12-2011

The Economics and Logistics of the Dual Harvest of Grain and Biomass in a Single-Pass

Matthew T. Wold
University of Nebraska-Lincoln, wold.matthew@gmail.com

Follow this and additional works at: http://digitalcommons.unl.edu/biosysengdiss

Part of the Biological Engineering Commons, and the Bioresource and Agricultural Engineering Commons

http://digitalcommons.unl.edu/biosysengdiss/28

This Article is brought to you for free and open access by the Biological Systems Engineering at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Biological Systems Engineering--Dissertations, Theses, and Student Research by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
THE ECONOMICS AND LOGISTICS OF THE DUAL HARVEST OF GRAIN AND
BIOMASS IN A SINGLE-PASS

By

Matthew T. Wold

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Master of Science

Major: Agricultural and Biological Systems Engineering

Under the Supervision of Professor Michael Kocher

Lincoln, Nebraska

December, 2011
The Economics and Logistics of the Dual Harvest of Grain and Biomass in a Single-Pass

Matthew T. Wold, M.S.

University of Nebraska, 2011

Adviser: Michael F. Kocher

Significant interest has developed in using cellulosic resources, especially crop residues, to create biofuels. Collecting these residues in a single-pass of the harvester across the field has the potential to be a low cost option. Two models have been developed; the first characterizes the in-field logistics of single-pass crop residue collection, the second the economics. These models allow the user to easily examine a wide variety of both grain-only and single-pass residue collection harvest cases. A variety of possible residue collection cases have been examined, and their effects both on harvester field capacity and harvest cost compared to grain-only harvest have been quantified. Systems where a harvester-towed wagon unloads collected residue directly at the field edge without any intermediary residue-hauling carts were generally the lowest cost. Cost-effective systems were shown to deliver crop residues to a biomass refinery at a mean cost of between $37 and $53 per metric dry matter ton depending on the acceptable reduction in harvester field capacity.
Acknowledgements

The author would like to extend his sincere thanks to all those who have provided guidance in this research.

My family for their confidence in me, support and encouragement throughout my life.

Dr. Michael Kocher for his guidance as an advisor and encouragement throughout this project.

Dr. Deepak Keshwani and Dr. David Jones for their expertise and guidance in serving on my graduate committee.

Claas, for their funding of this research and especially Maury Salz, Andrew Tayles, and Scott Wellensiek for providing expert advice and feedback throughout the project.

To all involved in this project, thank you.
# Table of Contents

Acknowledgements ........................................................................................................ iii

Table of Contents .......................................................................................................... iv

List of Figures .............................................................................................................. vi

List of Tables ................................................................................................................. ix

Chapter 1: Introduction ................................................................................................. 1

Chapter 2: Modeling the In-Field Logistics of Single-pass Crop Residue Collection ...... 2

2.1. Introduction .............................................................................................................. 2

2.1.1. Previous Simulations .......................................................................................... 3

2.2. Simulation Development ......................................................................................... 4

2.2.1. Objectives .......................................................................................................... 4

2.2.2. Structure ............................................................................................................ 5

2.2.3. Field Generation ............................................................................................... 6

2.2.4. Simulation Operation ......................................................................................... 8

2.2.5. Biomass Collection ............................................................................................ 11

2.2.6. Bale Collection ................................................................................................. 13

2.3. Simulation Inputs ................................................................................................... 16

2.4. Simulation Validation ............................................................................................. 19

2.5. Simulation Results and Discussion ........................................................................ 21

2.7. Conclusion ............................................................................................................. 28
List of Figures

Figure 1 Randomly generated yield map shown on the left and a histogram of the yields on the right in Mg·ha⁻¹ .......................................................... 8

Figure 2 Harvesting pattern. The harvester is indicated by the circle and the cart by the diamond. The black area denotes the area of the field which the model has completed harvesting .......................................................... 9

Figure 3 A loop turn (left) and a U turn (right) with the equations for time delay shown 10

Figure 4 Comparison of route distance and processor time for Vehicle Routing Problem (VRP) solution methods ........................................................................................................ 14

Figure 5 An example 8-bale pickup route generated by the Clarke-Wright savings algorithm .......................................................................................................................... 15

Figure 6 Comparison of route improvement methods ................................................. 16

Figure 7 Plot of harvester locations in research field ................................................. 21

Figure 8 The effect of grain cart(s) size and yield on harvester field capacity harvesting grain-only with the standard deviation of the results for 25 runs each shown by error bars. .................................................................................................................. 22

Figure 9 The effect of harvester biomass wagon capacity on field capacity for the cases of separate biomass and grain carts (Sep) and carts that can transport both biomass and grain (Both). The multiplier indicates the number of times the harvester’s grain tank will become full for each time the biomass tank becomes full. ................................................. 24

Figure 10 The effect of stopping to unload biomass and being able to unload biomass and grain simultaneously on field capacity .......................................................... 25
Figure 11 The effect of the harvester directly unloading biomass either to the field edge or to the specified grain offload locations compared to the case of harvesting without biomass collection (grain-only) ................................................................. 26

Figure 12 Time to collect bales for normal sized bale collector (8-3.625, or 12-2.718 m³ bales at once) and a large size collector (36-3.625 or 48-2.718 m³ bales at once) .......... 27

Figure 13 Harvest cost distribution for grain-only harvest with a single 35 grain cart. The 5th and 95th percentiles of the results are at 94.3 and 125.5 $·ha⁻¹, respectively .......... 44

Figure 14 Effect of various input parameters on the cost of grain-only harvest with a class 8 harvester and a single 35 grain cart .................................................................................. 45

Figure 15 Harvest capacity and cost for grain-only harvest with different cart sizes. Cost is represented by the boxplot; the bars represent the means, the boxes represent the 25th and 75th percentiles, and the whiskers the 5th and 95th percentiles. Harvester field capacity, read on the right axis, is represented by the diamonds ............................................. 46

Figure 16 Cost components for 1-35 case ........................................................................... 47

Figure 17 Effect of stopping to unload and simultaneous unloading for both carts .......... 49

Figure 18 Effect of stopping to unload and simultaneous unloading for separate carts ... 50

Figure 19 Effect of cart size for both carts ......................................................................... 51

Figure 20 Effect of cart size for separate carts .................................................................. 52

Figure 21 Marginal cost for the harvester-lowed biomass wagon directly unloading at a single location ........................................................................................................ 54

Figure 22 Marginal cost for the harvester-towed biomass wagon directly unloading at field edge .............................................................................................................. 55

Figure 23 Total costs per dry matter ton delivered ................................................................ 57
Figure 24 Mapped Regression Values for 1-35 Sep. With Bio Capacity and Without Bio Capacity represent the harvester’s field capacity when harvesting biomass and when not harvesting biomass, respectively. ................................................................. 58

Figure 25 Mapped regression coefficients for 1-35 to field edge................................. 59
List of Tables

Table 1 Corn biomass yields reported in literature .................................................. 17
Table 2 Corn biomass densities reported in literature. Sources followed by an asterisk (*) measured the density of only corn cobs themselves, not all the material that typically passes through a harvester ........................................................................................................ 18
Table 3 Harvester parameters used in all simulations unless otherwise noted .............. 19
Table 4 Cart parameters used in all simulations unless otherwise noted ......................... 19
Table 5 Fertilizer prices and nutrient content used in the model .................................. 35
Table 6 Nutrient content of corn residues ..................................................................... 36
Table 7 Harvester cost and power inputs ..................................................................... 37
Table 8 Cart capacity and cost inputs .......................................................................... 38
Table 9 Probability of years of ownership for all harvest equipment .............................. 39
Chapter 1: Introduction

There is a significant interest in developing renewable fuels to reduce our dependence on oil for transportation. Advanced biofuels, like cellulosic ethanol or pyrolysis oil have the potential to create a large amount of renewable fuels from biomass feed stocks. Crop residues have the potential to be a major source of biomass, since they are already being produced in combination with the crops and only minor modifications to the harvesting system are needed to collect them (U.S. Dept. of Energy, 2005). The largest source of crop residues is corn stover, which is the focus of this work. In single-pass harvesting the harvester tows a bulk wagon or baler, which allows both grain and biomass to be collected in the same pass across the field. Single-pass harvesting is an attractive option because it allows the biomass harvest to be completed in a smaller time window, and could reduce expenses by reducing the amount of equipment, labor, and fuel required compared to making a second pass to collect the biomass.

Though a few studies have examined single-pass harvesting, only a limited number of possible scenarios have been examined, usually over a small amount of land. Modeling has the advantage of allowing a wide variety of cases to be examined without the time and expense of in-field testing. The objective of this work was to investigate the logistics and economics of single-pass residue collection using computer models.
Chapter 2: Modeling the In-Field Logistics of Single-pass Crop Residue Collection

2.1. Introduction

Due to the rising price of crude oil and growing concern over the global warming potential of fossil fuel combustion, significant interest has developed in renewable sources of energy for transportation. The United States has established a goal of generating 36 billion gallons per year of renewable transportation fuels by 2022 (U.S. Dept. of Energy, 2011a). Biomass resources are able to provide a significant contribution to this goal either through cellulosic ethanol or advanced biofuels. It has been estimated that by 2022 between about 600 million and one billion dry matter tons of biomass will be sustainably available. Between 221 and 348 million tons of this material is from crop residues, with the largest portion, up to 67% of crop residues, coming from corn stover (U.S. Dept. of Energy, 2011b). It is projected that there will also be a significant demand for biomass to generate electricity directly or provide combined heat and power (U.S. Energy Information Administration, 2011).

Interest in corn stover is currently high due to its present availability with very limited change to agricultural practices. Numerous studies have indicated that it is possible to remove a portion of the corn stover without significantly affecting soil erosion or soil carbon levels. The exact amount that can be removed without affecting soil carbon is still being debated, but it is generally considered that removal rates of less than 25% of the total above ground stover have no significant impact (Blanco-Canqui and Lal, 2009; Wilhelm et al., 2007). This removal rate is fairly similar to the amount that would be removed by collecting the material passed through a corn combine harvester, which will
hereafter be referred to as a harvester, using an ear snapper header (Shinners et al., 2009b).

A number of studies have been conducted on single-pass, dual-stream harvesting, however only a very limited number of possibilities have been considered and the unique field conditions in each study makes it very difficult to compare them. Computer simulation offers the advantages of being able to analyze a wide variety of systems without incurring the expense of physical prototypes, and the ability to compare those systems equitably. This work developed a simulation to accomplish these goals.

2.1.1. Previous Simulations

Two notable simulations of in-field logistics of harvesting have been developed. Benson et al. (2002) developed a simulation of in-field grain handling using the ARENA simulation environment. An early version of the model was created in MATLAB, but the authors decided to switch to ARENA before it was complete to take advantage of Arena’s manufacturing oriented environment. ARENA has the advantage of being a graphical simulation language structured around manufacturing processes, which should allow for an easier understanding of the simulation compared to a textual programming language. However, ARENA does not have a simple way of dealing with the variable travel distances for grain carts, which move between a specified unload location and the moving harvester. This greatly increased the required complexity of the simulation.

Their simulation was structured to use a preprocessor, simulation engine, and postprocessor. The main function of the preprocessor was to divide the field into linear paths for the harvester(s) to follow, and created .txt input files for the simulation engine.
Dividing the field into 1-D segments reduced the complexity of the main simulation. The simulation advanced harvester(s), cart(s), and road transport(s) based on a discrete timing pulse. The postprocessor was developed as a Microsoft Excel macro. The simulation was validated by comparing results to the harvest of a 48.6 hectare field.

A similar model was developed by Busato et al. (2008) using the ExtendSim simulation platform. It was focused on optimizing the location of bins in the field for the harvester to unload into. The harvester directly unloads into these stationary bins without the use of intermediary of grain carts. The simulation functioned in a manner similar to Benson et al. (2002), but did not model grain carts which are almost always used by middle- to large-size farms in the United States.

The two simulations show that it is possible to develop a reasonable computer simulation of grain harvest, and that such a simulation can provide beneficial insights into optimizing the harvesting operation. Both of these simulations were designed to model grain harvest without considering biomass collection, which they did well, but both models’ designs would make it difficult to modify either of them to model single-pass biomass collection.

2.2. Simulation Development

2.2.1. Objectives

The primary objective of this research was to develop a simulation which can evaluate the logistics of combining biomass collection with corn harvest. The simulation must be able to model typical corn harvesting scenarios both with and without biomass collection so that comparisons can be made. Biomass harvesting cases include: a harvester-towed
baler, or a towed cart which either unloads into a tractor-towed cart or directly into a pile at the edge of the field.

The primary output of the simulation is field capacity (ha\cdot h^{-1}). The field capacity only quantifies the harvesting system’s in-field capacity, and does not include delays for travel between fields, repairs and adjustments, or operator breaks. Other outputs, such as the time the harvest spends stopped waiting for a cart and the time the cart(s) is idle, are available to aid in determining the factors most impacting field capacity. For the case of biomass baling, the simulation also outputs the time required to collect the bales.

2.2.2. Structure

Based on the authors’ experience with MATLAB and personal conversation with Dr. Benson (personal communication, 15 May 2010. Associate Professor, Department of Bioresources Engineering, University of Delaware), MATLAB was selected as the programing environment for the simulation. MATLAB has the advantage of being a high-level programing language with many more built-in functions than C, or another general-purpose language, while being much more flexible and customizable than ExtendSim or ARENA.

MATLAB is, however, a fairly expensive program and it can be challenging to keep track of input and output data. The expense of MATLAB was a concern since the model was developed with the potential to be used by extension educators. These drawbacks were overcome by developing a Microsoft Excel workbook as a user interface to track simulation inputs and analyze results. Using the MATLAB compiler, a standalone executable module was created, which can run on computers that do not have an installed
version of MATLAB, and can communicate with the Excel user interface. No MATLAB toolboxes are used in the model.

The user inputs parameters to characterize the system to be simulated into an Excel spreadsheet. Examples of input parameters include grain tank capacities, corn yield, grain cart speed, etc. Next, the user starts the simulation in MATLAB. The simulation advances in discrete time steps of 0.25 seconds. Once the simulation is complete, the user runs a macro in the Excel spreadsheet which updates and formats the results from MATLAB through the use of intermediary text files.

2.2.3. Field Generation

After getting the user inputs from Excel, the first step performed by the MATLAB simulation is to create a model of the field to use in the harvesting simulation. The user inputs the dimensions of the field and average grain and biomass yields. The field is currently limited to being rectangular in shape without obstacles. This restriction greatly reduces the complexity of determining harvester paths and is representative of many fields in the Corn Belt of the United States.

If arbitrary field geometry were allowed, it would be necessary to solve a version of the milling problem for each field geometry in order to determine routes for the harvester(s) to travel. The milling problem is in the Non-deterministic Polynomial-time hard (NP-hard) problem set and solutions can consume significant processor time (Arkin et al., 2000; Arkin et al., 2006). Simplified algorithms have been developed for vehicle routing on agricultural fields using GPS data (Oksanen and Visala, 2009); however they cannot
handle completely arbitrary field geometry and can take a significant amount of time to run.

The model has the ability to generate a random yield distribution in the field each time it is run. The yield variability is representative of actual fields and causes events such as harvester unloading to occur at different locations each time it is run. Other simulations have created this variability by periodically sampling probability distributions as the harvester advances (Benson et al., 2002). However, this sampling method does not model the spatial correlation between nearby locations in the field. Spatial correlation was developed by creating a random yield map using the diamond square algorithm, sometimes called a plasma fractal. This algorithm is commonly used in generating random terrain (Martz, 1997). The algorithm begins by creating a four-by-four matrix of uniformly distributed random numbers. Next, the matrix is doubled in size and new values created in-between each existing value using cubic interpolation. Then, this matrix is multiplied by an equally sized matrix of normally distributed random numbers. This process of expanding, interpolating, and multiplying repeats until the desired matrix size is achieved with the standard deviation of the random matrix decreasing each time. This decreasing variability creates spatial correlation in the yield map. Once the random map has been created, the values are adjusted to match a user-input average yield and range.

A sample field 0.804 km (½ mi) square created by the model is shown at the left in Figure 1 and a histogram of the generated yield is shown at the right. The field is divided into squares with sides the width of the harvester’s header for convenience. The range of yield was set to 50% of the average yield, based on yield variability observed in
published data (Scharf et al., 2006; Eghball et al., 2003). If needed, this value can be modified in the program.

![Randomly generated yield map and histogram of yields](image)

**Figure 1** Randomly generated yield map shown on the left and a histogram of the yields on the right in Mg·ha⁻¹

### 2.2.4. Simulation Operation

Once MATLAB model has generated the randomized yield map, the simulation of harvesting begins. The model first simulates advancing the harvester around the outside edges of the field, until a user-specified number of headland rows have been harvested. Then, the harvester makes a breakthrough pass approximately 72 rows (55 m (180 ft) for 76 cm (30 in) rows) over and continues harvesting this section, proceeding up one side and down the other until it is harvested, as shown in figure 2. Then the harvester performs another breakthrough pass and continues in this pattern until the field is harvested. This field pattern allows the harvester’s auger to reach over harvested area, except when making a breakthrough pass, so that it can unload on the go. Every time the harvester needs to unload while making a breakthrough pass the model adds a four minute delay to account for the time necessary for the harvester to make room for the cart to pull.
alongside, align with the cart, unload into the cart, the cart to pull away, and to resume harvesting.

Figure 2 Harvesting pattern. The harvester is indicated by the circle and the cart by the diamond. The black area denotes the area of the field which the model has completed harvesting.

Three types of turns were defined for the harvester in order to determine the turning time. The first is a 90 degree turn used while traveling around-and-around the field on the headland. This value can be input by the user and was set to 20 seconds for the simulations presented here. A loop type turn was defined as shown on the left in figure 3 with the equation for calculating the time in the turn shown below the diagram. The equation was derived by expressing the distance traveled in terms of turning radius and width. Speeds in the turn were estimated based on user-input speeds for harvesting and for the harvester moving across the field while not harvesting. A U turn is also shown in
Figure 3 with its associated equation for turn time. The turn times used compare well with the work of Hansen et al. (2005) on modeling row crop harvester turning patterns. These turning times are calculated based on the user-specified turning radius of the harvester. This is important because towing a wagon or baler behind the harvester will increase its turning radius.

![Diagram of turn types]

\[ T = \frac{2 \times R \times \left( \frac{1 - \left(\frac{W}{2R}\right)^2}{\tan^{-1} \left(\frac{W}{2R}\right)} + \frac{\pi}{2} + \cos^{-1} \left(\frac{W}{2R}\right) \right)}{0.75 \times \text{Harvesting Speed} + 0.25 \times \text{Empty Speed}} \]

\[ T = \frac{0.5 \times (\text{Harvesting Speed} + \text{Empty Speed}) + \frac{W - 2 \times R}{\text{Empty Speed}}}{\pi \times R} \]

**Figure 3** A loop turn (left) and a U turn (right) with the equations for time delay shown

As the harvester advances through the field its grain tank gradually fills, and it becomes necessary for a cart to come and unload the harvester. In the simulation a cart is assigned to a harvester so that it arrives just prior to the harvester becoming full. This is accomplished by periodically calculating the time until the harvester will be full, reducing this time by 50% to allow for field variability and harvester motion, finding the nearest available cart, and routing the cart to the harvester if it would arrive just in time. This cart assignment system ensures that a cart will arrive before the harvester is full, if one is available, while still keeping the carts available for as long as possible to unload other harvesters. When assigning carts to receive material from a harvester, the model
gives priority to carts that already have some material in them. Otherwise priority is given to the cart closest to the harvester.

Once a harvester has finished unloading into a cart, the model compares the available space remaining in the cart to the harvester’s tank size. If the cart cannot hold another full tank from a harvester the model first checks if there are any nearby harvesters with some material in them to top off the cart. If the load in the cart can be topped off the model simulates doing so, and then simulates the cart proceeding to a user-specified point to unload. The user may specify any number of unloading points, but they must be located at a headland. If more than one unload site is specified the cart will unload at the closest one to its location. If the cart does not need to unload it waits in place until assigned to unload a harvester.

The model assumes that there will always be something at the unloading sites in to which the cart can unload. This assumption was made because of the interest in determining the effect of biomass collection on harvesting efficiency. If the harvester is not the bottleneck of the system, then a change in harvester capacity would have limited or no impact on harvesting efficiency.

2.2.5. Biomass Collection

The model was developed to allow simulation of three distinct methods of biomass collection: “direct unloading”, “collection with carts”, and “baling”. Both direct unloading and collection with carts have the harvester towing a wagon which collects the biomass that flows through the harvester. Biomass yield is specified by the user as a mass fraction of grain, so it varies across the field with the grain yield according to the
randomly generated yield map. All biomass containers are assumed to be volume-limited therefore biomass moisture content is not relevant and only dry matter (DM) weights are tracked. Weight and volume of the biomass are correlated by a user-specified density.

In the “direct unloading” method of biomass collection, the harvester-towed wagon directly unloads biomass without using a cart as an intermediary. The model allows the user to specify whether the harvester unloads the biomass at the closest location where the carts can offload grain, or anywhere along the field edge. If the field edge offloading option is selected, when the harvester reaches the field edge, if the biomass wagon does not have enough available space to hold the biomass that will be harvested on the combine’s next pass through the field the model simulates unloading of the wagon, otherwise the model continues harvesting.

The method of “collection with carts” adds carts in the simulation which are capable of hauling biomass from the harvester to the biomass unloading location(s). The carts may be either carts that can only haul biomass and operate separately from the grain carts (referred to as “sep”) or carts that have separate bins, one for hauling grain, and one for hauling biomass (referred to as “both”).

In the “baling” method of biomass collection, a harvester-towed baler packages the biomass into bales. Bales are dropped as they are formed when the harvester is advancing through the field. It is also possible to simulate the use of a bale accumulator, which collects a number of bales and drops them in groups across the field. When a harvester drops a bale (or group of bales), its location in the field is stored in an array for later simulation and analysis of an operation to collect the bales.
2.2.6. Bale Collection

After completion of the simulated harvest with baling the model simulates collection of the bales. The most challenging portion of this operation is determining a route for the bale collector to travel. This type of problem is called the Capacitated Vehicle Routing Problem (CVRP) and has been shown to be in the Non-deterministic Polynomial-time hard (NP-hard) problem set.

Exact solutions for only up to about 100 vertices, bale drop locations in this case, are possible (Baldacci et al., 2008), but would consume a significant amount of processor time. In any case an exact solution is not required for the simulation since its goal is to model real world behavior. In the real world, it is very unlikely that an operator would choose the exact solution, but rather would likely follow a reasonably short route, which can be determined with heuristic algorithms.

A variety of classical heuristic and metaheuristic solution approaches have been developed for the problem (Laporte, 2009). Heuristic algorithms have the advantage of being straight forward to implement and typically run faster than metaheuristics, but may not produce as short of a route. Three heuristic algorithms were tested for bale collection: Clarke-Wright savings algorithm (Clarke and Wright, 1964), the Gillett-Miller sweep algorithm (Gillett and Miller, 1974), and an insert algorithm (Kay, 2009). These algorithms were implemented using a logistics toolbox for MATLAB called MatLog (Kay, 2009). These algorithms were compared to one another on the basis of route distance and processor time (using an Intel core2 duo processor) as shown in figure 4.
Fifteen repetitions with each algorithm for each combination of bale collector (8 or 36 bales) and each bale collection location (one corner of the field, or the center of the field) were performed on a 0.8 km by 0.8 km (0.5 mile by 0.5 mile) field with approximately 240 bales. In all four combinations, the savings algorithm took the least amount of processor time. The savings algorithm created, on average, the shortest route for the 8 bale capacity collector. The sweep algorithm was able to create slightly shorter routes for the 36 bale capacity collector, however it took 22 times as long to run. Based on these results, the savings algorithm was selected for the simulation.

The savings algorithm starts with a route from each individual bale directly to the bale collection site. It then merges one route with another choosing the pair that saves the most distance traveled (hence the name savings). This merging process continues until all possible merges have been made. A sample output route from the savings algorithm is shown in figure 5. Two important assumptions are made in creating this route. It was

Figure 4 Comparison of route distance and processor time for Vehicle Routing Problem (VRP) solution methods

The savings algorithm starts with a route from each individual bale directly to the bale collection site. It then merges one route with another choosing the pair that saves the most distance traveled (hence the name savings). This merging process continues until all possible merges have been made. A sample output route from the savings algorithm is shown in figure 5. Two important assumptions are made in creating this route. It was
assumed that the bale can be picked up from any direction. This is indeed the case of some bale collectors, such as the Stinger Stacker. Second, that the vehicle turning radius is effectively zero. This is certainly not the case, but solving the vehicle routing problem to account for turning radius would be much more difficult, and again the goal of the simulation is not to establish an exact time to collect bales, but rather to provide a basis for comparing multiple systems.

Figure 5 An example 8-bale pickup route generated by the Clarke-Wright savings algorithm

A number of methods are available for improving CVRP routes after they have been determined. Two improvement methods, exchange and crossover, and running both of them on the same route were compared to the savings algorithm by itself using the same method as above. It is apparent from the results shown in figure 6, that these improvement methods consume a great deal of processor time while resulting in only a
slight reduction in route distance. Therefore, the savings algorithm without route improvement was used in the simulation.

Figure 6 Comparison of route improvement methods

Once the route has been generated bale collection is simulated by advancing the collector along the route at a specified speed. Bale collectors typically have a minimum cycle time between picking up one bale and being ready for the next. The simulation accounts for this behavior by stopping the bale collector at the next bale and waiting until the cycle completes before continuing the bale collection operation. If a bale accumulator is used, the user may specify the number of bales that the collector can pick up in each batch. Once the collector is full of bales it follows the shortest route to the bale stack and the simulation assesses a time delay while the collector unloads the bales. The collector continues in this fashion until all bales in the field have been collected. Then, the simulation outputs the time required to collect the bales and the distance traveled by the collector.

2.3. Simulation Inputs

Once the model had been developed, it was necessary to define the input values to be used in this research. A number of different sources have provided data on biomass yield.
For this work, it was assumed that only the portions of the corn plant which typically pass through a harvester using an ear snapper corn header would be collected. This assumption was made because research has shown that use of a whole plant header significantly slows down the harvester (Shinners et al., 2009b), which would likely be undesirable for farmers since currently the revenue generated by biomass is quite small in comparison to the grain. Published measurements of biomass yield varied widely as shown in table 1. Halvorson and Johnson (2009) and Avila-Segura et al. (2011) report only the yield of cobs themselves, which were collected by hand. Ear snapping corn headers typically collect not only the cob, but also much of the husk, shank, and small amounts of stalk and leaves. The data from Sawyer and Mallarino (2007) are likely somewhat of an overestimate since not all the husks and shanks would be collected. Thoreson et al. (2010) reported a typical amount for cob collection equipment currently on the market. However, this equipment was designed to use fans to separate out other material from the cobs. Based on these sources the biomass yield was assigned to be 17% of the grain yield; although this can be changed by the user.

<table>
<thead>
<tr>
<th>Source</th>
<th>Corn Cob Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Varvel and Wilhelm, 2008)</td>
<td>“Cob biomass as a percent of grain biomass averaged approximately 20%”</td>
</tr>
<tr>
<td>(Halvorson and Johnson, 2009)</td>
<td>Mg/ha of cobs = 0.096*Mg·ha⁻¹ (of grain at 15.5% moisture w.b.)+0.436</td>
</tr>
<tr>
<td>(Avila-Segura et al., 2011)</td>
<td>1.21Mg·ha⁻¹ for 9.73Mg·ha⁻¹ corn (or 0.12 as a mass fraction)</td>
</tr>
<tr>
<td>(Sawyer and Mallarino, 2007)</td>
<td>2.41 DM Mg·ha⁻¹ of cobs, husks, and shanks for 9.1 Mg·ha⁻¹ of corn (or 0.26 as a mass fraction)</td>
</tr>
<tr>
<td>(Thoreson et al., 2010)</td>
<td>Typically 1.1 DM Mg·ha⁻¹ of cobs, for cob carts currently on the market</td>
</tr>
<tr>
<td>(Shinners et al., 2003)</td>
<td>2.19 DM Mg·ha⁻¹ for 13.08 Mg·ha⁻¹ corn (or 0.17 as a mass fraction)</td>
</tr>
<tr>
<td>(Shinners et al., 2009b)</td>
<td>1.8 DM Mg·ha⁻¹ for 13.0 Mg·ha⁻¹ corn (or 0.14 as a mass fraction), 2.1 DM Mg·ha⁻¹ for 14.7 Mg·ha⁻¹ corn (or 0.14 as a mass fraction)</td>
</tr>
</tbody>
</table>
Another important input to the simulation was the density of the collected biomass. Reported densities vary as shown in table 2. The values reported by Dunning et al. (1948) and Kaliyan and Morey (2008) are for only the cobs themselves and are not representative of the material that would actually be passed through a harvester. Based on the other sources, a midrange value of 96 kg·m\(^{-3}\) (6 lb·ft\(^{-3}\)) was chosen.

**Table 2 Corn biomass densities reported in literature. Sources followed by an asterisk (*) measured the density of only corn cobs themselves, not all the material that typically passes through a harvester**

<table>
<thead>
<tr>
<th>Source</th>
<th>Corn Cob Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Dunning, J.W., P. Winter, and D. Dallas, 1948)*</td>
<td>208 kg·m(^{-3}) (13 lb·ft(^{-3}))</td>
</tr>
<tr>
<td>(Kaliyan and Morey, 2008)*</td>
<td>146.8 kg·m(^{-3}) (9.14 lb·ft(^{-3}))</td>
</tr>
<tr>
<td>(Birrell, Dilts and Schlesser, 2006)</td>
<td>112-144 kg·m(^{-3}) (7-9 lb·ft(^{-3}))</td>
</tr>
<tr>
<td>(Thoreson, Darr and Webster, 2010)</td>
<td>96 kg·m(^{-3}) (6 lb·ft(^{-3}))</td>
</tr>
<tr>
<td>(Shinners et al., 2009a)</td>
<td>90-111 kg·m(^{-3}) (5.6-6.9 lb·ft(^{-3}))</td>
</tr>
</tbody>
</table>

Next the harvester specifications for the simulation were chosen to be representative of the current market and of a fairly typical size as shown in table 3. These values are used unless otherwise noted. The biomass tank capacity was sized to match the grain tank capacity based on the above specified biomass yield and density. With the assumed biomass yield of 17% of grain (mass) yield and a density of 96 kg·m\(^{-3}\), which results in a volume ratio of grain to biomass of 1:1.29. The biomass unload time was specified based on currently available cob collection equipment. Harvesting speed is kept constant throughout the simulation, based on recommendations from industry experts. Empty speed is the speed at which the harvester travels when not harvesting, and is used in calculating turning times.
Table 3 Harvester parameters used in all simulations unless otherwise noted

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Tank Capacity</td>
<td>11,630 L (330 bu)</td>
</tr>
<tr>
<td>Grain Unload Rate</td>
<td>116 L∙s⁻¹ (3.3 bu∙s⁻¹)</td>
</tr>
<tr>
<td>Biomass Wagon Capacity</td>
<td>15 m³ (530 ft³)</td>
</tr>
<tr>
<td>Biomass Unload Time</td>
<td>90 s</td>
</tr>
<tr>
<td>Harvesting Speed</td>
<td>8 kph (5 mph)</td>
</tr>
<tr>
<td>Empty Speed</td>
<td>12.9 kph (8 mph)</td>
</tr>
<tr>
<td>Header Size</td>
<td>12 x 30 in rows</td>
</tr>
<tr>
<td>Turning radius</td>
<td>7.19 m (23.6 ft)</td>
</tr>
<tr>
<td>-with towed wagon or baler</td>
<td>11.49 m (37.7 ft)</td>
</tr>
</tbody>
</table>

Cart parameters representative of currently available carts were used in the simulation as shown in table 4. In this paper the nomenclature used for carts is the cart grain capacity in cubic meters followed by either “grain”, “bio”, or “both” to denote carts that haul grain-only, biomass-only, or both grain and biomass, respectively. Biomass capacities for the carts were selected to pair exactly with the grain sizes given the assumed biomass density of 96 kg m⁻³ and mass harvest rate of 0.17 times grain mass. It is typical for loaded carts to travel slower than full carts; this behavior is simulated by using the specified unloaded and loaded speeds. The simulation calculates cart speed by linear interpolation between these two speeds for partially loaded carts.

Table 4 Cart parameters used in all simulations unless otherwise noted

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>26</th>
<th>35</th>
<th>53</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Tank Capacity</td>
<td>m³ (bu)</td>
<td>26.4 (750)</td>
<td>35.2 (1000)</td>
<td>52.9 (1500)</td>
<td>70.5 (2000)</td>
</tr>
<tr>
<td>Biomass Tank Capacity</td>
<td>m³ (ft³)</td>
<td>34.0 (1200)</td>
<td>45.3 (1600)</td>
<td>68.0 (2400)</td>
<td>90.6 (3200)</td>
</tr>
<tr>
<td>Grain Unload Rate</td>
<td>L∙s⁻¹ (bu∙s⁻¹)</td>
<td>264 (7.5)</td>
<td>292 (8.3)</td>
<td>469 (13.3)</td>
<td>588 (16.7)</td>
</tr>
<tr>
<td>Biomass Unload Time</td>
<td>s</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Unloaded Speed</td>
<td>kph (mph)</td>
<td>16.1 (10)</td>
<td>16.1 (10)</td>
<td>16.1 (10)</td>
<td>16.1 (10)</td>
</tr>
<tr>
<td>Loaded Speed</td>
<td>kph (mph)</td>
<td>12.9 (8)</td>
<td>12.9 (8)</td>
<td>12.9 (8)</td>
<td>12.9 (8)</td>
</tr>
</tbody>
</table>

2.4. Simulation Validation

The simulation was validated by extensive monitoring of simulation variables as it ran, a review of the simulation’s operation by experts in harvesting equipment performance,
and comparison to real world harvesting results. The first step in validating the model was monitoring simulation variables as it ran. One example of monitoring simulation variables as the simulation progressed is that the harvester and cart grain and biomass levels were plotted as the simulation progressed to monitor loading and unloading activity.

The model was reviewed with industry experts throughout the model development process. Their input was gathered on the assumptions made in developing the model and the reasonableness of the model’s results. Input from the industry experts was obtained on a number of items including harvester speed in turns, harvester turning radius, number of rows between breakthrough passes in the field, time delay for a harvester unloading while making a breakthrough pass, and cart operator behavior. They also recommended that harvester speed remain constant while harvesting as implemented in the simulation.

Lastly, the results from the simulation were compared to real world data from the University of Nebraska Agricultural Research and Development Center. The field used is located at 41.174°N latitude and 96.440°W longitude. GPS yield monitor data were gathered on a 32.4 ha (80 acre) field using two John Deere 9560STS harvesters with 8 row corn headers and two Brent 672 grain carts pulled by John Deere 7820 tractors. The two harvesters did not start harvesting the field at exactly the same time and one harvester stopped for a total of 10 minutes to address an issue. The average effective capacity of the harvesters was 2.65 ha·h⁻¹ compared to 2.82 ha·h⁻¹ from the simulation, a difference of only 6.5%. This difference can be explained primarily by the particular field geometry harvester paths as shown in figure 7. There was a grassed water-way which isolated a small section in the northeast corner of the field, greatly increasing the time
required to harvest this portion of the field. Also the north and south field edges were not straight which required the harvester to perform additional maneuvers. These factors likely account for the 6.5% difference between the simulation and measured results.

![Figure 7 Plot of harvester locations in research field](image)

2.5. Simulation Results and Discussion

Prior to using the simulation to evaluate biomass harvesting operations it was necessary to establish a baseline for typical grain harvesting. The 12 row harvester specified in Table 3 was paired with either one or two of each of the listed carts. Simulated harvesting was performed on fields with corn grain yields of 9.42 Mg·ha\(^{-1}\) (150 bu·acre\(^{-1}\)), 12.55 Mg·ha\(^{-1}\) (200 bu·acre\(^{-1}\)), and 15.69 Mg·ha\(^{-1}\) (250 bu·acre\(^{-1}\)). This allowed for the sensitivity of field capacity to yield to be determined. Each scenario was run a total of 25 times to estimate variation caused by differences in the randomly generated yield maps. Each time a scenario is run, a different random yield map is generated. The results are shown in figure 8 with the error bars on each column showing the standard deviation from the 25
runs. The results show that using larger or multiple carts improves field capacity much more at higher yields than at lower yields. The results also show that field capacity for the same cart configuration is always reduced by increased yield. This reduction can be attributed to the fact that if the harvester needs to unload while making a breakthrough pass it is assessed a delay of four minutes. As the yield increases the number of times the harvester unloads on a breakthrough pass also increases. The increase in field capacity for the 70 cart(s) over the 53 cart(s) was negligible, with the exception of a small increase in the highest yield case, indicating that the 70 cart size is beyond the point of diminishing returns for the combine field capacity.

**Figure 8** The effect of grain cart(s) size and yield on harvester field capacity harvesting grain-only with the standard deviation of the results for 25 runs each shown by error bars.

It is important to keep in mind that the goal of equipment management is not to get the highest field capacity, but rather the highest profit. If the highest capacity was the goal, then obviously two 35 carts should be used, maybe even the addition of a third cart would slightly improve efficiency, however this would likely not be cost effective. Performing
an economic analysis to determine the optimal case is beyond the scope of this study, and would likely be very dependent on characteristics particular to individual farms.

With the performance baseline for harvest without biomass collection established, simulations of grain and biomass collection could be run and compared with the grain-only performance to quantify the effect of adding the biomass collection to the grain harvesting operation. Simulations including biomass collection were run to determine the effect of the size of the biomass wagon behind the harvester on field capacity. Biomass wagon capacity is expressed as a multiple of harvester grain capacity. Simulations were performed for both separate grain and biomass carts operating independently (Sep), and carts that can haul both grain and biomass at the same time (Both). The number in front of the cart indicates the number of carts capable of hauling grain. So for example 2-26 Both indicates that there are two 26 type carts that can carry both grain and biomass, while 1-26 Sep indicates that there is one 26 grain-only cart and one 26 biomass-only cart. In the simulations, the harvesters were able to unload both grain and biomass on-the-go, however they could not unload both grain and biomass at the same time. This is representative of the difficulty of getting both carts aligned with the harvester simultaneously. The results of these simulations are shown in figure 9. The dashed horizontal lines indicate the capacity achieved without biomass collection for reference. The field capacity increases until the harvester biomass wagon capacity reaches two times the grain capacity. At this point the field capacity levels off. It is not possible to exactly reach the field capacity of the grain-only harvest because of the wider turning radius, and hence additional turning time required to operate the harvester while pulling the biomass wagon. Two main factors contribute to reduced field capacity for smaller
wagon sizes. First, the harvester biomass wagon fills more quickly so the cart has less
time to unload and return to the harvester before the harvester is full, increasing the
amount of time the harvester has to stop harvesting and wait for a biomass cart into which
it can unload. Second, the harvester has to unload more often while making a
breakthrough pass, incurring the 4 minute delay necessary for that unloading.

![Diagram showing combine biomass capacity compared to grain capacity](image)

**Figure 9** The effect of harvester biomass wagon capacity on field capacity for the cases of separate biomass and grain carts (Sep) and carts that can transport both biomass and grain (Both). The multiplier indicates the number of times the harvester’s grain tank will become full for each time the biomass tank becomes full.

Simulations were run to determine the effects of the harvester stopping to unload biomass (grain is still unloaded on the go) labeled as stop, instead of unloading on-the-go (labeled as non-stop), the harvester being able to unload grain and biomass simultaneously (labeled as simultaneous unloading, while the carts must still unload grain and biomass separately), and having both these effects (labeled stop and simultaneous unloading) as shown in Figure 10. The field capacity for harvesting without biomass collection (grain-only) is shown as diamonds for reference. The ability to unload grain and biomass simultaneously has a much greater improvement of the field efficiency for carts that haul
both without stopping to unload biomass, which is reasonable since this significantly reduces their interface time with the harvester. Separate carts do not often end up needing to unload the harvester at the same time, so this ability does not have as significant of an impact. The additional requirement of the harvester stopping to unload biomass greatly reduced field capacity as should be expected since a 90 second delay is incurred each time the harvester unloads. From these results it is apparent that single-pass harvesting systems should be designed to allow the simultaneous unloading of both grain and biomass on-the-go, if possible without significant cost increases.

![Figure 10 The effect of stopping to unload biomass and being able to unload biomass and grain simultaneously on field capacity](image)

Next, simulations were run to determine the effect of having the harvester unload biomass directly without a biomass cart as an intermediary (grain carts were still used). The harvester was tested for the cases of unloading the biomass at one edge of the field along the headland (to field edge), and bringing the biomass to one of the two specified
grain offload locations. For this testing the harvester’s biomass tank was sized so that it could make two complete passes (i.e. up the field and back down, (34 m$^3$ (1200 ft$^3$) biomass capacity) before becoming full so that all the biomass could be brought to one headland. The results show a significant capacity reduction for bringing the biomass to the grain offload locations due to the travel time incurred by the combine. Allowing the harvester to unload at the field edge, wherever it happens to be when turning, results in a much lower capacity reduction from grain-only harvest. However, this results in biomass piles being distributed along the field edge instead of at two locations which will likely result in additional time to collect the piles and could increase storage losses.

![Graph](image)

**Figure 11** The effect of the harvester directly unloading biomass either to the field edge or to the specified grain offload locations compared to the case of harvesting without biomass collection (grain-only)

The effect of bale size, bale collector capacity, and bale collection site location was analyzed as shown in figure 12. The normal sized bale collector has the ability to haul 8-3.625 m$^3$ (4X4X8ft) or 12-2.718m$^3$ (3X4X8ft) bales at once, while the large size collector
has a capacity of 36-3.625 m$^3$ (4X4X8ft) or 48-2.718 m$^3$ (3X4X8ft) bales. Three field locations to which all bales were delivered were tested: the extreme southwest corner of the field (corner), the exact center of the field (center), and the center of the south edge of the field (mid-edge). The case of the baler dropping a single bale and two bales at once was also examined. For the case of two bales at once, the bale collector was allowed to pick up both bales at once also. It was assumed that the bale collector would travel 16 kph (10mph) and require 12 seconds between bale pickups and 45 seconds to unload the bales. It is interesting that there is only a slight difference between the bale sizes. Picking up the bales in groups of two did significantly reduce the collection times indicating that the use of bale accumulators towed behind the baler would be beneficial.

![Figure 12 Time to collect bales for normal sized bale collector (8-3.625, or 12-2.718 m$^3$ bales at once) and a large size collector (36-3.625 or 48-2.718 m$^3$ bales at once)]
The results from the simulation compared well to real world data for grain-only harvest. This paper focused on applying the simulation to corn, but it can easily be applied to other crops. The simulation is able to model many of the single-pass residue collection systems currently under consideration and determine their impact on harvester field capacity. The model has the ability to quantify the effect of small changes in the harvesting system, for example increased grain tank capacity or decreased cart speed on field capacity. It can also be used to optimize typical grain harvesting systems in addition to its ability to model single-pass residue collection. The model could be used by farmers or extension agents to determine the impact of particular equipment purchasing decisions on a particular farm. The model could also be used by equipment manufacturers to optimize their harvesting equipment design by determining the impact of design decisions on harvester capacity.

2.7. Conclusion

A simulation for the in-field logistics has been developed, which is able to model a wide variety of scenarios including single-pass residue collection. The results showed that the addition of biomass collection in all cases considered reduced the field capacity of the harvester, however the amount of reduction is widely variable and could be quite small with certain systems. Future work is needed to understand the implications of these changes in field capacity on the overall economics of grain harvest and agricultural residue collection for energy uses.
2.8 References


Dunning, J.W., P. Winter, and D. Dallas, 1948. The storage of corncobs and other agricultural residues for industrial use, Agricultural Engineering. 29, 11.


Chapter 3: The Economics of the Dual Harvest of Grain and Biomass in a Single-pass

3.1. Introduction

The United States has set forth a goal of producing 36 billion gallons per year of biofuels by 2022 (U.S. Dept. of Energy, 2011). One of the major sources of feedstock necessary to reach this will be crop residues (U.S. Dept. of Energy, 2005). Since crop residues are already being produced as part of crop production, land use change and major changes in agricultural practices are not required to make residues available for biofuel production. These factors should allow for crop residues to be made rapidly available as a feedstock for biomass refineries. However, methods of collecting the residues either after or during crop harvest need to be developed and evaluated.

Economic models have been developed to examine different means of collecting crop residues. These models have been primarily developed from the perspective of a biomass refiner, and are thereby able to provide prospective refiners with feedstock cost estimates. However, this perspective makes these models less able to answer the questions that prospective producers will have about how residue collection will affect their specific operation. Examining the economics of biomass collection from the producer’s perspective is necessary in order to educate producers on how to determine if their farm is a good candidate for crop residue collection, and to find the best collection method for their specific farm. The ultimate control of the crop residue supply rests in the hands of the farmers, as they will be the ones who ultimately decide whether or not to collect residue on their farms.
The research presented here developed an economic model to examine single-pass crop residue collection from a producer’s perspective. The focus of this work is on corn residue collection though the model can be used to examine other crop residues. It draws on a previously published model of the in-field logistics of crop residue collection to characterize the effect of crop residue collection on harvester field capacity (Wold et al., 2011). Single-pass collection has the primary advantages of shortening the total harvest window (grain and biomass) and reducing the overall amount of labor required by completing all harvesting operations in a single-pass of the harvester across the field without the need for additional operations to collect the biomass.

3.2. Model Design and Overview

The economics model was developed as a Microsoft Excel spreadsheet. Excel was selected for this model primarily because of its ease of use and availability to a wide audience. The model is structured into a number of sheets: the first sheet establishes a general overview of the collection system while every other sheet represents a specific step in the collection operation. The model ends with the biomass delivered to the gate of a biomass refinery. The user enters the total number of acres over which the biomass is to be collected and the expected biomass collection rate, which is expressed as tons per acre, on this sheet. Each subsequent sheet will be discussed in the typical order of operations. Each sheet is isolated from others as much as possible for ease of use.

The model was originally designed for use with single static values in each cell, however in order to capture the variability of input values @RISK has been used to attach probability distributions to many of the input cells for the analysis presented in this work,
but the model can easily be used without @RISK. The use of these probability
distributions allows both the potential variation in biomass collection costs and the
sensitivity of the costs to various input factors to be understood.

For the results shown in this paper a biomass yield of 2.13 DM Mg·Ha$^{-1}$ was used based
on previous work (Wold et al., 2011). A 1619 hectare (4,000 acre) farm with 60% of the
farm in corn was assumed to be representative of an upper-middle-sized farm in the US
cornbelt.

3.2.1. Fertilizer

Fertilizer cost is an important factor in the overall cost picture and was difficult to
quantify since fertilizer cost has been highly variable in recent years, and estimates of the
nutrients removed in the stover vary widely. Fertilizer prices are calculated from
triangular distributions with the minimum, maximum, and average values. These values
were set to 20% above the minimum, maximum, and average nationwide values,
respectively, reported over the past five years (2006 to 2011) (USDA, 2011). The values
used in the model are shown in Table 5 with nutrient content (Zublena et al., 1997). The
input values were increased above from historic values by 20% to reflect forecasted
increase in average petroleum and natural gas prices in the near future compared to the
past five years since fertilizer prices correlate relatively closely with petroleum prices
(U.S. Energy Information Administration, 2011a). The triangular distribution actually
requires the most likely value to be used as an input instead of the average. The most
likely value was calculated using the average value for the past five years to input into the
distribution.
Table 5 Fertilizer prices and nutrient content used in the model

<table>
<thead>
<tr>
<th>Name</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Most Likely</th>
<th>N</th>
<th>P₂O₅</th>
<th>K₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrous ammonia</td>
<td>$660</td>
<td>$998</td>
<td>$885</td>
<td>82%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Diammonium phosphate (18-46-0)</td>
<td>$584</td>
<td>$1124</td>
<td>$784</td>
<td>18%</td>
<td>46%</td>
<td>0%</td>
</tr>
<tr>
<td>Potassium chloride</td>
<td>$370</td>
<td>$1128</td>
<td>$728</td>
<td>0%</td>
<td>0%</td>
<td>60%</td>
</tr>
</tbody>
</table>

For simplicity and because it results in an overall lower fertilizer cost it was assumed for this work that all phosphorus would be applied as diammonium phosphate (DAP), and the remaining nitrogen would be applied as anhydrous ammonia. The prices of each type of fertilizer are not independent of each other, as, for example, it would not be likely to have a very high price for anhydrous ammonia while having a very low price for DAP.

As previously mentioned, the price of fertilizer also correlates with the price of petroleum and natural gas. These correlations were input into the model as a correlation matrix. Neither petroleum nor natural gas prices are in the model; however, the price of diesel fuel is in the model as diesel fuel cost is included in the machinery cost estimates.

Fertilizer prices were correlated with diesel fuel prices, bypassing the intermediate correlations to petroleum and natural gas. The correlation matrix was developed using the last 15 years of fertilizer and diesel fuel price history (1996 to 2011) (USDA, 2011).

The user may either input their own values for N-P-K requirements or allow the model to calculate these requirements based on the fertilizer content of the removed stover. For this work it was assumed that all nutrients removed in the stover must be replaced. This certainly may not be the case, especially in the early years of residue collection, depending on soil conditions. However, at some point those nutrients will need to be replaced, and their removal in the stover needs to be assigned some type of economic
value. Estimates for the nutrient content of the residue removed are based on the average of three sources shown in Table 6. There is some diversity in the nutrient contents reported likely caused by different corn varieties and growing conditions which occurred in the research. It should be noted that Avila-Segura et al. (2011) and Johnson et al. (2010) report phosphorus and potassium as their elemental values (i.e. P and K alone), instead of as \(\text{P}_2\text{O}_5\) and \(\text{K}_2\text{O}\). Their values were converted to the latter form since it is more typically used by farmers and extension specialists who may be end-users of the model. Additional micronutrients or lime requirements were not addressed in this model.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>N</th>
<th>(\text{P}_2\text{O}_5)</th>
<th>(\text{K}_2\text{O})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Avila-Segura et al., 2011)</td>
<td>Cobs</td>
<td>0.303%</td>
<td>0.076%</td>
<td>0.770%</td>
</tr>
<tr>
<td>(Johnson et al., 2010)</td>
<td>Cobs</td>
<td>0.546%</td>
<td>0.115%</td>
<td>0.753%</td>
</tr>
<tr>
<td>(Sawyer and Mallarino, 2007)</td>
<td>Cobs</td>
<td>0.330%</td>
<td>0.107%</td>
<td>0.620%</td>
</tr>
<tr>
<td>(Sawyer and Mallarino, 2007)</td>
<td>Cobs, husks shanks</td>
<td>0.359%</td>
<td>0.150%</td>
<td>0.970%</td>
</tr>
<tr>
<td>Used in Model</td>
<td>Average</td>
<td>0.385%</td>
<td>0.112%</td>
<td>0.778%</td>
</tr>
</tbody>
</table>

### 3.2.2. Harvest Cost

The next portion of the model quantifies the harvest cost of the residues. This was done by comparing the cost of harvest without residue collection to cost with residue collection. Only the marginal cost incurred from adding residue collection was charged to the residue. The sheets for harvest costs with and without residue collection were based closely on a farm machinery cost spreadsheet developed by Dr. William Edwards (Edwards, 2009). The spreadsheet quantifies the equipment cost using the methods specified in ASAE standard EP496.3 with the data contained in D497.6 (ASAE Standard,
2006; ASAE Standard, 2009). Costs for depreciation, taxes insurance and housing, fuel and lubrication, labor, and repair were estimated using these methods.

Purchase prices for all equipment were estimated using list prices found on manufacturer’s websites. These prices are not meant to reflect a particular model or manufacturer, but rather to be representative of the industry as a whole. Purchase price was defined as 90% of the Manufacturer’s Suggested Retail Price (MSRP) as is typical for this type of analysis. For the research presented here only a single harvester was used for simplicity. A class 8 combine was chosen since it is one of the most common sizes currently produced and fit well with the size of the farm operation used in this study. The MSRP for the harvester and header used in this work is shown in Table 7. The engine horsepower shown in Table 7 was used in fuel consumption calculations according the ASAE standards.

**Table 7 Harvester cost and power inputs**

<table>
<thead>
<tr>
<th>Class 8</th>
<th>MSRP</th>
<th>Engine kW</th>
<th>Header Rows</th>
<th>Header MSRP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$400,000</td>
<td>317</td>
<td>12</td>
<td>$95,000</td>
</tr>
</tbody>
</table>

Cart sizes were selected to represent the typical size range used in corn harvesting on the size of farm used in this study. Tractors towing the carts were sized according to the cart manufacturer’s recommendations. Tractor and cart prices are meant to be typical of the industry. Tractor prices were estimated based on typical configurations. In this paper the nomenclature used for carts is the cart grain capacity in cubic meters followed by either “grain”, “bio”, or “both” to denote carts that haul grain-only, biomass-only, or both grain and biomass, respectively. Biomass capacities for the carts were selected to pair exactly with the grain sizes given the assumed biomass density of 96 kg·m\(^{-3}\) and biomass mass harvest rate of 0.17 times grain mass. Since bio and both carts are not currently available
for purchase, prices were set based on grain cart prices and the assumption that production volumes would be lower than grain carts resulting in higher prices. Tractors were sized for the bio and both carts by comparing the anticipated weight of the cart with the weight and tractor power recommendations for the grain carts. The carts along with cart towing tractors are shown in Table 8.

<table>
<thead>
<tr>
<th>Cart</th>
<th>Grain Capacity (m$^3$)</th>
<th>Bio Capacity (m$^3$)</th>
<th>Cart MSRP</th>
<th>Tractor kW</th>
<th>Tractor MSRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Grain</td>
<td>26.4</td>
<td>0.0</td>
<td>$35,000</td>
<td>130.5</td>
<td>$150,000</td>
</tr>
<tr>
<td>35 Grain</td>
<td>35.2</td>
<td>0.0</td>
<td>$46,000</td>
<td>164.1</td>
<td>$180,000</td>
</tr>
<tr>
<td>53 Grain</td>
<td>52.9</td>
<td>0.0</td>
<td>$105,000</td>
<td>249.8</td>
<td>$280,000</td>
</tr>
<tr>
<td>70 Grain</td>
<td>70.5</td>
<td>0.0</td>
<td>$130,000</td>
<td>335.6</td>
<td>$310,000</td>
</tr>
<tr>
<td>26 Bio</td>
<td>0.0</td>
<td>34.0</td>
<td>$50,000</td>
<td>115.6</td>
<td>$120,000</td>
</tr>
<tr>
<td>35 Bio</td>
<td>0.0</td>
<td>45.3</td>
<td>$65,000</td>
<td>141.7</td>
<td>$165,000</td>
</tr>
<tr>
<td>53 Bio</td>
<td>0.0</td>
<td>68.0</td>
<td>$80,000</td>
<td>193.9</td>
<td>$220,000</td>
</tr>
<tr>
<td>70 Bio</td>
<td>0.0</td>
<td>90.6</td>
<td>$95,000</td>
<td>249.8</td>
<td>$280,000</td>
</tr>
<tr>
<td>26 Both</td>
<td>26.4</td>
<td>34.0</td>
<td>$80,000</td>
<td>193.9</td>
<td>$220,000</td>
</tr>
<tr>
<td>35 Both</td>
<td>35.2</td>
<td>45.3</td>
<td>$110,000</td>
<td>249.8</td>
<td>$280,000</td>
</tr>
<tr>
<td>53 Both</td>
<td>52.9</td>
<td>68.0</td>
<td>$150,000</td>
<td>316.9</td>
<td>$300,000</td>
</tr>
<tr>
<td>70 Both</td>
<td>70.5</td>
<td>90.6</td>
<td>$180,000</td>
<td>395.2</td>
<td>$350,000</td>
</tr>
</tbody>
</table>

Farm diesel fuel price was set to log-logistic function fit to DOE diesel fuel spot prices for ultra-low sulfur diesel fuel on the gulf coast over a five year period ending July 2011 (U.S. Energy Information Administration, 2011a). This distribution was then shifted so that its mean value was $3.10 per gallon which is the approximate current price for farm diesel fuel. This price shift reflects forecasts for the average price of petroleum products to remain near current levels in the near future (U.S. Energy Information Administration, 2011b). These prices were used since off-road diesel is not taxed.
Interest rates were set to a triangular distribution with a minimum of 4%, maximum of 8%, and most likely of 6% based on current agricultural loan rates reported in a recent survey conducted by the Federal Reserve Bank of Kansas City (Henderson and Akers, 2011).

Farm labor wages were set to a triangular distribution with a minimum of $10\cdot h^{-1}$, maximum of $20\cdot h^{-1}$, and a most likely of $15\cdot h^{-1}$ based on estimates from an agricultural economist (Wilson, 2011).

Typically, the largest component of harvest costs is equipment depreciation. This makes the assumptions that drive depreciation costs important, particularly years of ownership and hours of use per year. It was assumed that all equipment used for harvesting will be purchased new and sold after the ownership period at a resale value determined by the equation in section 6.1 of ASAE standard D497.6. For this work the ownership period was set to a discrete distribution with values shown in Table 9. These values were based on input from industry experts for typical ownership periods of farmers purchasing equipment for their own use, not for custom operators. It was assumed that 60% of harvester hours were accrued during corn harvest, the remainder occurring for soybean harvest which is not included in this analysis. This is based on a fairly typical 60-40 split between corn and soybeans for farms in the Corn Belt. (ASAE, 2009)

<table>
<thead>
<tr>
<th>Ownership Period (years)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.1</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 9 Probability of years of ownership for all harvest equipment

For tractors used to tow the carts it was assumed that they would accrue 550 hours annually, which is the same value in work done by the University of Illinois (Schnitkey
and Lattz, 2008). This is assuming that no-matter the tractor size selected to tow the carts, there will be sufficient other uses for the tractor on the farm to accrue 550 hours per year. This assumption also means no cost or benefit is included for changing tractors on operations not a part of corn harvest. For example a farm switches from a 35 Grain cart to a 35 Both cart for biomass harvest, the farm will now need a 250 kW tractor instead of a 165 kW tractor. It is assumed that this 250 kW tractor will still be used 550 hours per year, like the 165 kW tractors did. The ability to do this in reality will of course depend greatly on the specific farm. If needing a 250 kW tractor meant for a specific farm retaining the 165 kW tractor, putting fewer hours on it, and only using the larger tractor for biomass harvest, tractor costs would be much higher than represented in this model. Analyzing these costs is beyond the scope of this research as it would be highly dependent on the particular farm and be very difficult to generalize to the industry as a whole.

Field capacities used for both grain-only and single-pass biomass harvest were generated using an in-field logistics model discussed in a previous work (Wold et al., 2011). The field capacities output from this model are representative of the capacity while in the field only, not including movement times between fields, maintenance, or repairs. To account for these inefficiencies, field capacities used in the economics model were adjusted to 90% of the field capacities output from the in-field logistics model. The in-field logistics model also outputs a standard deviation of the field capacities. This was used to create a normal distribution in @RISK for the field capacity estimates. Timeliness cost was not included in the analysis. The analysis of timeliness cost is dependent on a wide variety of
highly variable, location dependent factors, which would make it very difficult to quantify and is beyond the scope of this research.

3.2.3. Storage

In this model storage costs were limited to the reduction in DM content. It was assumed that the biomass will be stored uncovered at the field edge. This decision in the model development was primarily due to the low value of the biomass. Future work will examine other storage options. No charge was assigned to the land occupied by the biomass since the biomass was assumed to be delivered to a refinery or satellite storage location prior to spring planting. Based on estimates from industry experts a beta general distribution with both shape parameters set to 2, a minimum of 4%, and a maximum of 25% DM loss was used. Losses are anticipated to be highly variable and are significantly affected by biomass moisture content, weather conditions, and time in storage. This distribution was chosen to represent the wide variety of possible conditions.

3.2.4. Truck Loading

After storage it is necessary for trucks to be loaded with the biomass to transport the material to biorefineries. The loading and hauling costs were based on custom contractor costs, because of the need for a front end loader to load the trucks. It is unlikely that an individual farm would have sufficient needs to justify its own front-end loader, and a tractor or a skid steer with a loader would be both unwieldy and exceedingly slow to move the required amount of material. The model used a front-end cost of $80 h⁻¹ based on a published survey of custom operators (Tillinghast and Prosper, 2010). The density for biomass both while being loaded and in the truck during hauling was assumed to be a
triangular distribution with minimum, most likely, and maximum values of 96, 112, and 128 DM kg m$^{-3}$, respectively. This distribution represents the likelihood that the biomass will become denser during storage and loading process due to settling and compaction. An estimated loading cycle time of 50 seconds and a bucket capacity of 7.65 m$^3$ were used based on typical industry practice.

With biomass piles stored on the ground, some material must be left on the ground in order to prevent contamination with a large amount of dirt. For this work it is assumed that this loading loss would be 2% of the material remaining after storage.

3.2.5. Over-the-Road Hauling

Hauling over the road from the field to the biorefinery was assumed to be done by silage trailers. A 8.5x8.5x48 foot trailer (2.6x2.6x14.6 meters) was assumed. The density in the trailer was assumed to be the same as the density used for loading. The one-way distance traveled was set to a triangular distribution with a minimum, most likely, and maximum, of 1, 35, and 35 miles (1.6, 56.3, 56.3 km), respectively. This represents a draw radius of 25 miles with a winding factor of 0.4.

The cost charged for trucking was set at $1.73\cdot\text{mi}^{-1}$ ($1.07\cdot\text{km}^{-1}$) and $42\cdot\text{h}^{-1}$ while loading and unloading based on survey data from the American Transportation Research Institute (ATRI) (American Transportation Research Institute, 2008). The per mile rate is charged in both directions. The hourly rate is charged based on the loading time calculated as described in section 2.4, plus an estimated 10 minutes to unload the truck at the biomass refinery. Based on the assumed trailer volume and material density, the trucks will be limited by volume and not by weight even for very wet stover. This does
indicate that low cost densification methods may be beneficial in reducing transportation costs if the trucks could be loaded nearer to their weight limits.

3.3. Simulation Results

The results presented in the work have been selected to show the diversity of cases that the model is capable of examining and show some of the most likely scenarios. Unless otherwise noted the field capacity estimates were created by simulating the harvest of a quarter section of land (0.805 km square) with an average grain yield of 12.55 t·ha\(^{-1}\) (200 bu·ac\(^{-1}\)) and a biomass yield of 2.13 t·ha\(^{-1}\) at a density of 96.11 kg·m\(^{-3}\) (Wold et al., 2011). The biomass yield was determined based on a mass fraction of 0.17 of grain yield which represents a typical amount of material passed through a corn harvester using an ear snapping corn header without any modifications (Shinners, Binversie and Savoie, 2003).

3.3.1. Grain-Only Harvest

Before investigating biomass collection, it is first necessary to establish a baseline for grain harvest without biomass collection for comparison purposes. Figure 13 shows the output cost distribution for grain-only harvest with a single 35 grain cart. The noticeable right skew of the data is caused by the log logistic distribution used for diesel fuel price and the near exponential decrease in depreciation costs with ownership years. All cost distributions for grain-only harvest had similar shapes.
After seeing the distribution for the harvest cost, it was important to understand how the inputs into the economics model affected the overall harvest cost picture. This was done by individually varying one important input at a time from a typical value over a reasonable range. This was done for the same scenario shown in Figure 13, and the effect of each variable will be somewhat different for different scenarios. For example for scenarios with a higher capital cost, interest rate and years of ownership will be more important. The results of this study of inputs are shown in Figure 14 with the left axis scaled to a percent of the baseline cost. Baseline cost assumptions are represented by the horizontal line. The figure allows the effect of the change of a single variable from the baseline assumptions to be understood. Due to complex interactions between parameters the effect of changing multiple parameters simultaneously cannot be determined from
this figure. For example increasing the interest rate to 9% would increase costs to about 110% of baseline, but the model would have to be used to determine the effect of increased interest rate and increased corn acres. It is apparent from these results that labor is not as significant as many of the other input parameters.

Figure 14 Effect of various input parameters on the cost of grain-only harvest with a class 8 harvester and a single 35 grain cart

The cost of grain-only harvest was examined using the four different size grain carts in order to select the best cart combination to use for comparison to biomass harvest. One and two cart combinations were examined as shown in Figure 15. The plot was generated by taking 5000 samples (using the Latin Hypercube method) of the distributions described in section 2. The whiskers in the plot represent the 5th and 95th percentile of the results excluding some of the extreme values. The harvester capacity increases consistently from left to right across the chart, but the harvest cost is much more irregular. The lowest cost comes from either the 1-26 or 1-35, which are only slightly different. Though the other cases have a higher capacity, which causes a reduction in
annual hours, this is not enough to make up for increased cost. The significantly higher cost in the 53 and 70 cases is caused by the much higher purchase price of the carts and tractors. Because the 1-35 cart choice had a higher harvest capacity while remaining at the lowest harvest cost, the 1-35 case will be used for comparison to grain and biomass harvesting costs.

![Diagram](image)

**Figure 15** Harvest capacity and cost for grain-only harvest with different cart sizes. Cost is represented by the boxplot; the bars represent the means, the boxes represent the 25th and 75th percentiles, and the whiskers the 5th and 95th percentiles. Harvester field capacity, read on the right axis, is represented by the diamonds.

A cost breakdown for the 1-35 case is shown in Figure 16. By far the largest portion of the cost (63%) comes from capital recovery, i.e. depreciation and interest. The next largest portion (17%) comes from fuel and lubrication. As ownership period increases repair costs increase while capital recovery costs decrease.
Figure 16 Cost components for 1-35 case

3.3.2. Biomass Harvest with Carts

Now that a baseline cost for grain-only cost has been established, biomass harvest costs can be examined. In this section biomass harvest using a harvester-towed biomass wagon which unloads into tractor-towed biomass carts will be examined. Based on previous research, it was assumed that the harvester-towed wagon will be sized so that it can be unloaded every other time the harvester unloads (Wold, 2011). Since very limited information was available on the actual cost of biomass wagons, this wagon was assigned a list price of $50,000 making it comparable to carts.

All costs will be reported here as marginal costs, i.e. the increase in cost over grain-only harvest. In calculating these marginal costs, the same sample from each input distribution was used for both the cost of grain-only harvest and harvest of grain with biomass; i.e. the same fuel price, years of ownership, etc. were used for both grain-only and grain with biomass harvest, which means that the variability in the marginal costs comes from differences in the effect of these input values, not the values themselves. This method is
reasonable since the specific farm and economic conditions should be the same for either harvest system on a particular farm.

There are two major system constraints that have a major impact on the harvesting operation: stopping to unload biomass, and having to unload grain and biomass separately. These constraints would be determined by the specific design of the wagon and carts. Purchase prices were assumed to be the same for systems with and without these constraints as insufficient information is available to do otherwise. Biomass carts may either be towed by their own tractor and operate separately from grain carts, or be directly connected behind a grain cart so one tractor tows both carts at the same time. These cases will be referred to as separate and both, respectively.

The effect of the first two constraints was examined in Figure 17 for carts that haul both grain and biomass in a single cart. The left four cases are for one 36 both cart and the right four for two 36 both carts. These carts have the same grain capacity as the 36 cart used for the grain-only case in comparison among the single cart cases there was a significant increase in capacity, and hence slight reduction in cost for the non-stop simultaneous operation, while the other three cases had approximately the same level of performance. Non-stop operation allowed the harvester to continue harvesting during unloading while simultaneous unloading reduced the carts’ interface time with the harvester, which allowed the cart more time to unload before the harvester became full again. For the case of two both carts, simultaneous unloading did not have a significant impact on harvest cost or harvester capacity, but non-stop unloading significantly improved the harvester capacity. The lowest cost option was non-stop, simultaneous
unloading with a single 36 both cart, which added a mean cost of $35.54 ha\textsuperscript{-1} while reducing harvester capacity by 6.3%.

Next, the same cases were examined for separate grain and biomass carts. Figure 18 shows the same results except with one 36 grain and one 36 biomass on the left and two 36 grain and two 36 biomass carts on the right. From these results it is apparent that while non-stop harvesting did increase harvesting capacity somewhat, among the one 36 grain and one 36 biomass carts operated separately systems, there was minimal difference in the marginal cost of adding biomass harvest to the grain harvesting operation. It is also apparent that for the systems with two grain and two biomass carts operated separately the ability to unload grain and biomass simultaneously had minimal impact on marginal cost, unloading-on-the go more significantly reduced cost. All cases with a single grain
and a single biomass cart operated separately showed a reduction in harvester capacity. It will be important for the farmer to consider this and decide if his/her operation can absorb this reduction in capacity without incurring timeliness costs, otherwise other options such as purchasing a larger harvester will need to be examined.

![Figure 18 Effect of stopping to unload and simultaneous unloading for separate carts](image)

The effect of different sized carts for biomass collection was examined under the assumption that non-stop unloading was possible, but simultaneous unloading was not. Non-stop unloading was assumed because of its significant impact on harvester capacity. Simultaneous unloading was not assumed because of the difficulty in designing systems that could accomplish it. In Figure 19 the effects of different sizes of carts that haul both grain and biomass on marginal cost and harvester capacity were examined. The lowest marginal cost occurred with a single 26 cart, however the marginal cost was likely under
estimated as there was a reduction in field capacity of nearly 21%, which would likely incur timeliness costs not represented in this economic model. The single 53 cart comes close to the original capacity of the system at a reasonable marginal cost.

Next, cart sizes were examined using separate grain and biomass carts as shown in Figure 20. In comparing these results with the results from both carts it appears that a single 36 grain and a single 36 biomass cart operated separately is a good balance between harvester capacity and cost. This system reduces harvester capacity by only 5.5%, and increases the harvest cost by an average of $38.40 ha⁻¹. A 5.5% drop in harvester capacity is unlikely to have a major impact on an operation as to harvest the same area daily a 10 hour work day would only have to be extended by a half hour. However there are two major drawbacks to using separate grain and biomass carts. First, an additional operator
is required. It can be difficult for farms to find enough seasonal help for harvest, so an additional skilled operator could be difficult to find. Also, an additional tractor is needed to tow the biomass cart. The model assumes that this tractor will put on a total of 550 hours per year. Less than 200 hours per year are accumulated in its use towing the biomass cart, so the farm must have another 350 hours of use for it or the cost will increase.

3.3.3. Biomass Harvest with Only a Harvester-Towed Wagon

Another option for biomass collection in a single-pass is to have the harvester-towed wagon directly unload the biomass instead of using tractor-towed carts as intermediaries. The harvester-towed wagon’s capacity was sized to make one complete trip back and forth in the field before becoming full (32.7 m$^3$ or 1154 ft$^3$). In this system, the harvester
could either tow the wagon to a single location in the field to unload each time, creating a single large pile in the field, or simply unload the wagon as the harvester is turning on one edge of the field, creating a row of smaller piles across one edge. It was assumed that it would take the harvester one minute to unload the biomass in either of these cases. The primary advantage of either of these systems is the relatively low capital investment required when compared to systems that use carts to haul the biomass. Low capital investment has the benefit of reducing the risk assumed by the farmer in collecting biomass. If biomass collection does not work out for the farm there is not as much equipment that needs to be liquidated. The system was first analyzed for a single pile location as shown in Figure 21 for different grain cart combinations. For this system, switching to a larger single cart, or to two carts does not provide a significant benefit, since capacity is reduced primarily by harvester travel time to the biomass pile and biomass unloading time, rather than by waiting for a grain cart. The single 35 cart appears to be the best option, increasing harvest costs by an average of only $22.00 ha$^{-1}$; however harvester capacity is reduced by nearly 18%.
Figure 21 Marginal cost for the harvester-loaded biomass wagon directly unloading at a single location

The case of the harvester unloading the biomass as it turns on one edge of the field was examined in Figure 22. Harvester capacity is reduced less than the single unloading location case because of the greatly reduced travel time for the harvester. The best trade off in capacity and cost would again appear to be the single 35 cart option. For this option harvester capacity is reduced by 9% and costs increased by an average of $15.20 ha\(^{-1}\).

Another reasonable option, depending on the importance of harvester capacity to the farm, would be a single 53 cart which reduces harvester capacity by only 3%, which would hardly be noticeable, but has a marginal cost of $33.25 ha\(^{-1}\).
Single-pass biomass collection with a harvester-towed wagon directly unloading biomass is an attractive option. The capital investment and per hectare costs can be much lower than collection with intermediary tractor-towed carts, especially if the harvester can unload as it turns at the edge of the field. However, creating many smaller piles may have unintended consequences. The small piles will have a greater exposed surface area which could increase losses in storage, or make them more costly to cover. Small piles also have a greater footprint per unit mass in storage, this could make loading them into semi-trailers more difficult and increase the amount of biomass left on the ground.

Since timeliness costs are not included in this analysis, it is assumed that the farm can absorb the decrease in field capacity caused by the collection of biomass without
incurring any reduction in grain quality or quantity. This decision is ultimately up to the farmer. If the reduction in capacity is unacceptable, the farmer may need to purchase a larger harvester. The model is capable of simulating the effect of choosing a larger harvester. The analysis of a larger harvester is not presented here due to two primary issues. First, the decrease in field capacity caused by a good single-pass system is about 5 to 25%, but switching from a class 8 to a class 9 harvester increases capacity by 30% to 40%, which would result in significant excess capacity. Secondly, in moving to a class 9 harvester it becomes much more beneficial to use multiple carts, even for grain-only harvest than for a class 8 harvester. This would mean that the farmer would need to find another employee for harvest, which may not be desirable.

3.3.4. Overall Biomass Collection Cost

Now that a number of options have been examined for the single-pass harvest portion of the biomass collection system, the cost of the entire system will be examined up to the plant gate. In Figure 23 the costs for five of the most likely harvesting systems are examined with the addition of fertilizer, storage, loading, and trucking costs. Costs are expressed in dollars per dry matter metric ton delivered. Storage and loading dry matter losses are included in these cost values by reducing the number of tons that reach the processing facility, and thereby increasing the cost per delivered ton. Delivered costs are lowest for the cases without biomass carts (the three cases on the right-hand side of Figure 23).
Now that the costs have been determined, it is important to understand what factors affect these costs. A sensitivity analysis was performed in @RISK for the 1-35 separate case as shown in Figure 24. This chart shows the change in delivered cost of the biomass for an increase of one standard deviation in a given input, which allows the relative importance of these inputs to be assessed. Haul distance had the highest impact on the price, which indicates that densification methods may help reduce cost and that farmers with shorter haul distance will be more likely to profit from residue collection and hence participate in a biomass supply chain. The second highest sensitivity was to fertilizer cost. Additional research is needed to evaluate the accuracy and variability of the fertilizer rates assumed in this work, and to search for methods of reducing fertilizer requirements. The high sensitivity to DM loss indicates that efforts to reduce DM loss may be cost effective.
Figure 24 Mapped Regression Values for 1-35 Sep. With Bio Capacity and Without Bio Capacity represent the harvester’s field capacity when harvesting biomass and when not harvesting biomass, respectively.

Mapped regression values for the single 35 grain cart with the harvester-towed wagon bringing the biomass to the field edge are shown in Figure 25. The top three inputs remain the same. It is interesting to note the very low impact of farm wage. This would tend to suggest that farmers may be able to pay much higher wages to get more skilled employees, which increases harvest efficiency, since this has a larger cost impact.
3.4. Conclusion

An economics model has been developed which is able, in combination with a previously developed logistics model is able to quantify the cost of many different single-pass harvesting methods. The economics model could be used by farmers, extension agents, and equipment manufacturers to better understand the impact of a wide variety of factors on the cost of not only dual harvest of grain and biomass but also grain harvest itself.

Single-pass methods in which the harvester-towed wagon is directly unloaded into piles appeared to be the most attractive in terms of cost and performance.
3.5. References


Chapter 4: Conclusions

A model of the logistics and a model of the economics for single-pass grain and biomass collection have been developed. These models enable the user to quantify the effect of a wide variety of single-pass grain and biomass harvest, and grain-only harvest, systems on the field capacity and cost of the harvesting system. This work examined a number of different single-pass grain and biomass harvest operations in comparison to grain-only harvest. Results indicate that a wide variety of factors affect the single-pass system’s impact on harvesting, but that some of these methods can be relatively low cost and have only small impacts on the harvester efficiency. Significant results from the models developed in this work include:

- Large capacity grain carts increase harvester capacity but also tend to increase harvest cost
- Systems where the harvester directly unloads biomass without intermediary biomass carts had the lowest cost
- For systems where the harvester directly unloads biomass without biomass carts there is a significant advantage in both cost and capacity to having small piles distributed along the field edge instead of a single large pile
- Forcing the harvester to stop to unload biomass results in a significant reduction in harvester capacity but a relatively small increase in harvest cost
- The delivered cost had the highest sensitivity to haul distance, potassium chloride fertilizer price, and storage loss
Future work is needed to expand and apply these models to other single-pass harvesting cases and other crops, and to extend these models to two-pass collection systems. Also more research into the effect of biomass removal on fertilizer requirements and biomass storage losses are needed to better quantify these costs.
Chapter 5: Comprehensive Reference List


ASAE Standard, 2006. EP496.3 Agricultural Machinery Management,. 

ASAE Standard, 2009. D497.6 Agricultural Machinery Management Data,. 


Dunning, J.W., P. Winter, and D. Dallas, 1948. The storage of corncobs and other agricultural residues for industrial use, Agricultural Engineering. 29, 11.


<http://www.farmdoc.illinois.edu/manage/machinery/machinery_harvest.html> 
(accessed August 3, 2010).


Appendix A: Additional Scenarios

The effect of varying biomass to grain yield ratio was examined in the figure below. This has the effect of making the sizes of the grain and biomass tank no longer matched to a specific field area. Biomass yield ratio was varied from 0.1 to 0.4 for carts that haul both grain and biomass across different cart sizes. The ratio had little effect on harvester capacity until it reached 0.4, the highest level. This indicates that the exact size of the biomass tanks on both the carts and harvester-towed wagon are not exceedingly important, and that the system will be able to adapt to different harvest rates without significant variation in capacity.

The following three charts examine the effect of reduced speed of the harvester and cart(s) on field capacity. Along the horizontal axis the speed of the vehicle is expressed as a percentage of the baseline speed, followed by the name of the vehicle who’s speed is
reduced, either the harvester, the cart, or both of them. The horizontal grey line represents the capacity of the system with the baseline speeds. The figure below examines the case of grain-only harvesting with a single 35 grain cart. It is noticeable that reduction in harvester speed has a greater effect than reduction in cart speed and with both vehicles speeds reduced, the effect is nearly additive.

The next figure examines reduction in speeds for the case of a 35 grain and a 35 bio cart. Each case results in a reduction in capacity of approximately the same percentage as the respective case in grain-only harvesting.
The figure shown below shows the effect of reduced speeds for the case of a single 35000 L cart. These figures illustrate the important point that if biomass collection causes a reduction in vehicle speeds, even by a small amount, the reduction in system capacity will be pronounced. This is of particular concern for the harvester, since single-pass harvesting requires the harvester to tow a wagon which creates an increased draft, which may slow the harvester, especially in wet soil conditions.
The figure below examines the effect of using a larger harvester, a class 9, to make up for the lost capacity caused by the biomass harvest. The left four cases examine using the same carts that were used with the class 8 harvester, however these carts are significantly under capacity for the class 9. The right four cases examine using two 26 size carts, which gets the most capacity out of the larger harvester. The cases with the two 26 carts are significantly more expensive than the single cart, however the field capacity of the harvester is significantly increased. This increase in capacity could allow the farmer to expand his/her operation to more acres, which would reduce the cost.
Appendix B: Harvest In-Field Model Manual

Introduction

This model allows the user to examine the effects of a wide variety of system parameters on the harvester’s field capacity and the cost of harvest for both grain-only and single-pass biomass harvest scenarios.

It is suggested that you read this manual in its entirety before running the simulation for the first time. Also, try running one run of a simple grain-only scenario first to make sure that it works, and then work your way up to running multiple runs of multiple scenarios of with different biomass collection systems.

Caution

- Do NOT change the name of the Excel file, the MATLAB code references it by name
- The Scenarios tab must be the third tab in the Excel workbook for MATLAB to find it
- Do NOT move cells on the Scenarios tab, MATLAB uses absolute cell references
- The MATLAB executable draws values from the spreadsheet save file, so always save the spreadsheet before running the model
- If the MATLAB model locks up when it is running, select the figure and press “Ctrl+c” to abort

Model Setup

Open the Excel workbook entitled “HarvestSim080.xlsm.” If a security warning from Excel pops up, enable everything. Read the “Start Here” tab, if you have not already for a brief overview of how to use the model.
There are two primary methods for entering inputs into the model, entering inputs directly into the spreadsheet, or a wizard. The results of either method will be the same.

**Using the Wizard**

If you wish to use the wizard to define scenarios to be run, go to the “Scenarios” tab and press the “Start Scenario Wizard” button. The wizard allows you to interactively define scenarios. The opening screen of the wizard is shown in Figure 26. Begin defining a scenario by entering a name for your scenario in the scenario name field (indicated by A). This name allows you to keep track of your scenarios and does not affect the model results. Then, enter the number of times this scenario should be run in the box directly below the scenario name. Next, select the field to be used for the scenario from the list box (B). If you would like to view or modify the parameters for the field, press the view/modify button (C) which will take you to the screen shown in Figure 27 and discussed in the next section. Then continue to select the harvester, cart A, and cart B in the same manner as the field, be sure to select the number of each of these in the field to the right of the list boxes. There must be at least one harvester and one cart A, however there may be zero cart B’s, which is typically the case for grain only harvesting. Options for biomass harvest can be selected using the checkboxes and option buttons indicated by D. After defining the scenario you may either navigate to the next or previous scenario, or select that you are finished using the navigation buttons indicated by E. If the previous, next, or finish button is pressed the scenario parameters will be saved, press cancel to disregard them. The tabs at the top of the screen may be used to define parameters for single-pass baling or change simulation options.
Figure 26 Wizard main screen. A) Scenario name field  B) List box  C) Biomass harvesting options  D) View/Modify button for selected item in list boxes.  E) Navigation buttons

When any of the “View/Modify” buttons are pressed a window appears similar to the one shown in Figure 27, which is the wizard for the field. The name for the field (A) is used only to keep track of it and cannot be changed by the wizard once it has been created. To navigate between fields use the previous and next buttons (B). Fields, carts, and harvesters are stored in the order they were entered. No changes will be saved unless the save changes button (D) is pressed. To define a new field press the “New” button (B) and fill in all fields. For many of the inputs you can select either U.S. customary or SI units using the buttons shown by C. Metric units will be converted to and stored as their U.S.
customary equivalent. To select the current field and return to the scenario wizard, press the select button (E). Similar wizards are used to view and modify the cart(s) and harvester. These wizards are accessed by pressing the corresponding “View/Modify” button.

Figure 27 Field wizard

Once the scenarios have been defined using the wizard, press the “Finish” button (E in Figure 26), and enter the number of scenarios to run in the pop-up menu. If you wish to conduct an economic analysis of the scenarios proceed to the “Harvest With Bio” tab and enter values in the yellow highlighted cells. Next, proceed to the “Running the Model” section of this manual.
Using the Spreadsheet

The scenarios spreadsheet is arranged with each column from D to BQ defining a single scenario, with column D being the first scenario, E the second and so on. The value in cell D4 tells MATLAB how many simulations to run beginning with the first scenario. Each row defines a different parameter for the simulation. For a detailed description of these parameters see the “Description of Input Fields” section. The combine, field, cart A, cart B, baler, and bale collector are selected from dropdown menus. You can view the parameters used to define these objects by scrolling down, however do not modify them here. Go to the “Simulation Parameters” tab and find and modify the desired object there, as these values are brought to the “Scenarios” tab using lookup formulas.

Grain-Only Scenarios

To define a grain-only harvesting scenario, begin by selecting the combine, field, and cart A from the drop down menus. The cart A selected should haul only grain, this can be verified by examining rows 59 and 60 of the “Scenarios” tab. Next, enter the number of combines, number of cart A, and zero for the number of cart B. Then, select “None” for baler, and enter 0 for direct unloading in row 19. The options in rows 17, 18, and 20 have no effect on grain-only harvest. Finally, enter the desired refresh rate for the simulation in row 21 and then proceed to the “Running the Model” section of this manual.
Single-Pass Baling

Follow the same steps as described for grain-only harvest except select the desired baler and bale collection from the dropdown menus in rows 15 and 16, respectively.

Harvest Wagon Directly Unloading

To have a harvester-towed biomass wagon directly unload biomass without intermediary carts, follow the same steps as grain-only harvest, except enter either 1 or 2 in row 19 “Directly Unloading Biomass” as desired. Also, set “Allow Biomass to Overflow” in row 18 to 1. This will ensure that the harvester never gets stuck with a full biomass tank that it is unable to unload.

Single-Pass Harvest with Biomass Carts

To harvest biomass with biomass carts, follow the same steps as grain-only harvest, except cart A may either haul grain-only or haul both grain and biomass. If a grain-only cart is selected as cart A, select a cart that hauls only biomass for cart B. Also, the options in rows 17, 18, and 20 will have an effect. These options are described in more detail in the “Description of Input Fields” section of this manual.

Economic Analysis

The economic analysis for the single-pass harvest portion of the biomass supply chain is defined on two tabs of the spreadsheet “Harvest with Bio” and “Harvest without Bio”. Begin by reviewing the parameters highlighted in yellow on the “Harvest with Bio” sheet, which is used for calculating the cost of harvest with biomass collection. Most inputs are explained by cell comments. These comments can be read by hovering the
mouse over the red triangle in the upper right hand portion of the commented cell. Next, proceed to the “Harvest without Bio” sheet and enter values into the cells highlighted in yellow there. This sheet calculates the cost of grain-only harvest as a baseline. The cost of biomass collection is the difference between the cost of harvest with biomass collection and the cost of harvest without biomass collection.

**Running the Model**

Prior to running the model the first time, make sure that the HarvestSim080.xlsm and the MATLAB executable are in the same folder. Save the HarvestSim080.xlsm spreadsheet, the MATLAB model draws values from the saved file NOT the open workbook. Now, run the MATLAB executable. It is normal for it to take up to a minute or so before anything is displayed. The model will display a map of the field that will update as each run progresses; the frequency of these updates is controlled by the “Refresh Rate” parameter in the spreadsheet. At the top of this map, the current scenario, number of scenarios to be run, current run of the current scenario, number of runs to be completed for the current scenario, and the time the simulation has been running are displayed for your reference. You may abort the simulation at any time by selecting the map and pressing “Ctrl+c”. When you abort, results for all previous runs will have been saved.

The time it takes to run the model is highly variable depending on the inputs to the model, and the computer it is run on. If “Refresh Rate” is set to at least 5000, a good estimate is 30 seconds to a minute for each run.

**Processing the Results**
The MATLAB program outputs a .txt file for each scenario run and places them in the same folder as the MATLAB executable. These text files contain all major outputs from the simulation, however for ease of understanding they are brought into Excel using a macro.

Once the model has finished running, press the “Process Results” button on either the “Scenarios” or “Output” tab to start the macro that formats the results from the MATLAB program. The first time this macro is run, you will need to show Excel where each text file is located. In the popup menu navigate to the folder where the Harvest Simulation executable is, and select the first text file “Harvest_sim_sum1.txt” and press “open”. Repeat this process for all text files, one for each scenario you ran, ensuring that they are selected in numerical order. After the first time the simulation is run, Excel should remember where the text files are and select them by default. You will only have to press the “open” button.

Next, enter the number of the first and last scenario you wish to run economic analysis on in the prompts when they appear. Results from the economic analysis will appear below the results from the in-field logistics simulation. Running the economic analysis will not affect the results from the logistics simulation. These economic results are only for the single-pass harvest portion of the model.

Once the data processing is complete, you should be brought to the “Output” tab where you can view simulation results. Descriptions of the result values can be found in the “Description of Output Fields” section of this manual.
To save the results you may use the “Save Results” macro button which is found on the “Outputs” sheet. Simply follow the on screen menus to save the simulation inputs and results to another workbook.

**Description of Input Fields**

The parameters below are defined in the scenarios tab

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario Name</td>
<td>It serves no other purpose than to let you keep track of your scenarios</td>
</tr>
<tr>
<td># of Runs</td>
<td>Specifies the number of times the scenario should be run</td>
</tr>
<tr>
<td># of Combines</td>
<td>Number of harvesters to be used in the simulation</td>
</tr>
<tr>
<td>Combine</td>
<td>Drop down menu to select the harvester used</td>
</tr>
<tr>
<td>Field</td>
<td>Drop down menu to select the field used</td>
</tr>
<tr>
<td># of Cart A</td>
<td>Number of carts of type A to be used – must be 1 or greater</td>
</tr>
<tr>
<td>Cart A ID</td>
<td>Drop down menu to select the cart A used – typically the grain or both cart</td>
</tr>
<tr>
<td># of Cart B</td>
<td>Number of carts of type B to be used – may be zero</td>
</tr>
<tr>
<td>Cart B ID</td>
<td>Drop down menu to select the cart B used – typically biomass or none</td>
</tr>
<tr>
<td>Baler</td>
<td>Drop down menu to select the bale used – select “none” for no bale</td>
</tr>
<tr>
<td>Bale Collector</td>
<td>Drop down menu to select the bale collector used – if no baler is selected the collector selected does not matter</td>
</tr>
<tr>
<td>Stop to Unload Biomass?</td>
<td>1 - forces the harvester to stop when unloading biomass, 0 - allows biomass to be unloaded on-the-go</td>
</tr>
<tr>
<td>Allow Biomass to overflow?</td>
<td>1 - The harvester will continue harvesting when the biomass tank becomes full 0 – The harvester stops when full of biomass</td>
</tr>
<tr>
<td>Directly Unload Biomass</td>
<td>2 – The harvester directly unloads biomass at offload locations specified by the field 1 – The harvester directly unloads biomass along the field edge as it turns 0 – The harvester does not directly unload biomass</td>
</tr>
<tr>
<td>Simultaneous Cart Loading?</td>
<td>1 – The harvester may unload both grain and biomass at the same time 0 – The harvester must unload them separately</td>
</tr>
<tr>
<td>Refresh Rate</td>
<td>Time between refreshes of the simulation map in</td>
</tr>
</tbody>
</table>
seconds of simulation time. Does NOT affect results, only model speed

| Detailed Report? | 1 – Creates Harvest_sim_cart.txt, Harvest_sim_combine.txt, and Harvest_sim_other.txt which record major simulation parameters as the simulation progresses |

The parameters below are defined in the “Simulation Parameters” tab. “(E)” means that the parameter is used only for the economic analysis and has no effect on field capacity

<p>| Combine Name | - | Used to keep track of harvesters only |
| Grain Hopper Capacity | Bu | Capacity of the grain tank |
| Unload Rate | Bu/sec | Grain tank unload rate. Note is assumed to be constant and instantly on/off |
| Biomass Hopper Capacity | cu. Ft. | Capacity of the harvester’s biomass tank |
| Biomass Unload Time | Sec | Time to completely unload the biomass tank in seconds |
| Average Speed | mph | Speed the harvester travels while it is harvesting |
| Average Empty Speed | Mph | Maximum speed the harvester will travel in the field. Used for long turns and going to piles to unload biomass |
| Time for 90° turn | sec | Time for the harvester to make the 90 degree turns on the headlands |
| Number of Rows | - | Number of rows of the header |
| List Price (E) | $ | List price of the harvester |
| Horsepower (E) | Hp | Engine horsepower of the harvester |
| Header List Price (E) | $ | List price of the header |
| Biomass Wagon List Price (E) | $ | List price of the biomass collection wagon towed by the harvester |
| Name (if desired) | - | Used to keep track of fields only |</p>
<table>
<thead>
<tr>
<th><strong>Width of Headland</strong></th>
<th>ft</th>
<th>Width in the direction of the headland</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length of Field</strong></td>
<td>ft</td>
<td>Length of the field in the direction of the rows. Note: the simulation will round both length and width to be evenly divisible by the header width.</td>
</tr>
<tr>
<td><strong>Field Area</strong></td>
<td>acres</td>
<td>This is a calculated cell for the user’s reference only.</td>
</tr>
<tr>
<td><strong>Average grain yield</strong></td>
<td>bu/ac</td>
<td>Grain yield in bushels per acre</td>
</tr>
<tr>
<td><strong>Randomize Yield</strong></td>
<td>-</td>
<td>1 – the model will create a random yield map of the field. 0 – a constant yield will be used</td>
</tr>
<tr>
<td><strong>Biomass Yield</strong></td>
<td>-</td>
<td>Expressed as a mass fraction of grain yield. If the grain yield is randomized, the biomass yield will follow the randomized grain yield</td>
</tr>
<tr>
<td><strong>Biomass Density</strong></td>
<td>lb/cu. Ft</td>
<td>Density of the biomass</td>
</tr>
<tr>
<td><strong>Number of headland rows</strong></td>
<td>-</td>
<td>Number of rows for the header</td>
</tr>
<tr>
<td><strong>Row Spacing</strong></td>
<td>in</td>
<td>Row spacing of the header in inches</td>
</tr>
<tr>
<td><strong>Number of Offload Locations</strong></td>
<td>-</td>
<td>Number of locations in the field that the cart(s) can unload into. All offload locations are located at the bottom headland of the field, with a distance from the left edge specified by Offload # X</td>
</tr>
<tr>
<td><strong>Offload # X</strong></td>
<td>ft</td>
<td>Distance from the left edge of the field to # offload location</td>
</tr>
<tr>
<td><strong>Traffic Pattern</strong></td>
<td>-</td>
<td>For now this must be set to 1, which is the standard corn field pattern</td>
</tr>
<tr>
<td><strong>Cart Name</strong></td>
<td>-</td>
<td>Used to keep track of carts only</td>
</tr>
<tr>
<td><strong>Grain Tank Capacity</strong></td>
<td>Bu</td>
<td>Grain tank capacity of the cart</td>
</tr>
<tr>
<td><strong>Biomass Tank Capacity</strong></td>
<td>cu. Ft</td>
<td>Biomass tank capacity of the cart</td>
</tr>
<tr>
<td><strong>Grain Unload Rate</strong></td>
<td>Bu/s</td>
<td>Grain unload rate of the cart. Like the harvester it is assumed to be constant and instantly on/off</td>
</tr>
<tr>
<td><strong>Biomass Dump Time</strong></td>
<td>seconds</td>
<td>Time that it takes the cart to unload biomass</td>
</tr>
<tr>
<td><strong>Tractor Name</strong></td>
<td>-</td>
<td>For user reference only</td>
</tr>
<tr>
<td><strong>Speed Unloaded</strong></td>
<td>mph</td>
<td>Speed that the cart travels while completely empty</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td><strong>Speed Loaded</strong></td>
<td>mph</td>
<td>Speed the cart travels while completely full. Linear interpolation is used for carts partially full</td>
</tr>
<tr>
<td><strong>Cart List Price (E)</strong></td>
<td>$</td>
<td>List price of the cart</td>
</tr>
<tr>
<td><strong>Tractor List Price (E)</strong></td>
<td>$</td>
<td>List price of the tractor</td>
</tr>
<tr>
<td><strong>Tractor Horsepower (E)</strong></td>
<td>Hp</td>
<td>Engine, not PTO, horsepower of the tractor</td>
</tr>
<tr>
<td><strong>Bale Collector</strong></td>
<td>-</td>
<td>Name of Bale Collector</td>
</tr>
<tr>
<td><strong>Average Speed</strong></td>
<td>mph</td>
<td>Speed the bale collector travels between bales</td>
</tr>
<tr>
<td><strong>Min. time btw pickups</strong></td>
<td>sec</td>
<td>The minimum time between bales that the collector requires to cycle</td>
</tr>
<tr>
<td><strong>Max simultaneous pickups</strong></td>
<td>Bales</td>
<td>Maximum number of bales that the collector can pick up at one time. Used when the baler drops multiple bales at once.</td>
</tr>
<tr>
<td><strong>Bale Capacity</strong></td>
<td>Bales</td>
<td>Number of bales that the collector can haul</td>
</tr>
<tr>
<td><strong>Unload Cycle Time</strong></td>
<td>sec</td>
<td>Time it takes the collector to unload the bales</td>
</tr>
<tr>
<td><strong>Bale Offload X</strong></td>
<td>ft</td>
<td>X position to bring the bales to</td>
</tr>
<tr>
<td><strong>Bale Offload Y</strong></td>
<td>ft</td>
<td>Y position to bring the bales to</td>
</tr>
<tr>
<td><strong>List Price (E)</strong></td>
<td>$</td>
<td>Currently not used</td>
</tr>
<tr>
<td><strong>Horsepower (E)</strong></td>
<td>Hp</td>
<td>Currently not used</td>
</tr>
<tr>
<td><strong>Baler</strong></td>
<td>-</td>
<td>Name of the baler</td>
</tr>
<tr>
<td><strong>Baler Size</strong></td>
<td>cu. Ft</td>
<td>Size of the bale in cubic feet</td>
</tr>
<tr>
<td><strong>Bale Density</strong></td>
<td>lb/cu ft</td>
<td>Density of the bale in pounds per cubic ft</td>
</tr>
<tr>
<td><strong># of bales dropped at once</strong></td>
<td>Bales</td>
<td>Number of bales that the baler can drop at one location. Must be at least 1. Greater than 1 would represent using an accumulator</td>
</tr>
</tbody>
</table>
Drop Zone  ft  Specifies a distance from either headland for the baler to drop bales that have been made. Only effects completed bales that are “carried” on a accumulator.

List Price (E)  $  Currently not used

**Description of Output Fields**

All data field are reported with mean and standard deviation of results. Note that only the data fields relevant to the scenarios analyzed will be reported.

<table>
<thead>
<tr>
<th>Field</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario Name:</td>
<td>-</td>
<td>Used to keep track of the scenarios only</td>
</tr>
<tr>
<td>Date:</td>
<td>-</td>
<td>The data and time the scenario was run by the Matlab program. Note: Format cell as a date if it does not display correctly</td>
</tr>
<tr>
<td>Cells in report:</td>
<td>-</td>
<td>Used for the data processing macro only</td>
</tr>
<tr>
<td>Number of Runs:</td>
<td>-</td>
<td>Number of times the scenario was ran</td>
</tr>
<tr>
<td>Biomass at Offload N</td>
<td>Ft³</td>
<td>Amount of biomass accumulated at offload location N</td>
</tr>
<tr>
<td>Cart N Idle Time</td>
<td>Minutes</td>
<td>The amount of time that cart N was sitting idle</td>
</tr>
<tr>
<td>Cart N Move Time</td>
<td>Minutes</td>
<td>The amount of time that cart N spent moving, i.e. not loading, unloading, or moving</td>
</tr>
<tr>
<td>Combine N BioUnload Time</td>
<td>Bushels</td>
<td>The amount of time that combine N spent unloading biomass while stopped</td>
</tr>
<tr>
<td>Combine N Waiting Time</td>
<td>Bushels</td>
<td>The amount of time combine N spent stopped waiting for a cart (either grain or biomass) to unload it</td>
</tr>
<tr>
<td>Distance traveled to collect Bales</td>
<td>Feet</td>
<td>Distance that the bale collector traveled to collect all of the bales</td>
</tr>
<tr>
<td>Field Capacity</td>
<td>ac·h⁻¹</td>
<td>Capacity of the harvester in acres per hour</td>
</tr>
<tr>
<td>Grain at Offload N</td>
<td>Bushels</td>
<td>The amount of grain accumulated at offload location N</td>
</tr>
<tr>
<td>Harvest Efficiency</td>
<td>-</td>
<td>The efficiency of the harvester. The theoretical time to harvest the field</td>
</tr>
<tr>
<td>Table</td>
<td>Definition</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td><strong>Number of Bales Collected</strong></td>
<td>-</td>
<td>The total number of bales collected</td>
</tr>
<tr>
<td><strong>Time To Collect Bales</strong></td>
<td>Minutes</td>
<td>The time to collect the bales</td>
</tr>
<tr>
<td><strong>Total Time</strong></td>
<td>Minutes</td>
<td>The total time to harvest the field, not including bale collection</td>
</tr>
<tr>
<td><strong>Capital Recovery</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>Cost of recovering the capital investment in the equipment, also called depreciation cost.</td>
</tr>
<tr>
<td><strong>Taxes, Insurance, and Housing</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>Cost of taxes, insurance, and housing</td>
</tr>
<tr>
<td><strong>Total Ownership cost</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>Capital recovery plus taxes, insurance, and housing</td>
</tr>
<tr>
<td><strong>Repair cost</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>Cost of repairs to equipment</td>
</tr>
<tr>
<td><strong>Fuel and lubrication</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>Cost of fuel and lubrication</td>
</tr>
<tr>
<td><strong>Labor</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>Cost of labor to operate the equipment</td>
</tr>
<tr>
<td><strong>Total Operating cost</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>The sum of Repair, fuel and lubrication, and labor costs</td>
</tr>
<tr>
<td><strong>Total Ownership plus Operating cost</strong></td>
<td>$ / \text{acre}^{-1}$</td>
<td>The total cost of harvest</td>
</tr>
</tbody>
</table>