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THE EFFECT OF CONDITIONING SYSTEMS ON BALING AND HARVEST OF MISCANTHUS

A Thesis in

Agricultural and Biological Engineering

by

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ABSTRACT

Miscanthus is an emerging dedicated energy crop that will be crucial in helping to meet the goal set forth by the Department of Energy to produce 36 billion gallons of biofuels by 2022. While miscanthus provides excellent yield on marginal land, it is more difficult to harvest than many conventional energy crops such as corn stover and switchgrass due to its tall and rigid stalks. The harvesting of miscanthus was analyzed in this research to determine ways of cost reduction in the production of biofuels and to gather more information to be used in logistics models such as the BioFeed model.

In order to determine the best method to harvest miscanthus, a series of field tests was performed to compare existing conditioning methods. Data on the processing capacities, energy requirements, and bale quality were collected. The information shows differences between the steel chevron roll and flail conditioning modules. A self-propelled windrower with a discbine header and a large square baler were used to harvest the miscanthus from a 20-hectare field in Illinois. Crop was collected from the field to determine the effects of roll spacing, roll speed, and crop input on the quality of conditioning in a lab setting.

In the lab test the roll spacing was found to have the most significant impact on conditioning quality, shown by a 115% increase in conditioning over a 0.95 cm (75%) reduction in spacing. Increased roll spacing and speed were shown to decrease the amount of torque required to condition the miscanthus. In the field test, the windrower performed better statistically ($p < 0.001$) while using the flail conditioning module, increasing the average travel speed to 1.86 m/s, a 16% increase over steel roll conditioning. The fuel consumption of the windrower using the flail conditioning module (1.46 L/Mg DM) yielded a 17% reduction over the roll conditioning module (1.71 L/Mg DM) for windrower fuel consumption. The bales made from the flail-conditioned crop were also statistically shorter ($p = 0.068$) in length (2.49 m) and

higher ($p = 0.017$) in density (168.09 kg m^{-3}) than the length (2.54 m) and density (160.9 kg m^{-3}) of roll-conditioned bales, suggesting that the flail conditioning method did a better job of breaking up the crop and creating more fractures than the roll conditioning. The information obtained from this study helps to better predict machine and manpower requirements for miscanthus harvest as well as monetary and energy costs associated with those requirements.

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Chapter 1 - Introduction

In a world where the need for energy is ever increasing and the fossil fuels to provide that energy are dwindling, renewable and sustainable forms of energy are needed. Biomass and biofuels offer a very popular, low emission solution to the coming energy deficit. The US Department of Energy has decreed that by the year 2022 the annual amount of biofuels used will be at least 136 billion liters (US Department of Energy 2007). In order to meet this goal, more effective ways of providing the biomass to biorefineries are needed. Biofuels are a promising energy source; however they are not without certain drawbacks that need to be addressed before their use can effectively be adopted. Biomass can be defined as plant-derived organic matter which includes herbaceous and woody energy crops, agricultural food and feed crops, and agricultural or wood wastes and residues (National Renewable Energy Laboratory 2014). *Miscanthus x giganteus* (Miscanthus or Elephant Grass) is a sterile C4 grass that is being used as a dedicated energy crop due to its ability to grow on marginal land while still having high yields (Liu et al. 2012). Miscanthus can grow up to 3.5 m tall and net 5 to 55 Mg ha^{-1} of yield annually (Liu et al. 2012).

While the high yields are beneficial, the structure of the crop can cause issues for many types of traditional harvesting equipment. In particular, there is a need to convert the miscanthus in the field to a baled form that can be easily transported and stored. The stiffness and length of the stems make it difficult for traditional baler pickup heads to lift the crop into the compression chamber and make bales of adequate density. The completed research took an in-depth look at the machinery used to harvest miscanthus and incorporated the results into a logistics model to predict various aspects of miscanthus harvesting.

The use of dedicated energy crops such as miscanthus and switchgrass is important to the biofuel industry. While corn and soybeans can also be used to make ethanol, their use diverts these crops from the more important use of feeding the world's population. A dedicated energy crop's only use is to be converted into some form of energy. This alleviates the competition of also being used for food and feed production. In addition, most dedicated energy crops can grow on marginal lands which otherwise produce poor yields of traditional crops. Dedicated energy crops can be planted and harvested year after year with minimal upkeep. This makes them low cost and ideal for energy production as a farmer is able to plant these crops on previously unusable land for additional income.

To help alleviate problems in baling miscanthus, various types of conditioning systems can be implemented to break down the crop and make it easier to bale. Conditioning in this context refers to the breaking and weakening of the crop through some mechanical means such as feeding the crop through steel rollers or hitting the crop with steel flails. In theory, by weakening the crop through conditioning it will become easier to handle and bale, meaning that the miscanthus could potentially be harvested faster, baled denser, and stored in less space. By doing this the total cost of miscanthus from field to refinery will be reduced, a condition necessary for the growth of the biofuel industry.

Currently biomass is used to make energy, primarily by either burning in a power plant to generate electricity, or converting it into some form of biofuel such as ethanol which can then be used to power various other forms of machinery. Miscanthus is a popular biomass for burning because of its low carbon emissions and ash content. With increasingly more stringent regulations being implemented by the EPA on carbon emission, power plants are being forced to consider alternative fuels in order to cut their produced emissions. By co-firing their existing coal furnaces with miscanthus, power plants are able to lower the amount of carbon emissions without modifications to the existing furnace (Carroll and Somerville 2009). It is paramount to have a

sustainable, reliable, and cost effective supply system if biomass is going to become a primary form of energy production (Miao et al. 2012). Important areas to be researched include harvesting, transportation, and storage of biomass of which harvesting is the focus of this research. It is essential that the cost required in the production of biofuels be minimized so that the industry can grow and prosper.

The research described herein is primarily of interest to designers of the equipment being used to harvest miscanthus and the farmers growing the dedicated energy crops. Additionally, biorefineries may be interested in the effects that conditioned crops have on their respective processes. While these specific effects are outside the scope of the proposed research, biorefineries will still benefit from more easily storable biomass that can be supplied over longer periods of time.

The research provides a comprehensive evaluation of the effect of conditioning on the miscanthus harvesting process. The crop was mowed with a discbine and conditioned using the two most common existing techniques. The conditioned crop was then baled into large square bales to investigate the influence of conditioning on bale density. Machine parameters were recorded during harvesting to determine which conditioning method allowed for the highest throughput in the field as well as which method was most cost effective. From the research results, equipment manufacturers will be able to tailor their product lines to the biofuel industry and help to make the world's energy production more sustainable. Farmers will also be able to determine the feasibility of growing biomass as dedicated energy. Ultimately, this research will help the US meet the ambitious biofuel goal mandated by the Department of Energy.

Chapter 2 – Literature Review

2.1 INTRODUCTION

This literature review will cover the key aspects of biomass and biomass handling pertaining to the proposed research. Specifically past research pertaining to biomass, biofuel, biomass harvesting, logistics models, and data collection methods will be reviewed. The goal of this section is to provide the reader with the knowledge necessary to understand the proposed research and show the gaps in the existing research base.

2.2 ENERGY CROPS

Biomass is a feedstock that is gaining popularity for its use as a source of energy. Biomass can be defined as plant-derived organic matter which includes herbaceous and woody energy crops, agricultural food and feed crops, and agricultural or wood wastes and residues (National Renewable Energy Laboratory 2014). Currently corn is the most popular feedstock for producing biofuels, yielding approximately 75 to 250 million Mg DM each year (Perlack 2007). All forms of biomass should be used efficiently to make the best use of the resources available. For instance, food and feed crops should be used carefully, since increased use in energy production will take away from the more important use as food for the world's population. Wood and agricultural waste should also be used to advantage; however, waste is available in a limited supply and there are still potential consequences to its use. Corn stover is considered the cobs, stalks and leaves left behind when the corn grain is harvested (Buchanan et al. 2008).

While corn stover is a waste product that seems readily available, removing too much of it after harvest can lead to increased soil erosion which potentially offsets its value as a feedstock source (Buchanan et al. 2008).

It is particularly important to find a feedstock that can be used for energy production with minimal cost and energy inputs required. Dedicated energy crops are those that are grown solely for energy production, whether that is through combustion in a furnace or through production of liquid fuels. While increasing dedicated energy crop production has the potential to displace land needed for other uses such as feed crops, it can often be implemented on land that is currently unused and/or undesirable for other uses. Promising crops that fall into this category include woody crops such as willow and poplar or herbaceous crops such as miscanthus or switchgrass.

Figure 2-1. Willow from Lancaster PA (left), Miscanthus from Illinois (center), Switchgrass from Tennessee (right)

http://www.lancasterfarming.com/-Willow-for-Energy--School-Finds-Savings-in-Homegrown-Crop-#.VGI53fnF9zo http://www.extension.org/pages/26625/miscanthus-miscanthus-x-giganteus-for-biofuel-production#.VGI31_nF9zp http://www.agriculture.utk.edu/archivednews/releases/2008/0804-DOEgrant.htm

Woody crops are popular in Europe for co-firing in coal furnaces (Lavoie et al. 2007). Plots of willow are grown in rows and harvested on a three year-cycle during the fall/winter of the year. In order to harvest willow it is typically cut and fed through a chipper when the plant is between 40-50% moisture content (Lavoie et al. 2007). Willow can have yields between 10 and 20 Mg per hectare dry matter each year which exemplifies its potential as a dedicated energy crop (Lavoie et al. 2007).

In the United States, herbaceous energy crops are more common than the alternative woody crops. Switchgrass and miscanthus show some of the greatest potential as dedicated energy crops with potential yields of 5-23 and 5-44 Mg per hectare dry matter respectively (Lewandowski et al. 2003). Switchgrass is a C4 perennial warm season grass native to North America. It can grow in a variety of environments including low to high moisture soils and marginal lands with poor nutritive quality (Sokhansanj et al. 2009). Structurally it is similar to most prairie grasses, growing 1.5 to 3.7 meter tall with stand lives lasting approximately 20 years depending on the variety, management, and environment (Penn State Extension 1983). Some downsides to switchgrass include potentially difficult establishment and high establishment costs (Penn State Extension 1983). It is typically harvested once a year around September; however, it can be harvested multiple times during each growing season if short stand lives are not a concern (Sokhansanj et al. 2009).

Miscanthus is a C4 perennial warm season grass native to east Asia and capable of growing in a variety of climates (Lewandowski et al. 2003). Miscanthus has a rigid cane structure with nodes and internodes much like bamboo or sugar cane. Similar to switchgrass miscanthus stands can take 3-5 years to become fully established, but once established it can last 20-25 years (Lewandowski et al. 2003). While yields are best in soils that have a high water holding capacity, miscanthus is able to survive in soils of poor quality or low water holding capacity. Relatively low cost is required to maintain the stand due to miscanthus surviving well on marginal lands. For best results, miscanthus should be harvested once a year between January and March. It should be harvested after the first killing frost so that the moisture content of the plant can lower and the nutrients can move from the stems back to the roots. Harvesting at this point will reduce the yield by 25 percent; however, it will greatly increase stand persistence and overwintering (Lewandowski et al. 2003). It will also eliminate the need to dry the crop in the

field, making-one pass harvesting an option. Care should also be taken to harvest before new growth begins from the crowns to ensure maximum yield the following year.

Miscanthus can be used as a fuel source for combustion in furnaces and is typically co-fired with coal. The heating value of miscanthus is 17744 kJ/kg compared to coal which has a heating value around 30000 kJ/kg depending on the grade of coal (Collura and Azambre 2006). Miscanthus is a high quality fuel choice due to its low ash and trace element contents. The later the miscanthus is harvested the better the quality due to the leaching of elements back to the roots (Lewandowski et al. 2003). In addition to the benefits that miscanthus has concerning yield, maintenance cost, fuel characteristics and disease resistance, it also provides ecological benefits in the way of increased bird, mammal, and insect populations.

No biomass is perfect and miscanthus has some disadvantages associated with it as well. Miscanthus is expensive to establish, costing up to $6000/ha in 2003 (Lewandowski et al. 2003). Miscanthus also has poor overwintering during establishment making it easy for weeds or cold temperatures to wipe out stands before they become fully established. Like most biomass, it has a low energy density compared to coal or oil. Overall miscanthus is a promising candidate for biofuels which is why its harvest is the focus of the proposed research.

2.3 BIOFUELS

Global consumption of petroleum tripled from 1970 to 2006 and in 2013 the United States alone consumed 6.89 billion barrels of petroleum products (Ragauskas et al. 2006; U.S. Energy Information Administration 2014). With consumption only expected to increase, it’s no surprise that development of alternate renewable forms of energy is advancing. Biofuels represent a popular alternative to conventional petroleum and coal products because they are

renewable and can take the place of existing fuel sources without major changes to modern machinery.

Biomass can be used to make energy via gas, liquid, or solid media. Gas production via CH_4 or pyrolysis gas is difficult and not as common as liquid or solid media (Kitani et al. 1999). Liquid fuel can be developed either in the form of ethanol or biodiesel which can then be burned in combustion engines to generate power. Solid media is used as a fuel source to be burned in furnaces and is one of the simplest ways to extract energy from biomass. All three media provide their own advantages and disadvantages regarding how they are made and what fuel is produced. Some of the more popular methods will be elaborated upon in this review.

The simplest way to produce energy is to burn it in the solid form in a furnace. The heat energy is used to make steam which, in turn, drives a turbine for electricity production. This method has the advantage of displacing some of the greenhouse gases that coal which is the typical fuel source is currently producing (Carroll and Somerville 2009). It is not feasible to completely replace coal as the fuel source for furnaces because coal contains much more energy per unit mass than biomass. It would be very difficult logistically to supply enough energy and generate enough heat to completely replace coal which is why it is common to co-fire biomass and coal in a furnace. Biomass also contains minerals which after accumulation can cause problems with the operation of the furnace. If the biomass makes up approximately 10% of the total burn, the furnace can usually be operated without significant modification (Carroll and Somerville 2009).

Liquid fuel is made through either microbial or chemical means with the key steps being size reduction, pretreatment, hydrolysis, and fuel production (Carroll and Somerville 2009). No matter whether microbial or chemical means are used, the size of the input particles needs to be reduced and hydrolyzed to extract the sugars. Woody biomass requires substantially higher energy input to reduce its size when compared to herbaceous biomass (Carroll and Somerville

2009). Microbial and chemical conversion output the liquid fuels ethanol, alkanes, terpenes, or other alcohols (Carroll and Somerville 2009). Ethanol is a promising fuel that can be burned in engines at a higher efficiency than gasoline due to its high octane rating and lower heat value (Kitani et al. 1999). The higher efficiency and renewability make ethanol a very popular product for biorefineries. Currently, the US infrastructure is not equipped to run vehicles that are powered solely by ethanol because those engines would require higher compression ratios for operation (Kitani et al. 1999). This trend is beginning to changes as flex fuel vehicles are emerging and the fueling infrastructure is adapting. An intermediate solution is mixing the ethanol with gasoline to create 10% ethanol mixtures that function in current combustion engines without modification.

It is important that research continues in the biofuel field so that a cost effective infrastructure can be developed to replace fossil fuels. Producing ethanol from non-starch based feedstocks is also important because of the 136 billion liter ethanol goal, only 57 billion liters can be starch-based ethanol (Ma and Eckhoff 2012). Research into reducing the cost to make biofuels from field to refinery needs to be continued. Finding energy efficient ways to make denser bales is an area that still needs further research because the logistics cost to get biomass from field to refinery is strongly influenced by bale density (Sokhansanj, Webb, and Turhollow 2014). Finding ways to produce higher yields on marginal land is also an important focus for research. Any way that cost can be lowered and energy can be reduced in the production of biofuels will increase its acceptance and feasibility.

2.4 HARVESTING EQUIPMENT

Once a crop is grown in the field, the desired product needs to be removed and converted into a form that is easy to store and transport. Harvesting for this thesis is defined as the sequence

of operations that are used to remove the crop and move it to storage. Harvesting accounts for more than half of the biomass procurement costs (Lin et al. 2013). For most crops, the harvesting process begins with some form of cutting or mowing operation. Following cutting there is an optional conditioning operation that is used to alter the crop in some way for pre-storage processing. The final step is normally some sort of baling operation or other storage procedure.

Mowing is the first step in removing crops from the field. Some crops such as corn, wheat, and other grains are harvested with a combine which cuts the crop and removes the value added component (grain) from the plant. For plants that are grown for their biological mass such as forages and herbaceous biomasses, the crop is mowed without removing any portion of the plant. Mowing removes the majority of the above-ground portion of the plant from the roots so that it can be moved and further processed. The two most common forms of mowers that are used today are sickle-bar mowers and disc mowers (discbines). Sickle bar mowers use oscillating blades that pinch the crop between a moving blade and a stationary blade causing it to separate. Disc mowers are a series of small blades mounted on rotating discs. The discs rotate, propelling the blade into the crop and cutting it at the height of the blade. While sickle bars require less horsepower than disc mowers, their speed of travel is more limited by stand density. Fig. 2-2 shows a sickle bar mower and a disc mower.

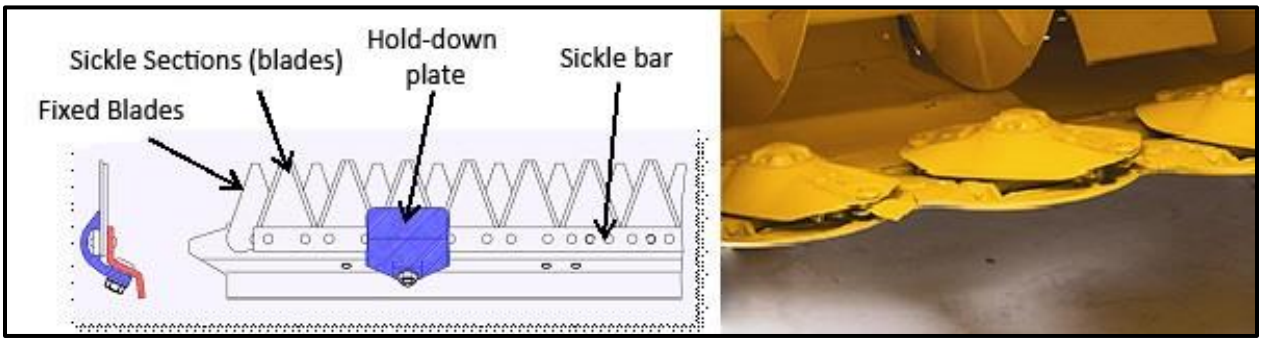

Figure 2-2. Sickle Bar Mower (left), New Holland Disc Mower (right)

http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1130447202&topicorder=4&maxto=13&minto=1 http://agriculture.newholland.com/us/en/Products/Hay-and-Forage-Equipment/Speedrower-Self-Propelled-

Miscanthus is normally harvested using a discbine because a sickle bar mower has a slow travel speed given the thick miscanthus stems. Discbines are able to cut through the miscanthus stems easier than the sicklebar and therefore obtain a faster travel speed through the field. This is important because maximizing speed maximizes the useful work done by each machine (Johnson 2012). Although the disc mowers used for hay are able to cut the miscanthus, they are operated slower than their normal capacity due to the miscanthus toughness (Liu et al. 2012). Current mowers also have some trouble cutting miscanthus at the optimum cutting height of 50 to 100 millimeters (Liu et al. 2012). To help alleviate issues in the operations after cutting, conditioning is performed on the crop.

Conditioning can be considered a mechanical operation used to break open the stems of plants. Conditioning was developed for forage harvesting to aid in the drying process of hay. Through conditioning, it is possible to achieve the same drying rate in the stems of a plant as the leaves (Taylor 1992). Most conditioning systems are implemented directly behind the mowing device so that crop can be mowed and conditioned in a single pass. Conditioners can feed the crop out the back into a windrow so that it is ready for the next step in the harvesting process or left in a form conducive to drying. Conditioning systems fall into either impeller/tine-type or roll-type conditioners (Taylor 1992).

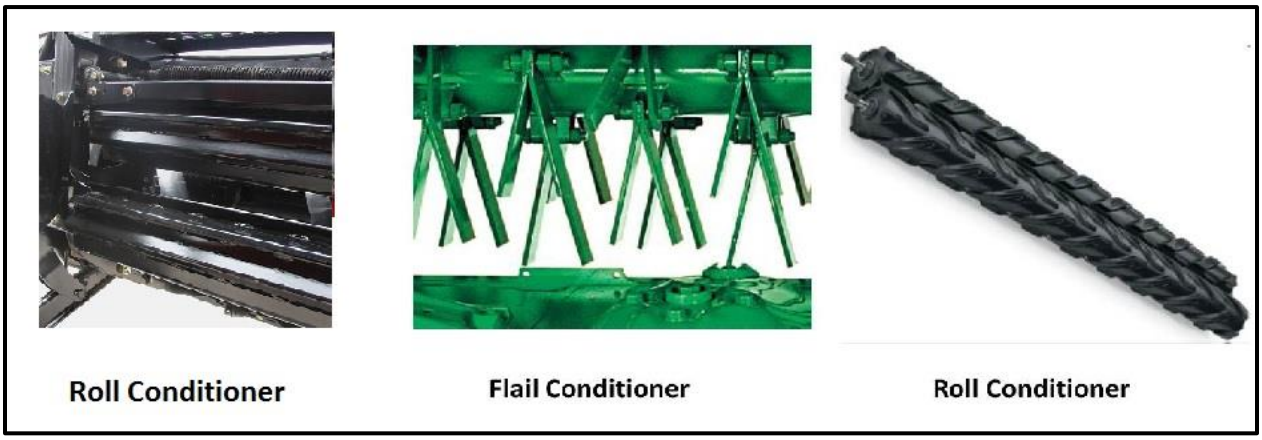

Figure 2-3. Paddle Roll Type Conditioner (left), John Deere Flail Type Conditioner (center), Chevron Type Conditioner (right)

http://www.macdon.com/products/a-series-mower-conditioner-pull-types
http://billsforagefiles.blogspot.com/2012_12_01_archive.html

Roll type conditioners consist of two rolls that force the crop between them to break the stems. One roll often has a male chevron and the other a female to help keep hold of the crop as it is pulled through the rolls. These rolls can either be made of steel, polyurethane, or a durable rubber. Other types of roll conditioners contain interlocking paddles mounted horizontally on the rolls that are used to pull the crop through and crimp the stems. Flail Type conditioners use metal flails to hit the crop after it is mowed to break the stems. As the crop is fed through the flails it is also rubbed against the conditioning hood which wears away at the stem's surface allowing moisture to escape more easily.

At the time of cutting, miscanthus should already be at a moisture content that is acceptable to perform the rest of the harvesting operations. It is still important to condition miscanthus for reasons other than further drying. Miscanthus is conditioned to shorten the pieces and create fractures in the crop stems. Thus, conditioning may make it easier to handle in later operations (Nixon and Bullard 2003). After being conditioned, the stems can be picked up easier by baling tines and can be compressed easier than unconditioned miscanthus (Fasick 2015). Not

all forms of conditioning are equal when it comes to miscanthus harvesting. While it is not known exactly which type is the best, it is expected that rubber rolls will wear out too quickly due to miscanthus' toughness and abrasive qualities. There are also clogging issues that tend to occur with certain types of flail conditioners. These issues are addressed in this research.

Once the crop is cut, conditioned, and in a windrow, it is ready for the final step in harvesting. Cut crop can either be baled or chopped. Crop with high moisture contents can be made into silage which does not require drying, and is uncommon with miscanthus harvesting so it will not be covered in this review. Baling requires that the crop be below moisture content thresholds to prevent spontaneous bale combustion and mold growth so it is dried before it is baled. A baler consists of a pickup head that uses some mechanism, normally tines, to pick up the crop and feed it into some form of compression chamber. The crop is then compressed and tied to form a bale that can be easily transported and handled from that point on. Once bales are made they are transported via skid steers or wagons to a storage location or a pickup point for long distance transportation. Balers come in three basic types: small square, large square, and round. An alternative to baling biomass is grinding and pelletizing it and storing it in bins. This is more commonly completed by the biorefinery than the farmer.

Figure 2-4. Small Square baler (left), Large Square Baler (center), Round Baler (right)

http://www.caseih.com/international-tr/Products/HayForage/SmallSquare/Pages/Models.aspx?p=y
http://agriculture.newholland.com/us/en/Products/Hay-and-Forage-Equipment/Large-Square-Ba
http://www.barhimp.com/equipment.php?comid=116&type=Round_Baler

Miscanthus resists being picked up by the pickup head on most balers in the unconditioned state (Nixon and Bullard 2003). This problem is worse in small square balers then the other two types because once picked up a small square baler uses metal fingers to push the crop horizontally into the compression chamber. Mechanically the machine struggles to push crop that is oriented parallel to the direction of the moving fingers. Large square and round balers are the primary types of balers used in miscanthus harvesting because of the lack of market for small square bales to biorefineries and due to the trouble small square balers have with crop handling. Making bales of uniform density is an issue with baling miscanthus. This can be caused by improper windrow formation or the size of the miscanthus being too long for the baler to properly handle. The last major problem with balers is the inability to pick up all biomass from the ground. Crop is wasted during baling from chamber losses and pickup losses.

Using a chopper to remove miscanthus from the field is currently a fairly uncommon practice; however, sometimes it is still performed in situations where compressed pellets are the end product. Crop can both be chopped while still standing or it can be picked up and chopped after being mowed. Fig. 2-5 shows an image of chopped miscanthus as well as a New Holland crop chopper. Chopping requires that a trailer travel through the field to catch the chopped crop while being harvested.

Figure 2-5. Chopped miscanthus (left), New Holland Chopper (right)

http://agriculture.newholland.com/PublishingImages/cnhimg/Products/NAR/FRSeries/Homepage_FR.jpg
http://elibrary.asabe.org/azdez.asp?JID=3&AID=45445&ConfID=t2015&v=58&i=2&T=2&redirType=

2.5 LOGISTICS MODELS

Logistics models are important in every industry because they provide a way to predict future events/costs or a guide of the best way to complete a task. Logistics models exist to help farmers predict crop yields, profits, labor, and required machinery for many popular crops. Currently there is a push to develop similar models that also work for biomass production. Two models that are currently being developed are the BioFeed Model and the Integrated Biomass Supply Analysis and Logistics Model (IBSAL). In developing these models, field tests are completed and specific data is recorded so that predictions can be made about how changing specific conditions will alter the outcomes of the model. It is important that the proper information is recorded so that the field tests are useful in the model parameterization.

Logistics models for biomass and biorefineries attempt to incorporate everything from the seeding of the crop to the time that it reaches the biorefinery. Detailed information must be recorded about every step of the process in between. The first stage of a complete model should include information on the soil type, seeding rate for stand, required establishment time, equipment needed as well as cost to operate that equipment, labor cost and predicted weather information. This information helps to model the parameters such as cost and maintenance of establishing a stand of biomass to a point that can be maintained. The second component of a complete model should handle the harvesting of the biomass. This includes the machinery required, the cost to operate that machinery (fuel consumption/maintenance), labor costs, some details about moisture content and plant composition, harvest date, time required to harvest, and bale handling or pelletizing information. The next portion of the model needs to cover the storage and transportation of the bales. This should include fuel costs, bale densities, travel distance required, storage information, and labor costs. The last portion of the model should cover the production of the biofuel and costs associated with that. This would include costs of the

required materials for production, machine operating costs, labor costs, production time, and storage costs. An optional addition to biomass models would be the cost of any transportation or storage required to get the product to the end user or vendor.

BioFeed is one such model that attempts to cover the biomass production process. BioFeed is a mixed integer linear programming model developed in conjunction with NEWBio (The North East Woody/Warm-Season Biomass Consortium) that focuses on the steps between harvest and delivery to the biorefinery (Shastri et al. 2010). The original BioFeed model was designed to work with switchgrass; however, the most recent version has been expanded to cover more types of crops including miscanthus as well as more facets of the various intermediate operations. It contains detailed information about equipment that is used in the harvest and handling of the biomass as well as details about the packing, transporting, and storing of the biomass (Shastri et al. 2010). Fig. 2-6 is the flow chart of potential operations that can be followed under the BioFeed model (Shastri et al. 2010).

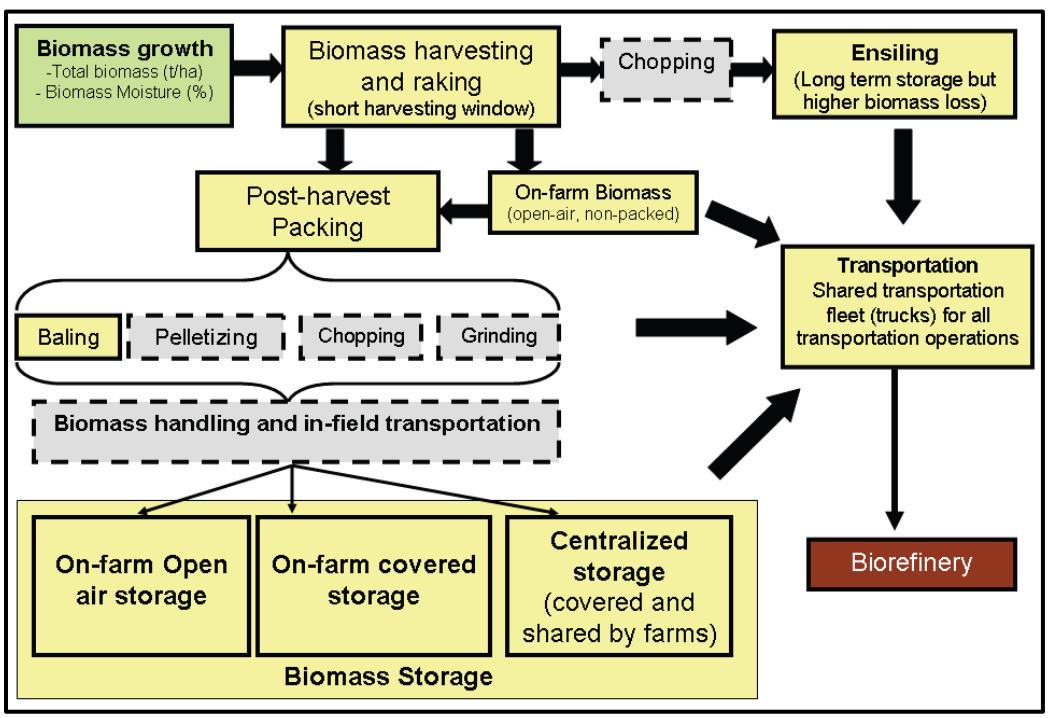

Figure 2-6. Flowchart for the BioFeed model

This model produces an optimum solution for production of biomass from field to refinery. The model outputs a cost per mega gram of product, as well as the various parameters of the model that need to be set in order to reach the optimum cost. While the model may be missing cost-adding steps or aspects in the overall process, its power comes from being able to compare the effect of changing individual parameters on the final cost of the biomass. For instance, if a new piece of machinery is purchased, the model will predict whether or not it will increase, decrease, or have no effect on the optimal cost and method of producing the biomass. This can help farmers to make decisions about farm operations and purchases.

The IBSAL model is the other well developed model that deals with biomass and its production. IBSAL was developed in EXTEND, a high-level object oriented simulation language (Sokhansanj et al. 2006). The model considers collection and storage of the biomass, and preparation and transport of the biomass (Sokhansanj et al. 2006). Different from the BioFeed model, IBSAL emphasizes weather and how it can affect the harvest and continuous supply of the biomass to the biorefinery. It also has the ability to predict the date that specific operations will be complete based on the equipment available and the predicted weather. Fig. 2-7 shows the general process flow of the IBSAL model from the required inputs to the output parameters and costs (Sokhansanj et al. 2006).

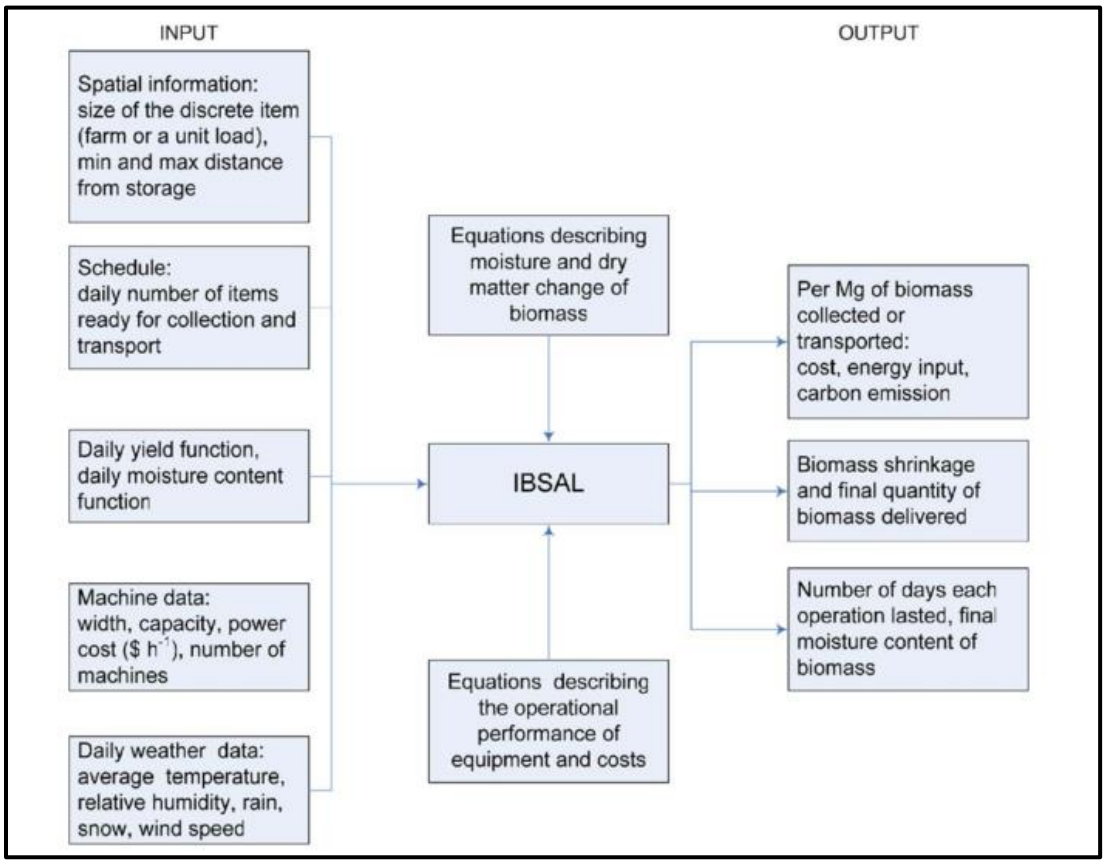

Figure 2-7. IBSAL model Flow Chart

The fundamental difference between optimization and simulation models is how they find their solution. Optimization uses rigid equations that, if run with the same input parameters, will always yield the same results. Simulation models however take variability and statistics into account when finding their solution. The solution found with a simulation model could be different from one time to the next depending on the seeding location of the random numbers used, even if the same input parameters are used. The BioFeed model is an optimization model meaning it will always produce the best possible answer based on the limits of the model whereas IBSAL could give an answer that is not necessarily the optimum answer depending on the seeding values. This should be kept in mind when using the model, for farm-level decision making. Regardless of the model type, it is always important to remember that these models are

just predictions based on relationships observed in actual trials and that there is no guarantee that the process will behave the same in real life.

2.6 DATA COLLECTION METHODS

To collect all the necessary information to run a logistics model for miscanthus harvesting, it is important to have a variety of different methods available. Many aspects of the data recording can be done by hand but it is often good to use automatic data collection methods for ease of collection. Collection should still also be used to verify that the information is being collected properly. There is a wealth of technology such as Global Positioning Systems (GPS), Controller Area Network Bus (CAN Bus), Data Loggers, and others to aid in data collection. This portion of the review will give a brief description on some of the key data collection tools that will be used in the proposed research.

In the proposed research it will be important to quantify how far the equipment is moving, its path through the field, and where bales are being dropped. Since the advent of GPS, many tractors and other pieces of equipment have been incorporating them into their control and design. By attaching a GPS to equipment moving through the field, different aspects of the field can be mapped out. For instance, value added time during harvest can be mapped as well as time spent turning or idle. Bale drop coordinates can be recorded and variations in the field can be tracked according to where they occur. The information provided by the GPS will be used to verify field size, distance traveled, bale locations, and travel speed. Additional verification of this GPS recording can be accomplished using hand held GPS devices to plot various point boundaries and locations of interest.

An important tool in modern agricultural data collection is the CAN Bus. The CAN bus is an array of sensors that record almost every important parameter with regard to equipment

operation. The CAN bus is able to record anything from the horsepower or tire pressure over time to the number of flakes in a bale. Additional equipment/software is required to understand the information that a CAN bus tracks. Software packages are available to view and process the data coming from CAN systems however they come at a cost to the farmer. Attempts to acquire the software for this research were unsuccessful so all of the data collection needed to be done by hand.

Fortunately, there are other data collection methods. One such method to measure fuel consumption is the top-off method. This is when the equipment is filled to a designated level at the start of operations and then refilled to the same level after operations. The weight of the fuel removed from the filling jugs was measured so that the fuel consumption could be calculated. Bale weights were also periodically measured using portable scales in the field. To make a scale with enough capacity to measure large square bales three tire scales were placed under a pallet. Bales were then placed onto the pallet and the weight on all scales was recorded to get a total weight. Data collection and accuracy is of the utmost importance because if it is not completed properly, new data will not be available until after the next growing season.

2.7 STATE-OF-THE-ART

Biomass and biofuels are crucial for the energy sustainability of earth as fossil fuel use continues to increase and supply continues to diminish. The world needs to have a well-developed infrastructure for alternative energy before fossil fuels run out entirely. The United States has taken action by requiring 136 billion liters of fuel to be made from renewable sources by 2022 (Oak Ridge National Laboratory 2011). This will require a substantial increase in biomass feedstock supply if the goal is going to be met. To meet the goal, higher yielding crops

need to be developed and efficient and cost-effective strategies to harvest them need to be devised (Heaton et al. 2008).

Miscanthus is a likely candidate for achieving the lofty biomass goals; however, conventional hay and forage equipment is not ideal for its harvest. Miscanthus provides many harvest difficulties due to its size and toughness. It is very difficult for conventional balers and hay handling equipment to move unconditioned miscanthus. The miscanthus is very tall so the tines have difficulty lifting the miscanthus into the compression chamber. The tines often leave sizable mass losses on the ground after picking up the windrow thereby reducing the final yield of the crop. Conditioning can be performed on the crop to help alleviate these problems, but some conditioning types cause binding of the crop which greatly slows down the throughput of the harvest. The performed research analyzed the conditioning of miscanthus to determine the most effective method to shorten and weaken the stems so that they can be handled and baled effectively. Currently, the selection of which type of baler is best for miscanthus harvesting is not well understood. While only a large square baler was available for the performed research, there is still a need to evaluate the use of a round baler in future research.

Chapter 3 – Goals, Objectives, Hypotheses

3.1 GOAL

To obtain important parameters for use in logistics models as well as determine which method of conditioning works the best for harvesting miscanthus based on throughput and bale density.

3.2 OBJECTIVES

1. Perform field trials to collect data on fuel consumption, travel speed, machine stoppage, bale handling, and harvesting capacity.
2. Determine the effect of conditioning on bale quality by measuring bale weights, lengths, and bulk densities.
3. Examine the effects of varied roll speed, roll spacing, and crop bundle size on conditioning quality through use of a conditioning roll test stand.
4. Run statistical analyses on field test data to determine the most effective conditioning method for miscanthus.
5. Run statistical analyses on lab test data to determine any trends associated with roll spacing, speed, and bundle size.

3.3 HYPOTHESES

This section contains all of the statistical hypotheses that were tested in the analysis of the data. The hypotheses were tested using varying statistical techniques

based on the specifics of each hypothesis to determine whether the conclusions being drawn from the data are statistically significant.

3.3.1 Bale Properties

The three hypotheses test whether the mean bale density, weight, and length are different for steel roll and flail conditioning.

H_o: The mean large square bale densities for steel roll and flail-conditioned miscanthus are equal.

H_a: The mean large square bale densities for steel roll and flail-conditioned miscanthus are not equal.

H_o: The mean large square bale weights for steel roll and flail-conditioned miscanthus are equal.

H_a: The mean large square bale weights for steel roll and flail-conditioned miscanthus are not equal.

H_o: The mean large square bale lengths for steel roll and flail-conditioned miscanthus are equal.

H_a: The mean large square bale lengths for steel roll and flail-conditioned miscanthus are not equal.

3.3.2 Time Study

The mean fuel consumption when harvesting with steel rolls and flails was tested for both the windrower and the baler. The average time it takes to drop a bale for both types of conditioning was checked. Finally the average travel speed per pass was tested for both vehicles to determine if there was a difference in the conditioning types.

H_o: The mean fuel consumption rates for steel roll and flail-conditioned miscanthus are equal for windrower cutting.

H_a: The mean fuel consumption rates for steel roll and flail-conditioned miscanthus are not equal for windrower cutting.

H_o: The mean fuel consumption rates for steel roll and flail-conditioned miscanthus are equal for large square baling.

H_a: The mean fuel consumption rates for steel roll and flail-conditioned miscanthus are not equal for large square baling.

H_o: The mean bale drop rates (s/bale) for steel roll and flail-conditioned miscanthus are equal for large square baling.

H_a: The mean bale drop rates (s/bale) for steel roll and flail-conditioned miscanthus are not equal for large square baling.

H_o: The mean average travel speeds for steel roll and flail-conditioned miscanthus are equal for large square baling.

H_a: The mean average travel speeds for steel roll and flail-conditioned miscanthus are not equal for large square baling.

H_o: The mean average travel speeds for steel roll and flail-conditioned miscanthus are equal for windrower cutting.

H_a: The mean average travel speeds for steel roll and flail-conditioned miscanthus are not equal for windrower cutting.

3.3.3 Lab Test

The effect that bundle size, roll speed and roll spacing had on the quality of conditioning and the peak torque seen was tested. The hypotheses for these tests are listed below.

H_o: The mean piece ratios (ratio of pieces out to pieces in) for miscanthus fed through the test table are equal for different roll spacing.

H_a: The mean piece ratios for miscanthus fed through the test table are not equal for different roll spacing.

H_o: The mean piece ratios for miscanthus fed through the test table are equal for different roll speeds.

H_a: The mean piece ratios for miscanthus fed through the test table are not equal for different roll speeds.

H_o: The mean piece ratios for miscanthus fed through the test table are equal for different bundle sizes.

H_a: The mean piece ratios for miscanthus fed through the test table are not equal for different bundle sizes.

H_o: The mean adjusted peak torques for miscanthus fed through the test table is equal for different roll spacing.

H_a: The mean adjusted peak torques for miscanthus fed through the test table is not equal for different roll spacing.

H_o: The mean adjusted peak torques for miscanthus fed through the test table is equal for different roll speeds.

H_a: The mean adjusted peak torques for miscanthus fed through the test table is not equal for different roll speeds.

H_o: The mean adjusted peak torques for miscanthus fed through the test table is equal for different bundle sizes.

H_a: The mean adjusted peak torques for miscanthus fed through the test table is not equal for different roll spacing.

Chapter 4 – Methodology

4.1 Introduction

A detailed plan is important for any research to allow complete understanding and repeatability for anyone wishing to verify the results. This section will describe in detail the steps that were taken and the information that was recorded in order to come to the conclusions found in this paper. The research was divided into the following categories: field testing, lab testing, and data analysis. A brief description of what was completed in each phase is given in the general overview section. Additionally, a full description of the field and equipment used in this study are provided. The method for setting up, operating, and collecting data from the equipment is detailed along with the methods that were used to analyze the collected data.

4.2 General Overview

The research can be roughly divided into three phases. The first phase consists of the field testing and the data gathered from these tests. In the field test a windrower was used to cut the miscanthus. The windrower can be equipped with either flail or steel roll conditioning modules. Half of the crop was cut using steel roll conditioning with the remainder using flail conditioning. A large square baler then baled the crop, and a front end loader was used to pick up and stack all bales at the edge of the field for transport. In the second phase, the crop collected from the field test site was used to perform a small scale conditioning test in a controlled lab setting. The crop was fed through a pair of steel conditioning rolls of varying speeds and spacing

to determine the effects on crop conditioning. The final phase covered the analysis of all data collected and the implementation into a logistics model to predict aspects of crop harvest and collection.

4.3 Field Description

The miscanthus field used for field test site is located just outside of Easton, Illinois at GPS coordinates 40.201434, -89.831220. The field is a farm and is approximately 20 hectares in size. Fig. 4-1 shows that the field is split into two sections by center pivot irrigation. The crop in the field is an accumulation of 2 years growth and the stand varies in density throughout the field.

Figure 4-1. Easton, Illinois Miscanthus Field (google maps)

The field was established in May 2009 with a miscanthus clone from greenhouses at University of Illinois at Urbana-Champaign (UIUC) turf farm, which was later planted on John Caveny's farm. The first harvest took place in April of 2010 and yielded 225 (3'x3'x8') large square bales weighing approximately 363 kilograms (800 pounds) each. In April 2012, the field was harvested for a second time yielding 1403 (3'x3'x8') bales. The third and most recent harvest was in April of 2013 by Aloterra Energy but the yield is unknown. The field was fertilized the same year it was seeded and natural rainfall was sufficient for establishment. The only time that the crop was irrigated was in 2012 with a central pivot irrigation system.

To account for the varying stand density the field was divided into 9.1 meter (30 feet) wide vertical strips that were alternately cut with the two conditioning types (Fig. 4-2). By doing this the harvesters were able to make an out and return trip for each row and each conditioning type saw similar field densities throughout the trial.

From the field, six samples were randomly selected from 1 m^2 sections in the field to get an idea of the yield and moisture content. In each section all crop was cut at the height of the disc blades and then weighed. The samples gave an estimated yield of 20.1 Mg/ha (w.b.) which was estimated along with a moisture content of around nine percent.

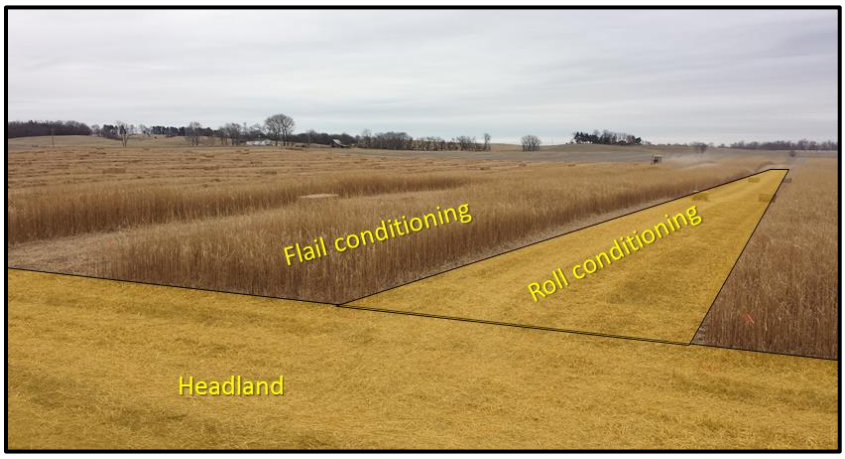

Figure 4-2. Crop division for treatments

4.4 Equipment

This section provides an overview of the equipment that was used in the completed research.

4.4.1 Harvest Equipment

Case New Holland (CNH) provided the required equipment listed below. The windrower has a wheelbase of 3.66 m, 226 engine hp, and a cutting width of 4.88 m. The windrower header is able to be equipped with either the flail or the roll conditioning module. The tractor pulling the baler has 313 engine hp with a CAN bus terminal/monitor in the cab for adjusting and recording tractor/baler operating parameters. The baler being pulled is commonly called a large square baler and can make 3x4x8 ft bales. The baler was run with two separate twines due to their availabilities at the time of harvest. The T6050 tractor was used exclusively for bale handling and the rustler expedited manual data acquisition throughout the field. The fuel tank was used for measuring fuel consumption at the field site.

- New Holland windrower: SPEEDROWER 240 (Fig. 4-3).
    - New Holland windrower header: DURABINE 416 BioMaxx
        - Steel Chevron Roll Conditioning Module
        - Flail Conditioning Module
- New Holland tractor: T8.330
- New Holland large square baler: BIGBALER 340 (Fig. 4-4)
    - New Holland 500lb Polypropylene baler twine
    - PKL 550lb baler twine
- New Holland utility tractor: T6050 (Fig. 4-5)

    - 840TL Loader attachment
- New Holland Rustler 120
- Mobile Fuel Tank

4.4.2 Field Data Acquisition Equipment

Penn State provided additional equipment required for data acquisition.

- Bale Analysis Equipment
    - Crop Moisture Probe
    - Tape Measure
    - 3 Intercomp drive on tire scales (used for weighing bales)
    - Wooden Pallet (used for weighing bales)
    - Bale Core Sampler (provided by INL)
- Material for tagging rows and bales
    - Spray paint (to make bales)
    - Flagging Tape
    - Handheld GPS Devices
    - Walking Wheels (distance measurement and GPS calibration)
- Fuel Consumption Equipment
    - Diesel Fuel Cans
    - Funnels
    - Acculab SVI-10A portable scale (used with top off method)
- Video Cameras
- Hard Drives for data storage

4.4.3 Lab Test Equipment

The equipment listed below was used in the Penn State Ag Engineering Building Shop to perform the lab testing.

- Conditioning Equipment
    - Hydraulic Power Pack
        - Kawasaki K3VL Pump
        - Elektrimax 31NCM-3-15-18 Motor
    - Conditioning Table
    - National Instruments Data Logger
        - NiCRO-9024 controller
- Drying Oven (moisture content measuring)
- Acculab SVI-10A Portable Scale
- 12V DC Power Supply
- Measuring tape
- Walk In Cold Storage Unit

4.5 Test Plan

This portion of the methodology covers everything needed to replicate the experiments for both the field and lab tests.

4.5.1 Field Test

The field test and harvest began on March 17, 2015 and lasted 5 days. The windrower arrived on the 16th of March at which time it was inspected and made ready for the harvest. The baler arrived on the 17th and was made ready that day to begin harvesting. It was necessary to check the ground to make sure that it wasn't too wet to run the equipment on while at the same time not having too much snow cover to interfere with the cutting and baling. It was also necessary to have clear skies so that the bales being made weren't soaked with water from rain. On the 17th of March these conditions were met and harvesting began.

Figure 4-3. New Holland SPEEDROWER 240 with DURABINE 416 BioMaxx Header

Figure 4-4. New Holland T8.330 with BIGBALER 340

Figure 4-5. New Holland T6050 with 840 TL loader

The actual harvesting of the miscanthus was a large multi-person operation. A custom harvest crew consisted of four operators to run the various equipment units. In addition to the operators, Penn State research team was on site to collect all data and to assist bale collection. Due to safety and liability concerns, no undergraduates were included in the field test.

Before dividing the land up for the two treatment types, headlands had to be cut on the north and south ends of the field, or top and bottom sides as shown in Fig. 4-1. The headlands served a dual purpose in the field test. Primarily they allowed for space where the windrower and

baler could efficiently turn around. Additionally the crop in headlands may contain more weeds, contaminated and low yield crops. Separating bales from headlands may allow higher quality bales. Once the headlands were cut, the land was divided into 9.1 meter (30 feet) wide strips oriented longitudinally (N to S, or Vertically). This allows for the 4.9 meter (16 feet) wide windrower header to make two 4.6 meter (15 feet) passes through each strip of crop. Every other strip was used for the same type of conditioning method so that the two conditioning types will cover similar crop conditions over the width of the field. In addition, this is a means to minimize the effect of field slopes on machine operating performance. GPS guidance was used to ensure that the windrower maintained course through the field and only removed the desired crop for each treatment.

Figure 4-6. Drone photo showing division of treatments

The harvesting consisted of two treatments (Fig. 4-7) due to equipment to be tested. The two conditioning types used were steel roll conditioning and flail conditioning where the goal was to determine which conditioning type allows for most efficient harvesting of miscanthus as well as its effect on bale density. The flail conditioner used was missing the proper sized drive sheave so one measuring 10 inches in diameter was used in place of the standard 7-inch sheave. This caused the flails to operate 40% slower than they typically would. The operations were performed at the maximum travel speed possible without causing excessive clogging or machine failure.

The first pass was done with the windrower which mowed, conditioned, and formed the crop into windrows. Once windrowed the second pass was for the baler to pick up the crop and make large square bales in the swaths. The time between mowing and baling is unimportant because moisture content and losses are not expected to change with time.

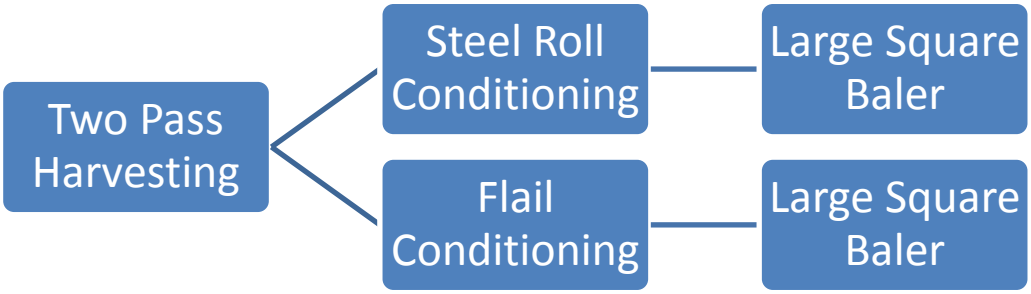

Figure 4-7. Treatment Type Breakdown

Data was collected during and after the harvesting operations. In order to record data for the time study, video cameras were positioned in the cockpit of each piece of equipment so that they could record when the machine was working, stopping, or turning. An additional camera recorded from the edge of the field to allow another perspective on the harvesting. After field harvesting, these videos were watched and several stop watches were used to measure the cycle time for the baler and the windrower. One cycle is considered to be the time it takes to bale or cut one windrow including the turning time at the end of a windrow. The turning time is defined as time from the end of one windrow to the start point of the next windrow. The amount of time that useful work was being done as well as time being wasted was measured for each cycle. The turning time was also measured for each cycle and was considered to be the time from when the row ended to the time the vehicle began harvesting the next row. While recording times the

number of times that the vehicle was forced to stop either due to crop jamming or machine malfunction was recorded. The amount of time it took to produce a bale was also recorded using a video camera located at the field edge.

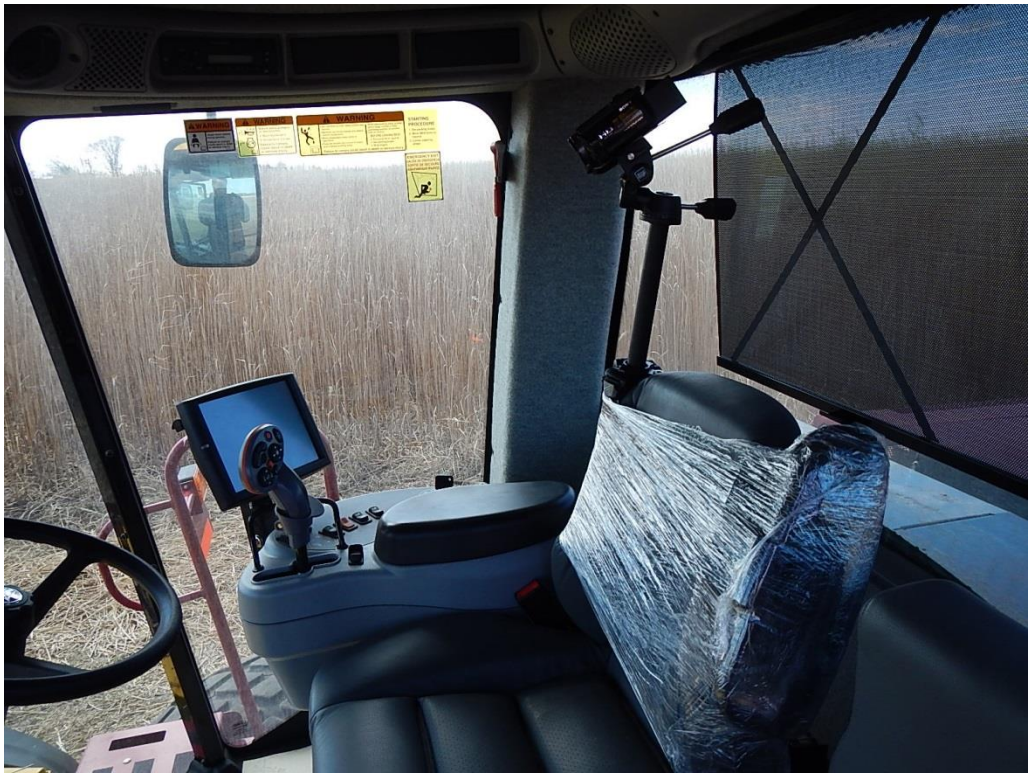

Figure 4-8. Windrower camera setup

At the end of each day or treatment the fuel for each vehicle was topped off and measured as well as the amount of crop area that had been processed. The top up method was used to keep track of the mass of fuel being poured which was later converted to a volume measurement. The fuel from the mobile fuel tank was pumped into a smaller five gallon fuel container. This container was then weighed using the Acculab scale which had a 10 kilogram capacity with a resolution of one gram. After dumping the fuel into the vehicle the container was weighed again to determine the amount of fuel added. This process was repeated until vehicle had been refilled to the same fuel position as before the operation.

Once the crop was cut, a handheld GPS device was used to measure the size of the swaths taken by the windrower in order to verify the area used for each treatment type. The GPS device was also used to record the drop locations of the bales in the field. The length of each bale was measured with a tape measure so that the density could be found with the bale height, width, and weight. Due to the bale scale on the baler being out of function, a random selection of bales from throughout the field was weighed using a portable bale scale. The portable bale scale was made by placing the three drive on tire scales under a wooden pallet. The bales could then be easily placed on top and the weight on all three scales read to get a final bale weight. Each scale had a capacity of 15000 kilograms with a resolution of five kilograms which was deemed sufficient for their function. By sampling weights over the field an average bale weight in the field was calculated. Several bales were sampled with a moisture probe and core sampler for another research project however those results aren't considered in this report.

Figure 4-9. Portable bale scale setup

An additional measure of how effective each conditioning type was is a distribution of the lengths of the crop in the windrow. A bundle from each windrow type was gathered and brought back to Penn State. The crop was sorted into bins of size 0.3 m (1ft) starting with pieces between 0 and 0.3 m length and increasing up to pieces between 2.4 and 2.7 m in length. Once sorted the number of pieces as well as the weight for each bin was tallied. A distribution of the sizes of miscanthus coming out of each conditioning type was then created and compared to see the differences.

Finally data was copied from the CAN bus so that additional information about the harvesting could be accessed through the FarmWorks program. A copy of FarmWorks couldn't be procured so the CAN data was omitted from the analysis; however, data manually collected from the field should cover all information contained in the CAN bus data. Once collected, the data was taken back to Penn State to be statistically analyzed. Along with the data several thousand stalks of miscanthus were cut from random locations throughout the field. The samples were brought back to Penn State and placed in cold storage below freezing for later use in the lab test portion of the study.

4.5.2 Lab Test

The lab test was performed in the agriculture engineering building at The Pennsylvania State University during the summer of 2015. Fig. 4-10 shows the conditioning table used to process the crop and record the relevant data. The table was manufactured for use in additional Penn State research in previous years (Fasick 2015), and was modified to more appropriately meet the needs for the tests at hand. The table consists of two enclosed steel crimping rolls driven with a hydraulic motor and a chain drive. A torque sensor and speed sensor are coupled between the output shaft of the motor and the chain drive to keep track of the table's mechanical

performance. The torque and speed are recorded by the data logger every millisecond. The rolls have different diameters and numbers of paddles requiring separate roll speeds to avoid interference. This is accomplished using varying sprockets run off of the same drive shaft. The table also has adjustable guides on the input side to maintain the crop bundle shape while being fed through the rolls. The specs for the conditioning table can be found below in Table 4-1. One objective of this test was to observe the effect of roll spacing on how well the crop was conditioned. For this reason the rolls were mounted in slots to allow for adjustable spacing. Unlike conventional conditioners that use spring tension to hold the rolls together, once set the spacing of these rolls was fixed for the set of experiments.

Figure 4-10. Hydraulic power pack, conditioning table, and data logger used in lab tests

Table 4-1. Conditioning table specifications

Number of Top Roll Fins	17 fins
Depth of Top Roll Fins	0.025 m
Number of Bottom Roll Fins	8 fins
Depth of Bottom Roll Fins	0.025 m
Top Roll Diameter	0.17 m
Bottom Roll Diameter	0.10 m
Roll Shaft Size	0.03 m
Roll Length	1.04 m
Max Hydraulic Motor Displacement	26.40 cm^3/rev
Max Hydraulic Motor Speed	2500 rpm
Max Hydraulic Motor Flowrate	63.33 L/min
Max Hydraulic Motor Power	17.47 hhp

The three variables being tested were roll spacing, roll speed, and the size of the crop bundle being fed. The response variables being monitored were torque on the drive shaft and how well the crop was conditioned. The effectiveness of conditioning was quantified in several ways. First, the weight of the crop that was conditioned out of the total crop fed into the rolls was measured and a percent weight conditioned was calculated. Second the number of internodes conditioned out of the total internodes fed into the rolls was measured to calculate a percentage of internodes conditioned. Finally the number of pieces greater than 3” in length coming out of the machine was compared to the number of stalks being fed in to calculate a piece ratio. Piece ratio is defined by:

$$Piece\ Ratio = \frac{Pieces\ Out}{Stalks\ In}$$

In order to simulate conditions closest to a February/March harvest the crop was pulled from cold storage directly before being conditioned. Cold storage was kept at 4°C which was

close to actual field conditions and helped to reduce moisture loss from the crop while it was being stored between experiments. It was also important that the crop have similar moisture content to crop found in the field. For long-term storage the crop was kept in a freezer at <-20°C to minimize crop moisture loss and quality change. The moisture content of the crop was monitored throughout the experiments as well by drying a representative sample each day and weighing the moisture in the crop.

The max bundle size that the conditioning rolls would be able to process without jamming was unknown before the experiment. A theoretical maximum for the rolls was found to be a 25 stalk bundle when the rolls were set to max speed and max spacing. Based on this the bundle size was increased at five stalk intervals starting at one stalk for each treatment until the crop could no longer be fed through at each spacing and speed. Table 4-2 summarizes all factor levels used in the treatments for the lab test and Fig. 4-11 shows the treatment combinations. The speed of the rolls was controlled with a flow control valve before the hydraulic motor. The flow was metered to the desired drive shaft speed of 250 rpm and 500 rpm which was also the speed of the top roll. At these speeds the position of the flow control valve was marked for ease and repeatability.

Table 4-2. Lab test factor levels

Roll Speed	250 rpm	500 rpm	-	-	-
Roll Spacing	0 cm	0.3175 cm	0.635 cm	0.9525 cm	1.27 cm
Bundle Size	1 stalk	5 stalk	10 stalk	15 stalk	20 stalk

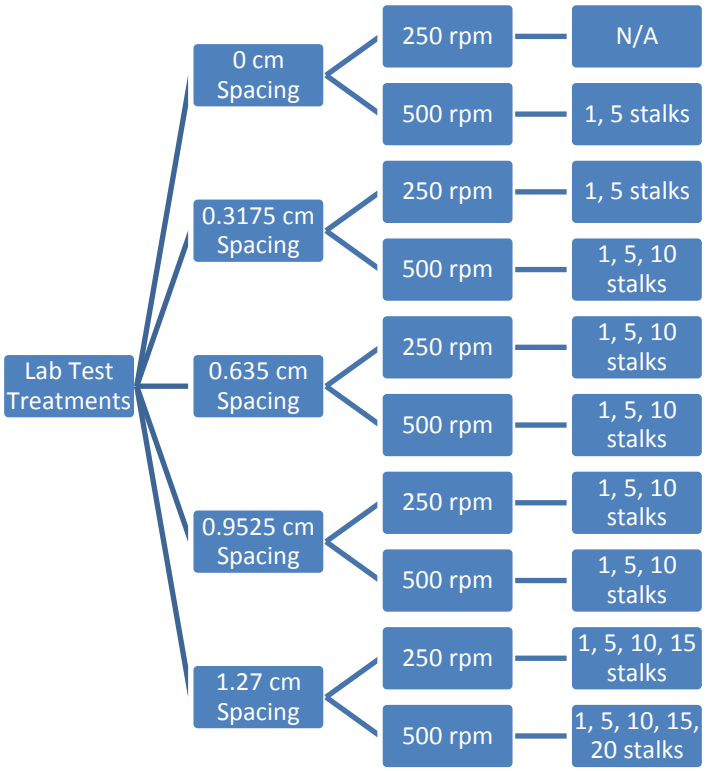

Figure 4-11. Treatment breakdown flowchart

To minimize error caused from changing speeds and spacing unnecessarily, all tests for a single spacing were performed in one sitting. Once the spacing was set at the desired level the first speed was selected. The crop was then set out in bundles matching the number of stalks required for each treatment. Each bundle had its circumference measured, stalks weighed, and internodes counted before being fed into the machine. Once ready, the rolls and the data logger were turned on and the bundle was conditioned. The pieces of crop coming out of the machine were then sorted, counted, weighed, and cleaned up so the next bundle could be run. Figs. 4-12 and 4-13 show samples of the crop after it has been conditioned. Each bundle size required three replications and the bundles were run at the same speed and spacing until the crop was jamming in the rolls. At this point the next speed would be selected and the process would be repeated. By performing all treatments for a set spacing at once, the error from constantly adjusting the

spacing of the rolls was minimized. The crop used for testing was immediately placed back in cold storage when testing was finished each day to minimize the loss in moisture from the hot summer weather.

Figure 4-12. Conditioned miscanthus

Figure 4-13. Close-up view of conditioned miscanthus from lab testing

4.6 Data Analysis

The hypotheses will be tested for statistical significance using Minitab software with ANOVA and 2 sample t-tests. The analyses will be performed on the vehicle speed, bale length, bale weight, bale density, fuel consumption, and bale drop rate for the field study as well as the effect of roll spacing, bundle size, and roll speed on conditioning quality and torque for the lab test. A 90% confidence level will be used in lieu of a 95% confidence level due to the variability in biological materials. The factors that are statistically significant will be further examined to explain their effect on the responses. Important parameters from the field study will be reported and used to increase the accuracy and thoroughness of the BioFeed model.

Chapter 5 – Results and Discussion

This section contains the results of both the field and the laboratory testing. The statistical analysis of the hypotheses from section 3.3 will be stated, followed by a brief discussion about the implications of these results, what they mean for industry, and how they affect future research. The statistical analysis is explored before the actual results to limit discussion on results that are not statistically significant.

5.1 Field Test

5.1.1 Effectiveness of Field Conditioning

5.1.1.1 Statistical Analysis

During the field harvest the length of 487 bales and the weight of 116 bales were measured. From this information as well as the bale cross-sectional area the density was calculated for each bale. With this data it is possible to compare the effect that the two conditioning methods, flail and roll, had on the physical properties of the bales. By using the 2 sample t-test in Minitab to compare the roll and flail conditioning, it was determined with 90% confidence whether or not the conditioning type had an effect on the physical properties. Based on the statistical analysis, bales made with the flail-conditioned crop were 1.5% shorter in length, 4% heavier in weight, and had a density 5% greater on average than those baled with the roll-conditioned crop. These trends are statistically backed by the p values listed in Table 5-1 where

any p value less than $\alpha = 0.1$ is considered to be significant causing a rejection of the null hypothesis that the means of the bale properties for the two conditioning methods are equal.

Table 5-1. Statistical Analysis of Bale Properties

Response	2 Sample t-Test P Value
Bale Length	0.068
Bale Weight	0.047
Bale Density	0.017

5.1.1.2 Results

Table 5-2 summarizes the results of the data collection on bale information. Prior to the field testing, it was expected that bales would have an average weight around 408 kilograms which is slightly less than the weights obtained in this study (Shastri et al. 2010). It is thought that the density throughout the bale was not uniform with the center having a far lower density than the outside. The roll-conditioned bales are longer; however, the baler was set to eject them at the same length. When the bales are ejected it is possible that the flail and roll-conditioned bales had the same length but the roll-conditioned bales relaxed more once free of the baler chamber walls. Fasick (2015) performed a bale compression study where it was proven that conditioned crop relaxes less than unconditioned crop. By this logic the roll-conditioned crop was less conditioned than the flail which resulted in the greater bale relaxation. The density of the flail-conditioned bales is greater than that of the roll-conditioned bales which is consistent with them having on average shorter lengths and higher weights. It is important that the highest density possible is achieved when making bales because shipping biomass is restricted primarily by the volume the bales take up and not the weight (Hofstetter 2011). The higher the density achievable in the bales, the more biomass that can be shipped per load which reduces the overall

transportation costs for biorefineries. Finally, it is important to note that all of the parameters have standard deviations that are larger than the differences in the mean values for roll and flail conditioning. This indicates that even though the parameters are statistically different, the two conditioning types still yield very similar results.

Table 5-2. Summary of Bale Properties

Response	# Sampled	Mean	Standard Deviation	P value
Roll Bale Length (m)	345	2.54	0.06	0.068
Flail Bale Length (m)	142	2.49	0.07	
Roll Bale Weight (kg)	63	452.50	32.25	0.047
Flail Bale Weight (kg)	53	470.79	31.53	
Roll Bale Density (kg/m^3)	63	160.90	11.66	0.017
Flail Bale Density (kg/m^3)	53	168.09	12.04	

Figs. 5-1, 5-2, and 5-3 show the average value of the data for the length, weight, and density measurements. On average the length of a flail-conditioned bale was 5 cm shorter than that of a roll-conditioned bale. Flail-conditioned bales on average also weighed 18.3 kg more than the roll-conditioned bales and had average bale densities of 8.2 kg/m^3 greater than the bales made from roll-conditioned crop. The baler was set to eject whenever bale length reached 2.44 m (8 feet). While some slight variation in this number is expected, the average lengths of the bales for both types of conditioning were five and 10 cm longer for flail and roll respectively. Fig. 5-4 shows a distribution of crop sorted by length from both the roll and flail-conditioned windrows after being cut. The flail-conditioned crop is broken up into smaller pieces than the roll-conditioned crop. Bales that are made from conditioned crop will relax a lesser distance after being ejected from the bale chamber than those that are unconditioned (Fasick 2015). The conclusion can be drawn that the longer stalks of miscanthus in the roll-conditioned crop are a

result of being less conditioned resulting in the greater relaxation distance and overall length after being ejected from the bale chamber.

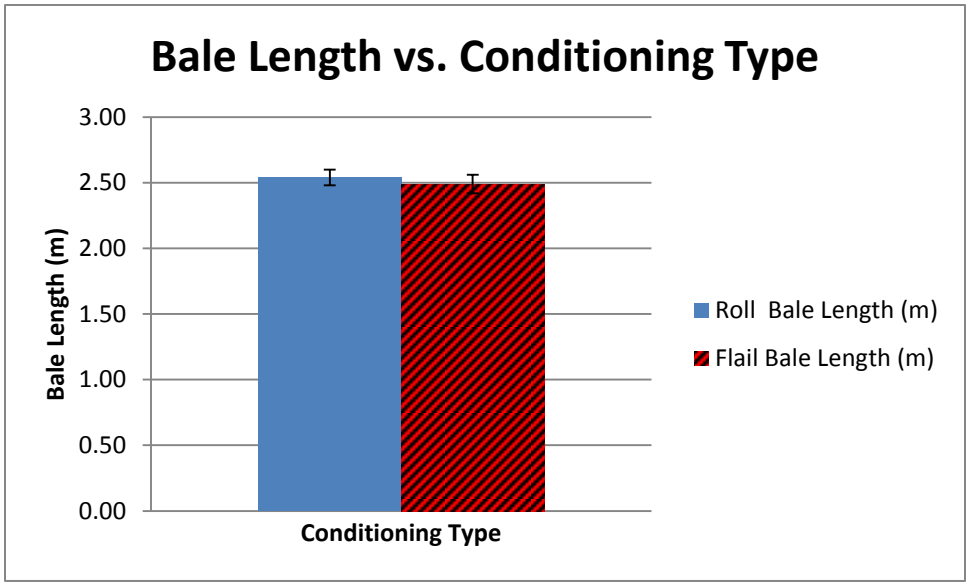

Figure 5-1. Effect of conditioning type on the length of large square bales

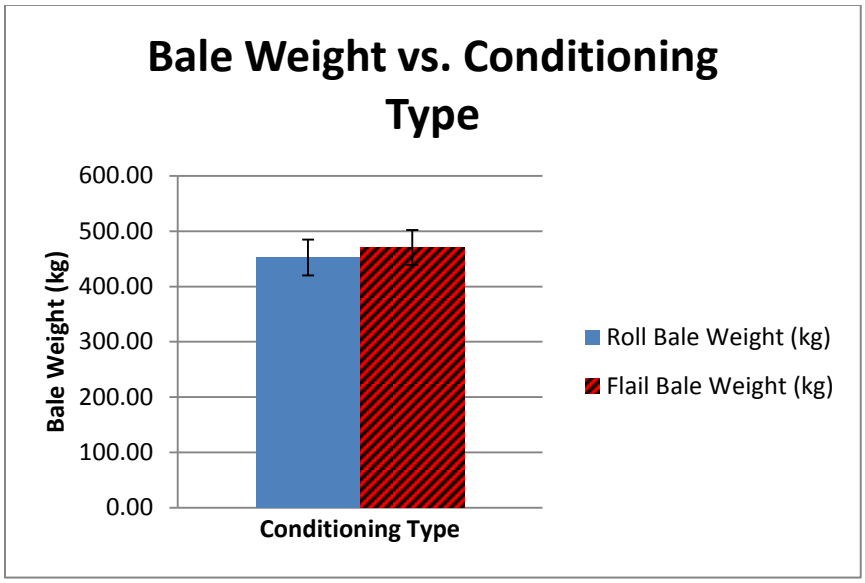

Figure 5-2. Effect of conditioning type on the weight of large square bales

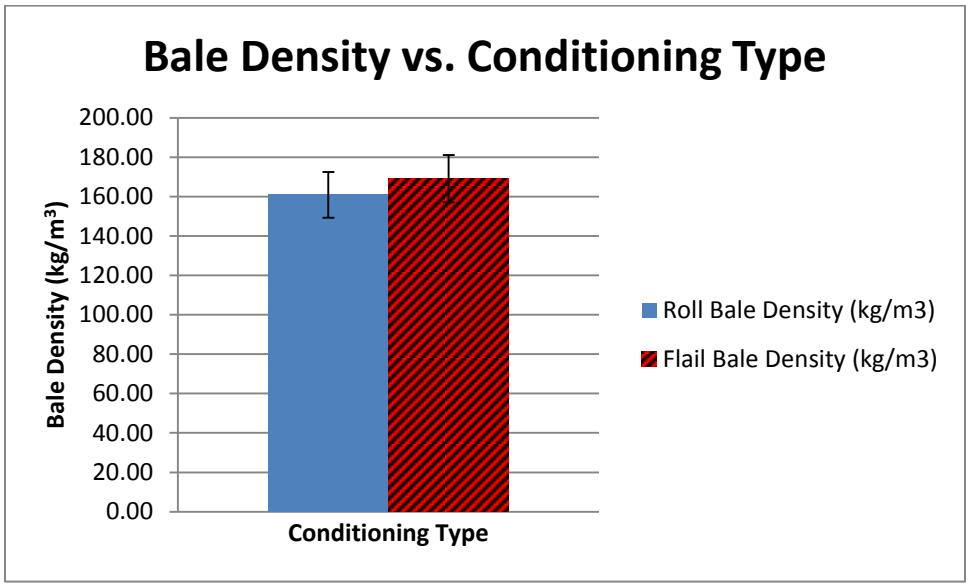

Figure 5-3. Effect of conditioning type on the density of large square bales

Figure 5-4. Left: Roll-Conditioned Crop, Right: Flail-Conditioned Crop

Table 5-3 and 5-4 detail the weight and number of crop pieces in each bin as well as the size range of each bin. The weight of the crop doesn't show the distribution percentages as well as the number of pieces does because a bin with smaller numbers of greater length pieces could weigh the same as a bin with many pieces of shorter length. The weight is still an important metric because field yield is typically given as a mass and not the number of stalks in the field. Using the percentages of weight one could predict how much of the yield will fall into a given size range.

Table 5-3. Distribution of conditioned crop by weight

Bin Min Size (m)	Bin Max Size (m)	Roll Weight (kg)	Roll % Weight	Flail Weight (kg)	Flail % Weight
0.00	0.30	0.47	3.41	0.63	7.95
0.30	0.61	0.30	2.17	0.45	5.68
0.61	0.91	1.16	8.41	1.41	17.80
0.91	1.22	1.94	14.06	2.57	32.45
1.22	1.52	2.74	19.86	1.96	24.75
1.52	1.83	3.09	22.39	0.87	10.98
1.83	2.13	2.52	18.26	0.03	0.38
2.13	2.44	1.42	10.29	0.00	0.00
2.44	2.74	0.16	1.16	0.00	0.00
Total	**-**	**13.8**	**100**	**7.92**	**100**

The distribution of pieces clearly shows that the flail conditioning method broke the crop up into smaller pieces than the roll conditioning method. Fig. 5-5 shows both distribution in one chart and makes the differences between them clear. Both conditioning types have a normal distribution of piece lengths; however, the flail conditioning is clustered toward smaller pieces. As stated earlier breaking the crop into smaller pieces will make it easier to handle and result in less bale relaxation. From the six preliminary samples taken from the field, the average length of a piece of miscanthus after being cut was 2.06 m. The conditioning samples show that the flail conditioning broke up all of the pieces in the windrow smaller than the average crop height, whereas the roll conditioned windrow had approximately 17% of the pieces being greater than 2.06 m.

Table 5-4. Distribution of conditioned crop by # of pieces

Bin Min Size (m)	Bin Max Size (m)	Roll Pieces	Roll % Pieces	Flail Pieces	Flail % Pieces
0.00	0.30	-	0.00	-	0.00
0.30	0.61	79	8.16	135	15.90
0.61	0.91	150	15.50	224	26.38
0.91	1.22	198	20.45	282	33.22
1.22	1.52	201	20.76	156	18.37
1.52	1.83	175	18.08	51	6.01
1.83	2.13	111	11.47	1	0.12
2.13	2.44	50	5.17	0	0.00
2.44	2.74	4	0.41	0	0.00
Total	**-**	**968**	**100**	**849**	**100**

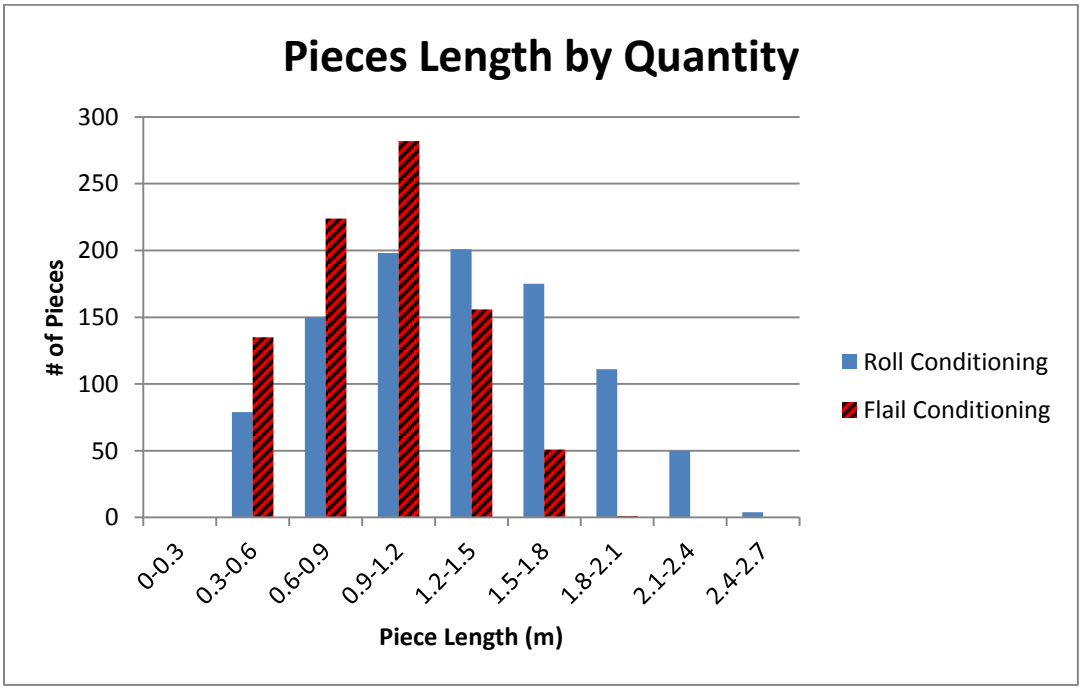

Figure 5-5. Distribution of pieces by size and conditioning type

It is also important to note that on the afternoon of March 19 there was slight rainfall at the Easton field site. To evaluate whether this rainfall influenced the weight data, a statistical comparison of means was first done between the weight of the wet bales and that of the dry bales. The analysis concluded that the weather was not a significant factor in the weight of the bales. Based on this result the statistical analysis comparing the effect of conditioning type on physical properties was carried out on the entire data set without discriminating between wet and dry bales.

Figure 5-6. Drone view of field nearing the end of harvest

5.1.2 Fuel Consumption

For logistics models, it is important to quantify fuel consumption for different operations. This helps with planning the amount of fuel needed at the field site as well as how much the total harvest is going to cost. Without a flow meter it is difficult to accurately measure the amount of fuel used in each vehicle. To solve this problem the top off method was used each day to get a

daily amount of fuel used in kilograms. Diesel fuel has a specific gravity ranging from 0.82 to 0.87 (Valero 2014). A value of 0.84 kilograms per liter was selected from the range to convert the mass of the fuel to volume.

The daily land area harvested by each vehicle was recorded with a handheld GPS so that the fuel usage per hectare was known for each treatment. By using the average bale weight an approximation of fuel consumption per Mg DM can also be found. Table 5-5 shows the values of fuel consumption rate while Fig. 5-7 displays it graphically.

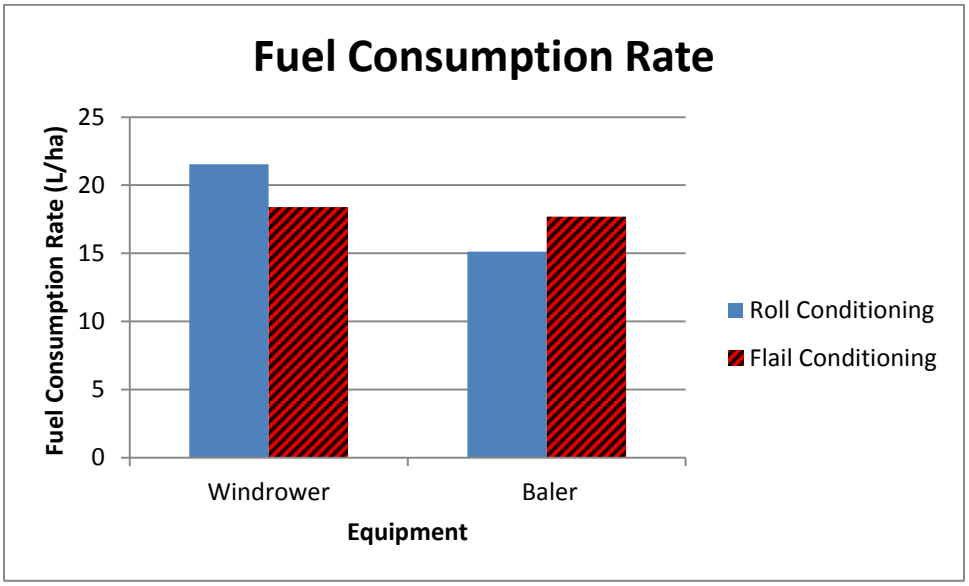

Figure 5-7. Fuel Consumption Rate

Table 5-5. Fuel Consumption Information

Equipment	Area Sampled (ha)	Fuel Consumption Rate (L/ha)	Fuel Consumption Rate (L/Mg DM)
Windrower Roll	11.91	21.53	1.71
Windrower Flail	10.37	18.4	1.46
Baler Roll	11.91	15.11	1.20
Baler Flail	5.31	17.67	1.40

During the field harvest the fuel consumed by both vehicles was measured four times and the area that had been processed on that fuel was recorded. The data was measured over 22 hectares for the windrower and 17 hectares for the baler. Due to this sampling technique, ANOVA and 2 sample t tests can't be performed with Minitab, however inferences can still be made from the data. First it can be seen that for harvesting miscanthus with these specific machines, operating the 168.5 kW (226 hp) windrower required more fuel for a given amount of land than the 233.4 kW (313 hp) tractor pulling the large square baler. Second it's important to note that each machine behaved differently for the two conditioning types. While the windrower used less fuel when operating with the flail conditioning module the baler was more fuel efficient per Mg dry matter when picking up the roll-conditioned crop. Due to the small number of data points it can't be said with certainty whether these trends would hold true across different machines or different operating conditions. With more research being done in this area there will eventually be enough data to statistically determine which conditioning method requires the most fuel.

5.1.3 Time and Motion Study

A time study is common practice in many areas of study to determine system cycle time, the efficiency of an operation, and how long it takes for each machine to accomplish various tasks. This data is important in logistics modeling of biomass harvesting because knowing the speed a machine is able to travel through a field can help predict operational costs as well as the timetable for the harvest. Traditionally this is done by observing a task with a stopwatch and a clipboard to record the time for the events along with a rating of how well the task was performed. To perform a time study of field operations it is necessary to see the vehicle start a task and finish a task that often occurs in locations separated by great distance. It is also

necessary to record this data in quick succession on multiple vehicles simultaneously so the harvest operation isn't interrupted. Performing this study at the time of harvest was infeasible due to limited manpower and mobility. The solution selected to facilitate study completion was to capture the harvest on video and perform the timing on a later date. Video cameras were mounted in the cab of both the windrower and baler in a position capable of capturing whether the machine was operating, turning, or stopping in the field. This allowed for accurate time keeping of both machines without the need for overwhelming man power or equipment. A third video camera was used by an operator outside of the cabs to record the equipment operation from an additional vantage as well as to capture when bales were dropped.

5.1.3.1 Statistical Analysis

A 2 sample t-test in Minitab were used with 90% confidence intervals to determine whether or not there was a difference in bale drop rate and travel speed during the operation. All assumptions were met to perform these tests accurately including the normality assumption determined by the distribution of the residuals. The resulting p values from the statistical analyses are shown in Table 5-6. As before, any time the p value is less than $\alpha = 0.1$ then the null hypothesis of equal means for both conditioning methods is rejected.

Table 5-6. Statistical Analysis of Time Study

Response	2 Sample t Test P Value
Bale Drop Rate	0.117
Baler Average Travel Speed	0.124
Windrower Average Travel Speed	< 0.001

Of the responses tested the only result that was significant was the average travel speed of the windrower. The other responses had p values just over 0.1 so their trends will still be commented on; however, it should be kept in mind that they aren't statistically significant.

5.1.3.2 Results

Fig. 5-8 shows the trend of the data related to the bale drop rate and Table 5-7 provides a summary for all the responses in this section. As can be seen in Table 5-7, on average it takes 54.9 seconds to make a roll-conditioned bale and 7.3 seconds or 13% longer to create a bale from flail-conditioned crop. This difference in drop rate is thought to be caused by the baler picking up material over a greater area for a flail-conditioned bale than for a roll-conditioned bale. The higher density of flail-conditioned bales suggests that more material is able to be packed into a single bale and in order to pick up more material a greater amount of time is necessary. It is also possible that the slower travel speed of the baler in flail-conditioned crop is the cause for the slower drop rate.

Table 5-7. Summary of Equipment Movement

Response	# sampled	Mean	Standard Deviation	P Value
Bale Drop Rate Roll	26 bales	54.91 s/bale	12.98 s/bale	0.117
Bale Drop Rate Flail	93 bales	62.20 s/bale	10.93 s/bale	
Baler Average Travel Speed Roll	28 rows	1.23 m/s	0.23 m/s	0.124
Baler Average Travel Speed Flail	21 rows	1.11 m/s	0.29 m/s	
Windrower Average Travel Speed Roll	45 rows	1.60 m/s	0.21 m/s	<0.001
Windrower Average Travel Speed Flail	42 rows	1.86 m/s	0.27 m/s	

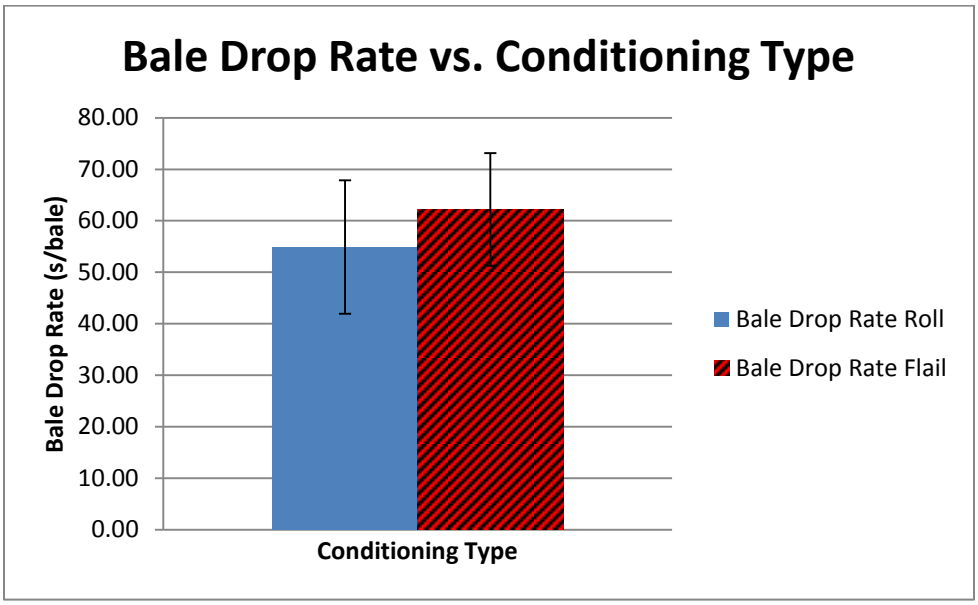

Figure 5-8. Effect of conditioning type on the rate bales are dropped

Statistically there is no difference between flail and roll conditioning for baler average travel speed. Fig. 5-9 depicts the trend of the data used in the statistical analysis. Visually from the data the baler appears to operate better with the roll-conditioned crop which would agree with the data on baler fuel consumption. For both cases of roll conditioning and flail conditioning the baler operated on average around 1.15 m s^{-1} or 4 km hr^{-1}. Shastri et al. (2010) found baler speed when harvesting miscanthus in another region of Illinois to be 9.6 km hr^{-1}, a little over twice the speed found in this study. It is possible that the crop at the Easton field site had a greater crop density from the two years of growth than the field used to calculate travel speed in the BioFeed model.

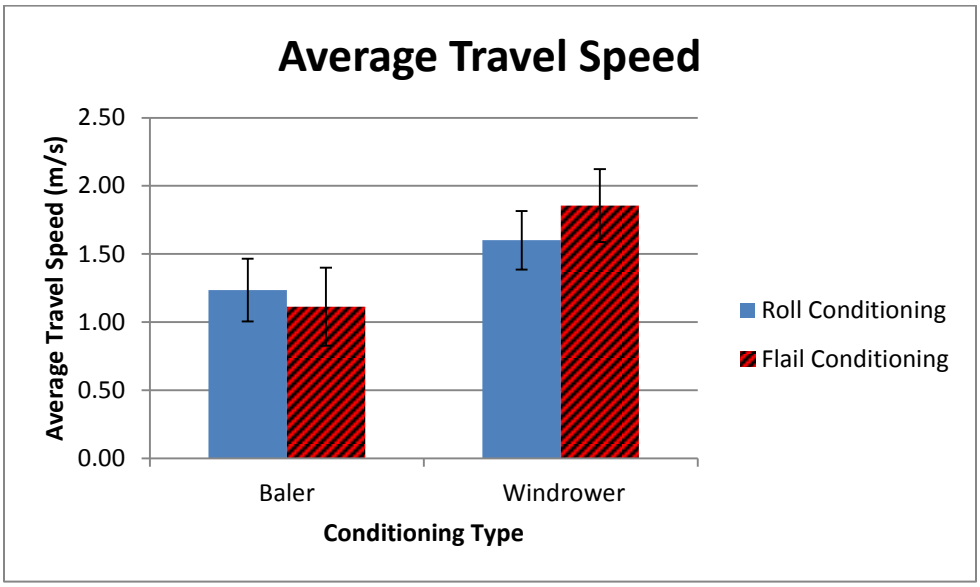

Figure 5-9. Effect of conditioning type on vehicle average travel speed

The null hypothesis for the effect of conditioning type on windrower average speed is rejected. The data used is portrayed graphically in Fig. 5-9 as well as numerically in Table 5-7. While cutting with the flail conditioning module the windrower was on average able to move 0.26 m s^{-1} or 16% quicker than the 1.6 m s^{-1} found while using the roll conditioning module. The faster travel speed is likely the cause of the lower fuel consumption rate for flail conditioning that was seen earlier. Fuel consumption rate is primarily controlled by how long the vehicle is operating, so faster travel speeds allow for less operating time and in turn lower fuel consumption (Kemmerer 2011).

Cycle time is important when planning a harvest to determine how many operators will be needed for a given number of machines. A cycle time for a harvesting operation is normally determined by taking the capacities for all the individual machines involved and calculating how much time is required for the equipment to process a set amount of land completely. For instance if there is a windrower, a baler, and a bale handler, the amount of time to cut, bale, and move the bales from 1 hectare for example would be the cycle time for that specific operation. Applying

the information from the previous example is helpful because the number of operators necessary to finish handling the bales just after the moment the baler finishes baling can minimize cost and time. If the windrower is operating sufficiently fast it is possible to only use two operators by having the windrower operator begin handling bales once finished cutting.

In order to gather the information necessary to perform such a study several times were defined. A unit of working time was considered to be the time required to either mow or bale the entire crop in one 4.57 meter wide (header cutting width) by 370 meter long (length of the field) path. Turn time was defined as the time from the end of travel time to the start of travel time in the next section. Stoppage time in either case was neglected so that the data would reflect an ideal model with no machine clogging or breakdown. The amount of land required for the headlands was found to be 1.8 hectares or 7.7% of the total available field area. The time it took to harvest the headlands for this field is unknown for this field because that land was used as a testing ground for setting up the machines. While the time to harvest this land should be similar to the times seen for the rest of the harvesting it is expected to take slightly longer due to the lack of adequate turning space in these areas.

As shown in Table 5-8, the windrower was able to complete a typical working unit in 235 and 203 seconds on average for roll and flail conditioning respectively with around a 30 second standard deviation. The baler was able to perform these same rows in 311 and 350 seconds on average for roll and flail conditioning respectively with around 70 seconds of standard deviation. Conditioning type has no effect on the turning time for either vehicle so it was neglected and an overall average turning time was found. For the windrower and the baler, respectively, the average turning times were 20 and 28.5 seconds with standard deviations of nine and eight seconds. The percentage of time spent turning for each pass through the field was found to be around 8.5% for both the baler and the windrower with exact values listed in Table 5-6.

Using these times, the number of rows in the field, and assuming that the operators work the same amount of time each day, a prediction for the amount of time an operator would have to perform the bale handling in a two operator three machine harvest can be found. Using the speeds listed in Table 5-7, a similar predictive analysis can be performed for any number of fields so long as the number of rows, operators, machines, and row length is known. The average yield over the entire field could also be used to get a processing time in terms of crop tonnage. While this information was gathered from only one field harvest, as more research is completed on this subject, more data will be available to form more accurate parameters for predicting field operations.

Table 5-8. Summary of Time Study Information

Response	Rows Sampled	Mean Time (s)	Standard Deviation Time (s)	Mean Time/Area (s/m^2)
Windrower Roll	45	234.88	33.47	0.302
Windrower Flail	42	202.73	28.04	0.261
Baler Roll	28	311.34	68.04	0.401
Baler Flail	21	349.84	72.69	0.450
Windrower Turning	87	20.12	8.94	N/A
Baler Turning	49	28.52	7.82	N/A
Windrower % Time Turning	87	8.56%	3.3%	N/A
Baler % Time Turning	49	8.27%	2.65%	N/A

5.2 Lab Test

This section will discuss and highlight the results of the lab test performed on the miscanthus brought back from Illinois. The three variables being tested for their effect on crop conditioning and peak torque are roll spacing, roll speed, and amount of material fed into the table. Effectiveness of crop conditioning was parametrized for comparison by calculating a piece ratio, defined in the methodology as the ratio for number of pieces coming out of the conditioner compared to the number being fed in. By quantifying conditioning in this way, the subjective human judgment was removed from evaluating conditioning quality and a number that was easily comparable was found. It is also known from Fasick's (2015) research that crop which is broken up more will relax less and allow for smaller bales to be made. These qualities are beneficial so a larger piece ratio will be considered more conditioned and better quality crop. The peak torque was measured for the time when the crop was being fed through the machine. In order to find the change in torque caused by the crop being fed through, an adjusted peak torque was found by subtracting the average torque reading while no crop was being fed through for each test. In each section the statistical analysis will be considered first to determine what parameters warrant further discussion.

While running the tests it was noted that the circumference of the bundles seemed to be the predominant cause of the rolls jamming as opposed to the number of stalks being fed through. To find out if this was the case a sequential SS test was performed in Minitab for circumference, number of stalks, and peak torque. The results were that the circumference of the bundle accounted for more of the variation in peak torque than the number of stalks by an order of magnitude. Instead of using the number of stalks as the predictor for the rest of the tests the circumference was used to represent the size of the bundle.

5.2.1 Statistical Analysis

The most appropriate test to measure the effect the three variables had on conditioning and torque is an ANOVA General Linear Model in Minitab. ANOVA allows for the test of the variables as well as their interaction effects on the response. Initially the interaction of all variables with each other was considered; however, the only one that was kept in the model was the spacing and speed interaction because none of the others could be estimated by Minitab. All of the assumptions necessary to perform the ANOVA test were met and confirmed by analyzing the residual plots. The p values from the analysis are listed below in Table 5-9. As before, a p value less than 0.1 results in a rejection of the null hypothesis that the respective variable does not affect the response. The exception to this is for the interaction effect where a p value less than 0.1 results in a rejection of the null hypothesis that the mean for the level of one factor does not depend on the value of the other factor level. If this interaction effect is significant then the interaction of the two variables must be considered when analyzing the main effects trends of each factor individually.

Table 5-9. Statistical Analysis for Lab Test

Variable	ANOVA P Value for Peak Torque	ANOVA P Value for Piece Ratio
Spacing	< 0.001	< 0.001
Speed	< 0.001	0.574
Circumference	< 0.001	0.32
Spacing*Speed	0.379	0.082
R^2 Value	96.07	81.11

The p values for the analysis indicate that roll spacing, roll speed, and circumference of the crop bundle are all statistically significant in predicting the adjusted peak torque. There is also no interaction effect between spacing and speed that is statistically significant so the trends

of these factors can be considered by themselves. For how well the crop was conditioned the roll spacing was the only variable to have a significant effect on the piece ratio. There is an interaction effect present between the speed and the spacing for piece ratio. In order to conclude the effect of spacing the interaction of the two terms needs to be checked as shown in Fig. 5-10. As can be seen the regardless of which speed is used the piece ratio follows the same trend with respect to roll spacing. The reason that the interaction was marked significant was the piece ratio for 0.3175 cm spacing where the piece ratio for the 500 revolutions per minute sample did not follow the expected trend. Based on this evidence and the trend present in spacing from 0.635 to 1.27 centimeters the effect of spacing on piece ratio will be considered on its own.

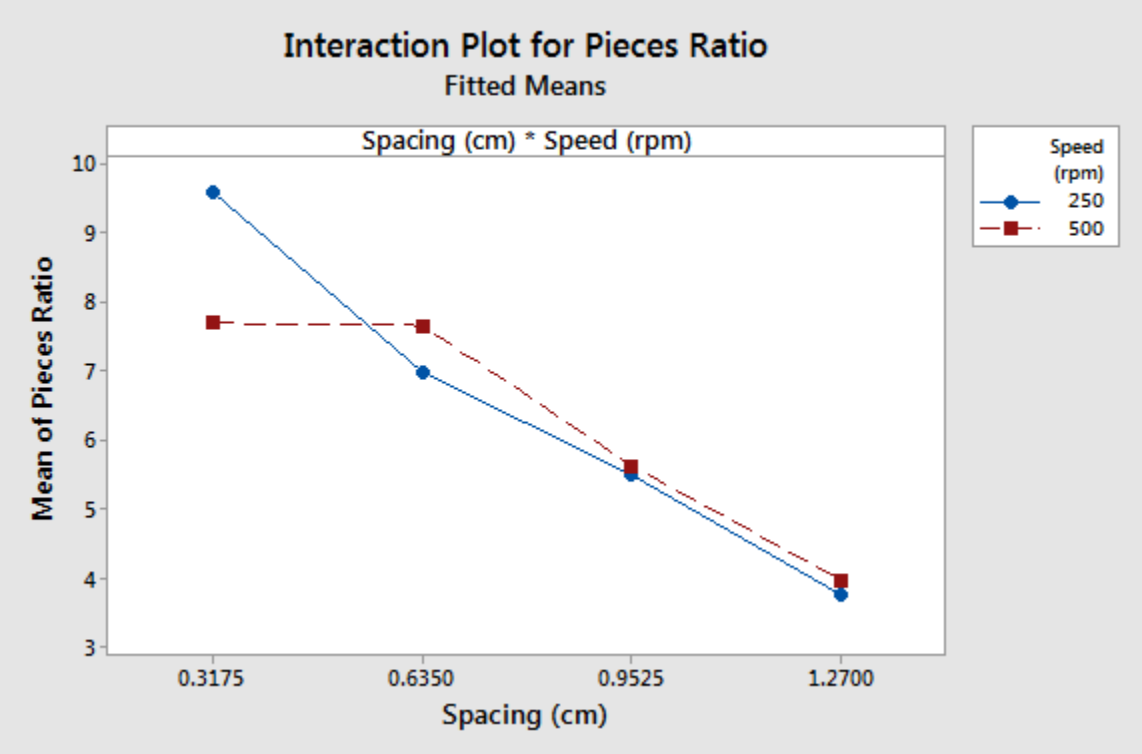

Figure 5-10. Interaction effect between spacing and speed for piece ratio

5.2.2 Results

5.2.2.1 Conditioning Effectiveness

Fig. 5-11 shows the effect of increasing the roll spacing on how well the crop was conditioned. As the rollers are pulled apart and the spacing becomes bigger the crop becomes less conditioned. When the rollers are close together the fins will interlock more forcing the miscanthus to be bent at sharper angles in order to make it through the rollers. This bending puts more stress on the crop forcing it to break into more pieces than a less stressed crop typical of being fed through greater roll spacing. For a roll spacing of 0.3175 centimeters the average piece ratio was 8.63. This means that on average every stalk of miscanthus that was fed into the conditioning table was broken up into 8 to 9 pieces. Breaking an approximately 10 foot long piece of crop that many times makes it much easier to handle and bale. The crop will no longer be as prone to jamming in the baler pickup and it will be easier to compact smaller pieces in the chamber with less bale relaxation and stress on the twine once it is ejected.

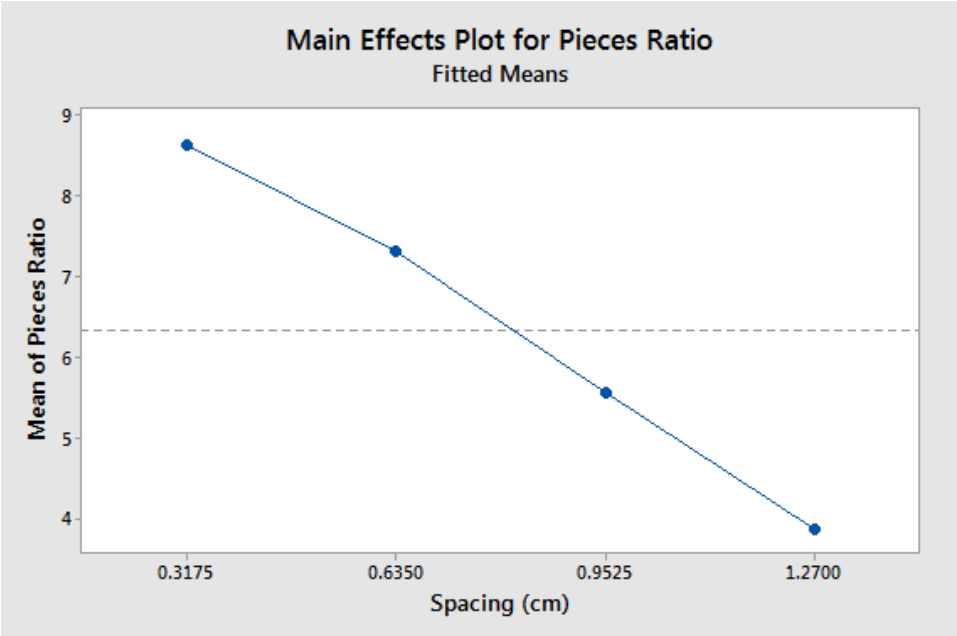

Figure 5-11. Effect of roll spacing on the piece ratio

5.2.2.2 Adjusted Peak Torque

The effective trends that roll spacing, roll speed, and bundle size have on the adjusted peak torque are clearly seen in Figs. 5-12, 5-13 and 5-14 respectively. Finding methods to reduce the torque required to condition crop will lead to smaller engine requirements and lower machine costs for consumers. As the roll spacing is made greater (farther apart), there is a decrease in the amount of torque applied on the drive shaft. It appears that there is an asymptote forming as the rolls are opened wider. Once the rolls get to a certain spacing it is expected that there will be no torque on the drive shaft except that required to run the rolls because the crop will freely feed through the gap in the rolls instead of being compressed and pulled through. It would be interesting to see if the roll spacing and torque ever converged to a linear relationship; however, no data was collected for smaller roll spacing because the interference in the machine fins made operation while crop was being fed through very unstable and dangerous.

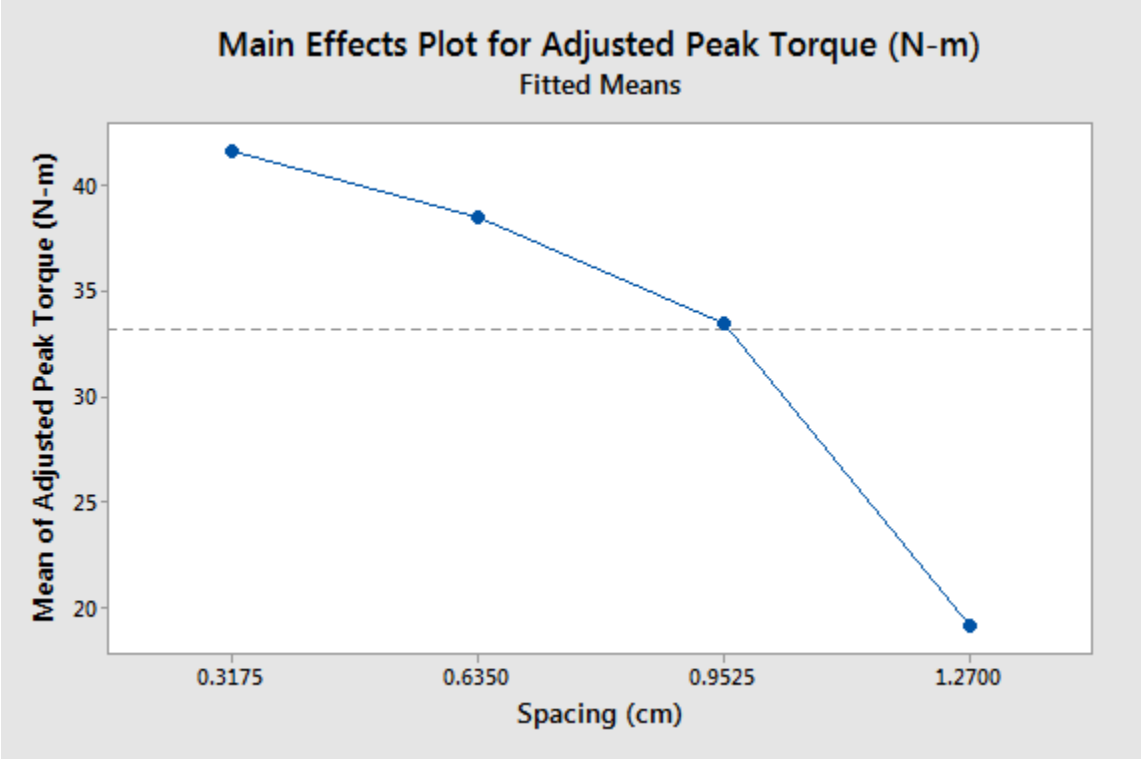

Figure 5-12. Effect of roll spacing on adjusted peak torque

As roll speed was increased from 250 to 500 revolutions per minute the peak torque on the drive shaft dropped 6 N-m or 20% to 30.1 N-m. This was expected considering torque and speed have an inverse relationship. While performing the tests it was noted that typically larger crop bundles could be fed through when the rolls were running at the higher speed. It could be that the additional energy stored in the higher angular momentum seen when the rolls are spinning faster is able to pull the crop through the rolls before the hydraulic motor is unable to provide sufficient torque.

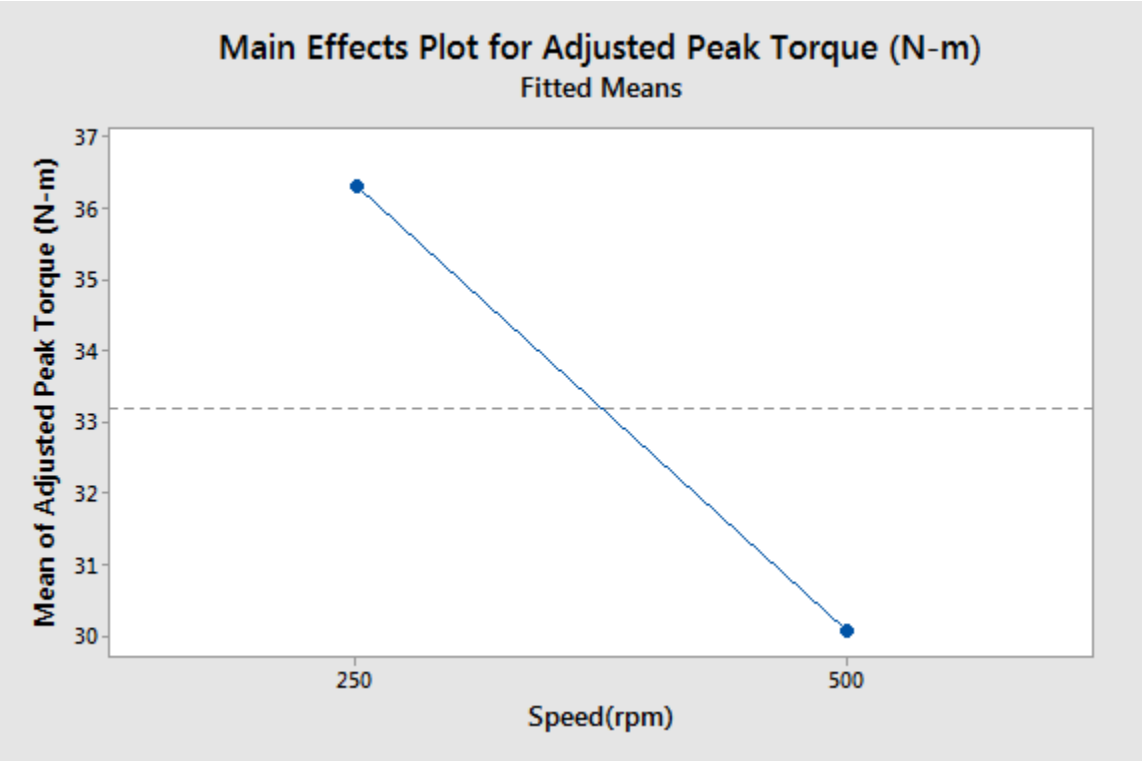

Figure 5-13. Effect of roll speed on adjusted peak torque

The effect of bundle size on the amount of torque required to condition the crop yielded a positive linear relationship. As the bundles increased in size the adjusted peak torque increased by around 7.5 N-m for every centimeter of circumference. Logically it's going to take an increasing amount of torque to condition crop as more is fed into the rolls. If more roll types were available it would be interesting to see how the torque trends compare over several kinds of rolls. It would also be useful to determine the capacities that each type of roll can handle without becoming bogged down and inoperable.

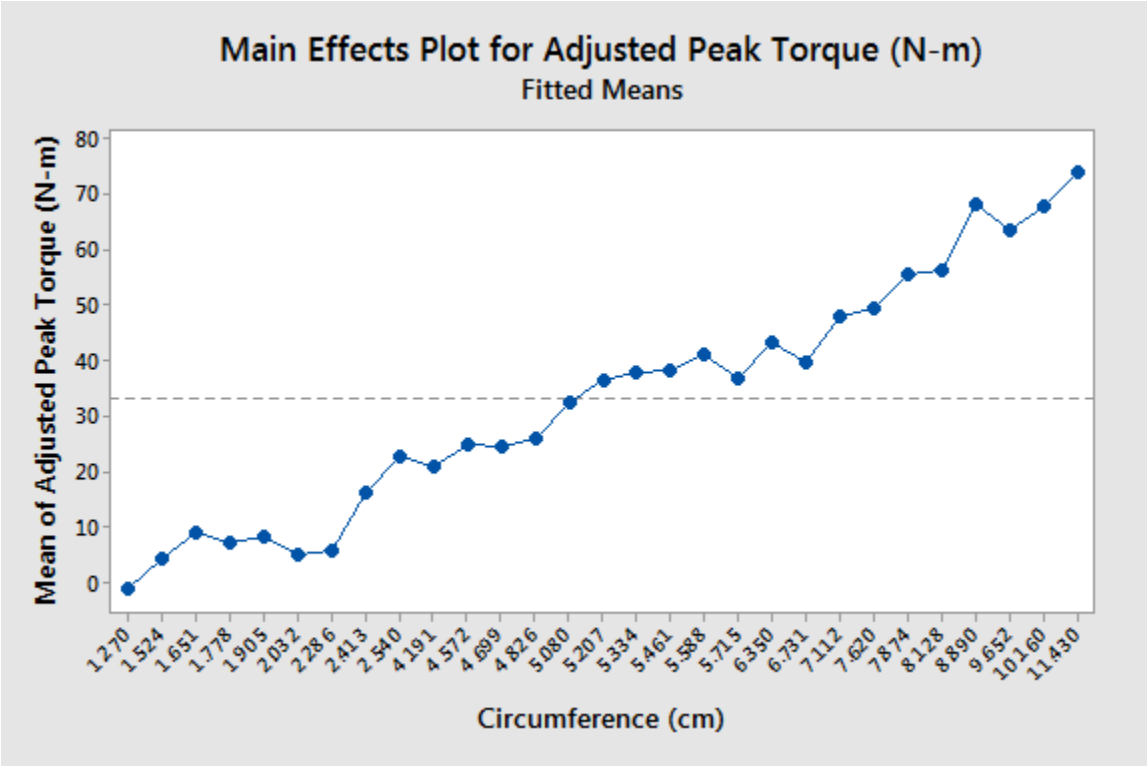

Figure 5-14. Effect of crop bundle circumference on adjusted peak torque

Chapter 6 – Conclusions and Recommendations

6.1 Conclusions

This miscanthus in the field test was cut and conditioned with both a steel roll conditioning module as well as a flail conditioning module. Once conditioned, the crop was baled into 3'x4'x8' large square bales. Statistically it is shown that the windrower performed much better when using the flail conditioning module then when the roll conditioning module was equipped. The number of times that crop jammed in the header forcing the windrower to stop decreased and the average travel speed through the field increased. This faster movement speed correlated with lower fuel consumption while using the flail conditioning module than the roll conditioning module. Consequently while the windrower performed better with the flail conditioning the baler performed worse. Statistically there was no difference in the number of times the baler was forced to stop or the average travel speed but the fuel that was consumed while harvesting the flail-conditioned crop was greater than when baling the roll-conditioned crop.

While baling the flail-conditioned crop it could be seen that the time it took to make a bale was greater than for roll conditioning. Flail-conditioned bales were also statistically contained more mass, were shorter, and had higher density than the roll-conditioned bales. This information suggests that the flail-conditioned bales took longer to produce because more mass needed to be picked up to make a bale. The shorter bale length is likely due to the crop being conditioned better and causing less relaxation after being ejected from the baler chamber. Crop from the Illinois harvest was brought back to The Pennsylvania State University to perform a series of lab tests regarding conditioning quality.

The cycle times for both conditioning types were found for cutting and baling miscanthus. This information is being used to further enhance the BioFeed model and allow for better cost predictions for biomass production. The information can also be used for field logistics planning to determine the number of operators and machines that will be required to finish a harvest within a given timeframe.

A conditioning table consisting of two steel crimping rolls was used to condition miscanthus and determine the effects of roll spacing, roll speed, and bundle size on the quality of conditioning. The tests found that statistically the spacing of the rolls was the only significant factor in how well the crop was conditioned. As the roll spacing was brought closer together the crop was broken into a greater number of pieces. This suggests that for roll type conditioning modules the spring force holding the rolls together should be increased as much as possible to a point where it isn't causing jamming or diminished travel speed. The more conditioned crop will create bales of higher density and reduce on storage and transportation costs. During the tests it was also found that tighter roll spacing, slower roll speeds, and larger bundle sizes caused the peak torque seen on the drive shaft for the rolls to increase. The torque being measured was the adjusted torque, where the average unloaded torque of the rolls was subtracted from the peak torque of the treatment.

6.2 Recommendations

More information on miscanthus harvesting still needs to be gathered to determine the best ways to harvest it and to create more thorough and accurate predictive models. A similar study should be performed with a round baler because the effect of conditioning types on round balers could be different than that of large square balers. One pass harvesters also exist where one tractor mows, conditions, and bales the crop simultaneously. It is likely that a one pass

harvesting system could decrease fuel and energy costs greatly over the current two pass systems. Bale handling is also an area that has not seen much research. The cost associated with moving all of the bales from the field to their storage/pickup location can vary greatly. It is unknown whether a bale wagon, a loader trailer combo, or simply using loaders will be the most effective at bale handling.

The lab test can be expanded to include different types of conditioning rolls as well as spring loaded spacing. The spring loaded spacing would make the lab setting more consistent with results seen by field machines and would allow for the testing of spring force on the effect of conditioning and capacity. Being able to test different roll configurations would help to determine of the current roll designs are truly the best available for conditioning miscanthus.

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