest biomass. Companies looking to locate a biorefinery need this information to determine if a supply of biomass in a given region could be economically feasible to harvest year in and year out. Accurate models, such as IBSAL, that predict harvest costs based actual field data have been lacking. These models are

crucial to the development of the biomass supply. The analysis of the AGCO field data and updates to the IBSAL model based on this data meet this need.

1.5 Experimental Plan

The following steps have been taken to complete this project.

1. The field data sets supplied by AGCO were analyzed for completeness, accuracy, and usefulness. Data sets that were missing datum points, had improbable datum points, were for extremely small field sizes, or excessive harvest rates were discarded. Data sets that were deemed useful were tagged with an alpha numeric label for tracking and then analyzed.
2. Machine data for the various pieces of equipment used for the AGCO project were collected and organized for use in this analysis. The data collected were machine specifications and retail costs.
3. Operational costs for each machine were developed for all machines used for the AGCO project. These costs are based on American Society of Agricultural and Biological Engineer (ASABE) standards EP496 and D497.
4. Excel spreadsheets were developed to calculate harvest costs for crop residues and energy crops using field data sets. The resulting cost were analyzed with respect to yield/take rate variation, harvest moisture content of the biomass, bale density, swath widths, field speed, and harvest method (single-pass vs two-pass for example).
5. The results of the analysis were used to create a modified IBSAL model that approximated the AGCO results. The modified IBSAL model was then used to explore a wide range of yield, bale, machine, fuel and labor cost that effect biomass harvesting

costs. The analysis of these results were used to develop strategies to minimize the effect of year to year variability common to the harvesting of crop residues and energy crops.

6. Based on the modified IBSAL model a decision tool for producers to determine whether or not to harvest crop residues was developed. This tool considers harvest system options, distance from biorefinery, crop residue “take rate”, and nutrient replacement costs in the decision tool.

1.6 Data Analysis

AGCO collected biomass harvest data for three years (2010, 2011 and 2012) from locations in Southwest Kansas, northwest Missouri and northwest Iowa. The collected data is for the harvest of crops residues (corn stover and wheat straw) and energy crops (switchgrass and energy sorghum). The AGCO harvest data for these crop years, harvest locations, and biomass crops were analyzed in this project.

The field data collected is specific to a location, crop type, and area harvested. Each specific data set that was found usable was assigned an alphanumeric tracking label. A data set usually consisted of number of hectares harvested, crop harvested, moisture content of harvested biomass, location, number of bales produced, weight of each bale, time to harvest, model(s) and sizes of machine(s) used, and fuel consumed to harvest the given area. The data was provided in a variety of forms that ranged from Excel spreadsheets that simply listed different data sets in table form to *.csv files that were read from machine ISOBUS/ CANBUS systems. As the data was collected by technicians that were charged with many tasks beyond just collecting biomass harvest data, some data sets were found to be incomplete. An effort was made to salvage certain data sets where a single datum point was missing and it was reasonable to make a calculation to fill in the missing data point. Where a missing data is calculated, ASABE machinery

management standards S495, EP496 and D497 were used. In cases where data sets were missing too many datum points to be considered credible, the data set was discarded. When calculations were used to fill in a missing datum point, the calculated item and data set was flagged and evaluated for accuracy by comparison to collected complete data sets. Most often, the missing datum was the fuel usage for a given area harvested. The ASABE EP496 outlines a procedure for calculating fuel usage based on machine parameters, crop type, and harvest rate. This procedure was used to replace the missing fuel usage data.

The Excel spreadsheets developed to analyze the harvest data were based on ASABE machinery management standards. These machinery management standards provide basic guidance and calculations for owner ship costs of equipment such as depreciation, insurance, storage, maintenance and repair. These spreadsheets were used to calculate the harvesting costs on a dry Mg basis for each data set collected for each of the crops harvested in the AGCO study.

1.7 Adjusting IBSAL Model to reflect calculated harvest costs

The data collected from the AGCO's High Tonnage Feedstock project was intended to provide field scale data to be used to better understand the cost to produce biomass for biorefineries. One of the tools to understand the cost of biomass harvesting over a range of variables is the IBSAL model. The conventional IBSAL model for single pass crop residue harvesting was modified to replicate the collected field data. This replication was accomplished by first using a log-log regression function within EXCEL to create a representative best fit curve for the analyzed field data. Through an iterative process, the IBSAL model was then modified to produces a curve that approximates the regression curve based on the collected field data.

1.8 IBSAL Modeling

The IBSAL model was developed to provide researchers, policy makers, and producers a tool to analyze the biomass supply chain (Biomass and Bioenergy Research Group, 2009). The model is constructed within ExtendSim simulation software (Imagine That Inc., San Jose, California). Within the IBSAL model, individual blocks representing different machines or steps within the biomass supply chain have been created. An example of one of these blocks is shown in Figure 1.2.

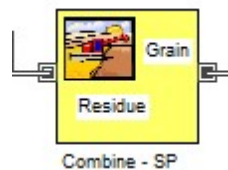


Figure 1.2 Example model block

Each IBSAL model block contains data tables and programming steps, which are depicted graphically, as shown in Figure 1.3 that will provide calculated results for the machine or step that the block represents. For the purpose of this analysis, the data tables within select blocks will be modified to reflect the AGCO project machine performance results.

Chapter 2 Analysis and Comparison of Crop Residues Using Single-Pass and Two-Pass Harvesting Methods

2.1 Introduction

In 2005, the report titled “*Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (generally referred to as the *Billion Ton Study*” or (2005 BTS) was published by the United States Department of Energy (DOE). The goal of this report was to develop harvest technologies that have the potential to replace about 30% of the petroleum based fuels with renewable fuels from agricultural sourced biomass for biofuels. Agricultural crop residues were considered to be a major portion of the billion ton supply of biomass that would be required to reach this goal. The report indicated that crop residue harvesting costs could be reduced because the harvesting methods for these feedstocks were not well established or poorly defined (Perlack, 2002). It was believed that advanced harvest equipment could reduce the cost of crop residue harvesting (Sokhansanj, 2003), especially for the crop residues corn stover and wheat straw.

In 2008, the DOE awarded five feedstock development grants to develop the harvesting methods for some of the biomass feedstocks outlined in the 2005 BTS and other studies. AGCO’s Hesston, Kansas division was one of the awardees of a development grant. Their project was titled “*Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to supply Crop Residues and A Herbaceous Energy Crops in a Diversified Large Square Bale Format*” (AGCO project). This project was intended to develop specialized equipment for biomass harvest focusing on crop residues such as corn stover and wheat straw and then conduct field scale tests of the developed equipment. The field scale tests provided actual harvest field data using the newly developed residue harvesting equipment. This

research project is a part of AGCO's original project and focuses on development of biomass harvest cost information using the data collected by AGCO (Herron, 2013).

In the field tests, single-pass and two-pass harvesting methods were studied and compared. It was believed that a single pass harvest system, where the combine tows a large square baler (LSB), would be a more economical way to harvest crop residues than traditional multi pass methods (Perlack, 2002).

The Objective of this research was to analyze the corn stover and wheat straw harvest data from the AGCO project and develop harvest cost information. The biomass harvesting costs, in \$/dry Mg, was calculated based on labor time investment, fuel inputs, and equipment (depreciation and wear) necessary to gather and deliver harvested biomass to the field's edge in the form of a large square bale.

2.2 Materials and Methods

2.2.1 Collected Data

In 2010, 2011 and 2012 AGCO collected field scale harvest data for collecting corn stover and wheat straw in Southwest Kansas, and northwest Iowa. Data was collected for two types of crop residue harvesting methods: two-pass harvesting and single-pass harvesting. The block diagrams in Figure 2.1 depicts the two harvesting methods considered in the AGCO project.

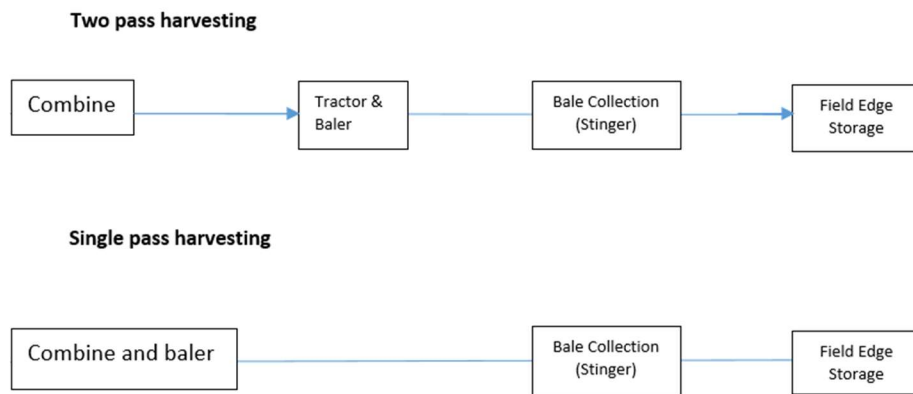


Figure 2.1 Two-pass vs Single-pass harvest system block diagrams

The AGCO two-pass harvesting system harvests standing corn or wheat residue without the combine stock chopper engaged thereby windrowing the residue behind the combine. Then the crop residue is baled in a second pass with a tractor and baler. The “take rate”, or amount of residue collected, with this method of harvesting is dependent upon how the combine header and baler pickup are set. The single-pass harvesting system consists of a towed baler with a custom built feed that collects and bales all residue that comes off the combine separation unit. The “take rate” for this harvesting method is dependent upon the setting of the combine header. In the case of corn, a corn head can be set to take only a portion of the plant (often all that is above

the ear), nearly all of the plant, or only the ear and husk. The small grain platform used for harvesting wheat can be set to take varying amounts of the wheat plant, by adjusting the height of cut of the header. The height of cut is usually set by the operator of the combine.

The two-pass method used by AGCO in this project is the simplest possible method, beyond single-pass harvesting that can be used to bale agricultural crop residues. However, it is not the only possible method used by producers to collect crop residues. There are several other methods of residue baling that are sometimes also called “two-pass” harvesting. These other residue harvesting methods add an additional stock shredder, windrower, rake or combination shredder and rake step between the combine pass and the baling pass (Sokhansanj, 2002; Khanna, 2016). This method of harvesting is also called “two-pass” because two passes, a shredder/windrower/rake step and baling step are used to collect the residue. The amount of residue harvested with these versions of two-pass harvesting are dependent upon how the shredder/windrower/rake are set. These versions of residue harvesting increases the amount of residue that can be collected as well as contaminates. AGCO did not harvest any residue using these methods and they are not included in this analysis.

The data supplied by AGCO was somewhat limited. Twenty-seven data sets for corn stover spanning three harvest years were supplied. Of these corn stover harvest data sets, only 21 were found to be usable. For wheat straw, only seven data sets from the 2011 harvest season were supplied. Of these data sets, only four were found to be useable.

The equipment used in the field scale tests to harvest crop residues is shown in Table 2-1. All of the equipment, save for the large square balers used were stock, commercial units. There were three sizes of corn head used in the tests, an eight row, twelve row, and sixteen row heads. The head sizes increased the swath width that the baler harvested in both the single and two-pass

harvesting methods. An eight row head resulted in the baler bale a windrow formed from a 6.1m swathe of corn. A twelve row head resulted in the baler baling a windrow formed from a 9.1m swathe of corn. The sixteen row head resulted in a baler swathe width of 12.2m. Unfortunately, none of the sixteen row head harvest data was found to be usable and was not included in any of the analysis.

Table 2-1 Equipment used to harvest crop residues

Machine	Model	Rated power	Working Width	Crop Used	Notes	Season Used
Combine	Challenger 560C	343 KW	9.1 m	Wheat	Harvesting	Summer '11
Combine	Challenger 560C	343 KW	8 ,12, or 16 row 6.1, 9.1 or 18.2 m	Corn Stover	Harvesting	Fall '10, '11, '12
Large Sq. Baler	LB34B	Na	na	Corn Stover	Towed by MF 8670	Fall '10, '11, '12
Large Sq. Baler	LB34B	Na	na	Corn Stover	Towed by Combine	Fall '10, '11, '12; Summer '11
Tractor	Massy 7499	164 KW	na	Corn Stover	Towed LB34B baler	Fall '11
Tractor	Massy 8650	179 KW	na	Wheat Straw	Towed LB34B baler	Summer '11
Tractor	Massy 8670	186 KW	na	Corn Stover	Towed LB34B baler	Fall '10
Bale Collector	Stinger 6500	227 KW	na	All	Picking up Bales	Summer/Fall '11

2.2.2 Data Analysis

The collected data can be broken down as follows:

Corn Stover

- Single-pass harvesting system using a combine and baler combination to bale the biomass. A Stinger bale collector was used to collect bales and move them to the field edge.
 - Two different header widths were used to harvest the corn 8 and 12 row corn heads (6.1m and 9.1m widths respectively)
- Two-pass harvesting system using a tractor and baler combination to bale the biomass that is left windrowed behind a combine harvester. A Stinger bale collector was used to collect bales and move them to the field edge.
 - The width of the header was not recorded but believed to have been an 8 row corn head (6.1m wide)

Wheat Straw

- Single pass harvesting using a combine and baler combination to bale the biomass and Stinger bale collector to collect bales and move them to the field edge.
 - 9.1m header width was used.
- Two-pass harvesting using a tractor and baler combination to bale the biomass that is left windrowed behind a combine harvester and Stinger bale collector to collect bales and move them to the field edge.
 - 9.1m header width was used to create windrows

The data was supplied in sets specific to a location, machine types and size, crop type, and area harvested. Each specific data set was assigned an alphanumeric tracking label. A

single data set consisted of crop harvested, location, number of hectares harvested, moisture content of harvested biomass, number of bales produced, weight of each bale, time to harvest, model(s) and sizes of machine(s) used, and fuel consumed to harvest the given area. The data is supplied in a variety of forms that ranged from Excel spreadsheets that simply listed different data sets in table form to *.csv files that were read from machine ISOBUS/ CANBUS systems. The data was collected by test technicians that were charged with many tasks beyond just collecting biomass harvest data, therefore some data sets were incomplete. An effort was made to salvage some data sets where a single datum was missing from the set and it was reasonable to make a calculation to fill in the missing information. ASABE machinery management standards S495, EP496 and D497 were used to calculate the missing information when this was done. In cases where data sets were missing too many datum, the data set was discarded. When calculations were used to fill in a missing datum point, the calculated item and data set were flagged and evaluated for accuracy by comparison to collected complete data sets. Most often, the datum point that was missing was the fuel usage for a given area harvested. The ASABE EP496 outlines a procedure for calculating fuel usage based on machine parameters, crop type, and harvest rate. When appropriate, this procedure was used to salvage a data set.

Excel spreadsheets were developed to analyze the harvest data. They were based on current ASABE machinery management standards S495, EP496 and D497. These machinery management standards provide basic guidance and calculations for owner ship costs of equipment such as depreciation, insurance, storage, maintenance and repair. These spreadsheets were used to calculate the harvesting costs on a dry Mg basis for each data set collected for each of the crops harvested in the AGCO study.

2.2.3 Assumptions

Machine costs can vary considerably based on the amount a given machine is used in a years' time. Machine cost are generally reported in dollars per hour of usage. Machines with low amounts of usage are more expensive to operate per hour than high usage machines. The relationship of annual usage to cost is a nonlinear, inverse power curve, which means that at low usage rates, machine cost can change significantly with small changes in annual usage (Herron, 2013). Actual annual machine usage values are difficult to obtain (personal communication Dr. Terry Griffin, Assistant Prof. Kansas State University, 2018). For the purpose of the newly developed residue collection equipment tested in the AGCO project, annual usage values can only be estimated. For this work, machine usage hours were based on ASABE D497 Agricultural Machinery Management Data for machine life. The hours used for machine cost calculations are shown in Table 2-2. The hours listed are similar to base case studies found in other work. (Sokhansanj, 2002).

Table 2-2 Machine usage assumptions

Machine	Typical Annual Machine usage
Swather	600
Tractor-56 Kw	1200
Tractor-186 Kw	1200
Combine	700
Baler	600
Rake	600
Bale Mover (Stinger)	1000

The assumption is made that all machines are considered to be one year old, have been properly cared for and regularly serviced per manufacture recommendations. While it is unlikely

that any operation will have a mix of equipment of this age, it is a stretch to make an assumption beyond this for any operation. Further, there was no attempt to consider costs based off of used or reconditioned machines. Making reasonable assumptions about what these machine costs might be are beyond the scope of this effort.

Labor assumptions were based on American Agricultural Economist Association assumptions as described in the USDA-NRCS Commodity Costs and Returns Estimation Handbook. A labor rate of \$16.93 per hour is used where machine operator labor costs need to be included. This is the mean labor rate is for the Agricultural Equipment Operator job classification in Iowa (BLS, 2018). Iowa was chosen because a large percentage of the data collected for harvesting corn stover was collected in this state.

No profits are considered in this analysis. Owners of any type of operation will have to have a profit in order to remain in business. However, the amount of profit required will vary dramatically based on each operation's whole farm profit strategy. One operation may consider biomass harvesting a cost of grain production similar to a tillage pass to reduce the amount of crop residue in the field. Such an operation may only wish to cover machine and labor costs for resources that would otherwise be idle. Another farming operation may consider biomass harvest as a core activity and expect to generate significant profits from the biomass harvest.

Allocating combine costs to the baling operation

A major consideration for this work was how to allocate combine costs for single pass residue harvesting. The assumption was made that only the incremental increase of the combine's operational cost should be carried forward to the baling operation of the crop residue, since the combine would travel through the field to harvest the crop regardless of residue harvesting. Therefore the assumption was made that only increases in fuel used, operational

time, and labor would be applied to the baling operation in the single pass harvesting scenario. It was expected that labor and harvest time would increase for the combine operation during single pass harvesting. Interestingly, there was not any conclusive evidence that the baling operation increased the time to harvest any crop. An example of the data collected for the harvest times for wheat straw and corn stover harvesting are shown in the Figure 2.1 below. This figure compares the harvesting rate of the different crops when towing or not towing a baler.

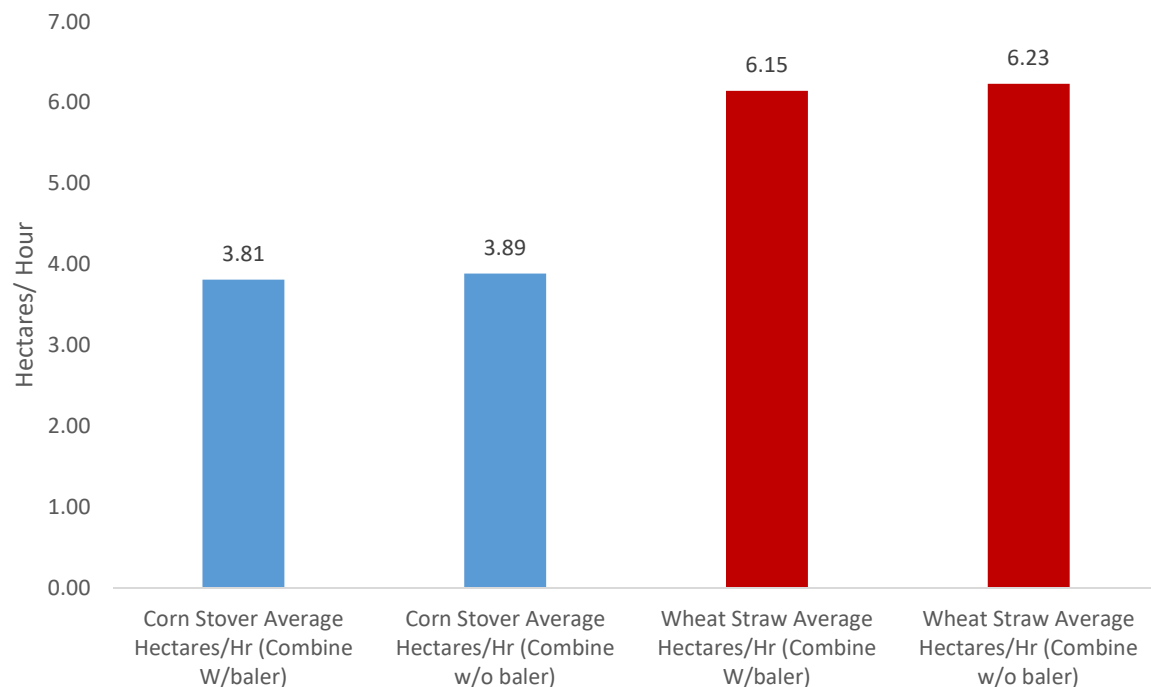


Figure 2.2 Harvesting rate comparison Single-pass vs Two-pass

The initial expectation was that there would be an increase in machine and labor time for the grain harvesting operation by adding the single-pass residue harvesting task to the grain harvesting operation. This expectation was not realized in the collected data. The comparison shown in Figure 2.2 would indicate that a combine towing a baler will only travel slightly slower than one without a baler behind it. Approximately 1-2% difference is shown in Figure 2.2 for both crop residues considered, but these values may not be reliable. While it is recognized that operator skill will influence harvester productivity (Pürfurst, 2011), in this case it is likely more

of a reflection of how the grain harvesting operation is managed. An illustration of this was that in certain individual data sets the combine towing the baler was actually more productive than a combine without a baler. The combine operators apparently tried to run the combines at maximum capacity to prove that the baler was limiting productivity. In other instances, operators would not run a combine near capacity if it meant that they would end up waiting for a grain truck when they had a full bin (Personal communication Maynard Herron, Engineering Manager Hay Tools AGCO, 2013).

Because the actual differences between one pass and two-pass harvesting rates observed were small, in the 1-2% range, it was decided for this analysis, that no combine machine or operational labor incremental costs would be transferred to the baling operation from the grain harvesting operation for the single pass baling scenario.

Incremental fuel costs were another matter and were included in the baling operation. In all single pass harvesting tests, the towed balers received its power from the combine. Any increase in the fuel usage of a combine towing a baler would be added to the cost of the baling operation.

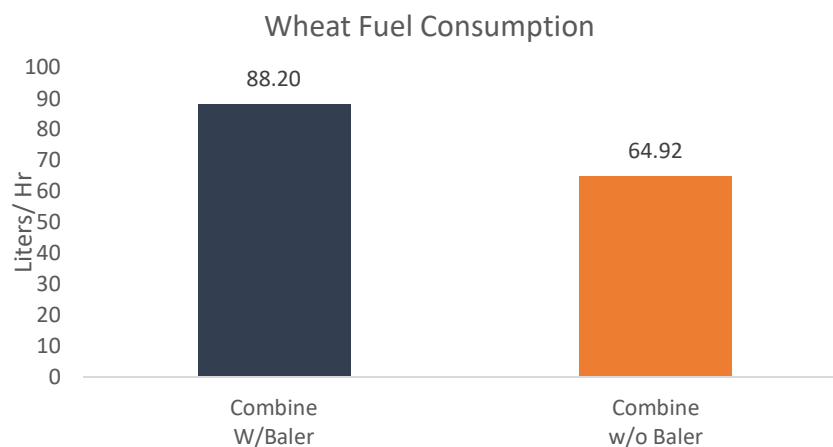


Figure 2.3 Fuel consumption harvesting comparison harvesting wheat with and without the combine towing a baler

Data collected during the wheat straw harvesting in 2011 gave a very clear indication of this incremental fuel difference, between single pass and two-pass baling. This difference is shown in the Figure 2.3 and is the basis for the decision to include incremental fuel cost in the harvesting calculations on the single pass baling operations. A similar difference in fuel usage was expected for the corn stover harvesting. However, a comparison between data points for a combine towing a baler and one that was not could not be made because of missing data in the provided data sets.

For the single pass harvesting system, the towed baler received all power necessary to perform the baling function from the towing combine. Since it was impossible to measure the extra fuel required for baling, the incremental fuel increase required for towing and powering the baler was calculated by following ASABE Standards EP496 and D497. It should be noted, that the data within D497 is dated and in need of updating (Personal communication Dr. Randy Taylor, Professor Oklahoma State University, July 18, 2017).

Once the bale was dropped in the field from either the single or two-pass harvesting operation a second machine was used to collect the bale and move it to the field edge into a temporary stack. A Stinger model 6500 Stacker bale stacker was used to collect the large square bales and move them to the field edge. Data for the collection operation was collected in the same fields as the single and two-pass data, often collecting bales from both harvesting operations in a single data set. The results for this operation are shown in Table 2-3. The collection costs, fuel usage and labor requirements are included in all values reported in Table 2-4 and Table 2-5 for corn stover and wheat straw harvest costs.

Table 2-3 Bale Collection Data from Stinger 6500

Harvest Year	Data set label	Crop	Field Size hectares	Quan. Harvested d. Mg	Cost at Field Edge \$/d. Mg	Fuel Usage liter/ d. Mg	Labor hr/ d. Mg
2011	HVNA	Wheat Straw	19.10	43.18	1.18	0.371	0.017
2011	HVNB	Wheat Straw	25.70	45.85	1.47	0.412	0.021
2011	II	Corn Stover	194.00	20.05	5.08	1.548	0.073

2.3 Results and Discussion

2.3.1 Harvesting Corn Stover

There were twenty-seven data sets for corn stover. Out of this number, 21 were found to be usable. The six discarded sets were missing enough information that they were unusable. Three of the data sets that were analyzed were lacking biomass moisture content, but were otherwise complete. These data sets were analyzed as described and the results are listed in Table 2-4. The data was analyzed to find the field edge cost of the biomass, fuel usage per dry Mg and labor input per dry Mg.

Table 2-4 Results of analysis for corn stover harvest data

Harvest System	Harvest Year	Header Type	Data set label	Take Rate dry Mg/ Ha	Field Size Hectare	Stover Moisture Content %	Biomass Cost at field edge \$/dry Mg	Fuel Usage liter/ dry Mg	Labor hours/ dry Mg
Single Pass Harvesting	2010	8 row	EBA10	1.52	33.43	30.3%	15.59	1.80	0.07
	2010	8 row	EBB10*	1.91	11.17	17.5%	13.66	2.15	0.07
	2010	8 row	EBC10*	1.93	20.48	0.0%	13.91	1.84	0.07
	2011	12 row	AA	0.96	5.58	53.0%	24.39	1.86	0.07
	2011	12 row	BB	0.89	25.62	59.4%	28.03	3.06	0.07
	2011	12 row	CC	1.01	5.58	57.4%	27.81	3.64	0.07
	2011	8 row	EE	1.63	3.28	57.5%	27.04	5.32	0.07
	2011	12 row	GG1	1.10	4.83	42.2%	19.59	1.89	0.07
	2011	12 row	GG2	1.04	22.46	38.3%	18.98	1.91	0.07
	2012	8 row	EMTBG1	11.46	25.74	17.0%	8.09	1.70	0.07
	2012	8 row	EMTBG3	4.73	5.26	17.0%	10.93	3.07	0.07
	2012	8 row	EMTBG4	4.75	2.10	17.2%	9.20	3.72	0.07
	2012	8 row	EMTBG5	5.41	2.39	17.1%	11.02	2.46	0.07
	2012	8 row	EMTBG6	4.59	3.60	17.1%	10.30	2.00	0.07
	2012	8 row	EMTBG7	4.09	9.27	17.1%	12.15	2.38	0.07
Two-Pass Harvesting	2010	8 row	EBD10*	1.97	29.95	0.00%	13.56	3.96	0.13
	2010	8 row	EBE10*	1.84	61.11	0.00%	16.25	4.45	0.15
	2011	8 row	JJ	2.50	17.40	9.26%	11.93	3.25	0.11
	2011	12 row	KK	1.18	25.70	8.27%	15.37	3.48	0.15
	2011	8 row	LL	2.46	31.16	8.67%	13.15	2.98	0.13
	2011	8 row	MM	2.46	40.47	8.58%	12.60	2.90	0.12

* Assuming 4552 kg/ha corn (180 bu/acre)

The 21 data sets that were provided contained some variability in several different aspects of each set. Some of the most noticeable variations were year to year (weather conditions during the growing season), corn head widths (8 row vs 12 row), moisture content of the stover, and collection take rates. These variations are very representative of production agriculture and provide a very realistic view of results that a producer might see season to season, farm to farm.

Over the three years of the project when data was taken, there was a large shift in weather patterns during the growing seasons. There were periods of excess rain fall and periods of drought which severely affected several locations where AGCO conducted field tests. The year to year weather variability does not directly appear in the data collected. It possibly affected the chosen “take rates” and the moisture contents at which the stover was harvested.

The size of the corn head used to harvest corn was based on the machines available for harvest at the different locations in the different years. The different sizes of corn heads should effect the productivity of both the grain harvesting and the stover harvesting operations. The larger sized corn heads should improve productivity and decrease costs for both single and two-pass harvesting. The balers in both types of harvesting would be working off of a larger swathe of crop and therefore have greater throughput, which should reduce harvesting costs. However, a closer look at the results show that some of the most costly stover to harvest was harvested with 12 row corn heads. The increased productivity, and corresponding cost reduction, that would be expected with the larger corn head is not shown in these results. In this case, the variability in “take rate” and stover moisture content more than offset the productivity gains a larger corn head could provide. Larger “take rates” will spread costs over more material and reduce the per Mg cost to harvest stover. Increased moisture content will increase baling and handling costs through the handling of water in the stover. Moisture will also change the biomass properties and have some effect on the energy to compress stover into a bale. These moisture related costs would be in addition to crop loss due to spoilage that might be seen during storage of the stover.

There are not any apparent trends that can be seen in the results when viewed in table format. A plot of the Field Edge Cost of Biomass vs Yield “take rate” from Table 2-4, shown in

Figure 2.4, provides a better depiction of the results. Trend lines for single pass and two-pass harvest data have been added.

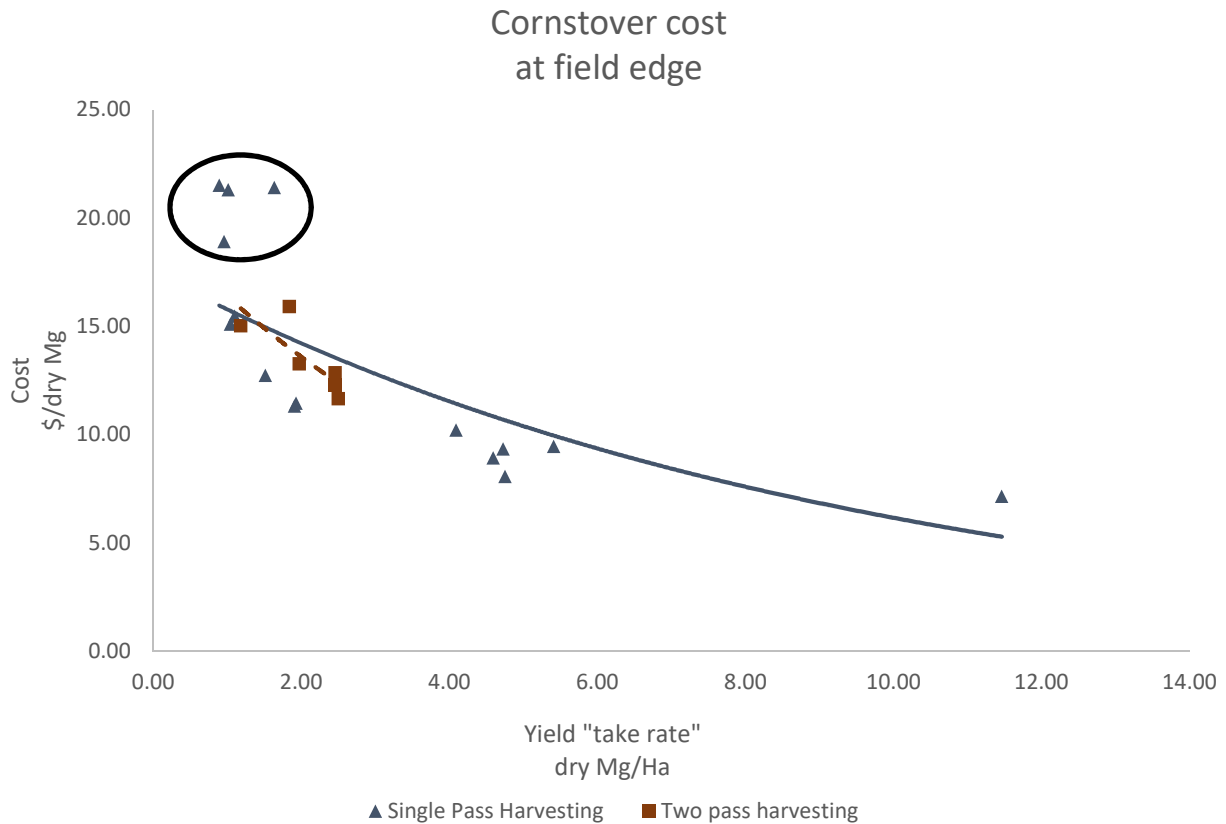


Figure 2.4 Plot of data from Table 2-4

The plotted data points and trend lines for the two different stover harvest systems seem to show little difference or gain in single-pass harvesting over two-pass harvesting. Considering that it requires an extra operator and tractor to harvest stover in two-passes, the data represented in this plot do not seem probable. On closer inspection there is a group of data points, which are circled in Figure 2.4 that are skewing the trend lines. Upon further investigation, this group of points correspond to harvest data for corn stover harvested above 30% moisture content. All of the two-pass harvest data points are for stover harvested below 10% moisture content, which is almost half the moisture content of the remaining single-pass harvesting data. Replotting the

data with the higher moisture content data points removed, as shown in Figure 2.5, show that single-pass harvesting is more slightly less costly or equal in cost when compared to two-pass harvesting.

The effect of stover moisture content on harvesting cost, and downstream storage losses due to spoilage, cannot be under stated. It does add to the cost of harvesting and spoilage losses can be significant if stover is baled at high moisture contents. These two factors will add an additional management decision to corn harvest. Corn grain in the ear dries faster, at almost two times the rate, than the rest of the plant (stover) (Huang, 2012). Producers may need to consider stover moisture content as an additional limiting factor for choosing when to harvest like they consider grain moisture content.

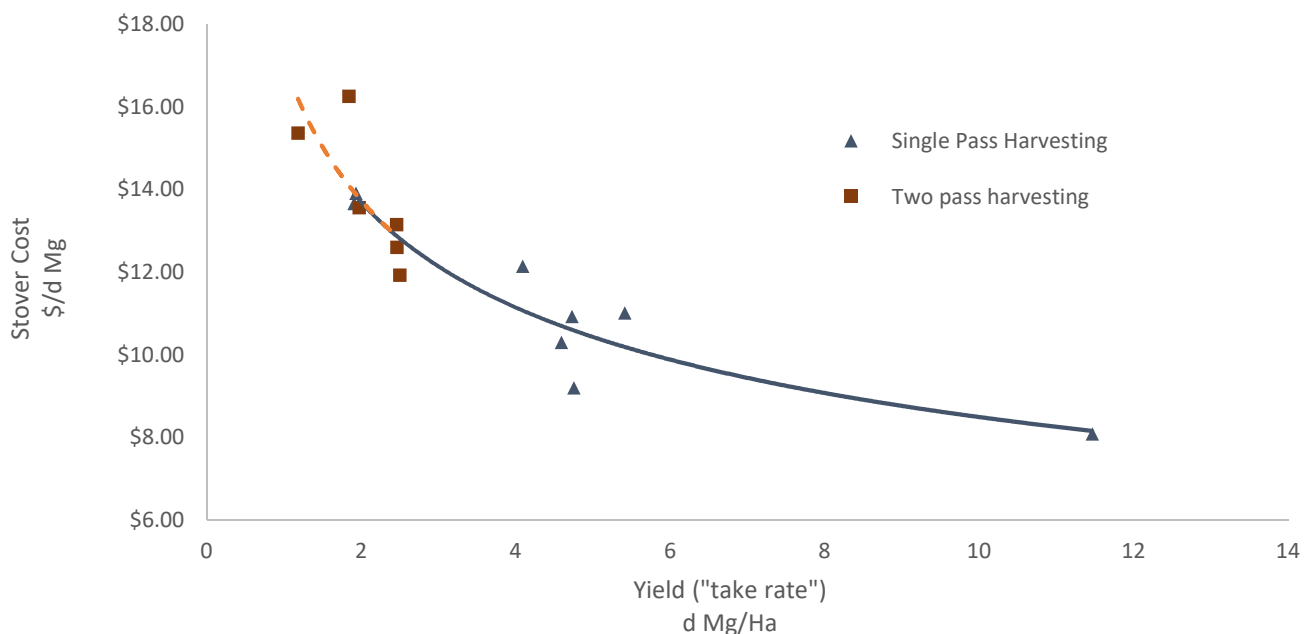


Figure 2.5 Table2-4 data plotted without stover harvested at M.C. greater than 50%.

With the high moisture single-pass stover harvest data points removed, as shown in Figure 2.5, single-pass stover harvesting is shown to be slightly less or equal in cost as two-pass harvesting. This result was not predicted in the reviewed literature (Perlack, 2002; Sokhansanj, 2003). The literature expected the cost to be much less. After looking more closely at the remaining field data shown in Figure 2.5, the two-pass stover was harvested at about 9% moisture content, compared to 17% moisture content in the single-pass stover, or almost half the moisture content. This difference in moisture content between the two data sets plays a role in this result. Further, the data for the two-pass harvesting was for “take rates” less than the single-pass “take-rates”. Since the generated curves for each data set are only valid for the range of the collected data, there is an amount of uncertainty in overlapping and comparing the curves outside their respective data ranges.

Single-pass harvesting should be more economical than two-pass harvesting because equipment and labor costs for a two-pass operation by nature are higher than a single-pass operation. For the single-pass operation, only the cost of the baler is applied to the baling operation as noted previously. In the two-pass harvest operation, at minimum there is an additional piece of equipment required, a tractor, and an additional operator, the tractor driver. Both of these items, along with the baler, are dedicated to the biomass harvest operation. Unlike the single-pass harvest operation where a separate tractor and driver are NOT required to operate the baler. A comparison of the equipment costs for the two harvest methods are shown in Figure 2.6.

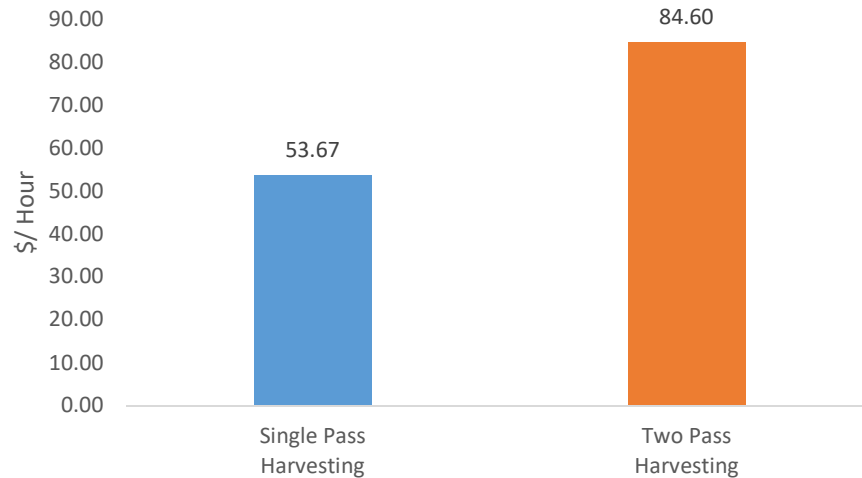


Figure 2.6 Equipment Cost Comparison Single-pass harvesting vs Two-pass Harvesting

Single-pass harvesting also enjoys a small fuel consumption advantage over two-pass harvesting. This advantage can be explained in that it is unnecessary to provide power to move a 9,100 kg tractor through the field on a separate pass to perform the baling operation. Only the extra fuel needed to power the baler and move it through the field is necessary for the baling operation in single-pass harvesting system. The difference in fuel usage is shown in Figure 2.7.

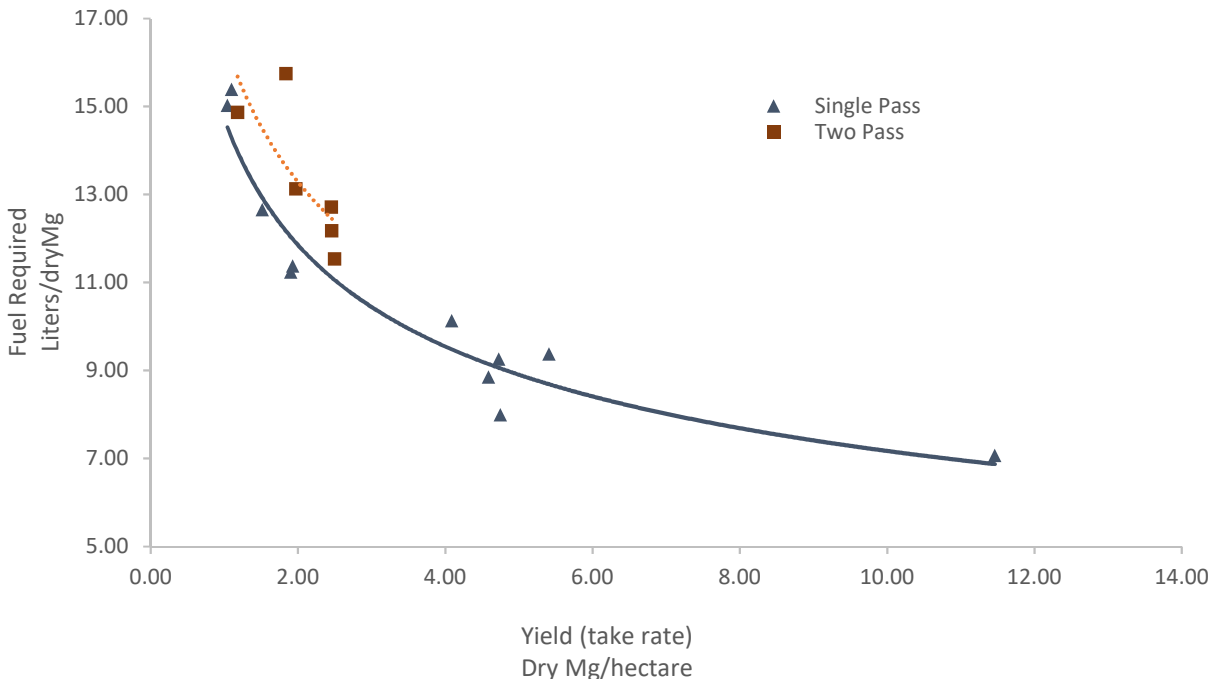


Figure 2.7 Comparison of Fuel Consumption Two-Pass Harvesting vs. Single Pass Harvesting

For this comparison, when fuel costs are averaged, there is a 37% fuel savings per dry Mg with the single-pass harvest method over two-pass harvesting. As shown in Figure 2.7, and would be expected, there is some variability to fuel usage from data point to data point for both single- and two-pass harvesting. The minor variability is due mostly to field conditions and regular variations in harvest operations. The larger variability shown is due to crop conditions. The two highest single pass data points shown in Figure 2.7, are for higher moisture content stover.

Single-pass harvesting also reduces the labor investment necessary harvest the stover compared to the two-pass harvesting method. A plot of the labor required, as shown in Figure 2.8, illustrates this. The labor requirement shown for single pass harvesting is that which is required to move bales to the field edge. There is not any extra labor required by the combine

driver to accomplish the baling task. All the labor of the tractor driver in the two-pass system is invested in the harvest of the biomass.

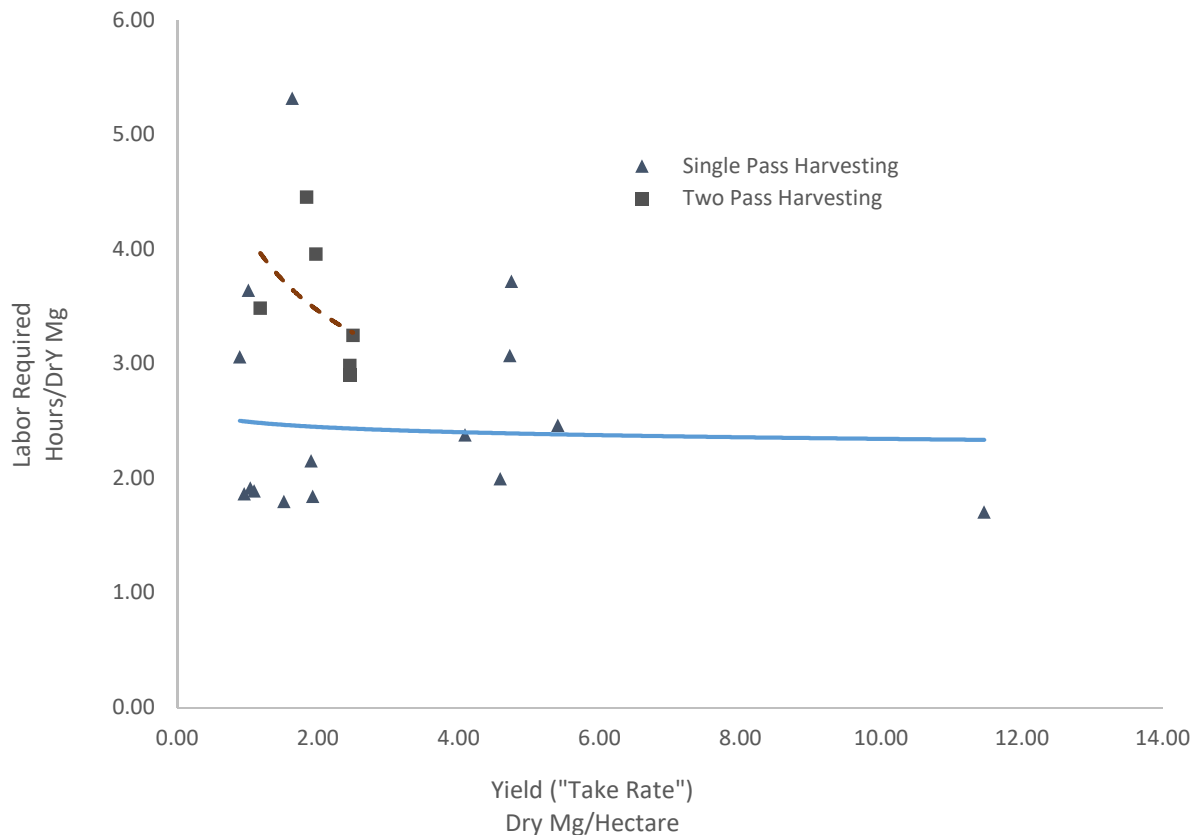


Figure 2.8 Labor Input Comparison Two-Pass Harvesting vs. Single-Pass Harvesting

Harvest labor is one aspect that will need extra consideration and ultimately education of custom operators and producers if single-pass harvesting is to be adopted over two-pass harvesting. Custom operators and producers generally are short of labor capacity at harvest time. This shortage of labor would advocate for the adoption of single-pass harvesting of the biomass because of the smaller labor cost. However, the labor cost savings is at the expense of an additional task that is required of the combine operator. The operation of the combine can be an intense operation that can require an operator to monitor many different aspects of the combine's operation. Adding an additional process for the combine operator to monitor may be met with

resistance from producers and combine operators. Automated operation of the baler and many of the operator tasks in combine operations (auto steer and automated header controls for example) could be used to offset these concerns.

Comparing the actual input of labor into the collection of corn stover, single-pass harvesting is significantly less. As shown in Figure 2.8, the labor required for single-pass harvesting is generally only that required to move bales to the field edge. Two-pass harvesting requires an additional operator, the driver of the tractor to tow the baler through the field, and therefore requires more labor.

One cost that is not considered in this analysis, and was not captured in the collected field data, is machine setup for field operation. Typically a combine is brought to the field for harvest minus the header, due to the width of the header and road width constraints. An amount of time is required to attach the header to the combine before the grain harvesting operation can begin. The addition of a baler to the harvester will require an additional item, the baler, to be towed to the field and then attached to the combine. The baler may be towed behind the combine or towed by a separate vehicle. If towed by the combine, very minimal extra cost will be incurred. If towed by a separate vehicle, then an additional cost for harvesting stover would be incurred. Further, a baler is a similarly complex machine as a combine. It will require an amount of service to prepare it for field operation (inspect machine, grease as required, make adjustments, and replenish twine stores). The addition of a baler to the harvest process would have a small cost effect when considering large harvest fields where setup costs could be spread over larger hectares and collected biomass Mg's. On smaller fields, this cost could be of greater concern.

2.3.2 Harvesting Wheat Straw

Wheat straw harvesting data was from 2011 from testing at Haven, Kansas was supplied for analysis. AGCO did conduct straw harvest testing in 2010, but the data was not supplied for analysis (Herron et al., 2013). Additional wheat straw collection data was to be collected at other sites, but due to a severe drought in Texas, it was only possible to collect data in Kansas (Herron et al., 2013). The data that was collected was limited to four usable sets: two single-pass harvesting data points, one-2 pass harvesting data point and a control, no straw harvest data point. The cost to harvest wheat straw is summarized in Table 2-5. For the single-pass straw harvesting system, a baler was towed behind the combine, baling all material ejected from the separation portion of the combine. Chaff and fines from the cleaning unit were not collected. For the two-pass harvesting system, the straw chopper/spreader was unhooked and moved aside in order to create a windrow behind the combine. The straw was baled in a second pass by a tractor towing a baler. No additional raking or windrowing pass was used to prepare the straw for baling as is sometimes used for collecting wheat straw. For both the single and two-pass harvesting methods, the baler was powered by the towing machine.

Table 2-5 Resulting values for wheat straw harvesting

Harvest System	Harvest Year	Header Type Platform Size	Data Set Label	Take Rate d. Mg/Ha	Field Size Hectare	Straw Moisture Content %	Biomass Cost at	Fuel Usage Liter/d. Mg	Labor Hr./ d. Mg
							field edge \$/d. Mg		
Single-Pass Harvesting	2011	9.1 m	AAW	4.06	3.12	6.62%	4.20	1.11	0.02
	2011	9.1 m	BBW	3.47	3.84	9.22%	2.39	1.30	0.02
Two-Pass Harvesting	2011	9.1 m	2AA	2.71	8.42	8.41%	6.44	3.18	0.06
Control Harvesting	2011	9.1 m	CWW	na	4.01	8.41%	na	na	na

Because of the limited data sets, it is difficult to draw significant conclusions from the straw harvesting data analysis. A simple comparison of the average field edge wheat straw harvest cost of the single-pass harvesting system (\$3.29/Mg) to the single two-pass harvest result (\$6.44/Mg), would indicate that single-pass harvesting is significantly less costly than two-pass harvesting. Fuel and labor inputs per dry Mg for the single-pass wheat straw harvest was also shown to be less than the two-pass method.

2.4 Conclusions

Field scale tests of advanced agricultural residue harvest equipment was conducted by AGCO Corp. The data was analyzed and the following conclusions can be drawn from the results.

1. Single-pass harvesting was shown to be less fuel intensive, and require less labor investment than two-pass harvesting on a per dry Mg basis. This appears to be consistent between corn stover and wheat straw.
2. Single-pass harvesting was not shown to be conclusively less costly than two-pass harvesting, though the fuel use and labor requirement results would seem to indicate that it is less costly.
3. Single pass harvesting equipment does not appear to affect the rate (speed) of harvest significantly. The results show only minor effect on harvesting rates from towing a baler and there is some indication operator actions may have had a large influence on these results.
4. Moisture content of the crop residues can increase harvest costs significantly. These cost increases can be significant enough to offset productivity gains from advanced harvest equipment and other harvest equipment features. Crop residues should be harvested at lower moisture contents to reduce harvesting costs.
5. The “take rate” or amount of residue collected effects the cost of the residue harvest. Larger “take rates” are more economical to harvest than smaller “take rates”.

Chapter 3 Analysis of Harvest Data for Switchgrass and Energy Sorghum as Energy Crops

3.1 Introduction

In the 2005 report, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (generally referred to as the *Billion Ton Study* or 2005 BTS) was published. The report explored if there was enough biomass in the United States to displace 30% of the nation's petroleum consumption. It is estimated that a billion tons of biomass is needed to offset 30% of the United States' petroleum consumption. The 2005 BTS identified agricultural energy crops as a source of biomass that could be developed over time. Switchgrass, miscanthus, and energy sorghum were some of the major crops that were identified as biomass sources that could be developed. The study noted that these crops did not have established collection methods that were specifically intended for their harvest, but used the same harvest systems as those used for collecting hay and forages for animal feed. It was assumed in the 2005 BTS that any necessary harvest methods needed to collect biomass would be developed as needed. Any costs that were considered in the 2005 BTS were based on existing harvest cost values available at that time, which were the published custom harvest rates for hay and forage crops.

Studies indicate that there are several areas of opportunity to reduce biomass harvesting costs. **Reducing harvesting steps, increased bale densities, wider harvest widths, and higher speed tractors are some of the hypothesized methods of reducing harvesting costs (Sokhansanj et al., 2003).** It was also noted that bioenergy feedstocks are more abrasive, and handled in much larger quantities, than conventional forages. It is believed that these feedstocks would cause greater wear on conventional forage harvest equipment compared to normal forage

crops. It is anticipated that equipment used to harvest and handle bioenergy crops would need to be designed to be more durable to handle the rigors of harvesting bioenergy crops (Sokhansanj, 2003).

In 2008, the DOE awarded 5 feedstock development grants to develop the feasibility of harvesting the bioenergy crops outlined in the 2005 BTS and other studies. AGCO's Hesston, Kansas division was one of the awardees of a development grant to develop equipment and conduct field scale experiments. Their project was titled "*Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to supply Crop Residues and A Herbaceous Energy Crops in a Diversified Large Square Bale Format*". This project focused on the harvest and collection of crop residues (corn stover and wheat straw) and purpose grown energy crops (switchgrass and energy sorghum). The project's intent was to answer many of the questions outlined in the BTS and challenges summarized from other published papers written in the early 2000's (Sokhansanj, 2003; Perlack et al., 2005).

As a result of work on the project, AGCO developed harvesting equipment and techniques specifically for harvesting switchgrass and energy sorghum for biomass. Large square balers that would achieve higher bale densities were a major development from the project. **Increased bale densities were one advance expected to reduce biomass harvest costs (Sokhansanj, 2003).** Besides developing harvesting equipment, AGCO conducted field scale production and harvest tests of the equipment harvesting switchgrass and energy sorghum. These field scale test resulted in the collection of harvest data for these crops to verify anticipated harvesting cost savings projected in earlier papers (Perlack et al., 2002; Sokhansanj, 2003).

The Objective of this research project was to analyze the collected field scale harvest data for switchgrass and energy sorghum generated by the AGCO project. The biomass

harvesting cost, in \$/dry Mg, was calculated based on labor, fuel, and equipment (depreciation and wear) investments necessary to gather and deliver harvested biomass to the field's edge.

3.2 Materials and Methods

3.2.1 Collected Data

In 2011 and 2012 field scale harvest data was collected for collecting energy sorghum and switchgrass near Camden Point, MO. As part of the 2008 Project, land had been leased and converted from traditional production agriculture to the production of these energy crops. The fields were of varied size, shape, and terrain. Switchgrass was planted in 2010 on several fields and harvested in 2011 and 2012. The heavy rains in 2010 and early 2011 created a number of ephemeral gullies that made these fields very rough in places. On other leased fields, energy sorghum was planted and harvested in 2011 and 2012. The fields of energy sorghum and switchgrass were located either side by side or within a few miles of each other. This colocation of test fields provides a good comparison between yields and harvesting costs between the two crops.

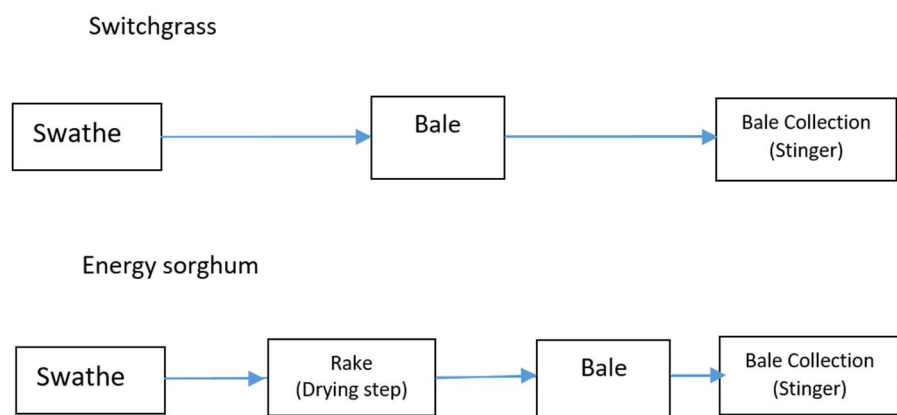


Figure 3.1 Harvest steps for Switchgrass and Energy Sorghum

The block diagrams in Figure 3.1 depicts the two different harvesting systems used for harvesting the two energy crops. The switchgrass harvest consisted of three steps: swathe, bale, and bale collection. The energy sorghum harvest consisted of four steps: swathe, rake, bale and bale collection. The raking step was the only difference between the harvesting systems for the two different crops. The equipment for the harvest of both crops was the same. In 2012, the harvest of both crops was nearly simultaneous with machines moving between fields of different crops on the same day. The equipment used to harvest the biomass crops at Camden Point, MO is shown in Table 3-1. Most of the equipment listed was used to harvest both crops. Different models of some machines were used in different years. The swather, tractors, baler, and bale collector used for switchgrass was also used for energy sorghum. The rake was the only piece of equipment used on energy sorghum not used for harvesting switchgrass.

Table 3-1 Equipment used to harvest switch grass and energy sorghum at Camden Point, MO.

Machine	Model	Rated power	Working Width	Crop Used	Notes	Season Used
Swather	MF 9635	142 Kw	3.9m Header	Sorghum/ Switchgrass		Fall '11
Swather	MF WR9770	164 Kw	3.9m Header	Sorghum/ Switchgrass	GPS set swath width 3.7m	Fall '12
Rake	Fella 1502		6.1m	Sorghum	Towed by MT445B	Fall '11 & '12
Tractor	Challenger MT445B	60 Kw	na	Sorghum	Towed Fella Rake	Fall '11 & '12
Large Sq. Baler	MF 2170 XD	NA	na	Sorghum/ Switchgrass	Towed by MF 8670	Fall '11 & '12
Tractor	MF 8670	186 Kw	na	Sorghum/ Switchgrass	Towed 2170XD Baler	Fall '11 & '12
Bale Collector	Stinger 6500	227 Kw	na	All	Picking up Bales	Fall '11 & '12

The raking step is the main difference between the harvest of switchgrass and energy sorghum. Switchgrass can be harvested at any point from late summer of a growing season to

just before the beginning of the growing season the following year. Ideally, for the maintenance of established switch grass stands, the conservation of nutrients, and the removal of compounds that can foul downstream process equipment, it is desirable to delay the harvest of switchgrass until six weeks after the first freeze. After freezing, the plant is allowed to dry to a point where it contains less than 20% moisture content and nitrogen and carbohydrates have had a chance to return to the root system for plant growth the following year (Mitchell, 2012). The crop is then harvested. Since the crop has dried down by this time, it can be baled directly behind the swather. A raking step would only be used in the harvest of switchgrass if a rain event occurred between the time that the crop was windrowed and could be baled or if the crop was extremely light and combining several windrows would improve the productivity of the baling step.

Energy sorghum, in contrast, requires a raking step. The crop is harvested after maturity and at or before the first freeze. The crop is a tall, high moisture, high yielding species that will not dry down on its own standing in the field. It is typically swathed wet, often at a moisture content near 70% (Zegada-Lizarazu, 2012), and dried in the windrow after swathing. The swathing process, besides windrowing the crop in preparation for baling, also conditions it to improve dry down (Savoie et al., 2002). The conditioning aspect of the swathing process cracks the exterior waxy layer of the plant which allows the moisture within the plant to escape more easily and speed drying (Bonner, 2012). The high yield of the crop results in windrows that are thick and heavy. Therefore, a raking pass is required to turn the windrow over and expose the crop on the underside of the windrow to sun and wind in order to finish drying the crop out. The drying step can take several days to accomplish and can, depending on weather conditions, require multiple rakings. This happened during the 2011 energy sorghum harvest at Camden Point, MO. During drying, on certain fields, rain events occurred requiring the crop to be turned

multiple times. One or more of the fields were initially windrowed in late October. Baling of these fields did not occur until early December. Baling was delayed because of rain events interspersed throughout the month of November (Herron, 2013).

3.2.2 Data Analysis

The data supplied for analysis was in sets specific to a location, machine type and size, crop type, and area harvested. Each specific data set was assigned an alphanumeric tracking label. A single data set consists of crop harvested, location, number of hectares harvested, moisture content of harvested biomass, number of bales produced, average weight of bales, time to harvest, model(s) and sizes of machine(s) used, and fuel consumed to harvest the given area. The data was supplied in a variety of forms that ranged from Excel spreadsheets that simply listed different data sets in table form to *.csv files that were read from machine ISOBUS/CANBUS systems. The data was collected by test technicians that were charged with many tasks beyond just collecting biomass harvest data, therefore some data sets were incomplete. An effort was made to salvage certain data sets where a single datum is missing from the set and it is reasonable to make a calculation to fill in the missing information. ASABE machinery management standards S495, EP496 and D497 were used to calculate the missing information when this was done. In cases where data sets were missing too many datum, the data set was discarded. When calculations were used to fill in a missing datum point, the calculated item and data set was flagged and evaluated for accuracy by comparison to collected complete data sets. Most often, the datum point that was missing in a given data set was the fuel usage for a given area harvested. The ASABE EP496 outlines a procedure for calculating fuel usage based on machine parameters, crop type, and harvest rate. This procedure was used to calculate missing fuel usage data.

The data was analyzed using spreadsheets. The calculations within the spreadsheets were based on current ASABE machinery management standards. These machinery management standards provide basic guidance and calculations for owner ship costs of equipment such as depreciation, insurance, storage, maintenance and repair. These spreadsheets were used to calculate the harvesting costs on a dry Mg basis for each data set collected for the switchgrass and energy sorghum.

3.2.3 Assumptions

Machine costs can vary considerably based on the amount a given machine is used in a years' time. Machine cost are generally reported in dollars per hour of usage. Machines with low amounts of usage are more expensive to operate per hour than high usage machines. The relationship of annual usage to cost is a nonlinear, inverse power curve, which means that at low usage rates, machine cost can change significantly with small changes in annual usage (Herron, 2013). Actual annual machine usage values are difficult to obtain (personal communication Dr. Terry Griffin, Assistant Prof. Kansas State University, 2018). For the equipment modified specifically for the harvest of biomass, the annual usage of a machine can only be estimated. Since the harvesting of switchgrass and energy sorghum is very similar to forage crops, annual usages of similarly built forage harvesting equipment was used. Machine usage hours were based on ASABE D497 Agricultural Machinery Management Data for machine life and AAEA assumptions. The hours used for machine cost calculations are shown in Table 3-2.

Table 3-2 Machine usage assumptions

Machine	Typical Machine Usage (in hours)
Swather	600
Tractor—56kW	1200
Tractor—142kW	1200
Baler	600
Rake	600
Bale Mover (Stinger)	1000

The assumption was made that all machines used to harvest biomass crops are one year old, have been properly cared for, and serviced accordingly. While it is unlikely that any operation will have a mix of equipment that is all one year old, it is unreasonable to make any assumption beyond that. Further, there was no attempt to consider costs based off of used or reconditioned machines. Making reasonable assumptions about what machine costs for used equipment might be beyond the scope of this effort.

A labor rate of \$16.93 per hour was used where machine operator labor costs need to be included. This is the mean labor rate is for the Agricultural Equipment Operator job classification in Iowa (BLS, 2018). Iowa was chosen because it is representative of the agricultural region that the switchgrass and energy sorghum were grown and harvested.

No profits are considered in this analysis. Owners of any type of operation will have to have a profit in order to remain in business. However, the amount of profit required will vary dramatically based on each operation's business strategy.

Bale collection and movement to the field edge was completed by a Stinger 6500 bale mover. Only three sets of data for the movement of energy sorghum bales from three different

fields were found to be usable. One data series for switchgrass was taken, but was found to be lacking too much information to be useable. The usable data and analysis results are shown in Table 3-3.

Table 3-3 Bale Collection Data from Stinger 6500

Harvest Year	Data set label	Crop	Field Size	Quan. Harvested	Number Bales	Cost at Field Edge	Fuel Usage	Labor
			hectares	Mg		\$/d Mg	liter/d mg	hrs/d Mg
2011	ECA11	Energy Sorghum	1.13	13.36	30	1.75	0.510	0.026
2011	ECB11	Energy Sorghum	1.90	24.31	54	1.80	0.420	0.028
2011	ECC11	Energy Sorghum	3.08	49.36	88	1.53	0.314	0.025

The results for the movement of bales off of the three fields shown in Table 3-3 were averaged and applied to both switchgrass and sorghum fields for the purpose of developing a field edge cost for the harvested biomass. This assumption was made because the fields were of similar terrain, field sizes, and soil conditions. An average value of \$1.69 per Mg to deliver switchgrass and energy cane biomass to the field edge was used where no reliable bale moving data was available. The three data series shown in Table 3-3 do correspond to other field data sets (swathing, raking, and baling) for some energy sorghum data points. In these instances the corresponding data for moving the biomass to the field edge is used in calculating the harvesting cost of the biomass for that particular data set.

3.3 Results and Discussion

The results of the data analysis for the 13 usable data series are shown in Table 3-4. There were seven usable data sets for energy sorghum and six usable sets for switchgrass. The usable data spans two crop years which had very different growing and harvest seasons. The different growing seasons produced very different crop yields, which in turn affected the harvest costs for each crop. The harvest season weather challenges also affected the cost of harvest as well by influencing harvest timing and steps.

The results shown in Table 3-4 include the costs for swathing, raking (for energy cane only), baling, and bale collection. One raking pass is assumed for each energy sorghum data set. It was reported that some of the 2011 energy cane fields were raked more than once, but the number of extra rakings were not noted in the provided data, so only one raking pass has been included in the table results.

Table 3-4 AGCO Data analysis results for energy crops

Crop	Harvest Year	Data set label	Yield (d.Mg/ha)	Field Size Hectare	Stover Moisture Content %	Biomass Cost at field edge (\$/d. Mg)	Fuel Usage (liters/d mg)	Labor (hrs/d.Mg)
Energy Sorghum	2012	SG12A	7.33	4.00	58.61%	12.07	113.27	0.14
	2012	SG12B	8.71	6.36	58.61%	10.87	104.38	0.12
	2012	SG12C	5.20	1.76	58.61%	14.57	120.28	0.18
	2012	SG12D	6.02	2.65	58.61%	15.07	107.78	0.17
	2011	ECA11	11.79	1.13	31.25%	9.66	117.61	0.11
	2011	ECB11	12.78	1.90	36.51%	9.50	103.42	0.11
	2011	ECC11	16.05	3.08	22.22%	6.92	90.58	0.08
Switchgrass	2012	SW12E	9.16	7.73	18.76%	11.14	93.29	0.10
	2012	SW12F	10.55	2.63	19.66%	8.69	89.35	0.09
	2012	SW12G	6.81	2.27	22.14%	14.22	95.93	0.13
	2011	SGAA11	5.79	2.78	18.90%	11.50	94.38	0.11
	2011	SGBB11	7.09	2.67	18.90%	10.01	93.32	0.10
	2011	SGCC11	5.10	4.65	18.90%	10.47	96.09	0.10

3.3.1 Harvesting Energy Sorghum

Sorghum harvesting data was collected for 2011 and 2012 crop years as shown in Table 3-4. The crop yield for the two years averaged 10.18 Mg/ha with collection costs averaging \$11.24 per dry Mg. On average 3.62 liters of diesel fuel was required to harvest and move a dry Mg of sorghum to the field edge. Labor required to harvest a dry Mg of sorghum averaged 0.13 hours (about 8 minutes per dry Mg) over the two years. The harvesting cost averages are broken apart in Table 3-5. This shows that baling accounts for the largest percent of cost and fuel required. Labor is almost nearly equally distributed between each step of the harvesting process. Swathing is the second largest harvesting cost and requires the second largest fuel requirement. Raking is shown as being the least costly part of harvesting energy sorghum. However, this is assuming that only one raking pass is required to dry the sorghum for baling.

Table 3-5 Average costs to harvest energy sorghum

Sorghum						
Operation	\$/dt	Percent cost	Fuel (liters/dt)	Fuel %	Labor (hrs/dt)	Labor %
Swathing Cost	3.02	26.9%	1.20	33.3%	0.031	24.1%
Raking Costs	1.42	12.7%	0.32	8.8%	0.035	27.0%
Baling Costs	5.10	45.4%	1.68	46.5%	0.037	28.7%
Collection Costs	1.70	15.1%	0.41	11.5%	0.026	20.1%
Averages/d Mg	11.24	100.0%	3.62		0.130	

These average results make sense in that the highest costs and fuel inputs are from the two steps that require some of the most expensive machines and require large energy inputs to be accomplished. The collection step does require an expensive machine, but fuel and labor inputs are relatively low. The raking step is the least costly, but is somewhat labor intensive. However, if multiple raking passes are required, raking will become a major cost very quickly. A single

raking pass will add about 12% to the cost of a dry Mg of sorghum biomass and 27% to the labor requirement as shown in Table 3-6.

Table 3-6 Harvest costs with two raking passes.

Sorghum (2 raking passes)						
Operation	\$/d Mg	Percent cost	Fuel (liters/d mg)	Fuel %	Labor (hrs/d Mg)	Labor %
Swathing Cost	3.02	23.9%	1.20	30.6%	0.031	19.0%
Raking Costs	2.84	22.4%	0.64	16.2%	0.070	42.5%
Baling Costs	5.10	40.3%	1.68	42.7%	0.037	22.6%
Collection Costs	1.70	13.4%	0.41	10.5%	0.026	15.9%
Averages/d Mg	12.65	100.0%	3.94		0.165	
Percent increase	12.6%		8.9%		27.0%	

The raking step was assumed to be only one pass that occurred just before baling. It was reported that one, unidentified field of energy sorghum was raked multiple times in 2012 (Personal communication Maynard Herron, Engineering Manager Hay Tools AGCO, 2013). The amount of raking required to harvest energy sorghum will vary based on weather and crop conditions. Raking has the potential of having a high amount variability and need from year to year and field to field. The maturity of the crop, weather conditions, and crop yield can all effect the amount of raking that might be required to harvest a given field. Drying time of the crop can be influenced by moisture content of the plant when it is swathed, the humidity during dry down, the amount of sunshine, length of daylight, and amount of wind will all influence the time required for crop dry down. Rain or snow events can add moisture back into the crop further lengthening the drying time. Raking is a management practice that can be used to speed the drying of the crop. In some cases, such as after rain events, it is the only way to get the crop to dry down enough that it can be baled. Energy sorghum, which is generally swathed while all or part of the crop is still green, can often take longer than two weeks to dry without turning or

raking the windrow (Bonner, 2012; Hess, 2007). Without raking to aid in dry down, some of the sorghum crop will likely spoil before it can fully dried out. A rain event will set the crop dry down process back and necessitate another raking pass. As noted, this happened multiple times to one field, which resulted in multiple raking passes before baling.

An estimation of how many times one of the test fields could have been raked between swathing and baling can be put together from historical weather data for the Camden Point, MO region in 2011. The energy sorghum fields were swathed near the end of October 2011. It was reported that some of the fields were finally baled in December 2011. Historical weather data from that area (<https://www.timeanddate.com/weather/usa/kansas-city/historic?month=11&year=2011>) indicates that 5 rain events occurred in the region during November of 2011: Nov. 2; Nov. 7, Nov. 9, Nov. 22, and Nov. 26. Two of the rain events occurred one day apart, making it highly unlikely that a raking pass was made between these events. This would leave the potential that 4 raking passes were made, one after each of the four other rain events, in an attempt to dry the crop before baling. A raking pass was calculated to cost \$1.42 per Mg of harvested dry biomass. The cost of harvesting energy sorghum from a field that required four raking passes would have increased the harvest cost of biomass of from that field by \$5.68 per dry Mg.

Crop yield can also influence the need for a raking pass. A light crop can sometimes dry without the need to rake. Air and sun can penetrate a light windrow adequately enough to dry the crop to a moisture content level that the material can be stored, generally considered to be below 20%. However, a light crop may still be require a raking step. In some instance it may be necessary to combine windrows to create large windrows that are more efficient to bale.

The two years for which the harvest data was collected at Camden Point, MO. were dramatically different with respect to crop yield. Growing conditions in each year was significantly different. Yield data for the two crop years is shown in Table 3-7. The 2011 energy sorghum crop yield was about double the 2012 crop yield due to more moisture being available to the crop during the growing season. In 2011, the average yield for the energy sorghum crop was 13.54 dry Mg/ha, while the average yield in 2012 was only 6.81 dry Mg/ha. The 2012 crop year was the beginning of a drought cycle, which is attributed to the reduced yields for energy sorghum. The yield variability between the two growing seasons resulted in wide swings in harvesting costs between the two years as illustrated in Figure 3.2. It also caused each year's harvest costs to differ substantially from the averages previously discussed. The weather during harvest in each year was also very different, which also had an effect on harvest costs. The 2011 crop was rained on a number of times after swathing, which necessitated a number of rakings of the crop to dry it out as noted previously. Again, since the number of raking steps used on each field was not recorded, only a single raking steps is included in the reported results for 2011.

Table 3-7 Yield comparison of Sorghum and Switchgrass collected data

Year	Sorghum dry Mg/Ha	Switchgrass dry Mg/Ha
2011	13.54	5.99
2012	6.81	8.84
2 year Ave.	10.177	7.416

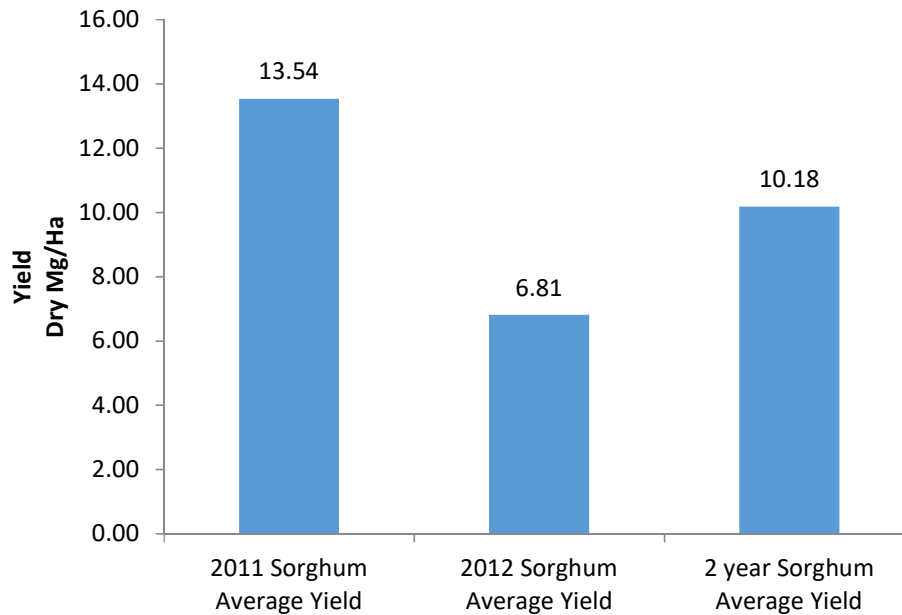


Figure 3.2 Sorghum Yield Comparison

3.3.2 Harvesting Switchgrass

Switch grass harvesting data was collected for 2011 and 2012 crop years. The crop yield varied considerably from year to year due to stand establishment and varied rain fall during the different growing season. The 2011 yield, as would be expected with switchgrass, was lower because it was the second season after planting, a time when the stand of switchgrass is still being established and a lessor yield is expected (Mitchell, 2012). The 2012 crop yield was much higher as the stand of switchgrass was close to being fully established and would have been considered to have been capable of producing close to its yield potential. Like the energy sorghum crop, the drought that was beginning in 2012 affected the switchgrass and yields were likely reduced some amount because of this. The difference in crop yields between the two growing seasons is shown in Figure 3.3.

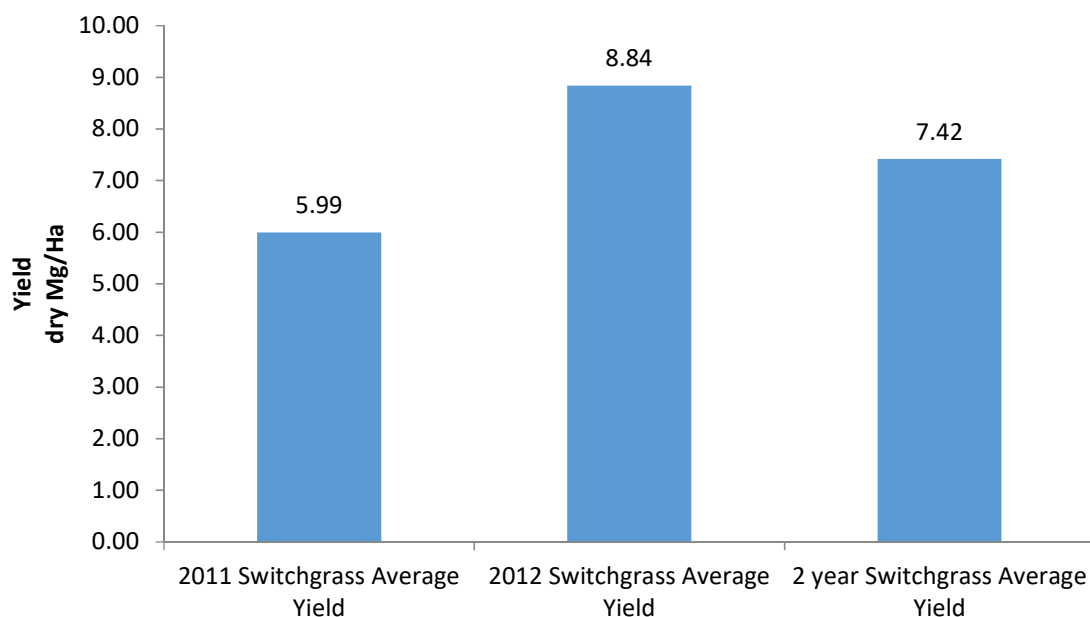


Figure 3.3 Year to Year harvest cost comparison of switchgrass

The two year average cost to harvest switchgrass is \$11.01 per dry Mg. The harvesting costs are split between swathing, baling, and bale collection. The cost for each step is shown in Table 3-8. Like energy sorghum, the bulk of the harvest cost, energy, and labor required is in the baling and swathing steps. Raking was not required before baling as the crop was dried while standing before swathing. Baling occurred directly after swathing, usually within the same day. In a few instances, the crop was baled the following day. No rain events were reported to have affected the switchgrass harvest.

Table 3-8 Switchgrass harvest costs

Switchgrass						
Cost item	\$/d Mg	Percent cost	Fuel (liters/d Mg)	Fuel %	Labor (hrs/d Mg)	Labor %
Swathing	3.33	30.3%	1.28	36.4%	0.035	33.2%
Baling	5.98	54.3%	1.83	51.8%	0.045	42.1%
Collection	1.70	15.4%	0.41	11.8%	0.026	24.7%
Ave cost/dry Mg	11.01		3.52		0.106	

Fuel required to harvest a dry Mg of switchgrass is 3.52 liters/Mg, with the largest percentage of fuel being used during the baling process. The labor required per dry Mg of switchgrass is 0.106 hours (about 6 minutes per dry Mg). Like harvest costs and fuel required, the bulk of the required labor to harvest switchgrass is in baling and swathing of the crop.

A raking step could be required in the harvest of switchgrass in some instances. Weather conditions and possibly crop conditions could require a raking step. Switchgrass is swathed after frost and the crop has dried standing in the field. However, management choices and weather conditions can dictate the need for a raking step in the harvest of switchgrass. A rain, or snow event, between swathing and baling, could necessitate the need for a raking step to dry the crop out for baling. Also, in some cases, an owner may make a management decision to swathe switchgrass before frost or the crop has fully dried while standing. This choice could be made to accommodate labor availability or weather expectations. The decision to rake will add production costs that the owner may view as justified in anticipation of crop loss charges (anticipated weather losses) or labor availabilities costs. The raking cost per dry Mg of switchgrass is anticipated to be similar to that of energy sorghum.

3.3.3 Comparison of Sorghum and Switchgrass Harvesting

As part of this analysis a comparison of the sorghum and switchgrass harvesting has been made. Both crops were harvested from adjacent fields and nearly at the same time in 2012. For the 2011 crop year, the switchgrass was harvested in January of 2012. The 2011 energy sorghum crop was harvested over several weeks from late October to early December. The timing difference between the two crop harvests was due mostly to wet weather in November 2011.

Harvesting costs were nearly the same for both crops, except for the raking step. Generally speaking, the raking step is the difference in the harvest cost for between switchgrass and energy sorghum. Crop yields were responsible for the rest of the cost difference between the two crops. Generally, if not for the raking step, energy sorghum was found to be less costly to harvest than switchgrass. Figure 3.4 is a graphical comparison and cost breakdown between the average harvest costs for these two crops.

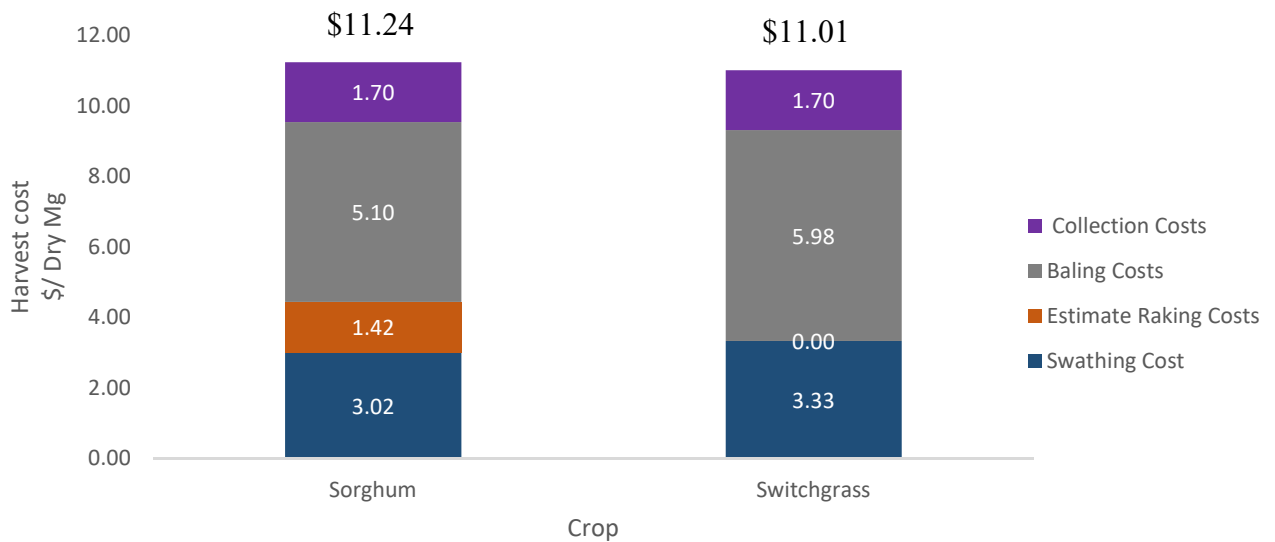


Figure 3.4 Average cost breakdown comparing sorghum and switchgrass harvesting

As shown in Figure 3.4, switchgrass is \$0.23 per Mg more economical to harvest than energy sorghum. The raking step has a large influence on the cost difference between the two

crops. Without that step, the cost of energy sorghum would be less than that of switchgrass. Switchgrass is shown to be more expensive to bale and swathe than energy sorghum. The higher cost for these two tasks for switchgrass is a function of the average yields. A higher yielding crop is more economical to swathe and bale as more biomass is present to spread equipment costs over. Looking only at the average harvest cost for switchgrass and energy sorghum is misleading. As crop yields vary, harvest costs also vary. Figure 3.5 illustrates how yields can effect harvest costs. The plotted data shown is of all the switchgrass and energy sorghum data points shown in Table 3-4. Power trend lines have been added to highlight the trends. As the yield per hectare increases, the cost to harvest energy sorghum decreases below the cost of switchgrass.

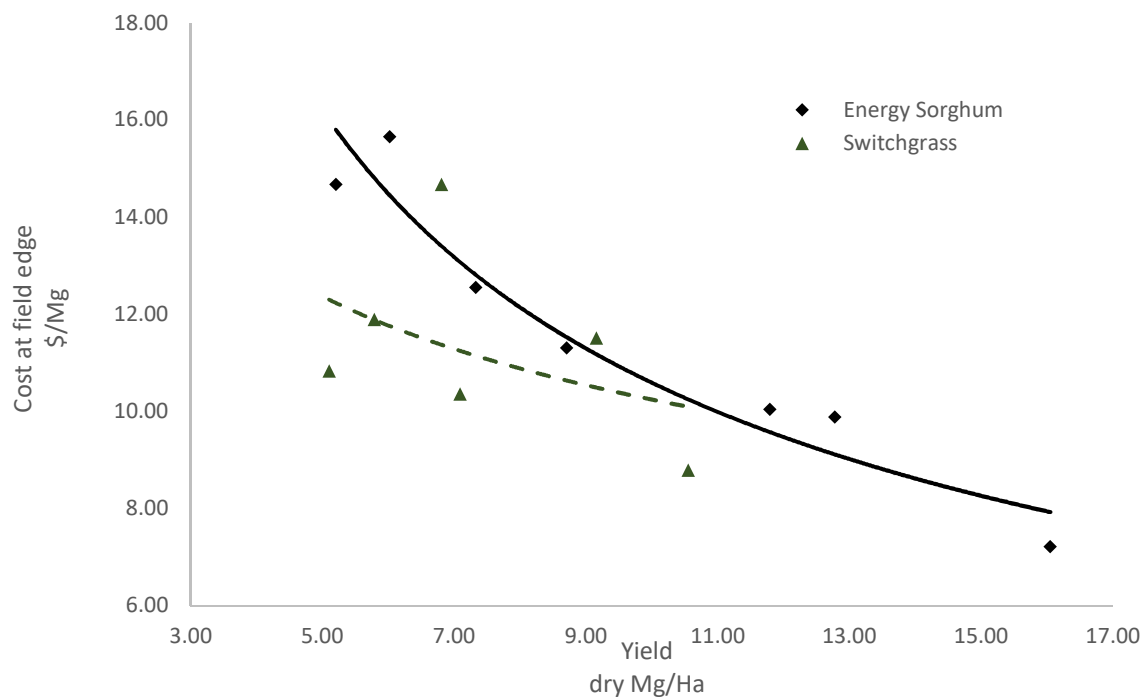


Figure 3.5 Comparison of Sorghum and Switchgrass harvest costs as yields increase.

Switchgrass will typically have an average yield potential of 5.2 to 11.1 Mg per hectare in normal dryland farming practices (Mitchell, 2016). Energy sorghum is somewhat drought tolerant and can have average yield potential above 20 Mg per hectare range in normal dryland conditions (Rooney et al., 2007). Based on these projected yields and the results from this analysis, energy sorghum could be the more economical crop to harvest. The caveat with this projection is the number of rakings a heavy energy sorghum crop could require. Only a single raking step is included in the harvesting costs shown in Table 3-4. If multiple rakings are regularly required, due to weather conditions or other reasons, then the yield cost advantage that energy sorghum has over switchgrass quickly disappears. More field scale tests over more years would provide a better understanding of this dynamic in crop profitability.

Labor and fuel requirement trends are related to yields show somewhat similar results as the overall cost comparisons. On average it requires 0.129 labor hours to bale a Mg of energy sorghum, while it only takes 0.106 labor hours to bale a Mg of switchgrass. Figure 3.6 illustrates the breakdown of the higher average labor input required to harvest energy sorghum as compared to switchgrass. Like costs, more labor is required to bale and swathe a dry Mg of switchgrass than is required to do the same tasks to energy sorghum. The higher labor requirement for these tasks is a function of crop yield. The greater yields of energy sorghum are more efficient to harvest. Again, the main reason that energy sorghum requires more labor than switchgrass is due to the raking step.

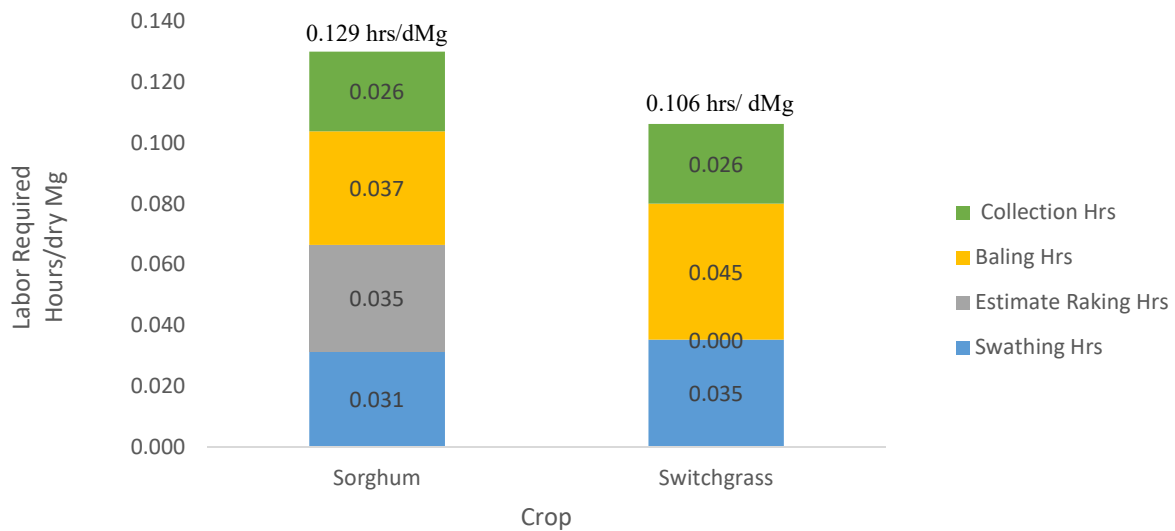


Figure 3.6 Comparison of Sorghum and Switchgrass harvest labor costs

A greater labor requirement to collect and move biomass to the field edge will remain for energy sorghum across all yields of switchgrass. It does narrow though, as shown in Figure 3.7, as yields increase to the expected maximum yield potential of switchgrass. At energy sorghum yield levels above that believed to be possible for switchgrass, the labor investment required to collect energy sorghum appears to be less than that of switchgrass. This labor prediction continues to include only a single raking pass. It is very possible at the higher yields of energy sorghum more raking passes would be required.

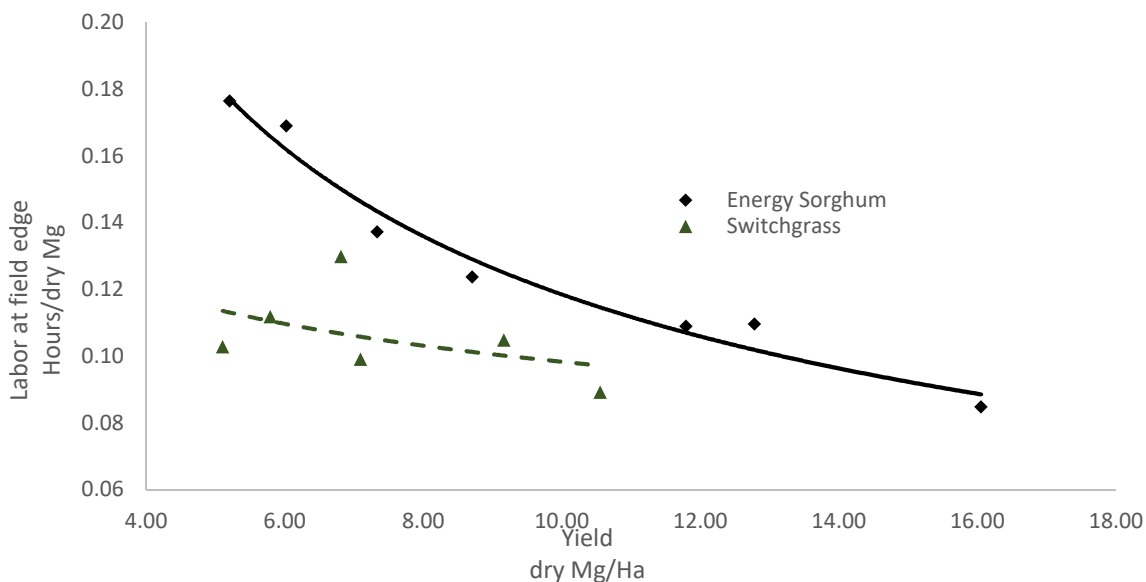


Figure 3.7 Labor investment comparison between Energy Sorghum and Switchgrass harvesting at the field edge

The fuel required for harvesting each crop is broken down in Figure 3.8. Again, like cost and labor, energy sorghum shows a greater fuel input requirement than switchgrass. Again, swathing and baling steps of the energy sorghum harvest require a little less fuel than that required for switchgrass. The raking step again offsets the reduced fuel inputs from the swathing and baling passes, making the energy sorghum harvest slightly more fuel intensive overall.

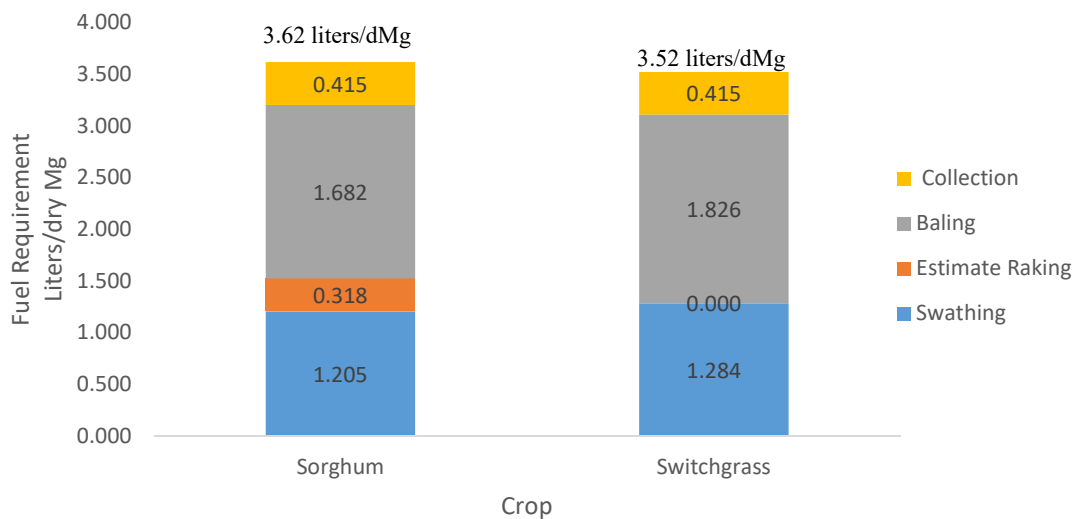


Figure 3.8 Comparison of Sorghum and Switchgrass harvest fuel costs

The higher fuel requirement for harvesting energy sorghum remains consistently above that of switchgrass at all yields levels, as shown in Figure 3.9. The trend lines show that as yields increase, the energy use premium of energy sorghum over switchgrass narrows. At yield levels above the expected maximum of switchgrass, unlike that for labor, energy sorghum fuel inputs still appear to remain higher than those for switchgrass.

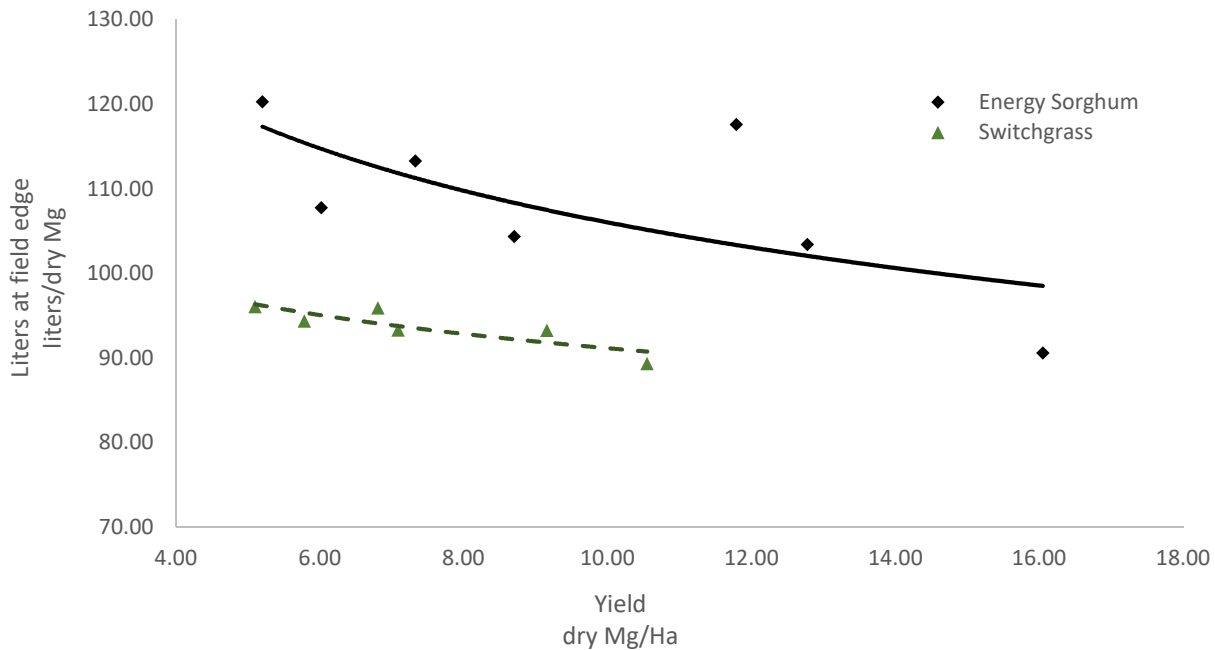


Figure 3.9 Field edge comparison of fuel requirements to harvest Energy Sorghum and Switchgrass

3.4 Conclusions

Crop yields have a significant effect on harvest costs. Greater yields spread equipment cost over more mass thereby reducing costs mass unit. A similar effect can be seen with labor and fuel inputs, but to a lesser degree. As yields increase labor and fuel requirements per dry Mg decrease.

Energy sorghum, while requiring an extra harvest step, can be more economical to harvest than switchgrass. This can only occur at yield levels equal to or above the maximum expected yield levels of switchgrass. This also assumes that only one raking pass is required prior to baling.

Energy sorghum will consistently require more fuel to harvest than switchgrass regardless of the crop yields. The amount of required labor to harvest energy sorghum can be less than that of switchgrass, but only at the highest yield levels.

The actual cost of harvesting a dry Mg of energy sorghum is highly dependent upon the number of raking passes necessary to dry the crop. An extra pass to turn a windrow over to aid in dry down of the energy sorghum can increase harvesting cost by 12%. Rain and snow events during the dry down phase of harvesting energy sorghum can dramatically increase the cost to harvest sorghum.

Year to year yield and weather variability can have large effects on crop yields and harvest costs. Producers will need to account for this variability as they consider whether to grow and harvest biomass for energy and which crop they will choose to grow.

Chapter 4 Harvest Cost Prediction using Modified Harvest Data within the IBSAL Model

4.1 Introduction

The Integrated Biomass Supply Analysis and Logistic (IBSAL) model was developed by Oak Ridge Laboratories as a tool to study the biomass supply chain. The model is based on published technical literature, accepted accounting conventions used in agriculture, and published standards of agricultural practice. **For the model to be useful by the builders of the bioeconomy, it must reflect current practices and equipment.**

In 2008, the DOE awarded 5 feedstock development grants to develop the feasibility of collecting feedstocks outlined in the 2005 BTS and other studies. AGCO's Hesston, Kansas division was one of the awardees of a development grant. Their project was titled "*Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to supply Crop Residues and A Herbaceous Energy Crops in a Diversified Large Square Bale Format*" (AGCO project). A portion of this project focused on the harvest and collection of crop residues (corn stover and wheat straw). This project was intended to develop new or modify existing equipment specifically for the harvest of biomass. The project was to go further and conduct field scale tests of the developed equipment. The field scale tests were intended to validate the value of the equipment developed. It was believed that a single pass harvest method, where the combine tows a large square baler (LSB), **would be a more economical way to harvest crop residues than traditional two-pass methods** (Perlack, 2002). In the conducted field scale testing newly developed single pass harvest equipment was shown to have reduced residue collection costs compared to traditional harvesting methods (Chapter 2).

The results of the field scale tests also would generate data that could be used for the further development of cost models that can be used to develop a biomass based bioeconomy.

The Objective of this work is to use the data collected during field scale testing to modify the IBSAL model to replicate the field scale results of the single pass crop residue

harvesting system that has been developed. This work will focus on replicating the baling of corn stover at 17% moisture content with the IBSAL model. The IBSAL model will then be compared to the extrapolated results from the field data over a common range of corn stover yield/"take rates" to compare the model over a wider range of harvest rates.

4.2 Materials and Methods

The development of the biomass to energy industry will require the construction of a large, capital extensive industry, from essentially nothing. In order to build such an industry many concerns must be overcome, adoption obstacles overcome, and large amounts of capital attracted. One of the key aspects of the biomass industry development is a steady supply of biomass from identified sources (Kenney, 2013). The collection system of the biomass supply is of particular importance because of its effect on the cost of the material. In order to study and streamline the biomass collection system, logistics models have been developed to perform these studies. The IBSAL model, which was developed by Oak Ridge National Labs (ORNL) is one of these (Sokhansanj, 2006). The IBSAL model is constructed within ExtendSim simulation software (Imagine That Inc., San Jose, California) and is available for download from the Bioenergy KDF website (bioenergykdf.net/content/ibsal). The Bioenergy KDF organization is a part of the U.S. Department of Energy (DOE) and is the repository of extensive amount of data and information regarding biomass availability in the U.S. The IBSAL model can be used or

modified by researchers, planners, and producers with a copy of ExtendSim software. The model is intended to be used to explore and study aspects of the biomass supply chain.



Figure 4.1 IBSAL main model dashboard

The complete IBSAL model as download from the KDF website, and represented by Figure 4.1, is made up of many different sub models that represent different methods of biomass collection for different biomass crops. Each of the sub models that represent the different biomass collection systems are constructed of blocks that represent each step of that particular biomass collection process. The purpose of this work is to replicate the single pass crop residue harvesting system within the IBSAL model in order to provide users of the IBSAL model with a more accurate representation of actual biomass harvest results.

The specific model used in this work is a subset of the downloadable model shown in Figure 4.1. This model, shown in Figure 4.2, is a simplified version of the overall IBSAL model specifically for single pass crop residue harvesting. There is less to this model compared to the downloadable model, which better lends itself to the needs of this project. This specific model was provided to the author by Dr. Shahab Sokhansanj in 2015 for the purposes of this work.

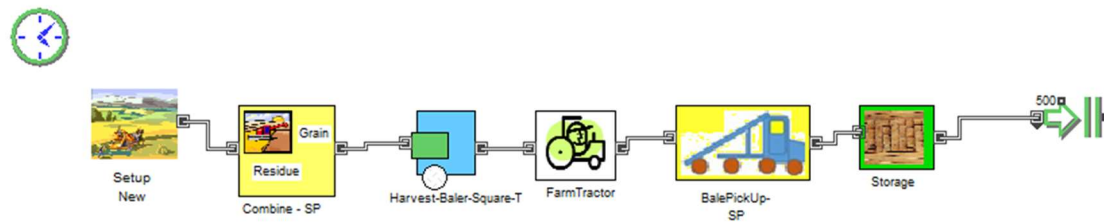


Figure 4.2 ExtendSim IBSAL model for single-pass crop residue harvesting

The model shown in Figure 4.2 can calculate costs, fuel use, labor and machine time requirements, biomass losses, and carbon emissions for the harvest of crop residues. For this work, only labor costs, harvesting costs, and fuel usage will be investigated. The single-pass crop residue harvesting model consists of four basic steps: crop harvesting, bale formation, bale collection, and bale storage. Machines represented by this model are a combine, a baler, and bale collection device. The tractor shown in in Figure 4.3 serves only as an input/output switch that simplifies the underlying model programing. It does not contribute cost, fuel, labor, or dry mass losses in the model results. Each of the other steps shown in the model contribute to the overall harvesting cost, fuel, labor, and dry mater losses of this collection system.

Table 4-1 Basic IBSAL model input variables example

Crop type				
1				
Corn	Wheat	Grass	Woody	
1	2	3	4	Crop Type
5.35	3	5	10	Biomass yield
1.6055	0.80275	1.6055	1.6055	Yield to be deducted for conservation (dry Mg/Ha)
0.5	0.65	0.95	0.95	Expected Biomass recovery
100,000	100,000	100,000	100,000	Annual mass demand for delivery (dry Mg)
500	1000	1000	1000	Number of items simulated
3	3	3	3	Row number

The IBSAL model used for this work is supported by a generic Excel spreadsheet file, IBSAL.xlsx, which supplies model input variables and is where model outputs are written after each model run. Model input variables are crop residue type, biomass yield, conservation reserve, take rate (harvested biomass yield), and biomass demand from a biorefinery as shown in Table 4-1. This model assumes all the residue collected will be collected at 17% moisture content. The Excel support file also supplies weather input data and available working days to the model. The IBSAL.xlsx file also contains a cost data base of machine costs and parameters that are used in the overall IBSAL model. General cost information for the machines represented by the model blocks can be found in this spreadsheet. For the purpose of this work, costs were developed in separate spreadsheets for the specific machines used by the AGCO project were performed. These costs were used to customize machine model blocks.

Cost values used in the IBSAL model were calculated using American Society of Agricultural and Biological Engineers (ASABE) machinery management standards S495.1 "Uniform Terminology for Agricultural Machinery Management", EP 496.3 "Agricultural Machinery Management" and D497.7 "Agricultural Machinery Management Data". These standards provide a framework with which to calculate hourly machine costs, annual fixed costs, and variable costs.

Included within these three cost values are cost estimates for machine maintenance, lubrication, insurance, machine storage, and interest. A number of assumptions were also necessary, such as the overhead labor related to operating a machine in the field. Where assumptions like this are made, conventions suggested by the USDA Natural Resources Conservation Service (NRCS) publication “*Commodity Costs and Returns Estimation Handbook*” of 1998 are used.

A single step within the IBSAL model shown in Figure 4.2 consists of a number of variable inputs and a series of equations that define the different functions of the given model step. Most often a given step is a machine operation. Input variables such as machine specifications, performance characteristics, and related cost values are used to describe a machine of the type needed for that step. Equations within the model step block mimic the functions of the defined machine. The equations used in a model block are either from applicable published literature or standards. A sample of the internal construction of an IBSAL model block is shown in Figure 4.3.

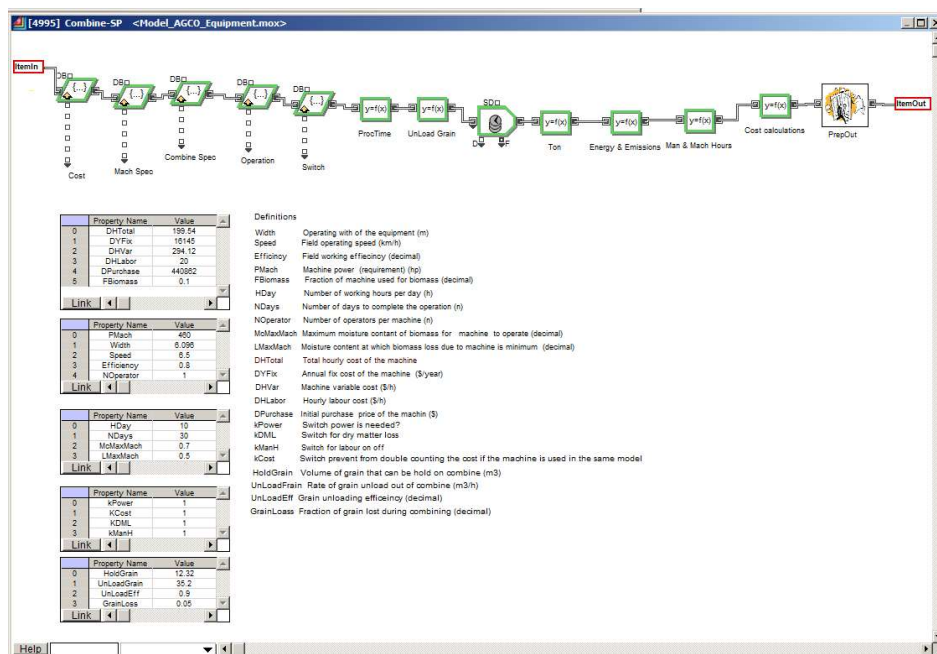


Figure 4.3 Example of inner contents of ExtendSim IBSAL model block.

A large percentage of the equations used in the IBSAL model are from the ASABE machinery management standards. The equations used calculate power requirements and fuel usage based on anticipated field speeds and efficiencies. These values can also be found in the ASABE standards. In select instances, equations from other peer reviewed publications are used to define certain power requirements or machine functions.

The machine variables define the aspects of the machine that make up a given step. Figure 4.3 shows the combine for single-pass crop residue harvesting. Engine power, header width, ground speed, variable and fixed cost values, and labor inputs are input into fields within the block to define the machine. The equation portion of a block pulls this data from these input fields. The model is also able to read information from previous blocks and the overall model. Results from the model are written to an output table spreadsheet in the supporting “IBSAL.xls” file.

In order to customize a model to a particular machine, the input variables of a block can be changed to match those of that machine. Figure 4.4 illustrates the variable inputs for a model block. To customize the single-pass harvesting model to the AGCO project, machine costs and data for the specific machines used were input in these variable blocks. Much of this information was generated through the data analysis work described in Chapter 2. For this work, the combine and square baler blocks shown in Figure 4.2 were modified to match the machines used in the AGCO project. The input variables for the combine and large square baler were changed to the values shown Table 4-2. It should be noted that the IBSAL model uses both

Table 4-2 Input variables used to modify single-pass harvesting to match AGCO harvest equipment

L34B Challenger Towed Large Square Baler Inputs		
Bale Mass	475	Mass of the bale (kg)
Pmach	150	Required machine power (hp)
DH Total	112.16	Total hourly cost of the machine (\$/Hour)
DYFix	4599	Annual fix cost of the machine (\$/Year)
DHVar	108.54	Machine variable cost (\$/Hour)
Dpurchase	142830	Initial purchase price of the machine (\$)

560C Challenger Combine Inputs		
Pmach	460	Required machine power (hp)
DH Total	204.12	Total hourly cost of the machine (\$/Hour)
DYFix	16145	Annual fix cost of the machine (\$/Year)
DHVar	199.54	Machine variable cost (\$/Hour)
Dpurchase	440862	Initial purchase price of the machine (\$)
Speed	6.5	Field operating speed (km/hr)
Header Width	6.1	Operating width of the equipment (m)

SI and English unit for inputs. Extra care was necessary to insure the proper units were used on variables entered into model blocks. Bale weights and field speed were input as SI units. Machine engine power input was in horsepower.

The screenshot displays the IBSAL model input interface. It features five tables for entering property names and values, each with a 'Link' button and navigation arrows. To the right is a 'Definitions' list for the properties.

Property Name	Value
0 DHTotal	199.54
1 DYFix	16145
2 DHLVar	294.12
3 DHLabor	20
4 DPurchase	440862
5 FBiomass	0.1

Property Name	Value
0 PMach	460
1 Width	8.096
2 Speed	6.5
3 Efficiency	0.8
4 NOperator	1

Property Name	Value
0 HDay	10
1 NDays	30
2 McMaxMach	0.7
3 LMaxMach	0.5

Property Name	Value
0 kPower	1
1 KCost	1
2 KDML	1
3 kManH	1

Property Name	Value
0 HoldGrain	12.32
1 UnLoadGrain	35.2
2 UnLoadEff	0.9
3 GrainLoss	0.05

Definitions

- Width: Operating width of the equipment (m)
- Speed: Field operating speed (km/h)
- Efficiency: Field working efficiency (decimal)
- PMach: Machine power (requirement) (hp)
- FBiomass: Fraction of machine used for biomass (decimal)
- HDay: Number of working hours per day (h)
- NDays: Number of days to complete the operation (n)
- NOperator: Number of operators per machine (n)
- McMaxMach: Maximum moisture content of biomass for machine to operate (decimal)
- LMaxMach: Moisture content at which biomass loss due to machine is minimum (decimal)
- DHTotal: Total hourly cost of the machine
- DYFix: Annual fix cost of the machine (\$/year)
- DHVar: Machine variable cost (\$/h)
- DHLabor: Hourly labour cost (\$/h)
- DPurchase: Initial purchase price of the machine (\$)
- kPower: Switch power is needed?
- KDML: Switch for dry matter loss
- kManH: Switch for labour on off
- KCost: Switch prevent from double counting the cost if the machine is used in the same model
- HoldGrain: Volume of grain that can be hold on combine (m3)
- UnLoadGrain: Rate of grain unload out of combine (m3/h)
- UnLoadEff: Grain unloading efficiency (decimal)
- GrainLoss: Fraction of grain lost during combining (decimal)

Figure 4.4 Example of variable inputs with in the IBSAL model.

Once the IBSAL single-pass harvest model was modified as shown in Figure 4.4, a set of field data was chosen to compare to model result to in order to verify results. The basic IBSAL model is based on biomass harvested at a moisture content of 17%. In order to modify the model to match field data it was necessary to select field data with a similar moisture content. Of the 15 single-pass corn stover harvest data sets collected, only five data sets fit this criteria. These five data sets, collected near Emmetsburg, IA in 2011, are listed in Table 4-3. These five data sets were collected from subset areas of the same larger field, and were the most complete data sets available at this moisture content level. Using this collected data, baling cost and fuel requirements were calculated (Chapter 2). The results of these calculations are shown in Table 4-3.

Table 4-3 AGCO Field data used for model modification work

Field Code	Actual MC	Bale Weight (kg)	Mass Harvested (Wet Mg)	Mass Harvested (Dry Mg)	Harvested Area Hectares	Biomass Yield (Wet Mg/Ha) Actual	Biomass Yield (Dry Mg/Ha) Actual	AGCO Baling Cost (\$/Mg)	AGCO Fuel Requirement (dry Mg/liter)
EMTBG3	17.0%	497	13.2	10.96	2.10	5.69	4.73	4.75	1.00
EMTBG4	17.2%	473	15.1	12.50	2.39	5.74	4.75	<u>3.36</u>	0.96
EMTBG5	17.1%	526	25.9	21.47	3.60	6.52	5.41	4.85	<u>0.86</u>
EMTBG6	17.1%	473	56.6	46.89	9.27	5.54	4.59	4.26	0.92
EMTBG7	17.1%	443	21.8	18.06	4.01	4.93	4.09	5.75	0.90

4.3 Results and Discussion

The baling cost and fuel usage requirements were plotted to begin the analysis and IBSAL modification work. In order to develop cost and fuel usage curves and cost equations, log – log regressions were conducted of the selected data points. Plots of the data used and the resulting regression equations were made for visual comparison. It was intended that the resulting regression equations would be used to create target curves for the modified IBSAL model to emulate. Upon analysis of the two initial plots of yield vs. baling cost and yield vs. fuel

requirements, two data point were identified as outliers and were removed. The two removed points have been bolded in Table 4-3for reference. The second round of plots, shown in Figure 4.5 and Figure 4.6, with the noted date points removed show an improved fit to the log-log regression equation that was found and plotted. The baling cost curve, shown in Figure 4.5, has a R^2 value that is low, meaning the shown curve does not fit the data very well. The confidence level of this curve is a little over 85% based on a P-test. Removal of additional or other data points in the attempt to improve the curve fit gave improbable curve forms. Therefore, it was decided to use the cost curve, and corresponding equation, shown in Figure 4.5 to base the IBSAL cost model modifications work on.

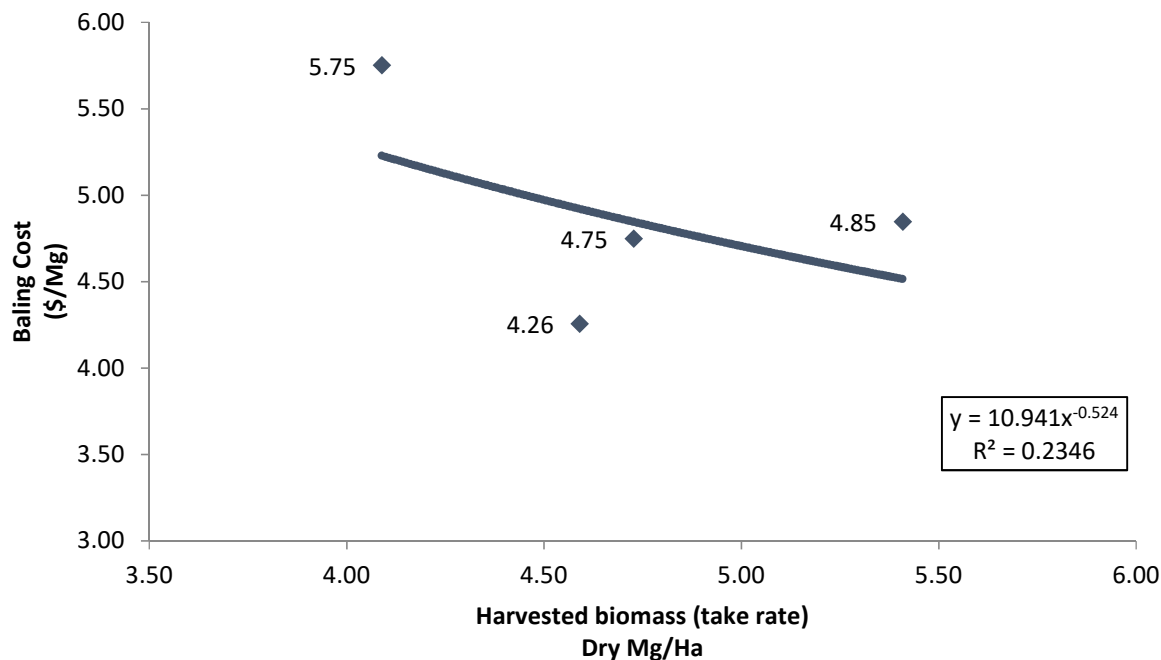


Figure 4.5 Single-Pass Corn Stover Baling Cost

The fuel requirement curve, which was also plotted and is shown in Figure 4.6, fit the remaining fuel data points much better. Again a log-log regression was preformed on the available data to develop this curve and corresponding equation. The R^2 value for the shown trendline was 0.69, showing a reasonably good fit. Confidence for this curve is about 85%, based on the P-test, the same as the cost curve. More data points for single-pass stover harevest,

harvested at a 17% moisture content, that the cost and fuel curves could be based upon would likely improve the quality and reliability of the shown curves. The curves shown in Figure 4.5 and Figure 4.6 were chosen to be the target curves that the modified IBSAL model should simulate as closely as practical.

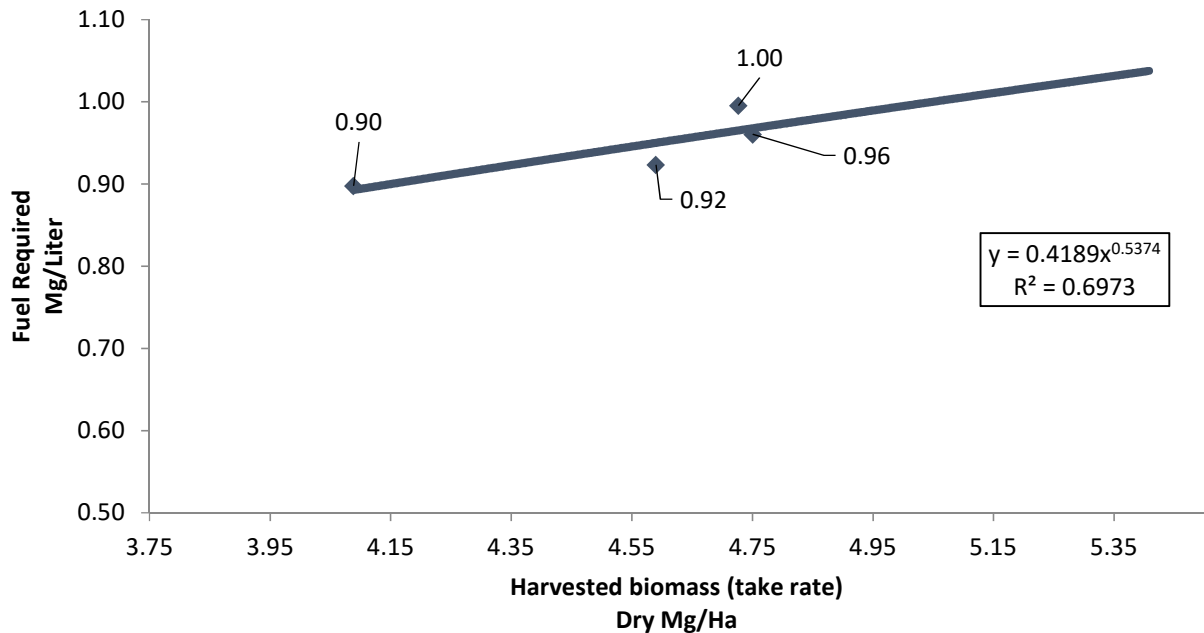


Figure 4.6 Single-Pass Corn Stover Baling Fuel Requirements

Actual modification to the IBSAL model was accomplished through experimentation with a goal of maximizing the R^2 value for the cost and fuel use curves. Initially, model runs used the default values within the IBSAL model, with only the machine specific variables shown in Figure 4.4 being the only modifications made to the model. A single model run consisted of modifying the supporting Excel spreadsheet model input sheet to match one of the “Dry Biomass Yield” values from Table 4-2. The results from a run were written to the “Output Tab” in the supporting Excel spreadsheet. The results from a run were then recorded in a separate spreadsheet. Two charts, stover harvest cost and fuel use, were created in the second spreadsheet

that were used to compare the results from the IBSAL model runs to the cost and fuel requirement values calculated from the collected and analyzed field data.

The initial modifications to the IBSAL model were limited to adjusting baler power, field speed, and bale weight (baler power and bale weight were adjusted in the baler model block and field speed was adjusted in the combine model block shown in Figure 4.2). These three variables were chosen to be modified because they are by nature ambiguous. Field speed can vary from place to place within a field as harvesting is conducted. Bale weights differ from bale to bale, as shown in Table 4-3. Further, baler power requirements are considered to be highly variable over the course of bale formation (Webster et al., 2013). A large number of model runs were completed with many different combinations of the three variables being used. Comparable results to the field data proved to be difficult to obtain.

In order to simplify the comparison work, initially only harvest cost comparisons between the field data and the modified IBSAL model were considered. Fuel costs are a part of

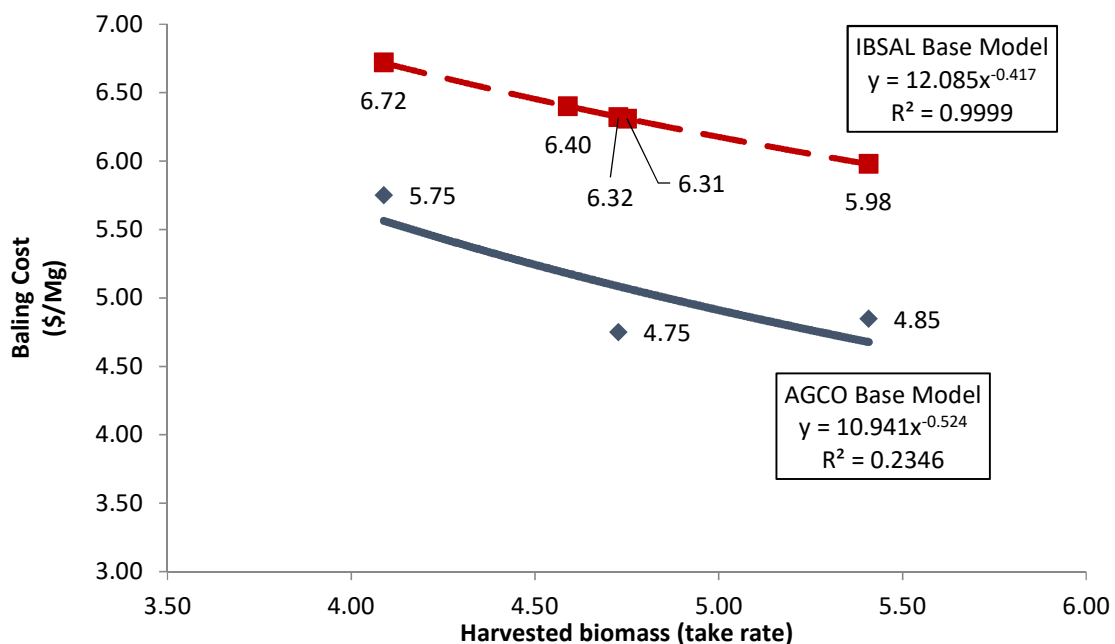


Figure 4.7 Initial comparison between the IBSAL model and field data cost curves

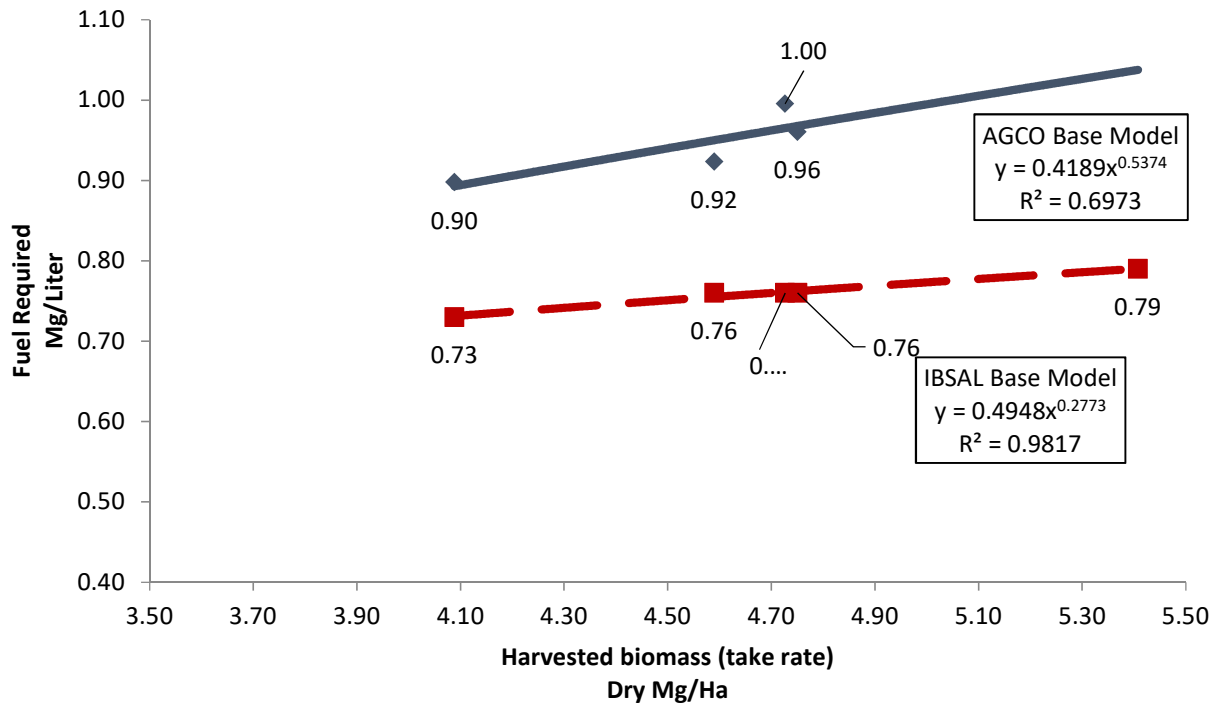


Figure 4.8 Initial comparison between IBSAL model and field data fuel use curves.

the calculated harvest costs and it was believed that if the harvest cost curves could be aligned, then the fuel requirement values would align as well.

Through experimentation, it was found that field speed had minimal meaningful effect on the cost results and was eventually fixed at 6.5 kph, which was the initial field speed assumption made within the original IBSAL model. Bale weight and baler power were found to have a greater effect on the cost curves. As work progressed, only these values were adjusted in the attempt to replicate the field data with the IBSAL model results. The initial IBSAL model result curves for cost and fuel use, and comparable field data results, are shown in Figure 4.7, Figure 4.8, and Figure 4.9. However, when the cost and fuel use curves based on the AGCO field data were compared to the resulting IBSAL model curves over an expanded range of harvest take rates (1.25 Mg/Ha to 14 Mg/Ha) the modified IBSAL model curve was found to be a poor comparison to the field data results. The comparison was made by calculating a percentage difference in the results at each data point in the expanded range and visually comparing the resulting curve of each data series

over the harvesting range. Figure 4.9 and

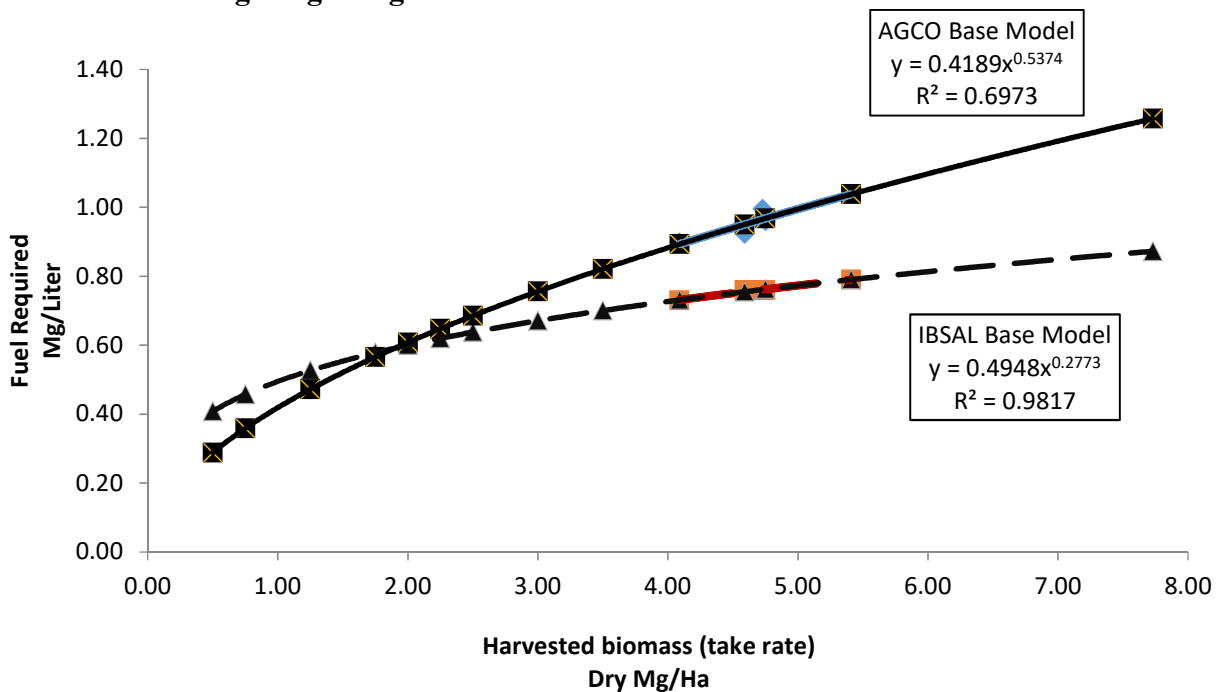


Figure 4.10 show a visual comparison of these results. The IBSAL model as supplied and modified as described, overestimated harvest costs between 6% and 12% over the field data curve predicted. The IBSAL model as modified and supplied, under estimated fuel usage by even larger margins in the 11% to 40% range.

After a large number of model runs, it became clear that the calculated results from the AGCO field data behaved much differently than those produced by the IBSAL model. The initial modifications to the IBSAL model involved varying the input variables within the model for bale mass, baler power requirements and field speed to a lesser extent. The resulting curves from these modified models would approach the AGCO results over the narrow range of the initial comparison, but would vary greatly over the expanded range of possible harvest rates considered in the second set of curves. Calculated costs within both the initial narrow range of harvest rates and then expanded harvest rates at best were only within 5 to 10 percentage points of the AGCO data. Based on these results, it was determined that other modifications beyond

input modifications were necessary to make the IBSAL model approach the AGCO results more closely were required.

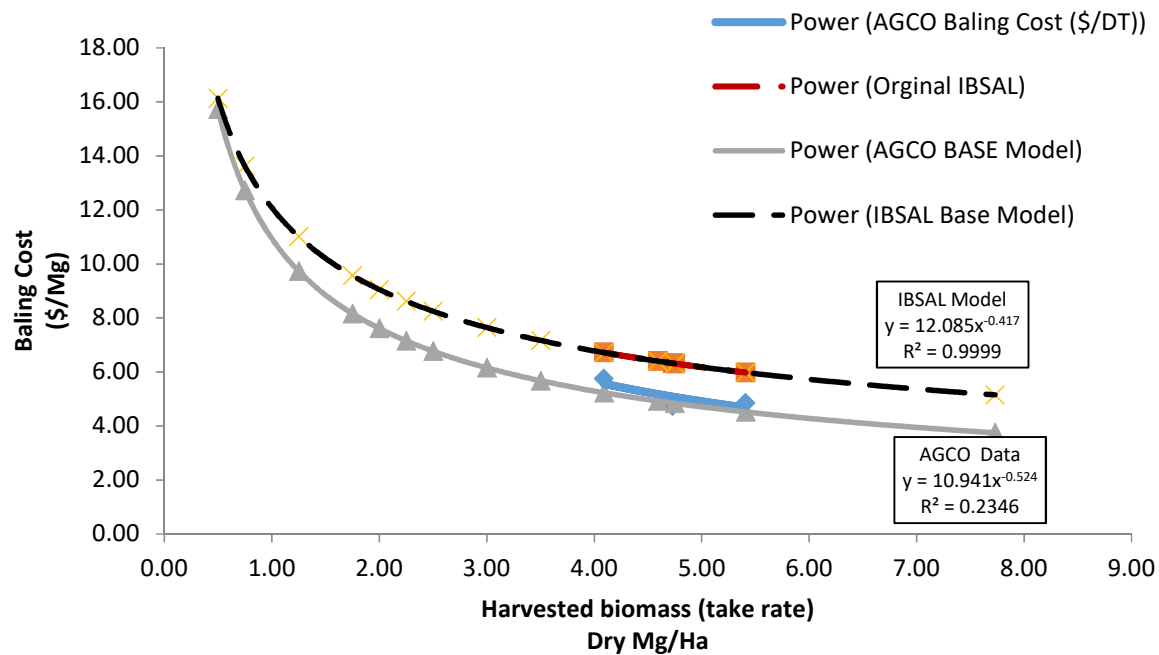


Figure 4.9 Initial comparison between AGCO curve and IBSAL fuel use curve

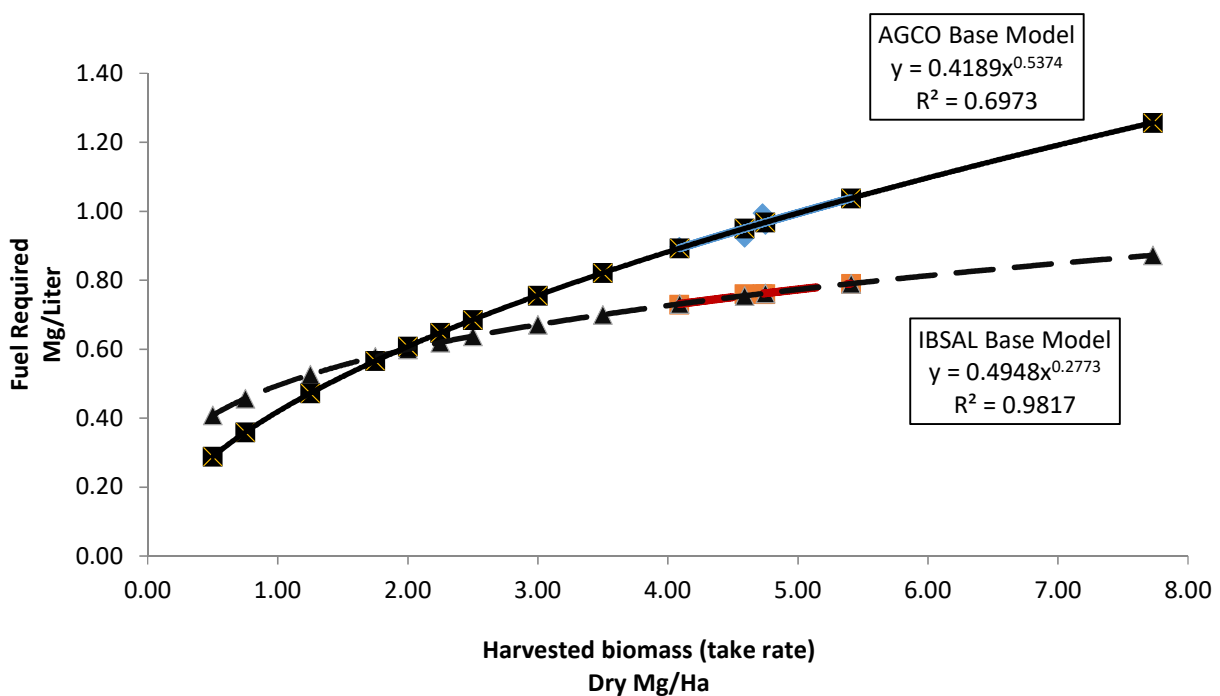


Figure 4.10 Comparison of baling field data and IBSAL model baling data fuel use curves over a range of harvest take rates.

After examination, the IBSAL model was found to be overestimating the harvesting cost and underestimating the fuel requirement per Mg of stover. Further, the input bale mass used in many of these initial model runs to achieve the shown result curves were significantly lower than what had actually been produced in the field scale tests. After consideration, it was determined that the IBSAL model was under estimating the power required to form bales compared to that required by the baler in the field scale tests. It was determined that other modifications should be made to the model than changes in input parameters. After investigation, it was found that the equation block ([1222][218]) within the SquareBaler-T block in the IBSAL model shown in Figure 4.2, contained the power requirement calculations for the large square baler. It was this equation block that was modified.

The power required by a large square baler is a combination of drawbar and rotary power. It is calculated as shown in Equation 4.1, 4.2, 4.3, and 4.4. These power equations are the basis for calculating fuel requirements and related costs for baling in the IBSAL model in equation block [1222][218].

$$P_{Baler} = P_{drawbar} + P_{rotary}$$

Equation 4.1 Total power required by baler

Where: $P_{drawbar}$ -- Power required to tow baler through field

P_{rotary} -- Rotary power necessary to operate baler

The drawbar power calculation is a straight forward calculation based on the mass of the baler and mass of the bale being formed Equation 4.2. While there is a potential for considerable variation in this value, due to rolling resistance variation in a typical field, this calculation was

left untouched. Drawbar power is a small percentage of the overall power required by a baler as it is operated in the field.

$$P_{drawbar} = k_2 S \left(\frac{(m_{bale} \cdot m_{baler})}{3600 k_3} \right)$$

Equation 4.2 Drawbar power required to tow baler

Where: $P_{drawbar}$ -- Power required to tow baler through field

k_2 -- Constant -- 1.06

k_3 -- Conversion coefficient -- 0.7

m_{bale} -- Mass of a fully formed bale in kg

m_{baler} -- Mass of empty baler in kg

The rotational power requirement of the baler is the larger percentage of required power necessary for baler operation. Rotational power necessary for bale formation is estimated with Equation 4.3. Rotary power consists of two components: the power necessary to overcome friction in the baler mechanism (unloaded baler operation) and the power required to form the bale. The unloaded baler power requirement was assumed to be 4 kW by the original IBSAL model. After consulting with a large square baler engineering manager it was realized this value was too low. A value of 11 kW was thought to be more realistic value and has been substituted into the modified IBSAL model block (personal communication Maynard Herron Engineering Manager Hay Tools, AGCO, August 17, 2018).

$$P_{rotary} = P_o + E \frac{\dot{m}}{3.6}$$

Equation 4.3 Rotary power required to operate a baler forming a bale

Where: P_{rotary} – Rotary power necessary to operate baler in kW

P_o – Base load to necessary to operate baler empty in kW

E – Energy required to form bale in kJ/kg

$\dot{m}$ – Baler throughput in kg/hour

The largest component of the power required to operate the baler comes from the energy necessary to form a bale. The energy required for bale formation can be estimated based on the energy necessary to compress the biomass and the bale's density. Equation 4.4 is used to calculate this energy is based on relationship between the pressure necessary to compress biomass and the resulting density. Equation 4.5 is the pressure density relationship which Equation 4.4 is derived from. The density pressure relationship is based on the experimental data. Values for k and n are generated through experimentation on specific samples of biomass. The original IBSAL model used values of n=.25 and k=26.9 to calculate bale formation energy.

$$E = \left(\frac{1}{((1-n)k)} \right) \left(\frac{\rho}{k} \right)^{\left(\frac{(1-n)}{n} \right)}$$

Equation 4.4 Energy for bale formation

Where: E -- Energy to necessary to form a bale kJ/kg

n – Constant pressure density, exponential

k – Constant pressure density

ρ – Bale density in kg/m³

$$\rho = kp^n$$

Equation 4.5 Biomass pressure density relationship

Where: ρ – Bulk density in kg/m³

p – Pressure in kPa.

n – Exponential constant

k – Constant

Using values $n=.25$ and $k=26.9$ in the energy equation, the IBSAL model did not produce results that were similar to the AGCO results, as demonstrated in Figure 4.9 and

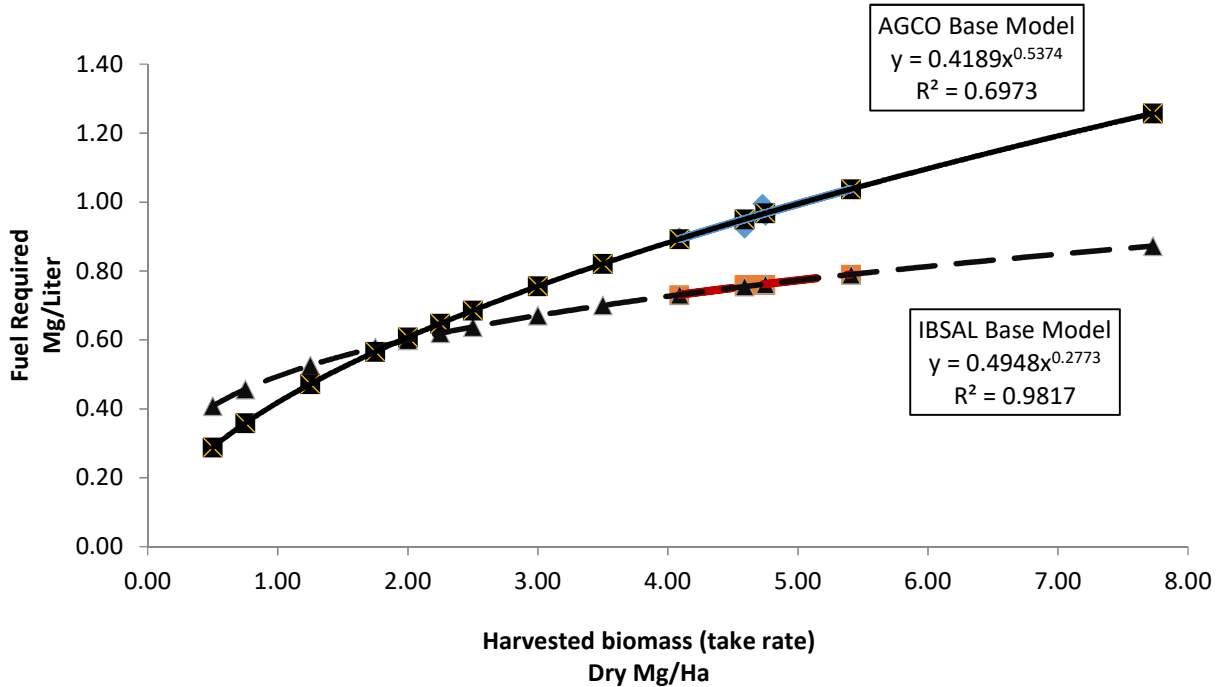


Figure 4.10. Research has shown that there is not a “one value” for both n and k (Van Pelt, 2003). These values vary with the material and moisture content of the biomass that is being compressed. Van Pelt found that the n and k values vary with differing corn stover moisture content. Corn stover values of k have been found to range from 20.3 to 27.7 for moisture contents of ranging from 13% to 20% (van Pelt, 2003). Values for n range from 0.25 to 0.32 over the same range of moisture contents (van Pelt, 2003). Van Pelt found that the average

values for dry corn stover (18.1%) were $k=24.7$ and $n=0.29$. Using these values in Equation 4.4 improved the fit of the IBSAL results to the AGCO data, but a better fit was desired. Through further experimentation it was found that values of $n=0.285$ and $k=26.4$ resulted in curves that fit the AGCO data closely.

The baler rotary power calculation within equation block ([1222][218]) of SquareBaler-T block in the single-pass harvesting IBSAL model was modified to use the constants in Table 3-7 and Table 4-4.

Table 4-4 Constants modified in Equation [1222][218] in Square Baler T block

Variable	Input
P_o	11 kW
k	26.9
n	0.285

After incorporating all the modification noted above, a modified IBSAL model for single-pass harvesting of corn stover was obtained. This model replicated the field data cost curve closely. Resulting harvest cost values were within a 1 to 5 % range for the all tested harvesting rates. Figure 4.11 demonstrates the closeness of fit between the field data based curve and the modified IBSAL model.

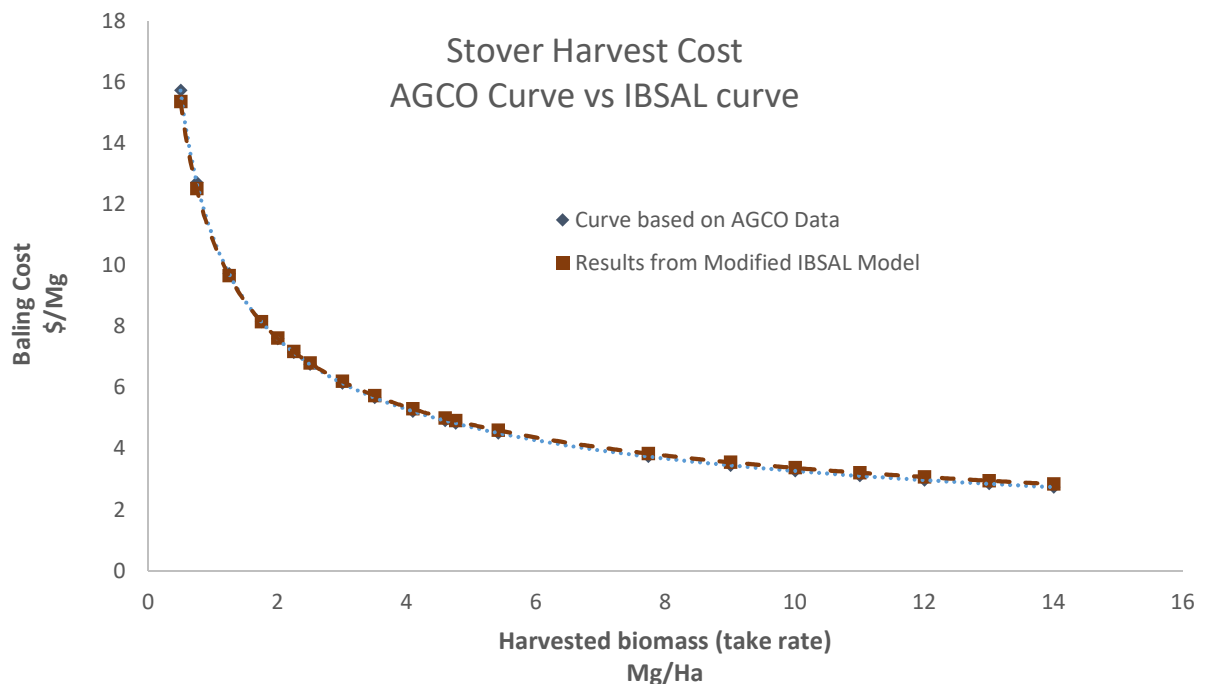


Figure 4.11 Comparison of AGCO field harvest cost curve to the IBSAL model harvest cost curve

The modified IBSAL model improved the fit between the field data fuel requirement curve and the IBSAL model fuel requirement curve. The IBSAL harvest fuel use curve is shaped differently than that of the field data results as shown in Error! Reference source not found.. At very small harvest rates, rates below 2 Mg/Ha, the model over predicts fuel requirements by 10% or more. At very large harvest rates, rates above 12 Mg/Ha, the model will under predict fuel requirements by 8% or more. In practice, harvest rates will tend to be above 2 Mg/Ha and below 12 Mg/Ha, which would be within the range where this model is most accurate.

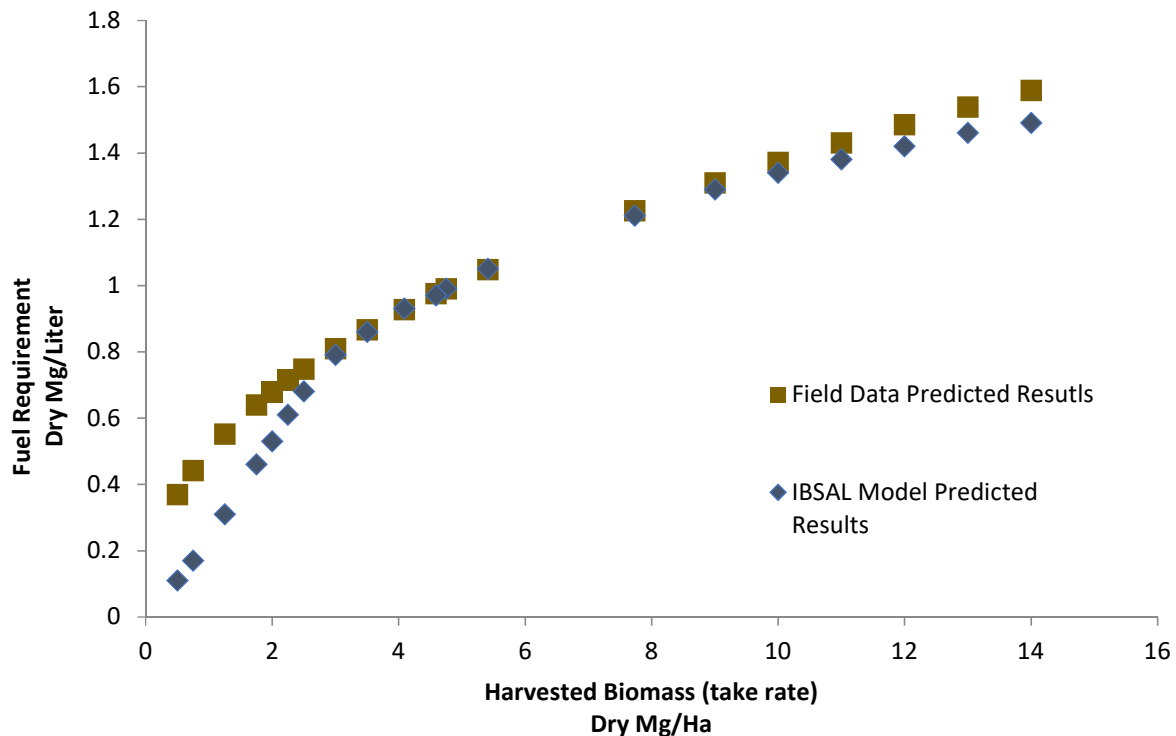


Figure 4.12 Comparison of AGCO field fuel use curve to the IBSAL model fuel use

4.4 Conclusions

The provided IBSAL model was modified to reflect single-pass harvest field data. The original model overestimated harvesting costs, under estimated fuel requirements and under estimated the power required to bale corn stover at 17% moisture content. The provided model was modified by changing cost inputs to reflect actual machine costs, machine input power, field speed, bale weight and coefficients that are part of the baler power calculations. The resulting model was able to replicate single-pass corn stover baling field data.

The field data that was used to create the target curve for which the model was modified to replicate, was very limited in range of “take rates” showed quite varied harvest costs and fuel uses within that. The modified IBSAL model is most valid within the limited range of the field data. Outside this range, the model results must be considered with caution. Additional data points taken over a larger range of harvesting rates would be beneficial. A larger range of “take rate” data points could be used to improve the confidence and validity of the modified IBSAL model over a wider range of harvest rates. Unfortunately, the cost to perform such field tests to obtain the desired data is quite large. Further, the required data should be collected at a moisture content near 17%, which increases the difficulty of obtaining it.

The single-pass IBSAL model itself needs further investigation to improve its accuracy. This work identify several assumptions that needed improvement. Given the size and complexity of the IBSAL model, minor errors and incorrect assumptions must certainly exist within it. Through continued use and investigation by those skilled in specific areas the model replicates or with actual data with which to compare the model to, improvements to the model can be made.

Further work should be done to improve “k” and “n” coefficients of the bale formation energy equation (Equation 4.4). These values are currently available for a small range of moisture contents. More field data should be collected and analyzed to provide a larger range of these values these to use for corn stover and other crop residues that the IBSAL model considers. Further, these values should become model input variables rather than fixed coefficients “hidden” within internal model calculations blocks.

Chapter 5 Effect of Biomass Variability on Harvest Costs

5.1 Introduction

Building a bioeconomy around biomass requires a system that can supply the feedstocks at reasonable costs over a range of variables. Crop residues are one potential feedstock that is under consideration. The collection of crop residues was the focus of the AGCO “*Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to supply Crop Residues and A Herbaceous Energy Crops in a Diversified Large Square Bale Format*” project to determine realistic and reasonable harvest costs for biomass crops. This project, developed a number equipment improvements and new pieces of equipment to reduce the cost to harvest crop residues for biomass. Field scale tests were conducted, and data was collected, on the equipment developments to develop realistic costs, and fuel and labor requirements. This data was intended to be used to improve logistic models used to study the supply chain of biomass for the bioeconomy.

The IBSAL model is a tool for producers, biorefineries, and planners to use to explore the logistics and costs of biomass for the bioeconomy. For the tool to be useful, the model must be updated to reflect field results. The IBSAL model for the single-pass harvesting of crop residues was modified to reflect the collected field data in Chapter 4. Coefficients and constants were developed based on the equipment used in a field scale study. The results from this study was used to modify the IBSAL model for single-pass harvesting. The resulting cost and fuel use curves were found to emulate curves developed directly from the field study data.

Much of the published work related to the cost of crop residue assumes one cost for the biomass as delivered to the throat of the biorefinery (Perlack et al., 2005; Perlack et al., 2011; Langholtz et al., 2016). This cost is then used for the basis of all the cost of the products from a

biorefinery. While, this simplifies the calculations related to studies for the development of a bioeconomy, it does not build robustness into the developing industry. One single price for a dry Mg of corn stover does not exist (Hess, 2007). Like the commodity crops that they are grown to produce, the cost of crop residue production will vary from year to year, field to field, and, potential, day to day. Crop residue cost variability comes from the variability of the crop residue itself, residue yield, field conditions, equipment size, machine settings, operator decisions, and fuel and labor costs.

Crop residue yield has the potential of being highly variable, even more than the crops it is sourced from. Unlike the grain being produced by the crop residue, it is not desirable to harvest, or “take”, all the crop residue from a field (Lipinsky, 1978; Larson, 1979; Klocke, et al., 2008). Therefore, harvesting costs related to yield become dependent upon the “take rate” at which a producer chooses to harvest crop residue. The “yield” of crop residue can vary considerably from year to year or day to day based just on the decisions of a producer and the available crop residue. A large amount of crop residue in the field does not guarantee a large residue harvest. Harvest rates can vary based on location, residue availability, previous crops, tillage systems, and the amount of residue that must be maintained in the field to prevent erosion. These values will be different in northwest Iowa compared to other locations such as western Nebraska locations (Gallagher et al., 2003).

Moisture content of the crop residue can vary over the course of a harvest season due to crop maturity and weather conditions. Early season crop residues contain more moisture due to plant physiology (Kenny et al., 2013). Weather events can increase moisture content in a fully dry crop also. Field conditions change based on crop yield and weather events, which can influence harvest speeds. Machine size and operator skill can influence the field efficiency of

the harvest operation and change the harvest cost of the residue (Perlack et al., 2002; Purfürst, 2011). Each variable changes the cost of harvesting crop residue.

Since there is a great potential for variability in the harvest cost of crop residues, it is important for producers, biorefinery operators, and planners to understand what the residue cost variability could be, what influences it, and how it might be mitigated. This work fills this need by exploring harvesting variability and its effect on harvesting costs. It also identifies some methods that can be used to mitigate cost variability in crop residue harvesting.

5.2 Materials and Methods

The AGCO project resulted in field harvest data for single-pass harvesting of the crop residues wheat straw and corn stover. The wheat straw field data was very limited and few conclusions could be drawn from it. The corn stover harvesting data was much more plentiful. Corn stover is also projected to be one of the most readily available sources of biomass for building a bioeconomy (Perlack et al., 2005).

The corn stover single-pass harvest field data was used to modify the IBSAL model in Chapter 4. This modified model was able to replicate collected field scale test results. The model that was developed in Chapter 4 will be used to explore cost variability in single-pass harvesting of the crop residue corn stover. It may be possible to infer harvesting trends for other crop residues such as wheat straw, but such inferences will be suspect absence additional field data for which to compare the base IBSAL model to. The following corn stover harvest variables will be explored: take rate, field speed, swathe width, bale density, stover moisture content, labor cost, and fuel costs.

Take rate. Harvest rate or “take rate” is explored within the investigation of all variables as they are considered. It is based on the available residue, machine settings, and producer decisions. The take rate is explored in a range from 2 dry Mg/Ha to 14 dry Mg/Ha. This range is based on costs and typical stover availability. A harvest rate below 2 dry Mg/Ha becomes extremely expensive to harvest because costs are spread over so few dry Mgs. Take rates above 14 dry Mg/Ha are rarely available as that would require corn yields approaching 15.6 Mg/ha. In 2017 only one county in the U.S. approached this level of production (Schnitkey, 2018). For agronomic purposes at least 1.6 dry Mg/Ha of crop residue must be left in the field to maintain soil carbon and provide enough ground cover to prevent erosion (Sokhansanj, 2006). Some studies suggest even more residue should remain on the soil surface to maintain soil moisture (Klocke et al., 2008; Van Donk et al., 2012),

Field conditions. Field conditions can limit the speed at which harvesting can be accomplished. Field harvest speeds are considered over the range of 5 KPH to 9 KPH. These are typical speed for which standing corn producing typical grain and stover yields would be harvested (ASABE, 2011). Speed outside this range would only be used in a low yielding poor crop conditions (speeds higher than 9 kph), in damaged crop, or in extremely poor field conditions (speeds below 5 kph). Within the given range, speed can vary greatly because of crop yield, field conditions, or operator choice.

Machine size. The swathe width for harvesting corn and corn stover is based on the number of rows on the corn head used for harvesting. Common corn row head sizes are 8 row, 12 row, and 16 row. These head sizes correspond to swathe width sizes of 6.1 m, 9.1 m, and 12.2 m. Harvest costs will be calculated for these three sizes of headers for comparison. A farmer will choose a combine header for harvesting corn based on the number of factors relating

to the individual's farming operation. Number of rows on the individual's planter, capacity of the combine used for harvest, the capacity of the grain handling facility used to take grain away from the combine, as well as other factors like the size of local farm road bridges that a producer must traverse can factor into the selection of the combine head by the producer. The choice of header is a major decision for the producer. The resulting decision can remain in effect in a farming operation for quite some time. The width of swathe can also influence the cost of residue harvest costs.

Bale Density. Increasing bale density was seen as one method of decreasing the cost of biomass. Producing dense bales decreases the amount of handling and transportation necessary to collect and move bales to the field edge, thereby reducing harvest costs. Further, heavier bales reduced the cost to load and transport biomass at from the field edge to the biorefinery. Dense bales do require more energy to form, as was discussed in Chapter 4, and is a cost that the producer must bear.

Moisture Content. The moisture content in corn stover varies over the course of a harvest season. Early in the harvest season, the corn grain can be dry enough for harvest, in the 15 to 20% range, while the corn stover may be much wetter. One rule of thumb is that early in the harvest season, the stover is often twice the moisture content of the grain (Nielsen, 1995). The stover moisture content can also vary from morning to night or day to day as result of overnight dew, rain events, and changes in humidity. As a result, moisture content of the stover as it is harvested can vary greatly. As moisture content of the stover varies, the mechanical properties of the stover changes, which in turn changes the energy required to compact stover into a bale varies (Van Pelt, 2003). As moisture content increases, the energy and power required to compact a bale decreases. As moisture content increase, the resulting bales are

heavier, owing to increased water content and require more power to move around. Data is available on the mechanical properties of corn stover at 18% and 33% moisture content (Van Pelt, 2003). The cost of harvesting corn stover at these two moisture contents is explored with the IBSAL model.

Labor and fuel costs. Labor and fuel costs will be explored as they also can vary. Labor costs will be explored at \$17, \$20, and \$23 an hour rates. These are representative rates that have been considered in various estimations for farm labor for machine operators (Bureau of Labor Statistics, 2017). Lower labor rates are attributed to lower skilled labor used for harvesting. Higher rates represent high skill or principal farm owners operating the harvesting equipment. Fuel rates will be considered at \$0.88 per liter and \$0.73 per liter. The fuel is considered to be No. 2 diesel purchased at a farm rate or untaxed. A representative fuel cost of \$0.88 per liter is for 2011 and 2012 when the field data was collected. A representative fuel cost of \$0.73 per liter is for 2018.

5.3 Results and Discussion

Take Rate. The basic shape of the harvest cost curve, as shown in Figure 5.1, for single-pass baling is an inverted power curve. This general curve shape is present in all the cost curves for the variables considered. As take rates increase, costs decrease. At low take rates, costs are higher and change dramatically with small changes in the amount of material collected. At high take rates, the costs are less and vary little with small changes in take rates. The different variables that have been considered will generally shift the curve up or down or will flatten or sharpen the arc of the curve, but the same basic shape remains.

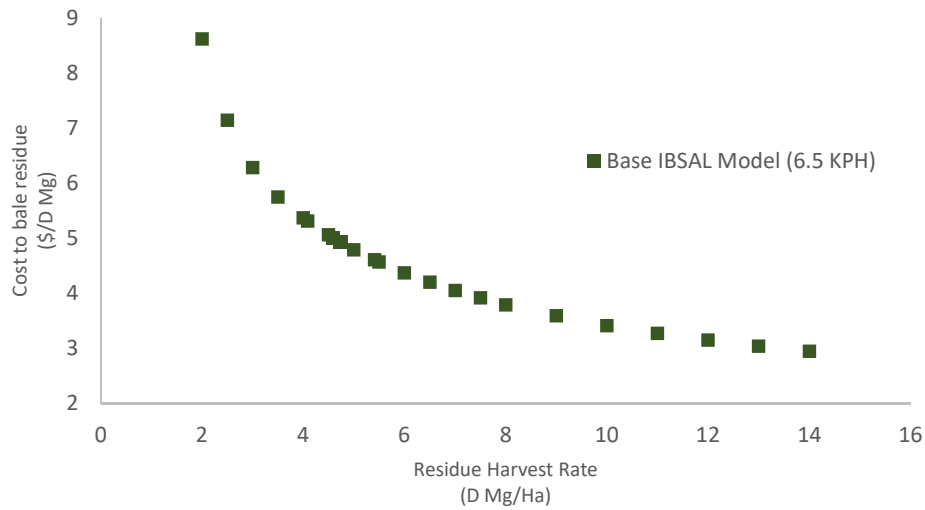


Figure 5.1 Basic IBSAL model results showing stover costs as take rate increases

Fuel use requirements vary with the amount harvested in the form of a power curve as shown in Figure 5.2. As take rates increase, more biomass per liter can be harvested. In general, at low take rates, larger shifts in fuel efficiencies occur with small changes in the take rate. At higher take rates, a small change in harvest rate will make a smaller change in baling fuel efficiency. Like harvest cost, the basic form of the curve remains roughly the same as the different variables were considered.

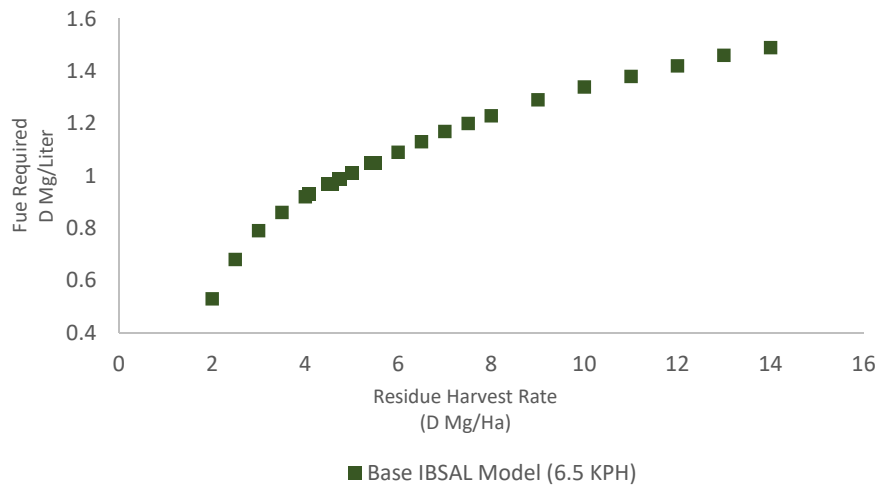


Figure 5.2 Basic IBSAL model results showing fuel requirements as take rates increase.

Field conditions. Model results indicate field speed during harvesting does affect costs. In general, higher speeds reduce cost, lower speeds increase costs. Figure 5.3 is a comparison of 4 kph, 6.5 kph, and 9 kph field speeds. A velocity of 6.5 kph is the default speed that the IBSAL model uses for the single-pass harvesting operation. It was used at the base speed to compare speed changes. Speeds higher than 6.5 kph are consistently less costly to harvest corn stover at than speeds lower than 6.5 kph. Cost, as it is related to field speed, is not a linear relationship. Harvesting stover at 9 kph, 2.5 kph more than the base speed of 6.5 kph, averages 9.3% less in cost to harvest stover then harvesting at the base speed. However, at 4 kph, 2.5 kph less than the base speed, harvesting costs average 18.9% more to harvest stover.

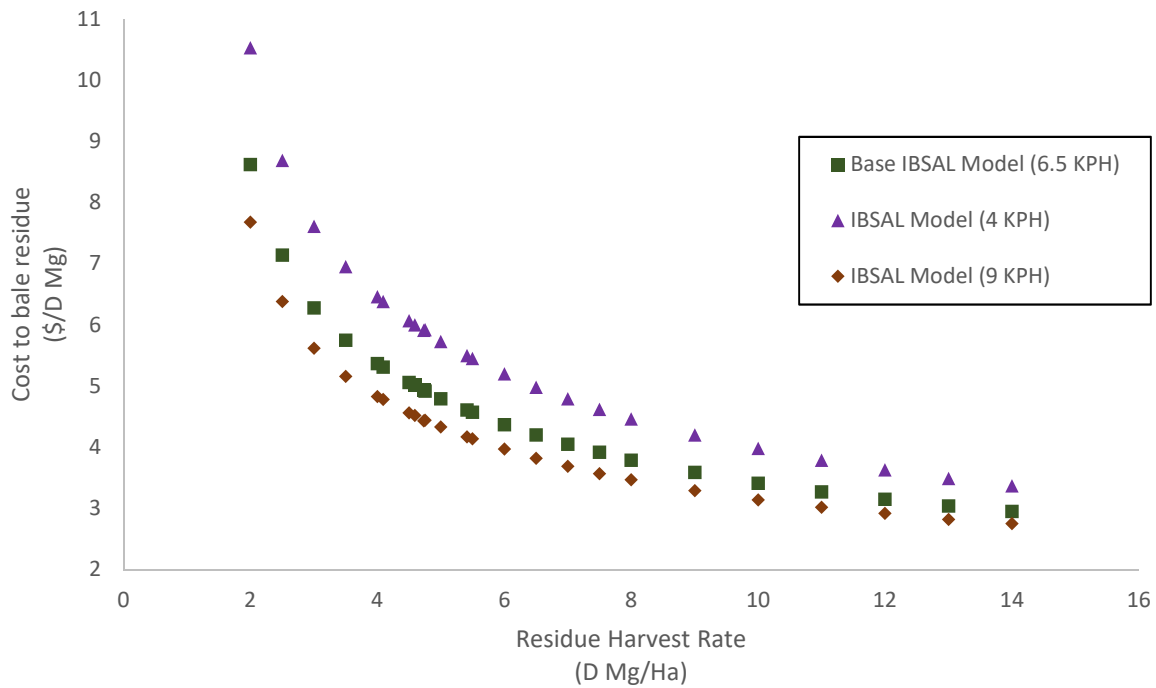


Figure 5.3 IBSAL model results showing the effect of harvest speed on residue harvesting cost

Fuel requirements decrease as harvesting speeds increase as shown in Figure 5.4. On average 3.6% more biomass can be harvested at 9 kph than at 6.5 kph for the same amount of fuel used. Fuel requirements increase nonlinearly as speed changes, just like harvest costs do as related to speed. Fuel requirements to bale stover at 4 kph are 8.7% more than those required to single-pass bale stover at 6.5 kph.

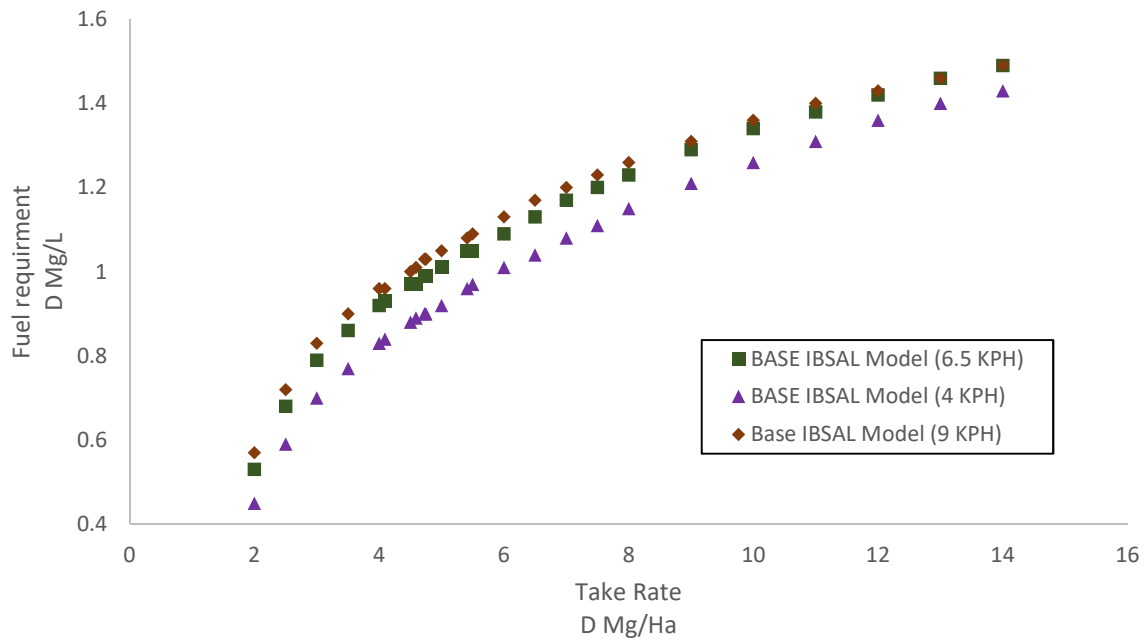


Figure 5.4 IBSAL model results showing the effect of harvest speed on residue harvesting fuel requirements

Machine size. As swathe widths increase harvest cost decrease as shown in Figure 5.5. Increasing the header size from an 8 row header, 6.1 m, to a 12 row header, 9.1 m. increases the swath width by 50%, and decreases the cost of baling a dry Mg of stover by 21% on average. Doubling the header size from an 8 row to 16 row, 6.1 m to 12.2 m, decreases baling cost by 32% on average.

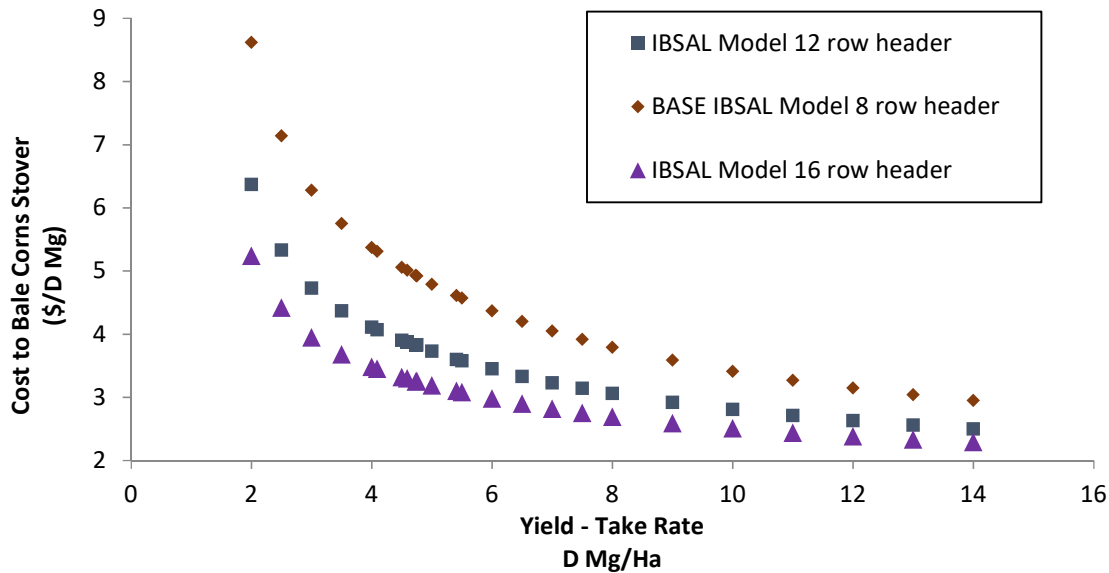


Figure 5.5 IBSAL model results showing the effect of swathe width on harvesting costs

The fuel required to harvest a dry Mg of corn stover decrease as header width increases across all take rates. On average, a 12 row head will harvest 21.8% more stover per a liter of fuel than an 8 row head. A 16 row head will harvest 36.9% more stover per liter of fuel.

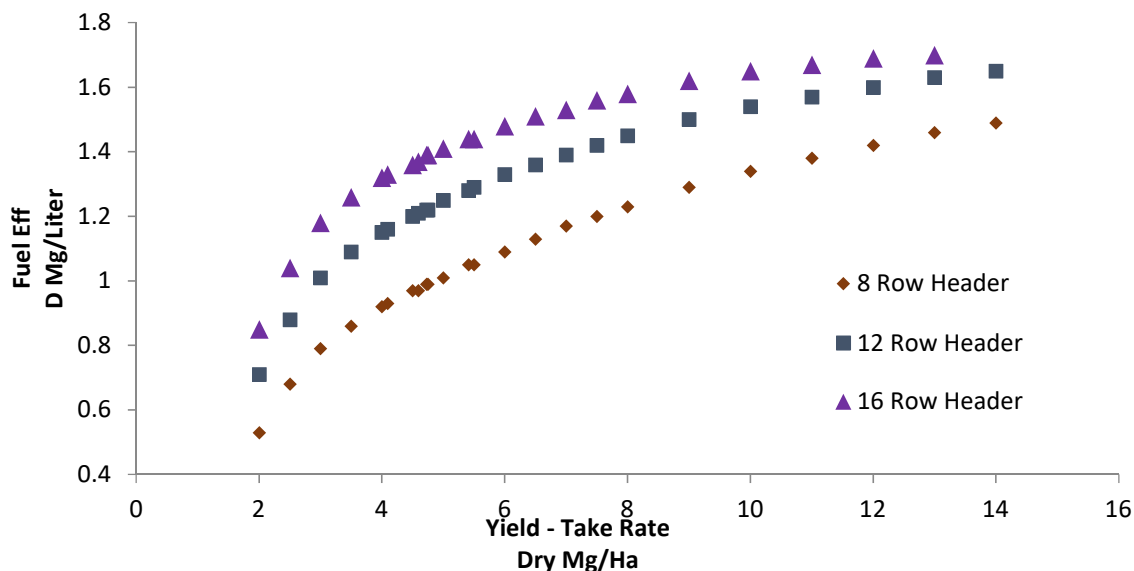


Figure 5.6 IBSAL model results showing the effect of swathe width on harvest fuel efficiency.

Bale Density. As bale density increases, baling cost increases as shown in Figure 5.7.

The base bale weight assumed in the IBSAL model used is 475 kg, or a bale density of 174.1 kg/m³. To explore the cost variability two bale weights were chosen for comparison: a 376 kg and a 581 kg. These weights were chosen because they are representative of the range of bale weight found in the collected field data. A 475 kg bale costs on average 14.6% more to form than a 376 kg bale. A 581 kg bale costs an average of 20.2% more to form than a 475 kg bale. The difference in cost between the three bale densities increases slightly as take rates increase. While baling costs increase as bale density increases, overall harvest costs decrease as fewer bales must be collected and transported to the field edge. Like all other costs, as take rates increase, baling costs decrease.

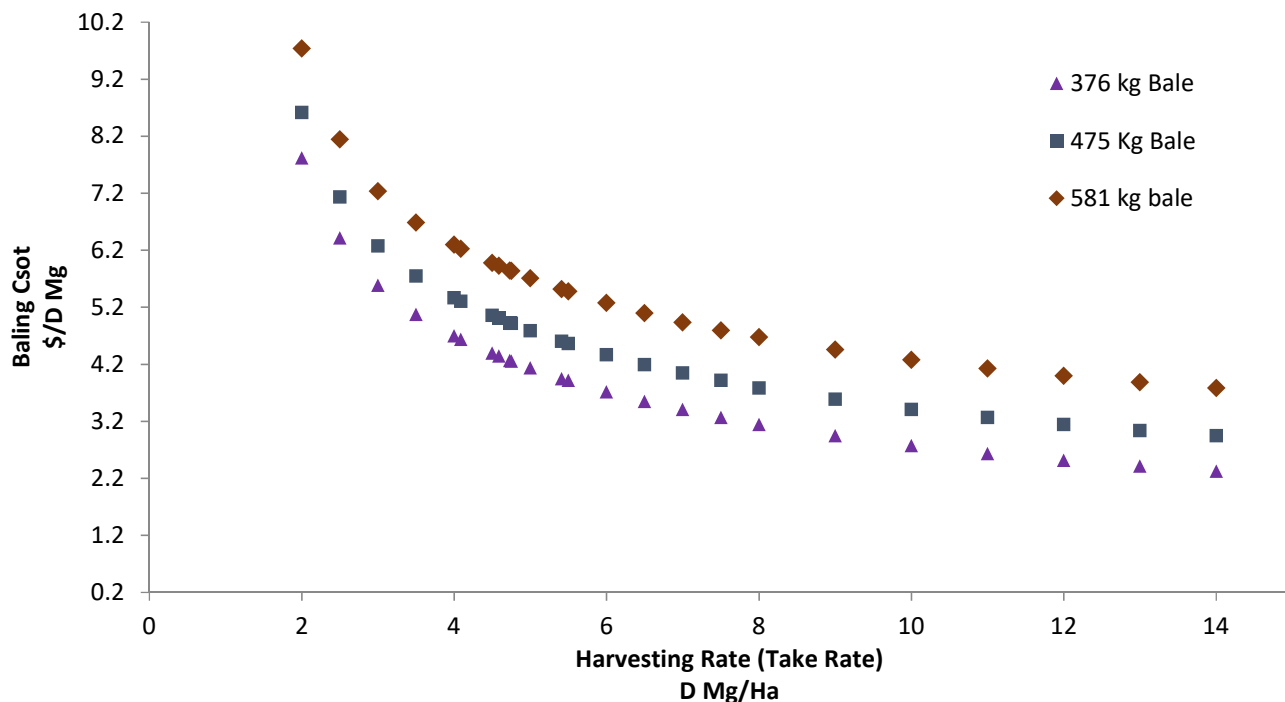


Figure 5.7 Bale density influence on baling cost

Fuel efficiency improves as harvest rates increase with heavier bales. Like baling costs, a lighter bale requires less fuel to form than a heavier bale. However, the reduction in fuel

required to form the bale is made up for in the fuel requirement of the whole harvest system. Lighter bales require many more trips to collect and move all the bales, and harvested biomass, to the field edge. The difference in efficiency of fuel per Mg of harvested residue increases as take rate increase. At a take rate of 2 dry Mg/Ha, the difference between 376 kg bales and 581 kg bales is only 24.5%. At the high end of the harvest range, 14 dry Mg/Ha, the difference is significant 64.4%.

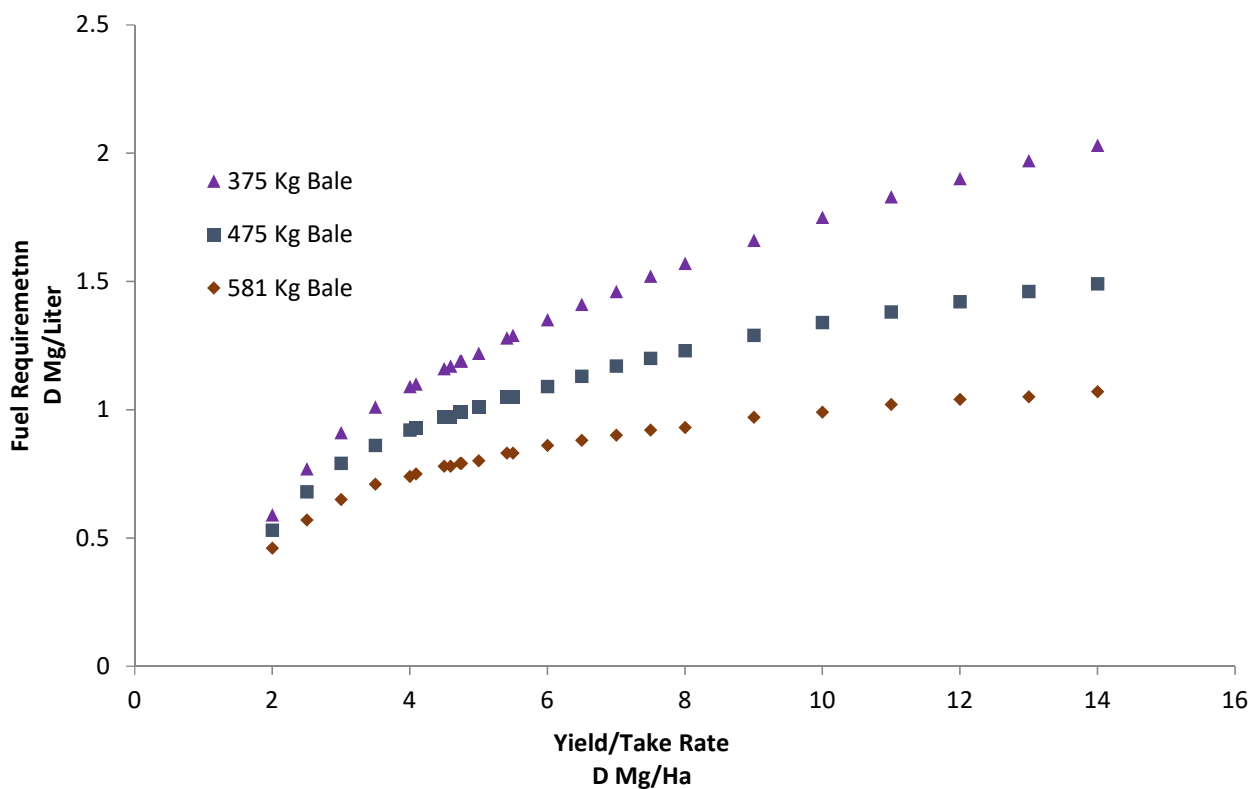


Figure 5.8 Baling fuel efficiency as bale density increases over a range of take rates

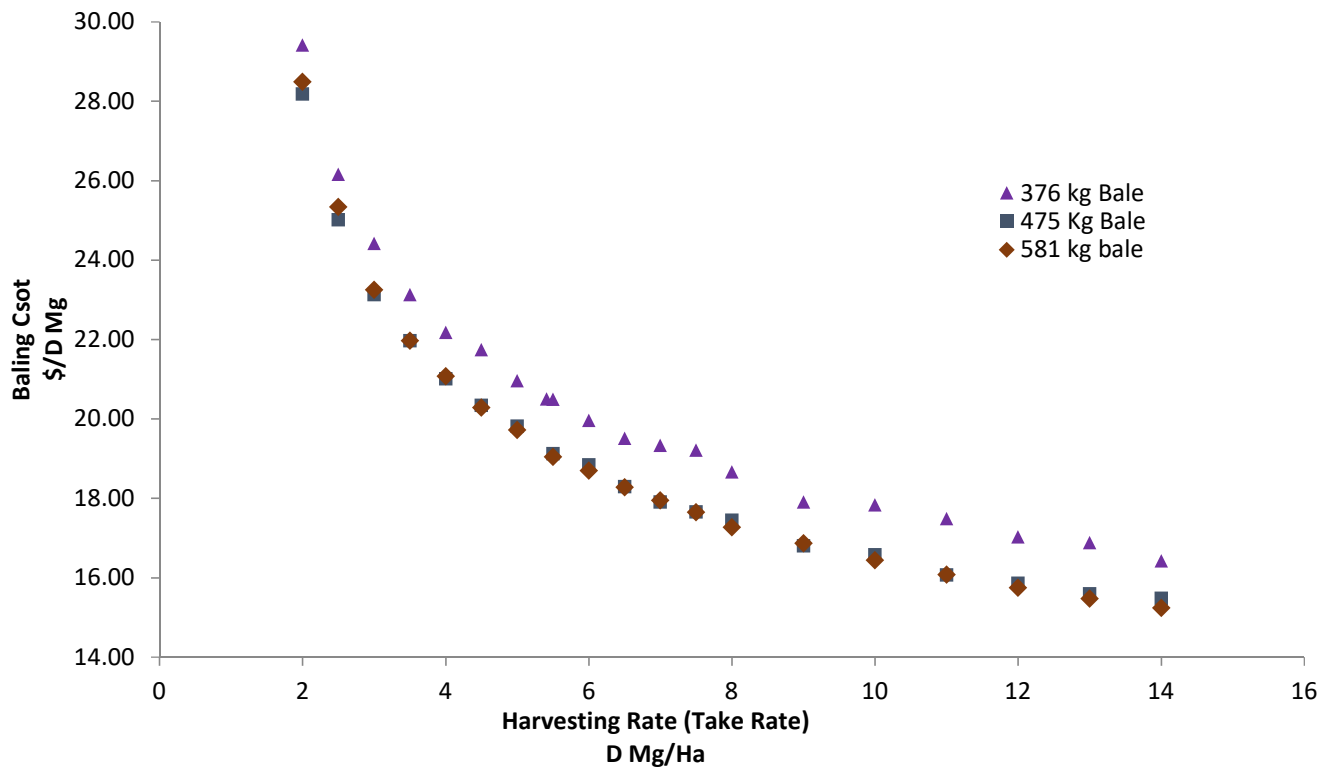


Figure 5.9 Comparison of total harvest cost as bale density increases.

As bale density increases, the cost to bale and move stover to the field edge decreases. Heavier bales, reduce the number of bales to handle, thereby decreasing the overall cost to bale, collect, and move stover to the field edge. The comparison of the baling and collection cost of all three bale weights considered is shown in Figure 5.9. The reduction in cost is not linear and decreases as bales become denser. A 475 kg bale is 6.36% less costly to work with than a 376 kg bale. However, the cost improvement from 475 Kg to 581 Kg is almost none existent. On average, there is only a 1% or less improvement in cost between the two heavier bale densities. This decrease in cost improvement is likely reflective of the energy required to form the heavier bales. The fuel usage comparison between the three bale densities is shown in Figure 5.10. There is less than 2% difference, on average, in fuel usage between the 475 Kg bales and the

581Kg bale. The fuel usage difference is much greater, 8.27% on average, between the 376 Kg bales and the 475 Kg bales.

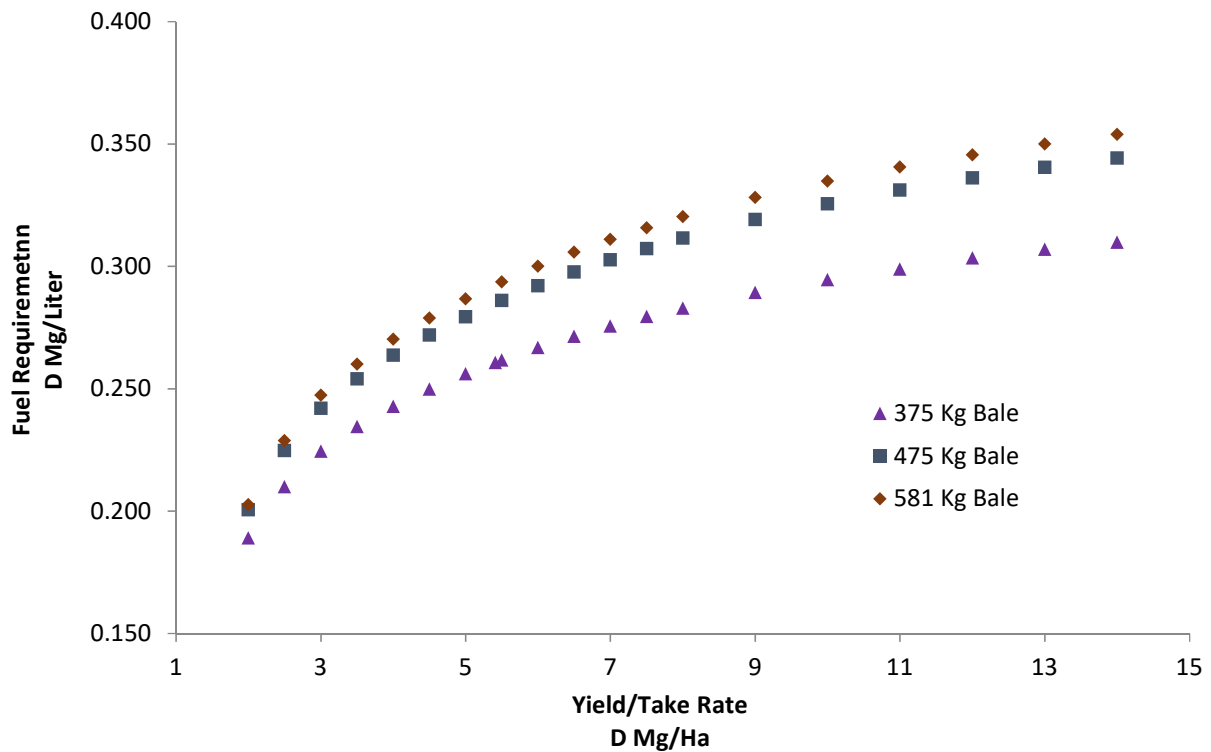


Figure 5.10 Comparison of total fuel requirements to bale and move stover to the field edge as bale density increases

These results would seem to indicate that while there are fewer bales to move as bale density increases there is a point at which the energy required to form a bale more than offsets the energy reduction trips necessary to collect dense bales would result in.

Moisture Content. Dry stover is harder to compact than wet stover (Van Pelt, 2003).

Consequently, the power required to form a bale from wet stover is less than that required for dry stover. This fact translates into baling costs and fuel efficiencies that would indicate baling stover at a higher moisture content is advantageous. The IBSAL model results do indicate that at low take rates, dry stover is slightly more economical to harvest than wet stover. However, as take rates increase, the wet stover becomes more economical to harvest. At take rates above 6 dry Mg/Ha wet stover is above 20% more economical to harvest than dry stover according to the IBSAL model.

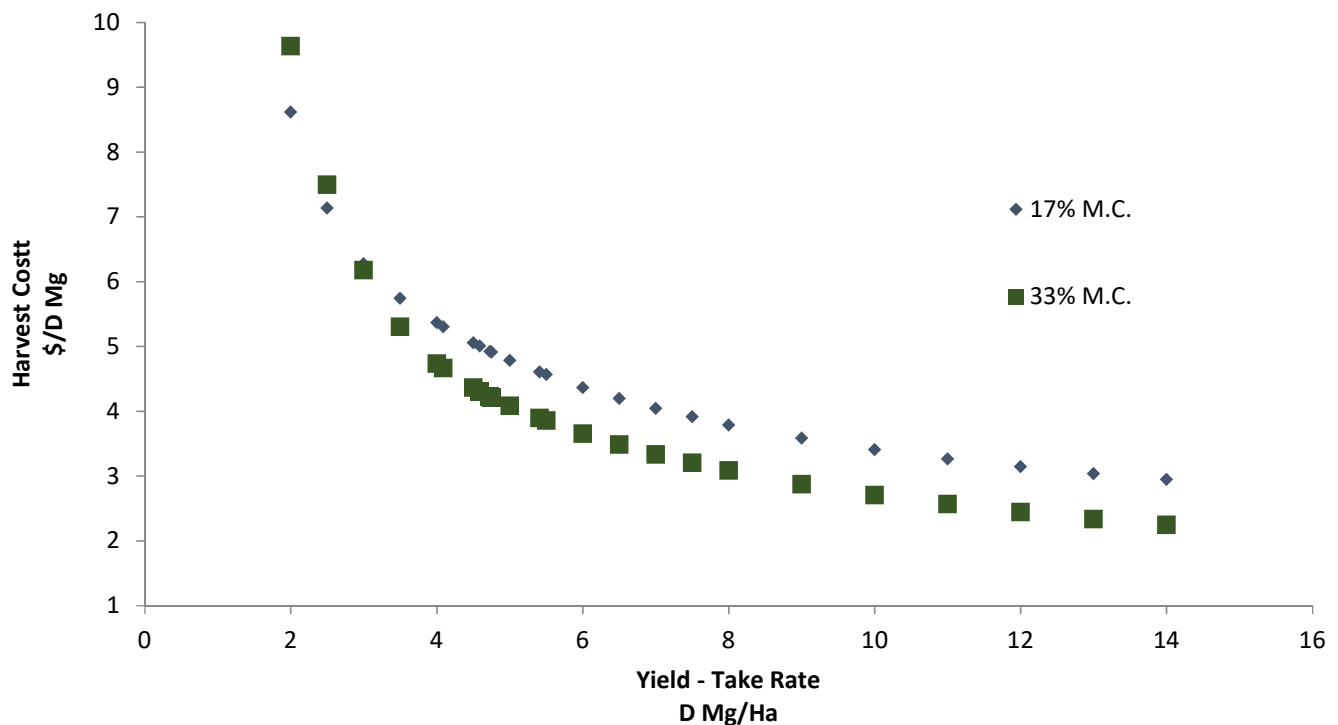


Figure 5.11 Effect of moisture content on baling costs

According to the IBSAL model, since dry stover is harder to compact than wet stover, the overall fuel efficiency of baling stover at low moisture content is less. On average, the IBSAL model reports that dry stover requires 16.5% more fuel to harvest than wet stover. Like baling costs, at low take rates, wet stover is slightly less efficient to bale, but once take rates are above 4 dry Mg/Ha, dry stover becomes more efficient to harvest according to the IBSAL model.

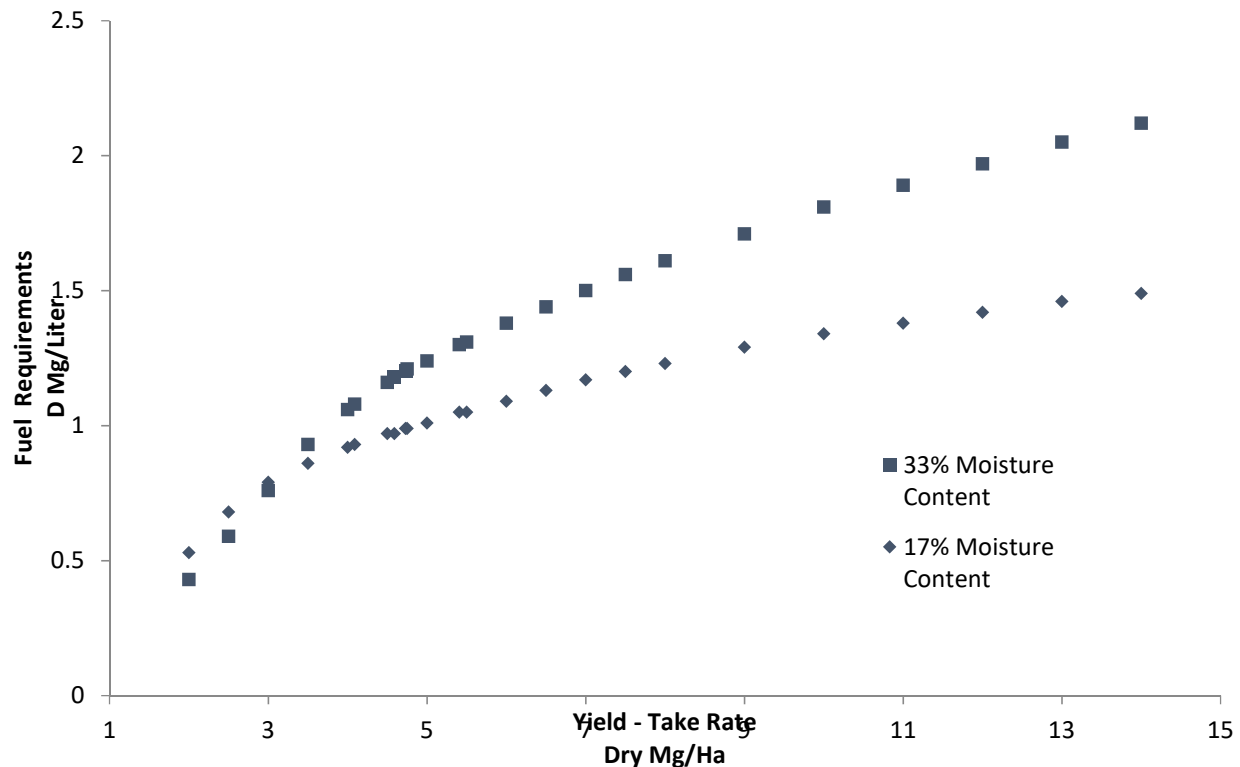


Figure 5.12 Effect of moisture content of biomass on baling fuel requirements

These results from the IBSAL model are not seen in the field test data. As can be seen in Table 2-4 in Chapter 2, the exact is opposite occurs. At higher stover moisture content, the cost and fuel required to harvest stover increases as bale moisture increases. This would indicate that the modified IBSAL model does not yet have the capability of predicting cost and fuel usage for stover moisture content above 17%.

Labor costs. The cost of labor has minimal effect on the cost of baling of stover in the single-pass system. Only an overhead charge of 20% of the production hours is applied to the actual baling step (USDA-NRCS, 1998). Labor is a small part of the overall cost of baling of corn stover. Consequently, it has a minimal effect on the cost of baling and differences of labor costs then become minimal. Over all the take rates considered, a \$6.00/hour labor rate change results in only a 1% or less change in the cost of baling.

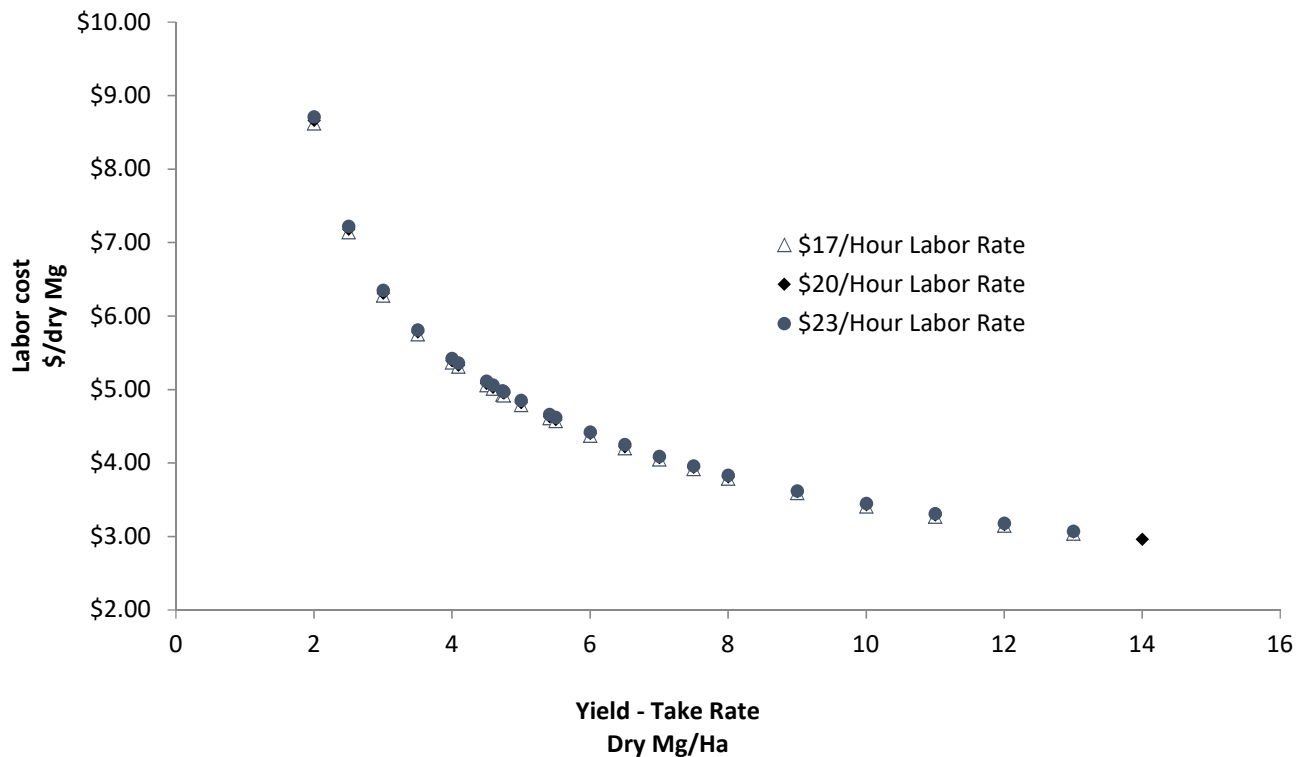


Figure 5.13 Labor cost effect on the cost of single-pass baling of corn stover

Vary Fuel Costs. Fuel cost have a greater effect to the cost of baling compared to labor cost. Regardless of take rate, fuel usage remains the same, therefore changes in fuel cost changes the cost of harvesting proportionally across the entire range of “take rates”. Two fuel costs were investigated, \$0.89/liter and \$0.72/liter. These costs are representative of fuel costs in 2011 and 2018 respectively. An increase in fuel cost does increase the cost of bale formation as would be expected. The effect though is muted. Over the two fuel prices considered, a 22.3% increase in fuel costs resulted in only 9.7% increase in baling costs.

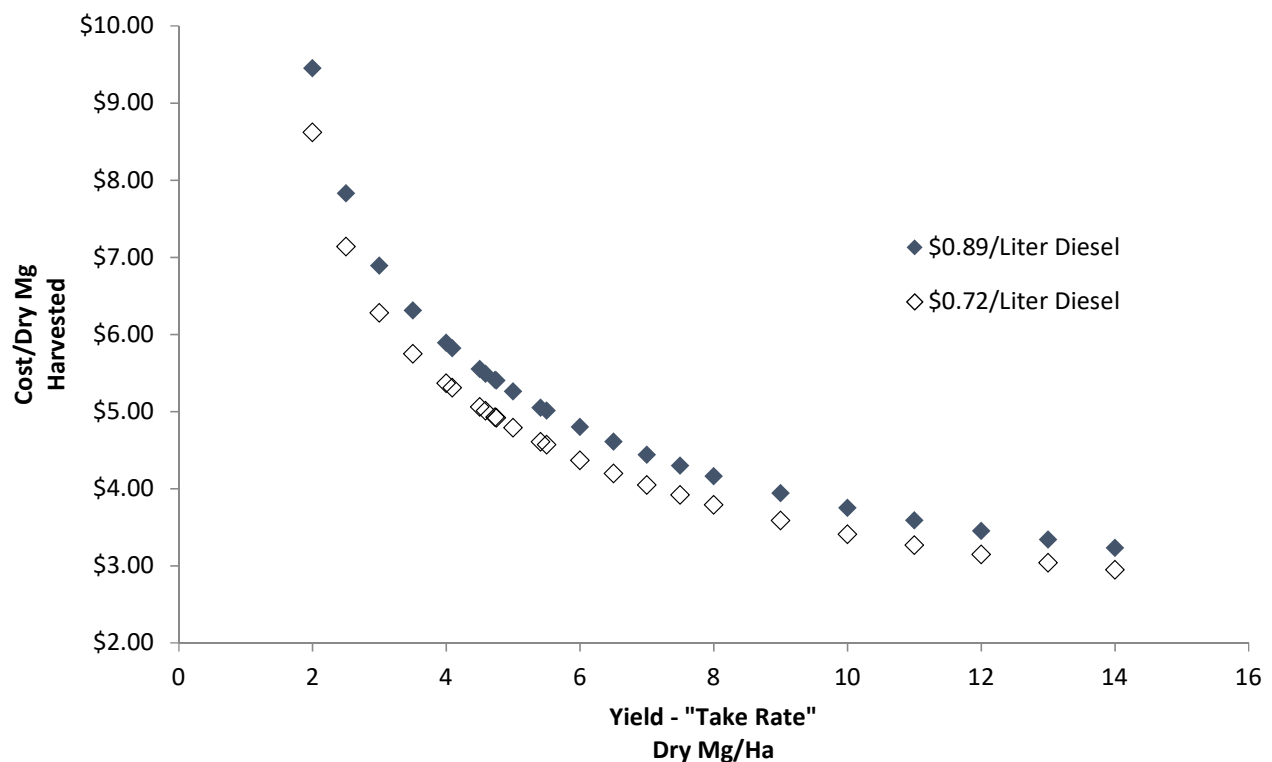


Figure 5.14 Fuel cost effect on single-pass baling cost of corn stover

5.4 Conclusions

In general, the cost of single-pass baling of corn stover varies with the amount of crop that is harvested. The more biomass per hectare harvested, large yields and larger “take rates”, spreads fixed and variable costs over more material and thereby reduces costs. Lower “take rates” are more expensive to harvest than higher harvest rates, as shown Figure 5.1. Likewise, as “take rates” increase, fuel usage per dry Mg. decreases. This study tracked and then plotted the results of each as each harvest variable was considered. In considering the resulting curves for each of the harvest variables, a consistent thread could be seen in each plot. Any change in a harvest variable that increased the residue harvest rate, or throughput of the baling step, reduced the cost of baling and improved the fuel efficiency of the process. Conversely, as harvest through put decreased, costs increased and efficiencies decreased.

Bale density variations must be considered within the context of the complete harvesting process. Bale density changes seemed to indicate that less dense bales were less costly and more fuel efficient to form than more dense bales when considered within the narrow scope of the baling process only. When the whole harvest process was considered, though, the dense or heavier bales became less costly and more fuel efficient harvest.

High moisture content stover harvest results from the IBSAL model were found to be unreliable and counter to field data that was previously analyzed. More work must be done to the IBSAL model before this variable can be effectively explored with it.

Labor and fuel costs do have an effect on costs, but the variations are proportional to their percentage of the overall cost of baling stover and the magnitude of price change. Labor is a very small part of single-pass baling and has a very small effect on cost. Fuel prices have a larger effect that is proportional to the amount of cost change per liter of fuel. A small

percentage change in fuel cost will have a very small change in baling costs. From this study, it would appear that a 1% change in fuel costs will result in about 0.5% change in harvesting cost.

From a producer's perspective, understanding changes in harvest costs and fuel requirements is an important consideration with crop residue harvesting. Unlike traditional crops where the harvest goal is to harvest as much material as possible, with crop residues, producers must choose how much residue is to be harvested. Producers will not have the luxury of considering each harvest variables individually as has been in this study. Producers will have to make their decision based on a collection of the variables. The value of this study to a producer is the understanding the cost and efficiency trends and then using them to guide harvest decisions.

In general, based on this work a producer will want to do the follow when considering the harvest of corn stover when using the described single-pass harvesting system.

- Maximize “take rates”, swathe widths, and field speeds
- Target a bale weight of at least 475kg. Weights above this do not seem to improve harvest costs by much and may actually begin to increase the cost of harvesting a Mg of stover.
- Labor rates have a very small effect on harvesting cost
- Fuel prices have a larger effect and should be taken into consideration in marginal profit situations.

Chapter 6 Corn Stover Harvest Decision Tool

6.1 Introduction

In 2005 a report titled *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (generally referred to as the *Billion Ton Study* or (2005 BTS) was published by the United States Department of Energy (DOE). The goal of this report was to consider if 30% of the United States petroleum based energy supply could be replaced by biomass. Agricultural biomass sourced material was considered to be a major portion of the billion ton supply of biomass in the short term. The report indicated that some of the available feedstocks could be too expensive to utilize for energy. Crop residues, corn stover and wheat straw, were among these feedstocks that were identified that harvesting methods that could be improved upon. The BTS 2005 called for the development of purpose built equipment to harvest (or collect) corn stover and wheat straw and to conduct field scale tests to accurately assess the harvesting costs for these materials.

In 2008, the DOE awarded five feedstock development grants to develop the feasibility of collecting some of the biomass feedstocks outlined in the 2005 BTS and other studies. AGCO's Hesston, Kansas division was one of the awardees of a development grant. Their project was titled "*Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to supply Crop Residues and A Herbaceous Energy Crops in a Diversified Large Square Bale Format*" (AGCO project). A portion of this project focused on the harvest and collection of crop residues (corn stover and wheat straw). This project was intended to develop specialized equipment for the harvest of biomass and conduct field scale tests of the developed equipment. The field scale costs would provide accurate harvest cost information based on the

newly developed equipment. This project was completed in 2013. The AGCO project resulted in the development of a number of new pieces of equipment and field scale biomass harvest data.

6.1.1 Problem Statement and Objective

The AGCO project was focused on the cost of collection or harvest of agricultural residues as were many of the other studies published prior to 2010. **These studies are considered from the perspective of the processors (biorefinery) who would convert agricultural residues into ethanol or other bio based products (Perlack et al., 2005; Perlack et al., 2011).** These studies do not consider the production decision to supply agricultural residues to the biorefinery from a producer perspective. Studies that have considered the harvest of corn stover from a producer's perspective only consider a conventional multi pass method of harvesting corn stover, (Hess, 2007; Khanna et al., 2016).

The objective of this work is to expand upon an existing cost prediction model, to develop a decisions tool for producers considering the harvest of corn stover. This decision tool will use updated cost information developed from field test data and new residue harvest equipment and techniques that were developed specifically for the harvest of crop residues. The decision tool compares the cost a producer would expect to see utilizing three different stover harvesting techniques: conventional multi pass, two-pass and single-pass methods.

6.2 Materials and Methods

Madhu Khanna and Nick Paulson, Department of Agricultural and Consumer Economics at the University of Illinois Urbana-Champaign, developed a cost model (Khanna model) to estimate a producer's cost to supply biomass to a biorefinery (Khanna, 2016). The Khanna model combines published nutrient replacement costs, shipping and handling costs, and

conventional stover harvesting costs to estimate stover supply costs a producer might incur when

	A	B	C	D	E	F
1			High	High	High	High
2	Rotation		Cont Corn	Cont Corn	Corn Bean	Corn Bean
3	Tillage Practice		Tillage	No Till	Tillage	No Till
4	Corn Yield (bu/acre)		158	158	180	180
5	Corn Yield (Mg/Ha)		9.92	9.92	11.30	11.30
6	Stover Yield (Mg/Ha)		9.92	9.92	11.30	11.30
7	Take rate %		30.00%	50.00%	30.00%	50.00%
8	Yield(Take Rate) Wet Mg/Ha		2.98	4.96	3.39	5.65
9	Yield (Take Rate) D Mg/Ha		2.53	4.21	2.88	4.80
10	Storage Loss (total)	7.0%	0.177	0.295	0.20168	0.336
11	Net D Mg/Ha		2.35	3.92	2.6794	4.47
12	Collection					
13	Mow	\$/d mg	16.44	16.44	16.44	16.44
14	Rake		11.69	11.69	11.69	11.69
15	Move to field Edge	\$/d mg	23.88	28.73	24.90	30.46
16	Cost Dry ton Field edge	\$/d mg	52.00	56.85	53.02	58.58
17	Collection Sub total	\$/Ha	122.30	222.84	142.07	261.60
18	Shipping	\$/d Mg				
19	Load at field edge	\$0.88	2.23	3.72	2.54	4.23
20	Truck to Depot(40 km)	\$3.86	9.76	16.26	11.12	18.53
21	Unload at depot	\$0.88	2.23	3.72	2.54	4.23
22	Store at depot	\$3.79	9.59	15.98	10.92	18.21
23	Load at Depot	\$0.99	2.51	4.18	2.86	4.76
24	Truck to Depot(40 km)	\$3.86	9.76	16.26	11.12	18.53
25	Unload at plant	\$0.88	2.23	3.72	2.54	4.23
26						
27	Storage, transport & loading		38.30	63.84	43.64	72.73
28	Agronomic Replacement costs					
29	Nitrogen	(\$/Ha)	6.81	11.34	7.75	12.92
30	Phosphorus	(\$/Ha)	2.22	3.70	2.53	4.22
31	Potassium	(\$/Ha)	12.78	21.30	14.56	24.27
32	Sub Total Fertilizer replace cost	(\$/Ha)	21.81	36.35	24.85	41.41
33						
34						
35	Total Cost of stover harvest (\$/Ha)		182.41	323.03	210.56	375.74
36	Breakeven Revenue plant gate (\$/Ha)		182.41	323.03	210.56	375.74
37	Breakeven price of Corn stover at Plant gate (\$/D Mg)		77.56	82.41	78.58	84.14
38	Desired profit (\$/D Mg)		9.92	9.92	9.92	9.92
39	Desired price of stover at plant gate (\$/D Mg)		87.48	92.33	88.50	94.06
40	Offered price at plant gate(\$/D Mg)		49.60	49.60	49.60	49.60
41	Above or below stover price (\$)		37.88	42.73	38.90	44.46

Figure 6.1 Base Khanna model recreated using SI units and modified to include a producer profit

supplying biomass to the biorefinery gate. The model also considers several different cropping systems a producer might be using, which in turn influences the amount of stover that a producer can safely remove without harming soil health and productivity. The cropping systems considered are corn-corn and corn-soybean rotations in full tillage and no-till production

systems. The basic model Khanna developed is shown in Figure 6.1. The model shown, includes a \$9.92/dry Mg profit margin that a producer might consider appropriate when supplying corn stover to a biorefinery (Sheehan, 2004).

In order to develop a more robust decision tool for producers to use, additional harvesting systems and an expanded range of yield or “take rates” were added to the base Khanna model to develop a decision tool for producers. Three basic harvesting methods a producer might consider using for harvesting corn stover are defined as follows.

- Conventional multi-pass harvesting consisting of these steps: stock shredding/mowing, raking, baling, and bale collection. The “take rate”, or amount harvested, for this method is controlled by machine settings during the shredding and raking steps. This method allows a producer to use commonly available collection equipment to harvest stover.
- Two-pass harvesting method consisting of these steps: harvest corn without stock shredder engaged (windrow the residue), bale in a second pass, and bale collection. The “take rate” for this method of harvesting is dependent upon how the corn head and baler pickup are set. This harvest system requires only conventional baler to bale corn stover.
- Single-pass harvesting method consisting of a single baling pass and a bale collection step. The baling pass is accomplished with a specialized baler towed behind the combine with a custom built feed that collects and bales residue that comes off the combine separation unit. The “take rate” for this harvesting method is dependent upon the setting of the corn head. This harvest system requires the use of a specialized baler for harvesting crop residue.

Harvesting cost for the three harvest systems used in the decision tool are derived from the Khanna paper itself and costs developed from field test data collected in 2010, 2011, and 2012 and analyzed in Chapter 2.

6.2.1 Data Analysis and Cost Prediction.

The cost for the conventional harvesting system used for this comparison were developed from the Khanna paper. The paper lists harvesting costs for each of the different steps within a conventional harvesting system. These costs are all shown as per hectare costs. Where yield of the biomass influences the cost of harvesting, baling, and bale collection, the “per hectare” cost is modified to reflect the appropriate cost. This work covers a larger range of yields than the Khanna paper and it was necessary to derive baling costs for these larger yields. Costs for varied yields were developed by performing an Excel linear regression based on the values given in the paper. The resulting equation was used to calculate baling cost/hectare based on yield.

Two-pass harvesting costs are based on field test data. Costs for two-pass harvesting were developed on per dry Mg bases from the data collected. Costs for yields over a wider range of yields were developed by performing a log-log regression based on the data collected and analyzed in Chapter 2. The resulting equation from the regression was used to calculate baling cost over the considered ranges of crop yields. Values from this equation were developed in \$/dry Mg. For comparison purpose with the Khanna model, these values were then converted to \$/hectare.

Single-pass harvesting costs are based on field test data in the same fields and at the same time as the two-pass harvesting data. Costs for single-pass harvesting were developed on per dry Mg bases for the data points collected. Costs single-pass baling were estimated using the cost equation developed in Chapter 4 for the target cost curve used to modify the IBSAL model. In

order to compare these results with the Khanna model these values were then converted to \$/hectares units.

The harvest or “take rate” in the Khanna model is explored over a range from 1.33 dry Mg/Ha to 6.90 dry Mg/Ha. This biomass yield range is based on corn grain yield from 7.53 Mg/Ha to 13.81 Mg/Ha and two different allowable “take rate” percentage assumptions for harvesting the available biomass. The assumptions are that only 30% of residue can be harvested in fields where conventional tillage practices are used and 50% of the residue can be harvested when no-till practices are used (Khanna, 2016).

The Khanna model itself, looks at four different variables in corn production that create eight separate conditions for a producer to consider when choosing whether to harvest corn stover. These treatments are: Tillage field preparation vs No-Till field preparation; corn – corn rotation vs corn – soybean crop rotation practices; high yielding crop vs low yielding crop; and two different “take rates” of 30% and 50%. The model makes a base assumption that stover removal from a tillage system must be limited to a 30% stover “take rate” in order to leave enough organic matter in the field to protect the soil from erosion and maintain soil carbon levels. An increased amount of stover, 50%, is allowed to be taken from No-Till using the assumption that there is a base amount of ground cover in place from previous crops already in place to protect the soil from erosion and no soil carbon is lost to a tillage step. For this study, these two “take rate” will be held constant.

The model used in this analysis assumes that all stover is harvested at 15% moisture content. Nutrient replacement rates are based on the amount of stover removed. Replacement rates are as follows: 3.5 kg nitrogen/d Mg stover removed, 0.8 Kg phosphate/d Mg stover removed, and 7.6 kg potash/d Mg stover removed. The model makes some basic shipping,

handling, and spoilage assumptions that are as follows: spoilage is considered to be 7%, a depot system is used, it is 40 km from the farm to the depot, 40 km from the depot to the plant gate, storage at the depot is a level cost, and each dry Mg of stover is loaded or unloaded four times.

A comparison spreadsheet decision tool that expands upon the Khanna model was constructed. It includes single-pass, two-pass, and conventional multi pass stover harvesting. The three harvest cases considered are shown in Figure 6.2. The Khanna paper only considered the breakeven price for corn stover harvest and did not consider an “offer to buy” stover price from the biorefinery or desired profit per dry Mg that the producer might demand. The model

	A	B	D	E	F	H	I	J	L
1	SINGLE PASS HARVESTING			TWO PASS HARVESTING			Conventional Harvesting		
2	Rotation		Cont Corn	Rotation		Cont Corn	Rotation		Cont Corn
3	Tillage Practice	Tillage		Tillage Practice	Tillage		Tillage Practice	Tillage	
4	Corn Yield (bu/acre)	120		Corn Yield (bu/acre)	120		Corn Yield (bu/acre)	120	
5	Corn Yield (Mg/Ha)	7.53		Corn Yield (Mg/Ha)	7.53		Corn Yield (Mg/Ha)	7.53	
6	Stover Yield (Mg/Ha)	7.53		Stover Yield (Mg/Ha)	7.53		Stover Yield (Mg/Ha)	7.53	
7	Take rate %	30.00%		Take rate %	30.00%		Take rate %	30%	
8	Gross Yield (Take Rate) Wet Mg/Ha 15% m.c.	2.26		Gross Yield (Take Rate) Wet Mg/Ha 15% m.c.	2.26		Gross Yield (Take Rate) Wet Mg/Ha 15% m.c.	2.26	
9	Net yield (Take Rate) Mg/Ha	1.92		Net yield (Take Rate) Mg/Ha	1.92		Net yield (Take Rate) Mg/Ha	1.92	
10	Storage Loss (total)	7.0%	0.134	Storage Loss (total)	7.0%	0.134	Storage Loss (total)	7%	0.134
11	Net to Plant gate D Mg/Ha	1.79		Net to Plant gate D Mg/Ha	1.79		Net to Plant gate D Mg/Ha	1.79	
12	Collection			Collection			Collection		
13	Single pass	\$/D Mg	8.01	Single pass	\$/D Mg		Mowing	\$/Ha	36.84
14	Two Pass			Two Pass	\$/D Mg	11.48	Raking	\$/Ha	11.69
15	Move to field edge	\$/D Mg	5.48	Move to field edge	\$/D Mg	5.48	Baling	\$/Ha	48.01
16	Cost/Dry ton @ Field edge	\$/D Mg	13.49	Cost Dry ton Field edge	\$/D Mg	16.96	Move to field edge (\$/Ha)	5.48	10.53
17	Collection Sub total	\$/Ha	25.91	Collection Sub total	\$/Ha	32.58	Collection Sub total	\$/Ha	107.07
18	Shipping & Handling			Shipping & Handling			Shipping & Handling		
19	Load at field edge (\$/Ha)		1.94	Load at field edge (\$/Ha)		1.94	Load at field edge (\$/Ha)		1.65
20	Truck to Depot 40 km (\$/Ha)		8.72	Truck to Depot 40 km (\$/Ha)		8.72	Truck to Depot 40 km (\$/Ha)		7.41
21	Unload at depot (\$/Ha)		1.94	Unload at depot (\$/Ha)		1.94	Unload at depot (\$/Ha)		1.65
22	Store at depot (\$/Ha)		8.57	Store at depot (\$/Ha)		8.57	Store at depot (\$/Ha)		7.28
23	Load at Depot (\$/Ha)		1.94	Load at Depot (\$/Ha)		1.94	Load at Depot (\$/Ha)		1.65
24	Truck to plant 40 km (\$/Ha)		8.72	Truck to plant 40 km (\$/Ha)		8.72	Truck to plant 40 km (\$/Ha)		7.41
25	Unload at plant (\$/Ha)		1.94	Unload at plant (\$/Ha)		1.94	Unload at plant (\$/Ha)		1.65
26									
27	Storage, transport & loading sub total (\$/Ha)		33.78	Storage, transport & loading sub total (\$/Ha)		33.78	Storage, transport & loading sub total (\$/Ha)		51.28
28	Agronomic Replacement costs			Agronomic Replacement costs			Agronomic Replacement costs		
29	Nitrogen (\$/Ha)		6.08	Nitrogen (\$/Ha)		6.08	Nitrogen (\$/Ha)		6.08
30	Phosphorus (\$/Ha)		1.98	Phosphorus (\$/Ha)		1.98	Phosphorus (\$/Ha)		1.98
31	Potassium (\$/Ha)		11.42	Potassium (\$/Ha)		11.42	Potassium (\$/Ha)		11.42
32	Sub Total Fertilizer replace cost (\$/Ha)		19.49	Sub Total Fertilizer replace cost (\$/Ha)		19.49	Sub Total Fertilizer replace cost (\$/Ha)		19.49
33	Other			Other			Other		
34									
35	Total Cost of stover harvest (\$/Ha)		79.17	Total Cost of stover harvest (\$/Ha)		85.84	Total Cost of stover harvest (\$/Ha)		177.84
36	Break Even Revenue at Plant gate (\$/Ha)		79.17	Break Even Revenue at Plant gate (\$/Ha)		85.84	Break Even Revenue at Plant gate (\$/Ha)		177.84
37	Break even corn stover price at plant gate (\$/Mg)		44.32	Break even corn stover price at plant gate (\$/Mg)		48.06	Break even corn stover price at plant gate (\$/Mg)		99.56
38	Desired profit (\$/D Mg)		9.92	Desired profit (\$/D Mg)		9.92	Desired profit (\$/D Mg)		9.92
39	Offered price of Corn stover at Plant gate (\$/D Mg)		54.24	Offered price of Corn stover at Plant gate (\$/D Mg)		57.98	Offered price of Corn stover at Plant gate (\$/D Mg)		109.48
40	Offered price at plant gate (\$/D Mg)		61.00	Offered price at plant gate (\$/D Mg)		61.00	Offered price at plant gate (\$/D Mg)		61.00
41	Above or below desired stover price (\$)		6.76	Above or below desired stover price (\$)		3.02	Above or below desired stover price (\$)		48.48

shown in Figure 6.2.

Figure 6.2 Base case producer decision models

6.3 Results and Discussion

The three base model variations shown in Figure 6.2 were used to build decision tables that a producer could use to consider different harvest systems, cropping rotations, tillage practices, and stover “take rates”. The decision tables provide the opportunity to evaluate the profitability for each variable scenario. Sample output images from the decision table are shown in Figure 6.3 to Figure 6.6. (Note: producer inputs are highlighted in light green.)

	A	B	C	E	F	G	H	I	J	K	L	M	N	O	P
1	Tilled Take Rate	30%		Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn
2	No Tilled Take Rate	50%		Tillage Practice	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage
3				Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210	220
4	Expected Profit/Dry Mg	\$ -		Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
5	Offer Price by Biorefinery (\$/D Mg)	\$ 50.00		Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
6	Replacement Nutrient	\$/Mg		Take rate %	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
7	anhydrous ammonia	623		Yield (Take Rate) Mg/Ha 15% m.c.	2.26	2.45	2.64	2.82	3.01	3.20	3.39	3.58	3.77	3.95	4.14
8	Dammonium Phosphate	516		Net yield (Take Rate) D Mg/Ha	1.92	2.08	2.24	2.40	2.56	2.72	2.88	3.04	3.20	3.36	3.52
9	Potash	399		Storage Loss (total)	0.134	0.146	0.157	0.168	0.179	0.190	0.202	0.213	0.224	0.235	0.246
10	Storage Loss %	7%		Net D Mg/Ha	1.79	1.94	2.08	2.23	2.38	2.53	2.68	2.83	2.98	3.13	3.27
31				Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage
32	Two Pass Conventional		Above or below profitable stover price (\$)	36.15	32.47	29.31	26.57	24.17	22.06	20.18	18.50	16.98	15.61	14.37	
33	Two Pass AGCO		Above or below profitable stover price (\$)	5.03	5.40	5.73	6.02	6.29	6.53	6.75	6.95	7.14	7.31	7.48	
34	Single Pass AGCO		Above or below profitable stover price (\$)	5.68	6.03	6.34	6.62	6.87	7.10	7.31	7.51	7.69	7.85	8.01	

Figure 6.3 Corn-corn rotation, tilled

	A	B	C	R	S	T	U	V	W	X	Y	Z	AA	AB	A
1	Tilled Take Rate	30%		Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn	Cont Corn
2	No Tilled Take Rate	50%		Tillage Practice	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till
3				Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210	220
4	Expected Profit/Dry Mg	\$ -		Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
5	Offer Price by Biorefinery (\$/D Mg)	\$ 50.00		Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
6	Replacement Nutrient	\$/Mg		Take rate %	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
7	anhydrous ammonia	623		Yield (Take Rate) Mg/Ha 15% m.c.	0.50	4.08	4.39	4.71	5.02	5.34	5.65	5.96	6.28	6.59	6.90
8	Dammonium Phosphate	516		Net yield (Take Rate) D Mg/Ha	3.20	3.47	3.73	4.00	4.27	4.53	4.80	5.07	5.34	5.60	5.87
9	Potash	399		Storage Loss (total)	0.224	0.243	0.261	0.280	0.299	0.317	0.336	0.355	0.373	0.392	0.411
10	Storage Loss %	7%		Net D Mg/Ha	2.98	3.23	3.47	3.72	3.97	4.22	4.47	4.71	4.96	5.21	5.46
31				No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till
32	Two Pass Conventional		Above or below profitable stover price (\$)	16.98	14.77	12.87	11.23	9.79	8.52	7.40	6.39	5.48	4.66	3.91	
33	Two Pass AGCO		Above or below profitable stover price (\$)	7.14	7.42	7.67	7.90	8.11	8.29	8.46	8.62	8.77	8.90	9.02	
34	Single Pass AGCO		Above or below profitable stover price (\$)	7.69	7.96	8.20	8.41	8.60	8.78	8.94	9.09	9.23	9.35	9.47	

Figure 6.4 Corn-Corn rotation, No-Till

	A	B	C	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1	Tilled Take Rate	30%		Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean
2	No Tilled Take Rate	50%		Tillage Practice	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage
3				Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210
4	Expected Profit/Dry Mg	\$ -		Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18
5	Offer Price by Biorefinery (\$/D Mg)	\$ 50.00		Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18
6	Replacement Nutrient	\$/Mg		Take rate %	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
7	anhydrous ammonia	623		Yield (Take Rate) Mg/Ha 15% m.c.	2.26	2.45	2.64	2.82	3.01	3.20	3.39	3.58	3.77	3.95
8	Dammonium Phospahte	516		Net yield (Take Rate) D Mg/Ha	1.92	2.08	2.24	2.40	2.56	2.72	2.88	3.04	3.20	3.36
9	Potash	399		Storage Loss (total)	0.134	0.146	0.157	0.168	0.179	0.190	0.202	0.213	0.224	0.235
10	Storage Loss %	7%		Net D Mg/Ha	1.79	1.94	2.08	2.23	2.38	2.53	2.68	2.83	2.98	3.13
31				Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Tillage
32		Two Pass												
33		Conventional	Above or below profitable stover price (\$)	36.15	32.47	29.31	26.57	24.17	22.06	20.18	18.50	16.98	15.61	14.37
34		Two Pass AGCO	Above or below profitable stover price (\$)	5.03	5.40	5.73	6.02	6.29	6.53	6.75	6.95	7.14	7.31	7.48
35		Single Pass AGCO	Above or below profitable stover price (\$)	5.68	6.03	6.34	6.62	6.87	7.10	7.31	7.51	7.69	7.85	8.01

Figure 6.5 Corn-Soybean rotation, tilled

	A	B	C	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB
1	Tilled Take Rate	30%		Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean	Corn Bean
2	No Tilled Take Rate	50%		Tillage Practice	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till
3				Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210
4	Expected Profit/Dry Mg	\$ -		Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18
5	Offer Price by Biorefinery (\$/D Mg)	\$ 50.00		Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18
6	Replacement Nutrient	\$/Mg		Take rate %	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
7	anhydrous ammonia	623		Yield (Take Rate) Mg/Ha 15% m.c.	3.77	4.08	4.39	4.71	5.02	5.34	5.65	5.96	6.28	6.59
8	Dammonium Phospahte	516		Net yield (Take Rate) D Mg/Ha	3.20	3.47	3.73	4.00	4.27	4.53	4.80	5.07	5.34	5.60
9	Potash	399		Storage Loss (total)	0.224	0.243	0.261	0.280	0.299	0.317	0.336	0.355	0.373	0.392
10	Storage Loss %	7%		Net D Mg/Ha	2.98	3.23	3.47	3.72	3.97	4.22	4.47	4.71	4.96	5.21
31				No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till	No Till
32		Two Pass												
33		Conventional	Above or below profitable stover price (\$)	16.98	14.77	12.87	11.23	9.79	8.52	7.40	6.39	5.48	4.66	3.91
34		Two Pass AGCO	Above or below profitable stover price (\$)	7.14	7.42	7.67	7.90	8.11	8.29	8.46	8.62	8.77	8.90	9.02
35		Single Pass AGCO	Above or below profitable stover price (\$)	7.69	7.96	8.20	8.41	8.60	8.78	8.94	9.09	9.23	9.35	9.47

Figure 6.6 Corn-Soybean rotation, No-Till

In this model, a producer is able to input desired harvest rate for a given tillage practice, expected profit, offer price for stover, and nutrient replacement costs. A range of yields are given for each cropping system and tillage practice. Output from the model is at the lower right of the tables shown. The relationship between offer price and desired profit for each yield and cropping system is illustrated in these tables. For example in Figure 6.4, for a 11.3 Mg/Ha yield in a corn—corn rotation in a no-till tillage situation, with an expected profit of \$.01 per dry Mg supplied to the biorefinery, a producer would expect that for a conventional stover harvest scenario, the producer would lose or be \$7.40 under the breakeven price for this yield, “take rate”, cropping system, and tillage practices. For the same scenario, if the producer was using a single-pass harvest system, the producer would see a net return of \$8.51 above the target profit of \$0.01. Changing the desired profit margin, changes how results are displayed. Any results value

displayed in red would return under a profit, or loss, under the target profit margin. Any value displayed in black, would return a profit above the desired target profit.

The decision model was used to explore the profitability of harvesting corn stover for a range of stover prices paid at the plant gate. The price range considered was \$40/dry Mg to \$90/Mg. Prices were considered in \$5 increments. The desired profit margin was set to be \$10/dry Mg. It is believed that producers would normally expect a \$10/Mg profit margin to be willing to supply corn stover to a biorefinery as suggested by Sheehan et al. In the scenario explored, the producer is assumed to be located 40 km from a storage depot and the depot is 40 km from the biorefinery plant gate. The stover is assumed to be harvested at an average moisture content of 15%. It is assumed a “take rate” of 30% is used for full tillage field preparation and 50% for no-till field preparation. Potential total available biomass yields range from 7.53 Mg/Ha to 13.81 Mg/Ha.

The decision model results for each of the tillage practices and crop rotation options considered are listed in Figure 6.7 through Figure 6.10. In general, the results indicate that fewer passes through the field reduce stover harvest costs, which, in turn, allows a lower “take rate” to be harvested profitably at a lower stover price offered by the biorefinery.

From these results single-pass harvesting system is capable of harvesting corn stover at the minimum desired profit of \$10/Mg at a “take rate” of 1.92 dry Mg/Ha at a stover price of \$55 per dry Mg. If the producer is willing to take a profit of less than \$10/dry Mg, a \$50/dry Mg price is feasibly harvested with this system. Any stover price above \$55/dry Mg is possible for a producer to harvest stover and make \$10/dry Mg profit. The two-pass harvesting system is also profitable to \$50/dry Mg, but with less than a \$10/dry Mg profit. A full profit of \$10/dry Mg is

possible for stover prices above \$55/dry Mg and a “take rate” above 2.08 d Mg/Ha. These results were consistent across all crop rotations and tillage practices.

The conventional multi-pass harvest system that was used as a comparison to the single and two pass systems was not profitable to harvest stover at low prices. The conventional harvest system generally did not provide a \$10/dry Mg profit until stover prices were above \$75/dry Mg in a no-till field preparation system. A producer could harvest stover at \$60/dry Mg for a small profit for a few select higher “take rate” situations in no-till system. Anything below \$60/dry Mg for a price and less than 4.27 d Mg/Ha was unprofitable. In the full tillage field preparation systems, stover could not be harvest at the desired profit level until the offer priced exceed \$80/dry Mg and “take rates” were above 3.39 dry Mg/Ha. At the lowest tested “take rate”, stover could not be harvested for the desired profit margin even at \$90/dry Mg.

	A	B	C	E	F	G	H	I	J	K	L	M	N	O	
1	Tilled Take Rate	30%	Corn Corn Rotation												
2	No Tilled Take Rate	50%	Tillage Practice	Tillage											
3	Expected Profit/Dry Mg	10	Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210	220	
4			Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81	
5			Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81	
6	Replacement Nutrient	\$/Mg	Take rate %	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
7	anhydrous ammonia	623	Yield (Take Rate) Mg/Ha 15% m.c.	2.26	2.45	2.64	2.82	3.01	3.20	3.39	3.58	3.77	3.95	4.14	
8	Dammonium Phospahte	516	Net yield (Take Rate) D Mg/Ha	1.92	2.08	2.24	2.40	2.56	2.72	2.88	3.04	3.20	3.36	3.52	
9	Potash	399	Storage Loss (total)	0.134	0.146	0.157	0.168	0.179	0.190	0.202	0.213	0.224	0.235	0.246	
10	Storage Loss %	7%	Net D Mg/Ha	1.79	1.94	2.08	2.23	2.38	2.53	2.68	2.83	2.98	3.13	3.27	
32	\$ 40.00	Two Pass Conventional	Above or below profitable stover price (\$)	56.15	52.47	49.31	46.57	44.17	42.06	40.18	38.50	36.98	35.61	34.37	
33		Two Pass AGCO	Above or below profitable stover price (\$)	14.97	14.60	14.27	13.98	13.71	13.47	13.25	13.05	12.86	12.69	12.52	
34		Singl Pass AGCO	Above or below profitable stover price (\$)	14.32	13.97	13.66	13.38	13.13	12.90	12.69	12.49	12.31	12.15	11.99	
36	\$ 45.00	Two Pass Conventional	Above or below profitable stover price (\$)	51.15	47.47	44.31	41.57	39.17	37.06	35.18	33.50	31.98	30.61	29.37	
37		Two Pass AGCO	Above or below profitable stover price (\$)	9.97	9.60	9.27	8.98	8.71	8.47	8.25	8.05	7.86	7.69	7.52	
38		Singl Pass AGCO	Above or below profitable stover price (\$)	9.32	8.97	8.66	8.38	8.13	7.90	7.69	7.49	7.31	7.15	6.99	
40	\$ 50.00	Two Pass Conventional	Above or below profitable stover price (\$)	46.15	42.47	39.31	36.57	34.17	32.06	30.18	28.50	26.98	25.61	24.37	
41		Two Pass AGCO	Above or below profitable stover price (\$)	4.97	4.60	4.27	3.98	3.71	3.47	3.25	3.05	2.86	2.69	2.52	
42		Singl Pass AGCO	Above or below profitable stover price (\$)	4.32	3.97	3.66	3.38	3.13	2.90	2.69	2.49	2.31	2.15	1.99	
44	\$ 55.00	Two Pass Conventional	Above or below profitable stover price (\$)	41.15	37.47	34.31	31.57	29.17	27.06	25.18	23.50	21.98	20.61	19.37	
45		Two Pass AGCO	Above or below profitable stover price (\$)	0.03	0.40	0.73	1.02	1.29	1.53	1.75	1.95	2.14	2.31	2.48	
46		Singl Pass AGCO	Above or below profitable stover price (\$)	0.68	1.03	1.34	1.62	1.87	2.10	2.31	2.51	2.69	2.85	3.01	
48	\$ 60.00	Two Pass Conventional	Above or below profitable stover price (\$)	36.15	32.47	29.31	26.57	24.17	22.06	20.18	18.50	16.98	15.61	14.37	
49		Two Pass AGCO	Above or below profitable stover price (\$)	5.03	5.40	5.73	6.02	6.29	6.53	6.75	6.95	7.14	7.31	7.48	
50		Singl Pass AGCO	Above or below profitable stover price (\$)	5.68	6.03	6.34	6.62	6.87	7.10	7.31	7.51	7.69	7.85	8.01	
52	\$ 65.00	Two Pass Conventional	Above or below profitable stover price (\$)	31.15	27.47	24.31	21.57	19.17	17.06	15.18	13.50	11.98	10.61	9.37	
53		Two Pass AGCO	Above or below profitable stover price (\$)	10.03	10.40	10.73	11.02	11.29	11.53	11.75	11.95	12.14	12.31	12.48	
54		Singl Pass AGCO	Above or below profitable stover price (\$)	10.68	11.03	11.34	11.62	11.87	12.10	12.31	12.51	12.69	12.85	13.01	
56	\$ 70.00	Two Pass Conventional	Above or below profitable stover price (\$)	26.15	22.47	19.31	16.57	14.17	12.06	10.18	8.50	6.98	5.61	4.37	
57		Two Pass AGCO	Above or below profitable stover price (\$)	15.03	15.40	15.73	16.02	16.29	16.53	16.75	16.95	17.14	17.31	17.48	
58		Singl Pass AGCO	Above or below profitable stover price (\$)	15.68	16.03	16.34	16.62	16.87	17.10	17.31	17.51	17.69	17.85	18.01	
60	\$ 75.00	Two Pass Conventional	Above or below profitable stover price (\$)	21.15	17.47	14.31	11.57	9.17	7.06	5.18	3.50	1.98	0.61	0.63	
61		Two Pass AGCO	Above or below profitable stover price (\$)	20.03	20.40	20.73	21.02	21.29	21.53	21.75	21.95	22.14	22.31	22.48	
62		Singl Pass AGCO	Above or below profitable stover price (\$)	20.68	21.03	21.34	21.62	21.87	22.10	22.31	22.51	22.69	22.85	23.01	
64	\$ 80.00	Two Pass Conventional	Above or below profitable stover price (\$)	16.15	12.47	9.31	6.57	4.17	2.06	0.18	1.50	3.02	4.39	5.63	
65		Two Pass AGCO	Above or below profitable stover price (\$)	25.03	25.40	25.73	26.02	26.29	26.53	26.75	26.95	27.14	27.31	27.48	
66		Singl Pass AGCO	Above or below profitable stover price (\$)	25.68	26.03	26.34	26.62	26.87	27.10	27.31	27.51	27.69	27.85	28.01	
68	\$ 85.00	Two Pass Conventional	Above or below profitable stover price (\$)	11.15	7.47	4.31	1.57	0.83	2.94	4.82	6.50	8.02	9.39	10.63	
69		Two Pass AGCO	Above or below profitable stover price (\$)	30.03	30.40	30.73	31.02	31.29	31.53	31.75	31.95	32.14	32.31	32.48	
70		Singl Pass AGCO	Above or below profitable stover price (\$)	30.68	31.03	31.34	31.62	31.87	32.10	32.31	32.51	32.69	32.85	33.01	
72	\$ 90.00	Two Pass Conventional	Above or below profitable stover price (\$)	6.15	2.47	0.69	3.43	5.83	7.94	9.82	11.50	13.02	14.39	15.63	
73		Two Pass AGCO	Above or below profitable stover price (\$)	35.03	35.40	35.73	36.02	36.29	36.53	36.75	36.95	37.14	37.31	37.48	
74		Singl Pass AGCO	Above or below profitable stover price (\$)	35.68	36.03	36.34	36.62	36.87	37.10	37.31	37.51	37.69	37.85	38.01	

Figure 6.7 Corn-corn rotation with full tillage

	A	B	C	Q	R	S	T	U	V	W	X	Y	Z	AA
1	Tilled Take Rate	30%		Corn Corn rotation										
2	No Tilled Take Rate	50%	Tillage Practice	No Till										
3	Expected Profit/Dry Mg	10	Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210	220
4			Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
5			Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
6	Replacement Nutrient	\$/Mg	Take rate %	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
7	anhydrous ammonia	565	Yield (Take Rate) Mg/Ha 15% m.c.	3.77	4.08	4.39	4.71	5.02	5.34	5.65	5.96	6.28	6.59	6.90
8	Dammonium Phospahte	468	Net yield (Take Rate) D Mg/Ha	3.20	3.47	3.73	4.00	4.27	4.54	4.80	5.07	5.34	5.60	5.87
9	Potash	362	Storage Loss (total)	0.224	0.243	0.261	0.280	0.299	0.317	0.336	0.355	0.373	0.392	0.411
10	Storage Loss %	7%	Net D Mg/Ha	2.98	3.23	3.47	3.72	3.97	4.22	4.47	4.71	4.96	5.21	5.46
30	\$ 40.00	Two Pass Conventional	Above or below profitable stover price (\$)	36.98	34.77	32.87	31.23	29.79	28.52	27.40	26.39	25.48	24.66	23.91
31		Two Pass AGCO	Above or below profitable stover price (\$)	12.86	12.58	12.33	12.10	11.89	11.71	11.54	11.38	11.23	11.10	10.98
32		Singl Pass AGCO	Above or below stover price (\$)	12.31	12.04	11.80	11.59	11.40	11.22	11.06	10.91	10.77	10.65	10.53
33														
34	\$ 45.00	Two Pass Conventional	Above or below profitable stover price (\$)	31.98	29.77	27.87	26.23	24.79	23.52	22.40	21.39	20.48	19.66	18.91
35		Two Pass AGCO	Above or below profitable stover price (\$)	7.86	7.58	7.33	7.10	6.89	6.71	6.54	6.38	6.23	6.10	5.98
36		Singl Pass AGCO	Above or below stover price (\$)	7.31	7.04	6.80	6.59	6.40	6.22	6.06	5.91	5.77	5.65	5.53
37														
38														
39	\$ 50.00	Two Pass Conventional	Above or below profitable stover price (\$)	26.98	24.77	22.87	21.23	19.79	18.52	17.40	16.39	15.48	14.66	13.91
40		Two Pass AGCO	Above or below profitable stover price (\$)	2.86	2.58	2.33	2.10	1.89	1.71	1.54	1.38	1.23	1.10	0.98
41		Singl Pass AGCO	Above or below stover price (\$)	2.31	2.04	1.80	1.59	1.40	1.22	1.06	0.91	0.77	0.65	0.53
42														
43	\$ 55.00	Two Pass Conventional	Above or below profitable stover price (\$)	21.98	19.77	17.87	16.23	14.79	13.52	12.40	11.39	10.48	9.66	8.91
44		Two Pass AGCO	Above or below profitable stover price (\$)	2.14	2.42	2.67	2.90	3.11	3.29	3.46	3.62	3.77	3.90	4.02
45		Singl Pass AGCO	Above or below stover price (\$)	2.69	2.96	3.20	3.41	3.60	3.78	3.94	4.09	4.23	4.35	4.47
46														
47	\$ 60.00	Two Pass Conventional	Above or below profitable stover price (\$)	16.98	14.77	12.87	11.23	9.79	8.52	7.40	6.39	5.48	4.66	3.91
48		Two Pass AGCO	Above or below profitable stover price (\$)	7.14	7.42	7.67	7.90	8.11	8.29	8.46	8.62	8.77	8.90	9.02
49		Singl Pass AGCO	Above or below stover price (\$)	7.69	7.96	8.20	8.41	8.60	8.78	8.94	9.09	9.23	9.35	9.47
50														
51	\$ 65.00	Two Pass Conventional	Above or below profitable stover price (\$)	11.98	9.77	7.87	6.23	4.79	3.52	2.40	1.39	0.48	0.34	1.09
52		Two Pass AGCO	Above or below profitable stover price (\$)	12.14	12.42	12.67	12.90	13.11	13.29	13.46	13.62	13.77	13.90	14.02
53		Singl Pass AGCO	Above or below stover price (\$)	12.69	12.96	13.20	13.41	13.60	13.78	13.94	14.09	14.23	14.35	14.47
54														
55	\$ 70.00	Two Pass Conventional	Above or below profitable stover price (\$)	6.98	4.77	2.87	1.23	0.21	1.48	2.60	3.61	4.52	5.34	6.09
56		Two Pass AGCO	Above or below profitable stover price (\$)	17.14	17.42	17.67	17.90	18.11	18.29	18.46	18.62	18.77	18.90	19.02
57		Singl Pass AGCO	Above or below stover price (\$)	17.69	17.96	18.20	18.41	18.60	18.78	18.94	19.09	19.23	19.35	19.47
58														
59	\$ 75.00	Two Pass Conventional	Above or below profitable stover price (\$)	1.98	0.23	2.13	3.77	5.21	6.48	7.60	8.61	9.52	10.34	11.09
60		Two Pass AGCO	Above or below profitable stover price (\$)	22.14	22.42	22.67	22.90	23.11	23.29	23.46	23.62	23.77	23.90	24.02
61		Singl Pass AGCO	Above or below stover price (\$)	22.69	22.96	23.20	23.41	23.60	23.78	23.94	24.09	24.23	24.35	24.47
62														
63	\$ 80.00	Two Pass Conventional	Above or below profitable stover price (\$)	3.02	5.23	7.13	8.77	10.21	11.48	12.60	13.61	14.52	15.34	16.09
64		Two Pass AGCO	Above or below profitable stover price (\$)	27.14	27.42	27.67	27.90	28.11	28.29	28.46	28.62	28.77	28.90	29.02
65		Singl Pass AGCO	Above or below stover price (\$)	27.69	27.96	28.20	28.41	28.60	28.78	28.94	29.09	29.23	29.35	29.47
66														
67	\$ 85.00	Two Pass Conventional	Above or below profitable stover price (\$)	8.02	10.23	12.13	13.77	15.21	16.48	17.60	18.61	19.52	20.34	21.09
68		Two Pass AGCO	Above or below profitable stover price (\$)	32.14	32.42	32.67	32.90	33.11	33.29	33.46	33.62	33.77	33.90	34.02
69		Singl Pass AGCO	Above or below stover price (\$)	32.69	32.96	33.20	33.41	33.60	33.78	33.94	34.09	34.23	34.35	34.47
70														
71	\$ 90.00	Two Pass Conventional	Above or below profitable stover price (\$)	13.02	15.23	17.13	18.77	20.21	21.48	22.60	23.61	24.52	25.34	26.09
72		Two Pass AGCO	Above or below profitable stover price (\$)	37.14	37.42	37.67	37.90	38.11	38.29	38.46	38.62	38.77	38.90	39.02
73		Singl Pass AGCO	Above or below stover price (\$)	37.69	37.96	38.20	38.41	38.60	38.78	38.94	39.09	39.23	39.35	39.47
74														

	A	B	C	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1	Tilled Take Rate	30%		Corn Bean										
2	No Tilled Take Rate	50%	Tillage Practice	Tillage										
3	Expected Profit/Dry Mg	10	Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210	220
4			Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
5			Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81
6	Replacement Nutrient	\$/Mg	Take rate %	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
7	anhydrous ammonia	565	Yield (Take Rate) Mg/Ha 15% m.c.	2.26	2.45	2.64	2.82	3.01	3.20	3.39	3.58	3.77	3.95	4.14
8	Dammonium Phospahte	468	Net yield (Take Rate) D Mg/Ha	1.92	2.08	2.24	2.40	2.56	2.72	2.88	3.04	3.20	3.36	3.52
9	Potash	362	Storage Loss (total)	0.134	0.146	0.157	0.168	0.179	0.190	0.202	0.213	0.224	0.235	0.246
10	Storage Loss %	7%	Net D Mg/Ha	1.79	1.94	2.08	2.23	2.38	2.53	2.68	2.83	2.98	3.13	3.27
32	\$ 40.00	Two Pass Conventional	Above or below profitable stover price (\$)	56.15	52.47	49.31	46.57	44.17	42.06	40.18	38.50	36.98	35.61	34.37
33		Two Pass AGCO	Above or below profitable stover price (\$)	14.97	14.60	14.27	13.98	13.71	13.47	13.25	13.05	12.86	12.69	12.52
34		Singl Pass AGCO	Above or below stover price (\$)	14.32	13.97	13.66	13.38	13.13	12.90	12.69	12.49	12.31	12.15	11.99
36	\$ 45.00	Two Pass Conventional	Above or below profitable stover price (\$)	51.15	47.47	44.31	41.57	39.17	37.06	35.18	33.50	31.98	30.61	29.37
37		Two Pass AGCO	Above or below profitable stover price (\$)	9.97	9.60	9.27	8.98	8.71	8.47	8.25	8.05	7.86	7.69	7.52
38		Singl Pass AGCO	Above or below stover price (\$)	9.32	8.97	8.66	8.38	8.13	7.90	7.69	7.49	7.31	7.15	6.99
41	\$ 50.00	Two Pass Conventional	Above or below profitable stover price (\$)	46.15	42.47	39.31	36.57	34.17	32.06	30.18	28.50	26.98	25.61	24.37
42		Two Pass AGCO	Above or below profitable stover price (\$)	4.97	4.60	4.27	3.98	3.71	3.47	3.25	3.05	2.86	2.69	2.52
43		Singl Pass AGCO	Above or below stover price (\$)	4.32	3.97	3.66	3.38	3.13	2.90	2.69	2.49	2.31	2.15	1.99
45	\$ 55.00	Two Pass Conventional	Above or below profitable stover price (\$)	41.15	37.47	34.31	31.57	29.17	27.06	25.18	23.50	21.98	20.61	19.37
46		Two Pass AGCO	Above or below profitable stover price (\$)	0.03	0.40	0.73	1.02	1.29	1.53	1.75	1.95	2.14	2.31	2.48
47		Singl Pass AGCO	Above or below stover price (\$)	0.68	1.03	1.34	1.62	1.87	2.10	2.31	2.51	2.69	2.85	3.01
49	\$ 60.00	Two Pass Conventional	Above or below profitable stover price (\$)	36.15	32.47	29.31	26.57	24.17	22.06	20.18	18.50	16.98	15.61	14.37
50		Two Pass AGCO	Above or below profitable stover price (\$)	5.03	5.40	5.73	6.02	6.29	6.53	6.75	6.95	7.14	7.31	7.48
51		Singl Pass AGCO	Above or below stover price (\$)	5.68	6.03	6.34	6.62	6.87	7.10	7.31	7.51	7.69	7.85	8.01
53	\$ 65.00	Two Pass Conventional	Above or below profitable stover price (\$)	31.15	27.47	24.31	21.57	19.17	17.06	15.18	13.50	11.98	10.61	9.37
54		Two Pass AGCO	Above or below profitable stover price (\$)	10.03	10.40	10.73	11.02	11.29	11.53	11.75	11.95	12.14	12.31	12.48
55		Singl Pass AGCO	Above or below stover price (\$)	10.68	11.03	11.34	11.62	11.87	12.10	12.31	12.51	12.69	12.85	13.01
57	\$ 70.00	Two Pass Conventional	Above or below profitable stover price (\$)	26.15	22.47	19.31	16.57	14.17	12.06	10.18	8.50	6.98	5.61	4.37
58		Two Pass AGCO	Above or below profitable stover price (\$)	15.03	15.40	15.73	16.02	16.29	16.53	16.75	16.95	17.14	17.31	17.48
59		Singl Pass AGCO	Above or below stover price (\$)	15.68	16.03	16.34	16.62	16.87	17.10	17.31	17.51	17.69	17.85	18.01
61	\$ 75.00	Two Pass Conventional	Above or below profitable stover price (\$)	21.15	17.47	14.31	11.57	9.17	7.06	5.18	3.50	1.98	0.61	0.63
62		Two Pass AGCO	Above or below profitable stover price (\$)	20.03	20.40	20.73	21.02	21.29	21.53	21.75	21.95	22.14	22.31	22.48
63		Singl Pass AGCO	Above or below stover price (\$)	20.68	21.03	21.34	21.62	21.87	22.10	22.31	22.51	22.69	22.85	23.01
65	\$ 80.00	Two Pass Conventional	Above or below profitable stover price (\$)	16.15	12.47	9.31	6.57	4.17	2.06	0.18	1.50	3.02	4.39	5.63
66		Two Pass AGCO	Above or below profitable stover price (\$)	25.03	25.40	25.73	26.02	26.29	26.53	26.75	26.95	27.14	27.31	27.48
67		Singl Pass AGCO	Above or below stover price (\$)	25.68	26.03	26.34	26.62	26.87	27.10	27.31	27.51	27.69	27.85	28.01
69	\$ 85.00	Two Pass Conventional	Above or below profitable stover price (\$)	11.15	7.47	4.31	1.57	0.83	2.94	4.82	6.50	8.02	9.39	10.63
70		Two Pass AGCO	Above or below profitable stover price (\$)	30.03	30.40	30.73	31.02	31.29	31.53	31.75	31.95	32.14	32.31	32.48
71		Singl Pass AGCO	Above or below stover price (\$)	30.68	31.03	31.34	31.62	31.87	32.10	32.31	32.51	32.69	32.85	33.01
73	\$ 90.00	Two Pass Conventional	Above or below profitable stover price (\$)	6.15	2.47	0.69	3.43	5.83	7.94	9.82	11.50	13.02	14.39	15.63
74		Two Pass AGCO	Above or below profitable stover price (\$)	35.03	35.40	35.73	36.02	36.29	36.53	36.75	36.95	37.14	37.31	37.48
75		Singl Pass AGCO	Above or below stover price (\$)	35.68	36.03	36.34	36.62	36.87	37.10	37.31	37.51	37.69	37.85	38.01

Figure 6.9 Corn-soybean rotation with full tillage

													B					
	A	B	C	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC			
1	Tilled Take Rate	30%		Corn Bean														
2	No Tilled Take Rate	50%	Tillage Practice	No Till														
3	Expected Profit/Dry Mg	10	Corn Yield (bu/acre)	120	130	140	150	160	170	180	190	200	210	220				
4			Corn Yield (Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81				
5			Stover Yield (W Mg/Ha)	7.53	8.16	8.79	9.42	10.04	10.67	11.30	11.93	12.55	13.18	13.81				
6	Replacement Nutrient	\$/Mg	Take rate %	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%				
7	anhydrous ammonia	565	Yield (Take Rate) Mg/Ha 15% m.c.	3.77	4.08	4.39	4.71	5.02	5.34	5.65	5.96	6.28	6.59	6.90				
8	Diammonium Phosphate	468	Net yield (Take Rate) D Mg/Ha	3.20	3.47	3.73	4.00	4.27	4.54	4.80	5.07	5.34	5.60	5.87				
9	Potash	362	Storage Loss (total)	0.224	0.243	0.261	0.280	0.299	0.317	0.336	0.355	0.373	0.392	0.411				
10	Storage Loss %	7%	Net D Mg/Ha	2.98	3.23	3.47	3.72	3.97	4.22	4.47	4.71	4.96	5.21	5.46				
29	\$ 40.00	Two Pass Conventional	Above or below profitable stover price (\$)	36.98	34.77	32.87	31.23	29.79	28.52	27.40	26.39	25.48	24.66	23.91				
30		Two Pass AGCO	Above or below profitable stover price (\$)	12.86	12.58	12.33	12.10	11.89	11.71	11.54	11.38	11.23	11.10	10.98				
31		Singl Pass AGCO	Above or below stover price (\$)	12.31	12.04	11.80	11.59	11.40	11.22	11.06	10.91	10.77	10.65	10.53				
32																		
33	\$ 45.00	Two Pass Conventional	Above or below profitable stover price (\$)	31.98	29.77	27.87	26.23	24.79	23.52	22.40	21.39	20.48	19.66	18.91				
34		Two Pass AGCO	Above or below profitable stover price (\$)	7.86	7.58	7.33	7.10	6.89	6.71	6.54	6.38	6.23	6.10	5.98				
35		Singl Pass AGCO	Above or below stover price (\$)	7.31	7.04	6.80	6.59	6.40	6.22	6.06	5.91	5.77	5.65	5.53				
36																		
37																		
38	\$ 50.00	Two Pass Conventional	Above or below profitable stover price (\$)	26.98	24.77	22.87	21.23	19.79	18.52	17.40	16.39	15.48	14.66	13.91				
39		Two Pass AGCO	Above or below profitable stover price (\$)	2.86	2.58	2.33	2.10	1.89	1.71	1.54	1.38	1.23	1.10	0.98				
40		Singl Pass AGCO	Above or below stover price (\$)	2.31	2.04	1.80	1.59	1.40	1.22	1.06	0.91	0.77	0.65	0.53				
41																		
42	\$ 55.00	Two Pass Conventional	Above or below profitable stover price (\$)	21.98	19.77	17.87	16.23	14.79	13.52	12.40	11.39	10.48	9.66	8.91				
43		Two Pass AGCO	Above or below profitable stover price (\$)	2.14	2.42	2.67	2.90	3.11	3.29	3.46	3.62	3.77	3.90	4.02				
44		Singl Pass AGCO	Above or below stover price (\$)	2.69	2.96	3.20	3.41	3.60	3.78	3.94	4.09	4.23	4.35	4.47				
45																		
46	\$ 60.00	Two Pass Conventional	Above or below profitable stover price (\$)	16.98	14.77	12.87	11.23	9.79	8.52	7.40	6.39	5.48	4.66	3.91				
47		Two Pass AGCO	Above or below profitable stover price (\$)	7.14	7.42	7.67	7.90	8.11	8.29	8.46	8.62	8.77	8.90	9.02				
48		Singl Pass AGCO	Above or below stover price (\$)	7.69	7.96	8.20	8.41	8.60	8.78	8.94	9.09	9.23	9.35	9.47				
49																		
50	\$ 65.00	Two Pass Conventional	Above or below profitable stover price (\$)	11.98	9.77	7.87	6.23	4.79	3.52	2.40	1.39	0.48	0.34	1.09				
51		Two Pass AGCO	Above or below profitable stover price (\$)	12.14	12.42	12.67	12.90	13.11	13.29	13.46	13.62	13.77	13.90	14.02				
52		Singl Pass AGCO	Above or below stover price (\$)	12.69	12.96	13.20	13.41	13.60	13.78	13.94	14.09	14.23	14.35	14.47				
53																		
54	\$ 70.00	Two Pass Conventional	Above or below profitable stover price (\$)	6.98	4.77	2.87	1.23	0.21	1.48	2.60	3.61	4.52	5.34	6.09				
55		Two Pass AGCO	Above or below profitable stover price (\$)	17.14	17.42	17.67	17.90	18.11	18.29	18.46	18.62	18.77	18.90	19.02				
56		Singl Pass AGCO	Above or below stover price (\$)	17.69	17.96	18.20	18.41	18.60	18.78	18.94	19.09	19.23	19.35	19.47				
57																		
58	\$ 75.00	Two Pass Conventional	Above or below profitable stover price (\$)	1.98	0.23	2.13	3.77	5.21	6.48	7.60	8.61	9.52	10.34	11.09				
59		Two Pass AGCO	Above or below profitable stover price (\$)	22.14	22.42	22.67	22.90	23.11	23.29	23.46	23.62	23.77	23.90	24.02				
60		Singl Pass AGCO	Above or below stover price (\$)	22.69	22.96	23.20	23.41	23.60	23.78	23.94	24.09	24.23	24.35	24.47				
61																		
62	\$ 80.00	Two Pass Conventional	Above or below profitable stover price (\$)	3.02	5.23	7.13	8.77	10.21	11.48	12.60	13.61	14.52	15.34	16.09				
63		Two Pass AGCO	Above or below profitable stover price (\$)	27.14	27.42	27.67	27.90	28.11	28.29	28.46	28.62	28.77	28.90	29.02				
64		Singl Pass AGCO	Above or below stover price (\$)	27.69	27.96	28.20	28.41	28.60	28.78	28.94	29.09	29.23	29.35	29.47				
65																		
66	\$ 85.00	Two Pass Conventional	Above or below profitable stover price (\$)	8.02	10.23	12.13	13.77	15.21	16.48	17.60	18.61	19.52	20.34	21.09				
67		Two Pass AGCO	Above or below profitable stover price (\$)	32.14	32.42	32.67	32.90	33.11	33.29	33.46	33.62	33.77	33.90	34.02				
68		Singl Pass AGCO	Above or below stover price (\$)	32.69	32.96	33.20	33.41	33.60	33.78	33.94	34.09	34.23	34.35	34.47				
69																		
70	\$ 90.00	Two Pass Conventional	Above or below profitable stover price (\$)	13.02	15.23	17.13	18.77	20.21	21.48	22.60	23.61	24.52	25.34	26.09				
71		Two Pass AGCO	Above or below profitable stover price (\$)	37.14	37.42	37.67	37.90	38.11	38.29	38.46	38.62	38.77	38.90	39.02				
72		Singl Pass AGCO	Above or below stover price (\$)	37.69	37.96	38.20	38.41	38.60	38.78	38.94	39.09	39.23	39.35	39.47				
73																		

Figure 6.10 Corn-soybean rotation with no-till

The sensitivity to nutrient cost variability was tested with the decision tool also. Nutrient replacement costs do have an effect on the profitability of harvesting stover. Changes in replacement nutrient application rates or the cost of a given nutrient can change the profitability of stover. Table 6-1 illustrates the relationship between a change in the nutrient application rate or cost and the resulting change in the production cost of a dry Mg of corn stover. Taken

individually, the change in rates or nutrient cost do not result in a substantial change in the production cost of stover. Collectively, however, in marginally profitable stover harvest situations the nutrient replacement costs can switch a stover harvest from profitability to a loss. Since nutrient replacement occurs many months after a residue harvest, often the next spring after soil testing indicates the necessary replacement rate and actual nutrient costs can be priced, what seemed like a profitable decision at harvest may no longer be a profitable decision.

Table 6-1 Stover cost sensitivity to changes in nutrient cost replacement rate.

Nutrient	A 0.5 kg change in nutrient replacement rates	For a \$100/Mg Change in nutrient cost
	Results in stover cost change (\$/Mg)	Results in stover cost chan (\$/Mg)
Anhydrous Ammonia	0.49	0.51
Diammonium Phosphate	0.70	0.21
Potash	0.34	1.16

Not included in this decision tool is the conservation cost incurred by a producer when removing stover. Crop residue plays a role in preventing soil erosion and water loss from a field. While soil erosion costs are difficult to quantify, some water retention values related to stover removal have been put forth (Klocke et al., 2008; Van Donk et al., 2012). In water short growing regions, such as western Kansas and Nebraska, it is believed that 50 to 120 mm of annual precipitation can be retained in the soil when 100% ground cover is maintained. Maintaining this extra moisture potentially could increase soybean yields by 1340 kg/ha or corn yields by 8300 kg/ha in a water limited area such as western Kansas or Nebraska. Any stover harvest rates that take residue ground cover would conceivably “cost” the producer crop yields.

6.4 Conclusions

The objective of developing a decision tool for producers to use to consider whether or not to harvest corn stover profitably was achieved. A decision tool based on conventional multi-pass stover harvesting techniques, a modified two-pass system, and a newly developed single-pass harvesting system using specialized equipment for the harvest of corn stover was developed. The decision tool includes other factors that producers should consider when harvesting corn stover, such as nutrient replacement costs, and shipping and handling costs that can be modified to the producer's location. The decision tool can provide guidance regarding stover harvesting "take rates" and what an offered stover price might be considered profitable.

The decision tool as currently constructed is limited to basic parameters of tillage practices, crop yield, corn stover "take rate", expected profit, biomass purchase price, nutrient replacement costs, and storage losses. The model has the potential to be modified to include many other variables and factors that a producer may wish to consider when harvesting corn stover for sale to a biorefinery. Factors such as bale weight, machine size, field speeds, and stover moisture content could be added to the decision tool. Other variables of importance can be incorporated into this model to provide even better guidance to a producer regarding the decision to harvest residue or not.

Using the base values considered in this analysis, generally, corn stover cannot be harvested profitably with a conventional harvesting system in a full tillage cropping system for an offered stover prices below \$65/dry Mg. Advanced harvest systems and techniques show that corn stover can be harvested with a small profit in a similar cropping system below \$50/dry Mg. Higher "take rates" are generally more profitable to harvest.

The nutrient content removed by supplying stover to a biorefinery in this decision tool show only a minor effect on the cost to the producer. However, nutrient replacement costs may be effected over more than a subsequent planting season by the removal of the stover. Other effects, such as greater erosion and leaching may also have an effect on the needed nutrient replacement rates.

Chapter 7 Conclusions, Recommendations, Limitations, and Future Work

Field scale tests of advanced agricultural residue harvest equipment found that equipment specifically designed for the harvest of crop residues does reduce harvesting costs.

Single-pass harvesting is fuel intensive and requires less labor investment than two-pass harvesting per dry Mg. This appears to be consistent between corn stover and wheat straw. Single-pass harvesting was not shown to be conclusively less costly than two-pass harvesting, though the fuel use and labor requirement results would seem to indicate that it would be less costly. **Single-pass harvesting equipment** does not appear to affect the rate of the grain harvest.

Moisture content of the crop residues can increase harvest costs significantly. These cost increases can be significant enough to offset productivity gains from advanced harvest equipment and other harvest equipment features. Crop residue should be harvested at lower moisture contents to reduce harvesting costs for bioenergy uses.

The “take rate” or amount of residue collected affects the cost of the residue harvest. Larger “take rates” are more economical to harvest than smaller “take rates”. “Take rates” have a significant effect on harvest costs. By spreading equipment cost over greater amounts of harvested biomass, harvesting costs per Mg can be reduced significantly. This is consistent across crop residues and purpose grown crops. Larger “take rates” do increase fertility costs to the producer and effect crop moisture availability.

Energy sorghum can be more economical to harvest than switchgrass in spite of an extra harvest step. In purpose grown crops such as switch grass and energy sorghum, crop yield can offset the cost of extra steps required for one crop compared to another. Energy sorghum

which requires an additional harvesting step, was shown to be equally profitable to harvest as switchgrass which requires fewer steps to harvest. The gains from higher yields for energy sorghum can be large enough to offset the additional step, and associated cost, in the harvesting process.

Energy sorghum will consistently require more fuel to harvest than switchgrass regardless of the crop yield. The extra raking pass incurs an energy charge that switchgrass does not have. The amount of required labor to harvest energy sorghum can be less than that of switchgrass, but only at yield levels equal to or above the largest potential yields of switchgrass as shown in this analysis.

The cost of harvesting a dry Mg of energy sorghum is highly dependent upon the number of raking passes necessary to dry the crop. An extra pass to turn a windrow over to aid in dry down of the energy sorghum can increase the harvest cost by 12%. Rain and snow events during the dry down phase of harvesting energy sorghum can dramatically increase the cost to harvest sorghum. Year to year yield and weather variability can have large effects on crop yields and harvest costs. Producers will need to account for this variability as they consider whether to grow and harvest biomass for energy and which crop they will choose to grow.

The IBSAL model was modified to reflect single-pass harvest field data. The original model significantly under estimated the power required to bale corn stover at 17% moisture content. The model was modified by changing cost inputs to reflect actual machine costs, machine input power, field speed, bale weight and coefficients used in baler power calculations. The resulting model was able to replicate single-pass corn stover baling field data.

The IBSAL model does provide similar results to field data. While variances may exist between the base model and field data, the model can be used to understand cost and fuel use trends as harvest rates are increased or decreased.

Increasing baler throughput decreases harvesting costs. Any reasonable step that can be taken that will increase the amount of material baled per hour will decrease costs. Increased throughput will also decrease the amount of fuel required per dry Mg of residue harvested. Any step or factor that decreases throughput will increase costs and fuel requirements.

Large “take rates” are less costly and more fuel efficient to harvest compared to small “take rates”. At low “take rates”, small changes in the take rate will have large effects on the cost and fuel efficiency of the baling step. At large “take rates”, small changes in the take rate will have less of an effect on the cost and fuel efficiency of the baling step.

As bale densities increase, the cost of baling crop residues increases, BUT the overall collection cost decreases. Correspondingly, fuel requirements increase as bale densities increase. Less dense bales appear to be less costly and more fuel efficient, when only the baling step is considered. However, when the whole residue harvest system is considered, dense bales become less costly and more fuel efficient.

Residue moisture content does change the cost of harvesting crop residues. As moisture content increases, residue harvesting costs increase. It was found that moisture content variability cannot be reliably modeled within the IBSAL model at this time.

Labor and fuel costs do have an effect on costs, but the variations are proportional to their percentage of the overall cost of baling stover and the magnitude of price change. Labor is a very small part of single-pass baling and has a very small effect on cost. Fuel prices

have a larger effect that is proportional to the amount of cost change per liter of fuel. A 1% change in fuel costs appears to result in about 0.5% change in harvesting cost.

A producer considering the harvest of corn stover when using a single-pass harvesting system will want to:

- Maximize “take rates”, swathe widths, and field speeds
- Target a bale weight of at least 475kg. Weights above this do not seem to improve harvest costs by much and may actually begin to increase the cost of harvesting a Mg of stover.
- Labor rates have a very small effect on harvesting cost
- Fuel prices have a larger effect and should be taken into consideration in marginal profit situations.

A decision tool based on conventional three pass harvesting techniques, modified two-pass systems and newly developed single-pass harvesting equipment for the harvest of corn stover was developed. The tool includes other factors that producers should consider when harvesting corn stover, such as nutrient replacement and shipping and handling costs. The model can provide guidance regarding stover harvesting “take rates” and profitable stover prices. The model has the potential to be modified to include many other variables and factors that a producer may wish to consider when harvesting corn stover for sale to a biorefinery.

Corn stover cannot be harvested in a reliably profitable manner with traditional harvesting systems for prices below \$70 a dry Mg in a no till cropping systems, and nearly \$85 a dry Mg in a full tillage system. Using advanced harvest systems that were developed and tested by AGCO, corn stover can possibly be harvested profitably as low as \$45/dry Mg. Higher “take rates” are generally more profitable to harvest.

7.1 Limitations/Future work

In general, more work should be done to verify or quantify the costs associated with the one pass baling operation as these costs will likely remain a concern for producers and custom harvesters who may consider using the system. Producers and custom operators will be interested in these results because of harvest productivity and cost concerns. One aspect of the single-pass harvesting system that remains undefined is the setup time required for the single-pass harvesting system. The amount of labor required to get the single-pass system into the field and in operation remains undefined.

The field scale data that was used to as a base to as modified the IBSAL model was very limited in range and quite varied within the range of “take rates” recorded. The modified model is only reasonably valid across this narrow range of collected “take rates”. Additional data over a larger range of “take rates” would provide a more robust target curve with which to base modifications of the IBSAL model and would increase the validity of the resulting model. The needed data should be collected at 17% moisture content, which will increase the difficulty of collecting a large amount of data over a larger range of “take rates”.

The single-pass IBSAL model itself needs further investigation to improve its accuracy. This work identified several assumptions that need improvement. In particular, more work should be done to improve the coefficients within the model that are part of the bale formation energy calculation. Some of these coefficients should be made into variable inputs instead of constants. Additional, the model should incorporate a way to model a larger range of residue moisture content. The collection of corn stover over a typical harvest season will be over a large range of moisture contents.

Given the size and complexity of the IBSAL model other areas within the model likely need improvement. Input variables that reflect nutrient replacement requirements, soil moisture conservation, and soil carbon maintenance for different soil types, geographic regions, or annual rain fall amount could be valuable additions to the model. Continued use and investigation of the IBSAL model by those skilled in areas the model replicates will ultimately improve the quality and utility of it.

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