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A MISCANTHUS CONDITIONING AND BALE COMPRESSION ANALYSIS

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by

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ABSTRACT

Miscanthus can be difficult, expensive and inefficient to harvest and handle because of its stiff stalk, tall height and high yield. In order to decrease the cost and increase the efficiency of harvesting miscanthus, the process of harvesting miscanthus was examined. The goal of this research was to examine conditioning techniques for miscanthus, following mowing and prior to small square baling, in order to evaluate the effect of conditioning on bale density, and both the compressive forces and energy consumption required to compress baled miscanthus.

Three conditioning methods were tested with miscanthus. Prior to baling, smooth roll conditioning, crimp conditioning and no conditioning were tested to evaluate their effects and compare crop properties after conditioning. After the miscanthus conditioning tests, the crimp conditioning system and no conditioning were selected to be evaluated further and small square bales of miscanthus were made from both types of conditioning. After making small square bales of miscanthus, the bales were compressed with a small square bale lab scale bale compressor. During the compression process, the forces, energy consumption, peak power, and instantaneous densities were measured and calculated. Switchgrass bales were subjected to the same process for comparison purposes.

The crimp conditioning method, when used on miscanthus, produced a wave in the crop along its length and significantly changed the crop properties. When the crimp conditioned crop was compared to the unconditioned crop, during the bale compression process, the average compressive force, peak power, energy and specific energy consumption were all statistically less than the unconditioned crop at a 95 % confidence level. In addition, a longer holding time between the compression and retraction phases statistically decreases the length that miscanthus bales bounced back and relaxed; this related to less stress and strain on the bale twine or wire that held the compressed bale together. Conditioned miscanthus bales behaved statistically similarly to switchgrass while unconditioned bales were statistically more difficult to compress, requiring approximately 60% higher compressive forces and consuming 59% more specific energy than conditioned miscanthus.

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Chapter 1 - Introduction and Justification

Developing alternative fuel sources has become a substantial topic for researchers and institutions worldwide, as well as several governmental agencies in the U.S. Alternative fuel sources are those other than petroleum-based products which help decrease the dependency on crude oil. Some of the fastest growing and potential alternative energy sources are biofuels produced from biomass feedstocks. There are many different types of biomass crops such as warm season grasses, woody crops and agricultural residues; each has their own benefits and challenges. Miscanthus and switchgrass are examples of biomass crops that can be used as an alternative energy source. However, the processes and machinery used to convert the crop into a useable energy source is complicated and undeveloped. To alleviate this complexity, this research examined questions about machine methods and systems of harvesting miscanthus and switchgrass.

In the U.S., the Energy Independence and Security Act of 2007 mandated that 22 billion gallons of biofuels be used annually in the transportation industry by 2022; this subsequently was revised to 36 billion gallons per year (U.S. Department of Energy, 2013). This increased biofuel production could reduce the amount of petroleum-based fuels used in this country by up to 30 percent initially and also provide a boost to the agricultural, transportation and machinery industries (U.S. Department of Energy, 2013). This boost and fuel shift has long been a goal of politicians, researchers and those wishing to move towards more sustainable energy practices. The Department of Energy has also stated that, “employment in the U.S. biofuels industry has grown by 8.9% annually since 2004 and represents 20,680 direct jobs (and tens of thousands of indirect jobs) and is expected to continue growth” (U.S. Department of Energy, 2013). The U.S. Department of Energy states that continuing to develop and improve the bioenergy industry in the U.S. will lead to the availability of lower cost fuels and the increased success of several other industries as they move to more sustainable practices (U.S. Department of Energy, 2013).

Often times, energy crops can be grown on land that is not suitable for traditional food production crops, which is the case in both Pennsylvania and the northeastern United States. In 2009, the U.S. produced 11 billion gallons of renewable biofuels and 15.2 billion in 2012, which is shy of the Department of Energy's goal of 22 billion gallons (Ma, 2012). Because the current production is much less than the desired amount, precise strategic actions must be taken to establish a sound bio-based energy industry. This can be completed by having a low cost, stable supply of biomass feedstocks in large quantities (Buchanan et al., 2008).

There are many different biomass crops such as agricultural residues and woody crops that are being pursued for biofuel use; however, dedicated biomass energy crops can provide profits to not only the grower but also the biorefinery that converts the crop into fuel from land that may have been unused or unfarmed in the past. Miscanthus is becoming more popular as a biomass energy crop, because of its high yield, high fiber and low ash content; which is why miscanthus is a excellent opportunity for meeting the governmental goals for increased production (U.S. Department of Energy 2011). In addition, switchgrass has been a popular biomass energy crop under examination for the past several years.

The Department of Energy (2011) has stated, in updates to the biomass energy act, that "several commercial manufacturers are evaluating and developing equipment specifically designed to harvest and handle miscanthus, but at present, hay mowers, conditioners, and balers are used". To move further towards the governmental energy goal, several actions must be taken. Development of efficient harvesting methods and equipment are needed to remove miscanthus from fields and transport it to storage facilities in a low cost, timely fashion. Further research is needed to examine technical problems in the harvest process, to develop strategies to minimize the amount of mass lost in field operations, and to increase bale density and overall cycle efficiency of the machine systems used during the harvest process.

The three major components in the harvest and logistics processes are on-farm operations, highway transportation and storage operations (Liu et al., 2013). In particular, research is warranted on the on-farm operations, which can include field preparation, planting, growing, harvesting, and transporting biomass to an on-farm storage location. Previous studies on biomass crops have shown that the costs of harvesting, transporting and storing are the most substantial when examining the entire cycle cost from (Liu et al., 2013). Typical miscanthus and switchgrass harvesting operations can include mowing and conditioning the crop as well as baling the crop with either a large square baler or a round baler. Biomass crops, especially miscanthus, by nature have a very low bulk density. The low bulk density combined with the unproven method of using conventional agricultural harvesting equipment on this newly realized potential biomass energy crop, leads to poor machine functionality and increased operation costs (Liu et al., 2013).

More efficient harvesting systems and technologies that match the farm's size and yield will help reduce costs throughout the biofuel production process (Liu et al., 2013). Examining the technology used during the harvest and handling process of both miscanthus and switchgrass will lead to strategies in reducing costs. These cost savings during harvest can then be translated to the biorefinery as well and aid in producing lower cost biofuels. To meet the bioenergy requirements outlined by the Department of Energy, the harvesting, storage and transportation process for miscanthus must be examined and improved. This research focused on examining the effects of conditioning systems for miscanthus on their ability to produce a denser bale with less energy, as well as examining some key parameters during the bale compression process for miscanthus and switchgrass.

Chapter 2 - Literature Review

This literature review examined the research already completed in the area of biomass feedstock utilization for biofuel production. The review began by examining the different types of biofuels and biomass that are being used today and then focused on dedicated energy crops, specifically miscanthus and switchgrass. To understand how to utilize miscanthus and switchgrass, the current harvesting technologies were examined, and the importance of densification was explained. A bale compression and brief logistics discussion was presented. Finally, a state-of-the-art description for miscanthus harvesting systems was described to explain the gaps in current published research so as to provide a justification summary for this research study.

2.1 Biofuels

In the U.S. and most other countries throughout the world, liquid fuels are used as a major source of energy for numerous activities and machines. These fuels are used to power cars, busses, farm equipment, airplanes and trains. Typical liquid fuels, such as gasoline, ethanol, diesel, jet fuel, and compressed natural gas, are used and will continue to be used in the future (Ting, 2009). Increased biofuel creation, which could come from several biomass crops, is a more sustainable way of reducing the amount of petroleum-based fuels currently used. From biomass crops, more ethanol as well as biodiesel can be produced. Biodiesel is a vegetable oil or animal fat based diesel fuel. Biomass can also be used to produce gases such as methane and pyrolysis gas, which can be used as a power source in certain applications (Ting, 2009). Finally, many solid fuels can be produced from biomass, which can be directly burned as a fuel source in pellet stoves and in co-firing heat and power generation plants.

Biomass has been given a broad relationship called 7F, because it has a role in food, feed, fertilizer, feedstocks, fuels, fibers and fine chemicals (Kitani, 2009). This is a representation of the many different products that can come from biomass crops and shows how they are used in many different industries such agriculture, transportation, chemical production and value added commodity products. Often times, many of the 7F products can be produced along with the alternative fuel because they are either by-products or leftovers in the biofuel production process. Kitani, (2009) suggests that, not only does biomass create a huge opportunity for growth in the biofuel industry, it also provides room for growth in all of the other industries incorporated within the 7F relationship. Increasing production of biomass for one particular field or area will lead to increased bio-product production in several other fields as well.

The biofuels, value-added products, power and heat production processes originate at what is often referred to as a biorefinery. The number of these facilities within the U.S. is growing on a yearly basis. Biorefineries want and need biomass to meet certain requirements, so that the refinery is efficient and economically beneficial. One biomass requirement, as explained by Ileleji (2007), is that there must be a consistent supply of low cost, high quality biomass all year long. Ileleji (2007) also explains that the biomass feedstock cost is the most influential cost to the success of the refinery in producing fuels, power, heat and chemicals. The methods currently used by biomass feedstock producers to harvest and deliver biomass to the biorefineries are not meeting these requirements. This develops a strong barrier to entry for the biorefinery and leads to biofuels not being competitive with petroleum-based fuels. To minimize this barrier to entry, as well as make biorefineries more profitable, the efficiency of harvesting methods, transportation and storage of biomass must be increased. This will help minimize the input cost that biorefineries face and help them produce more biofuels, to achieve the overall biofuel production goals developed by the Department of Energy and United States Department of Agriculture. Kitani (2009) makes a point to explain that when the goal is to reduce the amount of petroleum-based fuels used in the U.S., we should not use an excessive amount in the harvest, transportation and processing of biomass feedstocks. This justifies the significance of further examination of the biomass harvesting process for biofuel production.

2.2 Energy Crops, Specifically Miscanthus

In the world of biomass today, there are many different types of crops that can be considered biomass feedstocks. To simplify this designation, biomass crops can be divided into food crops, woody crops and dedicated energy crops. The food crop group consists of crops that can be either used as a food source (for humans or animals) or as a biofuel feedstock, as well as those crops whose primary function is a food resource in which their residues can be used for biofuel production. Some examples of these crops are corn and corn stover, sorghum, canola, sugar cane, barley, soybeans and wheat (Buchanan, 2008). The controversy that can arise with these types of crops is the “Food vs. Fuel” debate, in which there is a struggle between using food crops for fuel production when these crops could be used to feed more people throughout the world. In particular the food crop residues, for example corn stover, are useful because the stover can be used for biofuel production after the corn grain is harvested for food production purposes.

The woody biomass group consists of logging residues, forest thinnings, pulpwoods, mill residues and urban woods waste (U.S. Department of Energy, 2011). These types of biomass are conventionally not used for many other purposes and often are just left to decay. These biomass crops can be converted into biofuels and other value added products. The final classification of biomass crops is the dedicated energy crops such as switchgrass, miscanthus, poplar, pine, willow and eucalyptus. These crops are typically grown for the sole purpose of biomass feedstock creation. Energy crops have the desired qualities that biorefineries look for such as high yields, minimal quality variability and easier accessibility to the energy within (Ileleji, 2007). However, each energy crop has its advantages and disadvantages that need to be considered when determining which is best for individual farmers and biorefineries.

In Perlack’s (2007) presentation, he determined that there are 342 million acres of crop land with an additional 39 million acres of idle cropland and 68 million acres of pasture land in the United States. This shows that there are plenty of opportunities for increased energy crop production, especially by using the idle crop land. Although the idle land is often less productive, many biomass crops can produce the same yield in these areas as land that is considered more productive because of the hearty nature of energy crops. In figure 2.1, the resource potential, in million dry tons of biomass per year, is shown and is based on reasonable assumptions of trends and start up times for crop production.

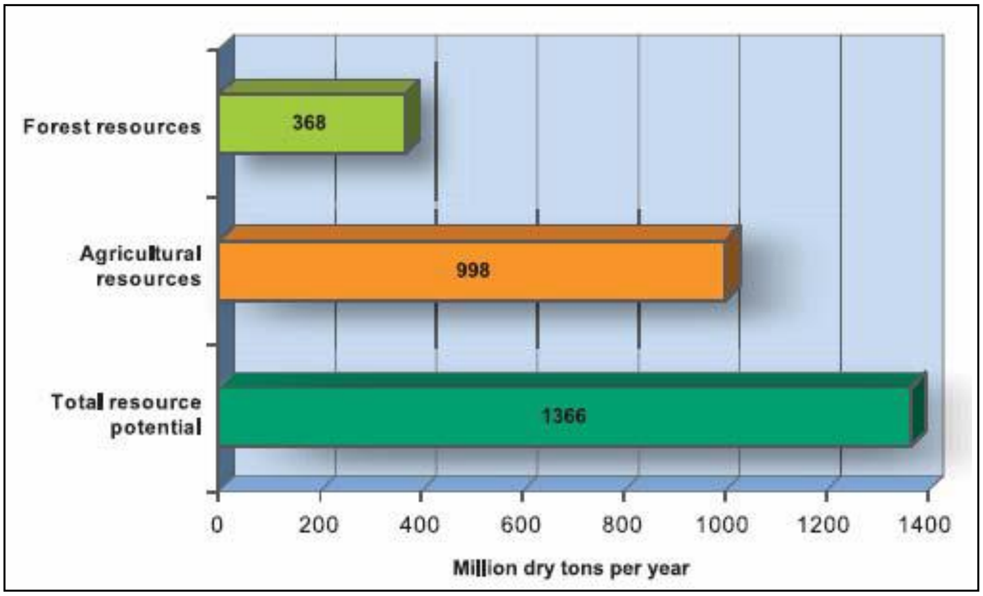

Figure 2.1 - Biomass potential in the contiguous U.S. (Perlack, 2007).

Miscanthus, in particular, is an energy crop with extreme potential because of its high fiber yield and relatively low required inputs and ash content. Miscanthus grows very dense, typically around 5-10 plants per square foot. There has not been a significant disease or pest problem found that decreased the yield or growth ability, which also makes it an attractive crop. Perlack et al. (2011) explains that miscanthus is a relatively long-life perennial crop that was discovered in Japan and is comparable to bamboo, as it can grow to an average of nine feet in height. Miscanthus is a rhizomatous C4 grass; however, the structure of the plant is very similar to a woody crop in terms of stiffness and rigidity. The stiffness allows the crop to easily bend without breaking and requires a large force to crush or break the stem. These properties can pose several harvesting and handling problems. For this reason, Perlack states that there is a need for specialized harvesting equipment to handle miscanthus more efficiently and increase the current yield, which is about nine tons per acre.

2.3 Current Biomass Harvesting Technologies

Previous studies have shown that the harvesting, transportation and storage costs of herbaceous biomass are the highest percentage of total cycle costs; reducing these costs is important and deserves further examination (Liu et al., 2013). This section will focus on the current harvesting techniques and machinery used.

Biomass crops, in general, are typically harvested with one of two methods; utilizing current hay and forage equipment to mow, condition and bale the crop or, chopping the crop and storing the crop by means of mass bulk storage systems. There have been several studies completed on the harvest, transportation and storage of switchgrass, which is a dedicated energy crop like miscanthus; however, there is a lack of published studies on miscanthus. Therefore there are benefits to examining the results of harvest studies on switchgrass for comparison purposes to miscanthus.

2.3.1 Mowing

When utilizing current hay and forage equipment, the first process completed is mowing and conditioning the crop with a mower-conditioner. The two most common mower types that are used today are sickle bar mowers, which operate at lower travel speeds and require less input horsepower, and disc mowers, which can operate at higher travel speeds but require a larger input horsepower. Once the crop is cut, it is then conditioned by one of several methods, within the same machine. Conditioning of hay and forage crops is required to allow moisture to escape from the crop faster and to allow the crop to dry faster (Taylor, 1992). However, moisture is not as large as a concern with biomass because the crop has typically dried enough before it is being harvested.

Several lab scale tests have been completed on cutting miscanthus so as to simulate the mowing process. Liu et al. (2012) studied miscanthus and examined the shearing strength, tensile strength, bending strength as well as cutting energy and force. They found that at lower internodes, the straight stalk pieces between the knuckles, the forces, energy and strengths are much higher than the upper internodes. In terms of a mower, this means that if the miscanthus is mowed close to the ground, significantly higher forces and energy can be expected. No specific relation was made to other crops. Suggestions were also made for designing a blade to cut miscanthus in order to minimize the required forces and energy.

2.3.2 Conditioning

There are two main types of conditioning methods used today, namely a roll type conditioner and an impeller type conditioner. Roll type conditioners utilize two rotating rolls that crimp, compress and crush the crop as it flows between them. These rolls can be a variety of different sizes and shapes and are made out of either steel, rubber or polyurethane material (Taylor, 1992). Impeller type conditioners utilize either rubber or steel fingers that rotate around a central hub. When these fingers come in contact with the crop they beat and force the crop against a shield that removes the waxy coating and breaks the stem; this aids in the drying process. In a study by Womac et al. (2012) of switchgrass harvesting, the drying time of switchgrass was not affected by the conditioning method and no conclusion was reached on the effect of conditioning on bale density.

According to Shinners et al. (2006), crimping rolls have many deep lugs or fins that bend and break the crop while it moves through intermeshing, non-contacting rolls. Crushing rolls flatten crop as it passes through rolls with very small clearances between the two rolls. Some crushing rolls can have lugs to help improve crop feeding through the rolls, but these lugs are often much smaller than crimping roll lugs. Specific crushing area, as explained by Shinners et al. (2006), is the amount of area where the clearance between the two rolls can be adjusted extremely close so as to crush and break the stalk fibers. Large intermeshing rolls with large fins or lugs have less specific crushing area than rolls with smaller fins; however, the larger intermeshing fins feed crop more aggressively and can provide an excellent crimping effect. Figure 2.2, developed by Shinners et al. (2006), shows several different types of conditioning roll designs tested.

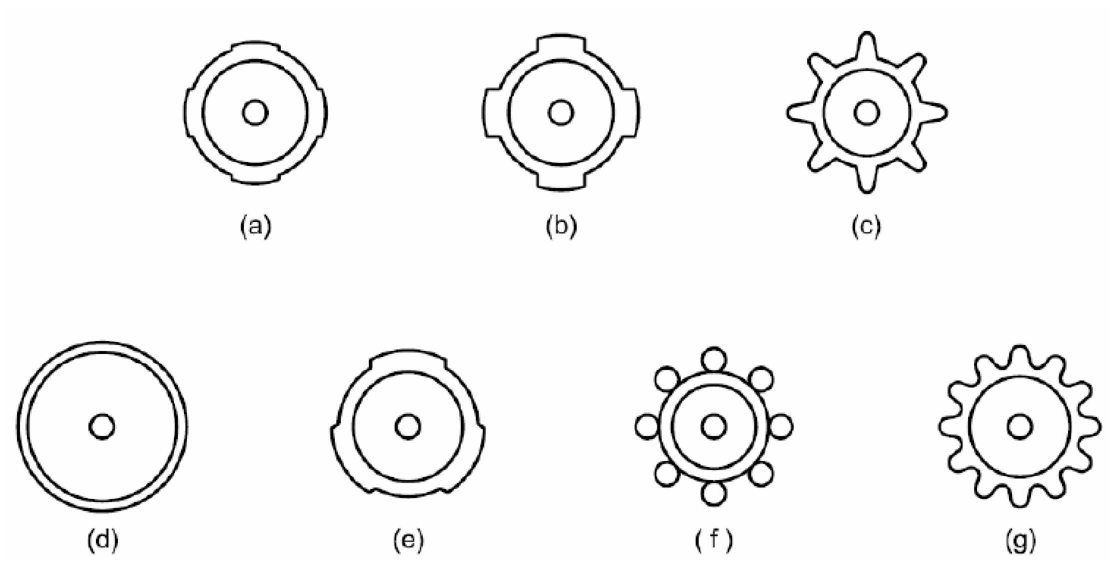

Figure 2.2 - Conditioning roll types (Shinners et al. 2006).

The conclusions from the study focused both on the fastest drying rate, and the quality of conditioning between the rolls. Rolls (f) and (g) in figure 2.2 produced the most conditioned or most thorough conditioning because these rolls crimped and crushed the crop as a result of the high number of deep lugs and the consistent roll clearance (Shinners et al., 2006). In terms of alfalfa, these rolls increased the drying rate when compared to typical urethane rolls typically used in a mower conditioner. However, rolls (f) and (g) in figure 2.2 were much nosier and had some interference during operation between the two rolls.

CNH Industrial produces both a steel roll with fins, as well as a chevron patterned rubber roll for current production machines. Conventionally, these rolls are used for hay and forage crops to help the drying process. Other manufacturers produce similar rolls and these rolls have been on the market for many years. Figures 2.3 and 2.4 show the steel roll and chevron rubber rolls respectively.

Figure 2.3 - New Holland steel roll conditioning.

Figure 2.4 - New Holland rubber roll conditioning.

2.3.3 Baling

After mowing and conditioning, the crop is subsequently baled using a round or square baler. The choice of producing either a round or square bale is up to the farmer and often depends on what type of baler is currently owned. Utilizing equipment that is already owned, reduces the investment cost that the farmer faces (Cundiff and Grisso, 2011); however, each bale type has its own advantages and disadvantages. Round bales have the ability to shed water much better than square bales, which can allow round bales to be stored more easily in the field and for longer periods of time at a lower cost (Liu et al., 2013). Large square bales have a greater bulk density and are easier to transport and move than round bales. They also have higher field efficiency because square bales can be ejected from the baler without stopping during operation (Liu et al., 2013). Large square balers have a higher upfront cost than round balers, which makes purchasing them more difficult for smaller scale operations (Remoue, 2007). Storage of square bales is more difficult than round bales because they must be under a structure or out of the weather to decrease mass loss due to weathering.

Square bales can come in two forms, either large or small square bales. Small square bale technology was developed long before large square balers and is often used by smaller farmers in certain specialty areas, such as horse operations. Shinners et al. (1995) explains that one of the major differences between small square balers and larger square balers is the pre-compression chamber. Crop is fed into this chamber where it is compressed slightly until a relatively large amount of crop is accumulated. Once this has occurred, the crop flake is pushed from the pre-compression chamber into the main chamber and added to the main bale. Because of this difference, a higher bale density can be achieved with a large square baler, as compared to a small square baler.

The forces inside a large square baler can be extremely large, and previous studies have found that these forces often change depending on the crop type. As a result, the bale density of different baled crops can also be different, depending on crop type, moisture and other factors. Afzalinia and Roberge (2008) examined the forces within a large square baler for barley and wheat straw. An analytical model was developed to explain the pressure distribution within the baler and the model was tested and evaluated through a field test with a large square baler outfitted with data acquisition equipment. By knowing the pressure distribution and forces within the baler for these crops, proper baler design can be ensured. However, barley and wheat straw were the only crops examined and applicability of this model for other crops is unknown.

2.3.4 Chopping

When biomass crops are harvested utilizing the chopping method, either a pull-type chopper or self-propelled chopper is used. Groothuis and Womac (2012) examined these methods with switchgrass and found that there were no major issues with the ability of these current production machines to effectively chop switchgrass. In a study and model of miscanthus harvesting by Shastri et al. (2010), they found that chopping miscanthus was a possible harvesting method; however, they expected the cost of this option to be the highest of all possible options when comparing several bailing types and mower conditioners. Once the crop is chopped, it is transported by a chute on the machine into a truck that then transports the chopped crop to a storage location. These storage locations require more space than bales require and must be covered to prevent weathering of the crop. Benefits of chopping the crop include a one pass trip through the field rather than multiple trips with mowing, baling and bale collection.

Once the biomass arrives at the biorefinery and is unloaded, there is no need to de-bale the crop or remove baler twine as would be required with baling the crop (Groothuis and Womac, 2012). A switchgrass study by Groothuis and Womac (2012) found that the average density of the chopped crop was 87 kg/m^3 on a dry basis and 100 kg/m^3 on a wet basis, which is much less than the density found by Kemmerer (2011) of 180 kg/m^3 on a dry basis when baled with a large square baler. Shastri et al. (2010) found that the estimated delivered cost of chopped miscanthus was 62.92 $/Mg while the estimated cost of round baling miscanthus was 47.88 $/Mg; large square bales were not examined.

2.4 The Significance of Densification

The purpose of baling a crop is to compact the crop into a package that is easier to handle and transport. In terms of biomass, the crop often needs to be transported further than hay and other forage crops, because it is traveling to a biorefinery and not just from the field and back to the barn on the same farm. Liu et al. (2013) state that the key to optimizing the harvest and transportation processes is bulk density. This is because transportation costs are very high and, therefore, the more trips that are needed to move the crop, the higher the total cost will be. If the bulk density of the biomass feedstock is increased, fewer trips will be needed and the costs will be decreased. For example, Kemmerer (2011) found that a bale density of approximately 200 kg/m^3 will adequately load a flatbed truck to the on-road weight limit. Through a study on biomass crops, Shinners et al. (2010) concluded that the bale density of perennial biomass crops needs to be increased by 20-30 percent from the current bale density commonly produced, in order to be at the economically efficient point during the transportation process.

The bale densities that can be achieved depend not only on the type of harvesting and packing equipment, but also on the type of crop and moisture content (Kemmerer 2011). Although conventional forage crops can be baled to achieve the maximum density needed to achieve on-road transportation limits, biomass crops are still below the limit. Because of this, other methods of densification have been examined after the crop has been harvested by chopping. Types of densification methods include on farm pelleting, cubing, briquetting and extrusion. However, Shastri et al. (2010) found that the cost of compressing miscanthus post-harvest, before transportation to the biorefinery, is still more expensive when compared to baling. The only exception was the grinding option, which showed an insignificant decreased cost of only about 1$ per Mg as compared to baling the miscanthus crop.

In a study by Ma and Eckhoff (2014) the unit transportation costs were evaluated for baled miscanthus at three different densities (150, 140 and 130kg/m3). The study found that when using a contract pricing model and looking at both fixed and variable costs, the lowest unit cost per bale corresponded to the densest bales. In this case, this was the 150 kg/m3 bales; therefore, the importance of increasing the density of miscanthus bales is significant and it is unclear how much further unit costs can be decreased if the density of miscanthus bales can be increased further.

2.5 Compression and Densification

A study by Miao et al. (2012) examined the energy requirements for the densification of loose miscanthus and switchgrass with a medium-scaled compressor. The purpose of the study was to understand the energy required to compress the crop, to better determine how to increase efficiency during the transportation of the crop to the biorefinery. The results showed that miscanthus had a higher pressure required for compression than switchgrass, which means more energy is required. Figure 2.5 shows the relationship of the energy required to compress miscanthus in both the unground and ground forms.

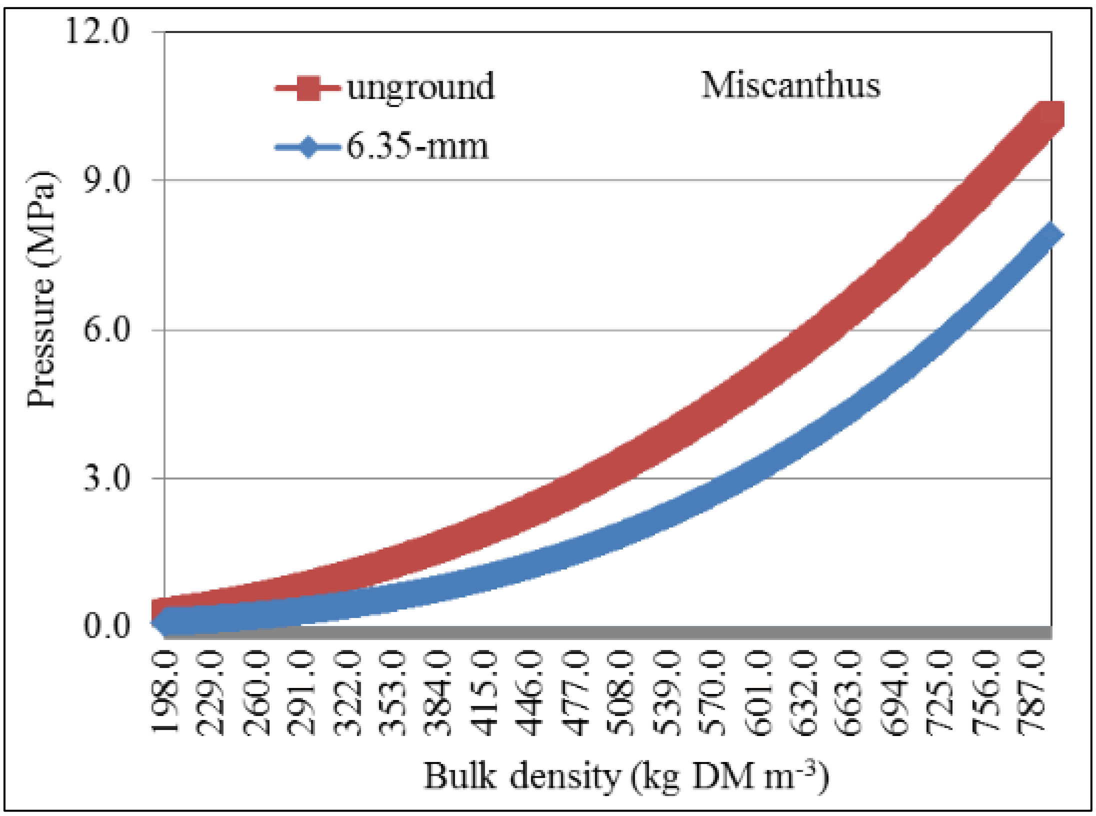

Figure 2.5 – Loose miscanthus compression testing (Miao et al. (2012).

The graphed curves are significant because, in the case of baling the crop in the field, they show that more energy is required, along with a higher pressure, to compress miscanthus to the same bulk density than would be required to compress processed (in this case ground) miscanthus. In a similar study of indiangrass, switchgrass, corn stover and wheat straw, Hofstetter and Liu (2011) concluded that a smoother textured crop surface allows for the crop to be compressed with less pressure, because the coefficient of sliding friction is less. It was also found that stiffer crop stalks required a higher pressure to achieve the same density. By examining this study, we can see that changing the properties of crop before compressing allows for less energy input in achieving the same density.

In work completed by Hofstetter (2011), a lab scale small square bale compressor was designed and built. The compressor was then used to compress small square bales of indiangrass, switchgrass, corn stover and wheat straw. Hofstetter was able to use an equation to predict the nonlinear pressure versus density relationship for each of these crops, as they all have slightly different equation constants. The energy, specific energy and power required to reduce the small square bale volume, or increase the density, was examined for each crop type. Different compression speeds were explored and the study found that higher compression speeds will increase the required energy and power within the same crop type. When comparing the energy and power required between crop types, the order of increasing power and energy changes between the slow and fast speeds. In general, the study found that switchgrass is the most difficult crop to compress of the crops tested and comparisons between crops must be made across a common bale volume reduction or common density range.

2.6 Harvest and Transportation Logistics

According to Liu et al. (2013), a complete logistics system for biomass handling is described as one that begins with the crop in the field and is completed with a consistent 24/7 supply of biomass to the refinery for constant operation. The effect of optimizing or increasing the efficiency of a single process within the logistics process is a total cost reduction. However, the result from optimizing one process does not always result in total cost reduction, because it is possible for another process' costs to increase as a result of optimizing the first process. This is why when examining the harvest of biomass crops, it is important to understand the complete logistical system and the measurements used to quantify and compare different systems. Figure 2.6 shows a typical logistics chain for biomass utilization.

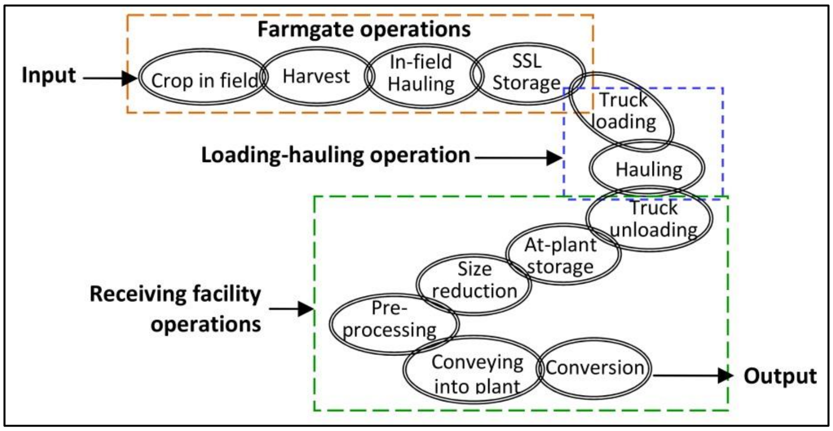

Figure 2.6 - Machine logistics chain (Liu et al., 2013).

Under each broad process or step, there are several different options and methods available depending on crop type and end use. For example, when harvesting miscanthus, there are many choices available such as mowing, chopping and baling with several different types of machines as well. However, harvesting is only one part of the entire system of converting the crop into a useable biofuel. This proposed research will focus on the farmgate operations shown in figure 2.6. This includes examining the harvest of biomass crops and looking at individual processes of harvesting equipment, so that future machine modifications can be made.

2.7 State-of-the-Art of a bale density and bale compression analysis

Miscanthus has an extreme amount of potential for growth as a feedstock for biofuels and other value-added products. The examined literature describes that biorefineries struggle to have low cost and high quality supplies of biomass all year long. If this was not an issue, biorefineries would be able to compete with petroleum-based fuel sources more easily. The key to solving this issue has been identified as increasing the efficiency and decreasing the cost of the harvesting, transportation and storage processes of various biomass crops. Particularly in the harvest of miscanthus, further focus must be directed specifically at the machines used in the harvesting process and their operation.

The mechanical properties of miscanthus pose harvest and handling issues because of the crop's stiff stalk, tall height, high yield and dense growth. Further examination is required to determine if current production hay and forage equipment can be utilized, as they are produced today, to harvest miscanthus effectively and efficiently or if modifications will be needed. For example, there have been no published studies examining the effects of different conditioning methods on miscanthus and the subsequent effects on bale density and furthermore bale compression. A substantial increase in bale density would directly decrease the cost of transportation.

There is a lack of published studies that have explored compressing small square bales of miscanthus. Comparisons of the required compressive forces, power and energy for miscanthus to switchgrass would be beneficial. A higher relaxed bale density, the density of the bale after it is allowed to relax after a compression, can provide a measure of a bales ability to be stored and the bales susceptibility to breaking and or falling apart during storage. Additional examination of the small square bale compression process can provide additional information about crop parameters and optimum bale compression procedure.

Chapter 3 - Goals, Objectives, Hypotheses

Utilizing biomass feedstocks for biofuel production is vital to decreasing the amount of petroleum-based fuels used in the U.S., as well as worldwide. In particular, increased miscanthus production provides an excellent opportunity for increasing the amount of renewable biomass feedstocks that are produced for biofuel production. However, the current harvesting and logistics technology used today can be largely inefficient.

The goal of this research was to examine conditioning of miscanthus following mowing and prior to baling in order to evaluate the effects on bale density and the required forces and energy consumption required to compress baled miscanthus. Decreased forces and energy consumption during the bale compression process can be directly related to the actual bale creation process. Also, this research further examined the small square bale compression process by comparing miscanthus with switchgrass. The outcomes obtained from achieving this goal are decreased harvesting and transportation costs from increased bale densities with a lower energy input during the bale making and bale compression processes. Knowledge to refine current designs of production equipment for better use when harvesting miscanthus and other biomass energy crops was also obtained.

The objectives associated with this goal statement were to:

1. Evaluate the effects of a crimp conditioning method on miscanthus by comparing the maximum compressive force, peak power and specific energy consumption required to compress small square bales of conditioned and unconditioned miscanthus.
2. Test and examine the effects of different compression holding times, successive compressions, the bale relaxation and volume reduction process for conditioned and unconditioned miscanthus.
3. Compare the maximum compressive force, energy consumption, and bale relaxation for conditioned miscanthus and unconditioned miscanthus to the results of both spring and fall harvested switchgrass during the small square bale compression process.

4. Calculate the pressure versus density relationship for the compression of baled miscanthus.

The following hypotheses were tested:

The first hypothesis focused on comparing miscanthus conditioned with a crimp conditioner to unconditioned miscanthus. The specific energy used during the first cycle of the bale compression process was used to evaluate the effect of conditioning over a common density range to eliminate errors and normalize the data.

H_o = The mean specific energy consumption of crimp conditioned miscanthus and unconditioned miscanthus, over a common density range, is statistically equal during the small square bale compression process.

H_a = The mean specific energy consumption of crimp conditioned miscanthus and unconditioned miscanthus, over a common density range, is not statistically equal during the small square bale compression process.

The second hypothesis focused on comparing the bale relaxation of miscanthus conditioned with a crimp conditioning method. To quantify the bale relaxation, the relaxed bale volume, as a percent of initial bale volume, was compared between conditioned miscanthus at two compression cycle holding times of 150 and 5 seconds respectively.

H_o = The mean relaxed small square bale percent volume reduction for crimp conditioned miscanthus, for a hold time of 150 seconds as compared to a 5 second hold time after the first compression cycle, is statistically equal.

H_a = The mean relaxed small square bale percent volume reduction for crimp conditioned miscanthus, for a hold time of 150 seconds as compared to a 5 second holds time after the first compression cycle, is not statistically equal.

The third hypothesis focused on comparing miscanthus to switchgrass. The specific energy used during the bale compression process was used to compare the two crops. The results were compared over a common density range for normalization purposes.

H_o = The mean specific energy consumptions of crimp conditioned miscanthus, unconditioned miscanthus, spring harvested switchgrass and fall harvested switchgrass over a common density range are statistically equal during the small square bale compression process.

H_a = One of the mean specific energy consumptions of crimp conditioned miscanthus, unconditioned miscanthus, spring switchgrass and fall switchgrass, over a common density range, is not statistically equal during the small square bale compression process.

Chapter 4 - Methodology

The methodology for this research is outlined in this section. To answer and evaluate the hypotheses, the methodology consisted of four phases:

Phase I: Switchgrass small square bale compression

Phase II: Miscanthus conditioning method study and small square baling

Phase III: Miscanthus small square bale compression

Phase IV: Data analysis and hypothesis testing

Figure 4.1 provides a flow chart showing the key aspects of the research. Phase I began by obtaining small square bales of switchgrass from both a fall and spring harvest. The switchgrass was grown near Julian, PA and the switchgrass bales were then compressed using a lab scale small square bale compressor. Phase II examined the effects of conditioning miscanthus subsequent to mowing and before baling. The miscanthus was grown on a mine reclamation site near Alton, WV. A table-top conditioning device was used to condition miscanthus in a way not currently used in production machines, utilizing slightly different crimping rolls. Another conditioning method utilizing flat steel roll conditioning was explored. Finally miscanthus conditioned with the crimping rolls, and also unconditioned crop, was baled using a small square baler. In Phase III, similar to the switchgrass compression, the required forces and energy consumption during the compression of small square bales of miscanthus were examined through lab testing. Finally, in phase IV, the data collected was analyzed and used to test the hypotheses.

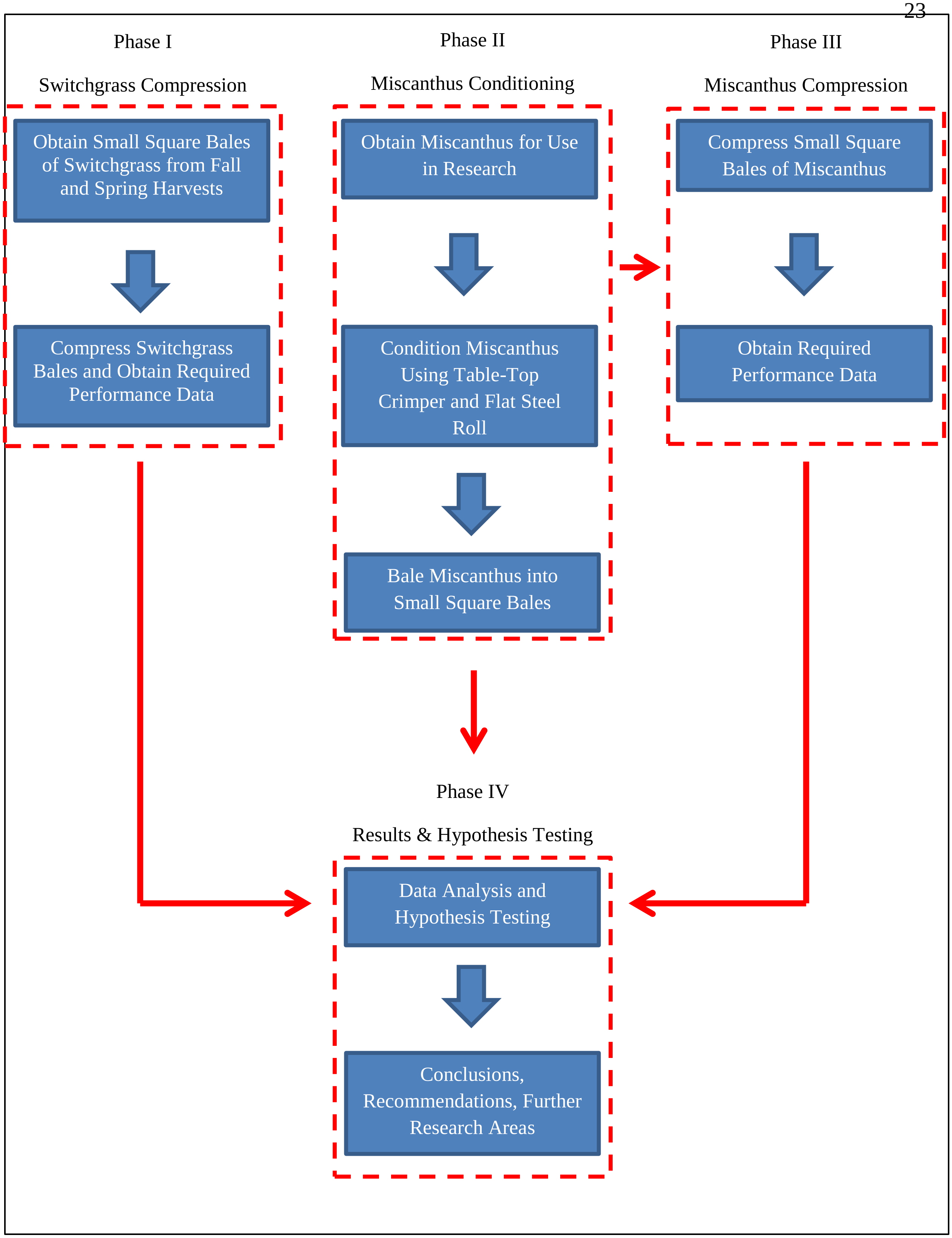

Figure 4.1 - Miscanthus conditioning methodology overview flowchart.

Chapter 5 - Miscanthus Conditioning and Baling

The first study completed was the miscanthus conditioning and baling study. The results of this study were then used to design and carry out the small square bale compression testing for miscanthus.

5.1 Materials and Test Procedure

The miscanthus crop that was used for all the experimental tests in this research was grown in Alton, West Virginia on mine reclamation sites managed by the West Virginia Department of Environmental Protection in conjunction with West Virginia University. The crop stand was mixed between 3 and 4 years old and was mowed in May of 2014 using a disc mower without any type of conditioning system. The miscanthus variety was miscanthus giganteus. The miscanthus was gathered by hand in the field and transported back to University Park, Pennsylvania for the experimental tests in a large box truck. Once arriving on campus, the miscanthus was stored in one of the Penn State farm operations barns. The truck was weighed with a drive-on scale before and after unloading and approximately 1725 kilograms of material was obtained. Because the crop was mowed in late spring, grass clippings were mixed in with the miscanthus, adding to the total weight. The grass was separated out by hand before the miscanthus was used, in order to eliminate any changes in moisture and or inconsistent amounts of grass mixed in with the miscanthus that was baled. Two conditioning systems, smooth steel roll conditioning and crimp conditioning, were used to examine the effects of conditioning on miscanthus.

5.1.1 Smooth Steel Roll Conditioning

The first method of conditioning miscanthus examined was a smooth steel roll conditioning system. The goal of this system was to examine how miscanthus would respond to being compressed and flattened by a steel roll. This system would not bend or form the miscanthus in any way; rather, it would simply break the crop fibers along its length and flatten the crop while maintaining full crop length and straightness. The current production New Holland steel roll conditioning system, discussed previously, uses a steel roll. However, these rolls have fins welded to the outside to improve feeding through a disc mower. This steel roll conditioning test was designed to use smooth steel rolls so as to remove any effects from the fins and focus completely on understanding compressive force from the rolls and the ability to crush miscanthus and break the stalk fibers longitudinally along the crops length.

In the first experiment, a common pull type lawn roller was used to simulate a smooth steel roll conditioning system. The lawn roller was filled with water to increase its weight to provide a larger compressive force on the miscanthus. The lawn roller drum was approximately 0.4 meters in diameter and 0.6 meters wide. Therefore, when filled with water, the roller weighs approximately 90 kilograms. An additional 170 kilograms of small suitcase weights were added to the lawn roller frame to increase the total weight to 260 kilograms. Miscanthus was laid on a concrete floor in a pile slightly smaller in width than the roller and approximately two inches high. The lawn roller was then pulled over the crop with a utility vehicle at 1.5 kilometers per hour. Six replications were made for this test. The lawn roller can be seen in figure 5.1.

Figure 5.1 - Lawn roller smooth roll conditioning.

In a second experiment, a commercial Sakai double drum asphalt roller was used to condition miscanthus with a smooth roll conditioning technique. The miscanthus was laid out, similar to the lawn roller experiment, in a pile approximately two inches tall and slightly smaller than the width of the roller which was approximately one meter wide. The rated crushing force on the Sakai roller is between 26,700 and 35,500 N. The roller was driven straight over the crop at approximately 1.5 kilometers per hour. A second test with two passes with the drum roller was made over the same miscanthus after inspection of the quality of conditioning.

5.1.2 Crimp Conditioning

A crimp conditioning table was designed and built to examine the effects of both crushing and crimping effects on miscanthus. Current hay equipment can include both rubber rolls with a chevron pattern as well as steel rolls with the chevron pattern. The fins or lugs on these rollers are typically 0.02 meters deep (refer to figure 2.3). The conditioning rolls used in this experiment were taken from a pre-1980's hay crimper. These rolls have fins approximately 0.03 meters deep. These crimp conditioning rolls are more similar to other conditioning rolls because the fins are not in a chevron pattern rather they are parallel to the roll width within the machine.

In the conditioning table, the top crimp conditioning roll is 0.2 meters in overall diameter and has a solid shaft with the fins welded on to a larger concentric frame; this results in a gap between the fins and the solid shaft center. The bottom roll is smaller in diameter, 0.1 meters, than the top roll and has the fins welded directly to the solid steel shaft with no gap between the fins and steel center. The top roll has 17 fins and the bottom roll has 8 fins, providing a specific speed ratio between the rotational speeds of the rolls. The crimp conditioning table can be seen in figure 5.2. Table 5.1 shows additional specifications of the crimp conditioning rolls. The conditioning rolls were removed from the original hay crimper and shortened to a smaller length in order to be installed in the lab scale table top device. The table top frame was designed to hold the crimping rolls and provide easy adjustments in the amount of space the fins interlock. A hydraulic motor uses hydraulic power to rotate a chain and sprocket connected to the top conditioning roll. As the top roll is powered and rotates, the lower roll rotates as a result of the interlocking fins.

Figure 5.2 - Crimp conditioning table.

Table 5.1 - Crimp conditioning table specifications.

Top Roll	0.25 meters fins - 17 fins
Bottom Roll	0.25 meters fins- 8 fins
Top Roll Diameter	0.17 meters
Bottom Roll Diameter	0.10 meters
Shaft Spacing / Roller Interlock Amount	0.14 meters / interlock amount 0.02
Roll Shaft size	0.03 meters
Roll Length	1.04 meters
Hydraulic Motor Specs	CASAPPA Max Displacement 26.4 cm^3/rev, max rpm 2500, max flowrate 63.33 l/min max 17.47 hhp

Conditioning tests were performed using tractor hydraulics from a Deutz 6250 with a maximum hydraulic flow rate of 56.8 liters per minute. Once the tractor was running and the hydraulic lines were connected to the hydraulic motor, the tractor throttle was adjusted to adjust the hydraulic flow rate and reach the desired operating roll speeds. As the rolls are rotating, the miscanthus crop is fed into the input side of the conditioning rolls by hand and then picked up on the output side of the table. Typically, between six and ten miscanthus stalks were fed through the rolls at one time. The maximum number of stalks that can be fed through the rolls at one time is a result of the roll spacing. Quality of conditioning must be continually examined, so roll spacing was adjusted to ensure each stalk fed through is fully conditioned as it leaves the rolls on the output side of the table. Figure 5.3 shows miscanthus being conditioned in the conditioning table.

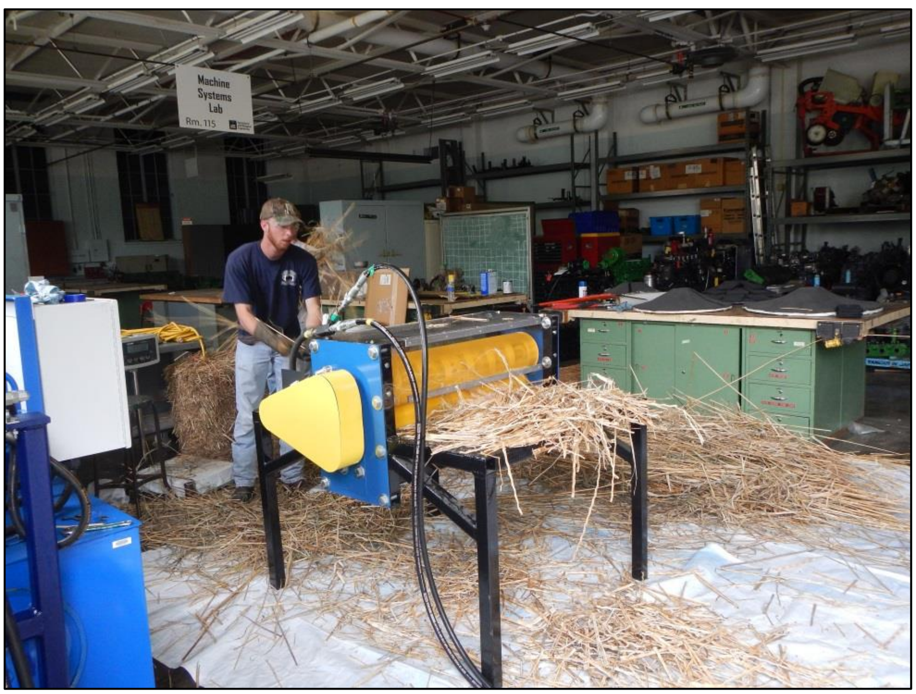

Figure 5.3 - Conditioning testing with crimp conditioner.

5.1.3 Small Square Baling

The conditioning tests were completed for two purposes; to be able to see the visual effects of crimping miscanthus when compared to a straight unconditioned piece and also to provide a significant amount of conditioned miscanthus for subsequent baling and bale compression. A New Holland 575 small square baler was used to bale miscanthus for subsequent bale compression testing. The baler was borrowed from Penn State Farm Operations and was a fully operational baler currently used for hay crops throughout the hay season. Miscanthus was baled in two forms; the conditioned crop from the table top crimper as well as unconditioned crop. A preliminary test was completed in which the baler was attempted to be used to bale full length pieces of miscanthus. After this test, it was confirmed that full length miscanthus cannot be effectively baled with a small square baler, because of the extremely long length and the crop's stiffness. The miscanthus cannot be picked up by the baler header or fed into the chamber by the baler forks. To eliminate this problem, the unconditioned miscanthus was cut into approximately 0.4 meter lengths using a circular chop saw before it was baled. This unconditioned cut crop length is approximately the same length as the conditioned crop, when it exits the conditioning table because it breaks into smaller pieces after conditioning.

To begin baling the miscanthus, the baler was first used to bale the grasses and miscanthus residues that were filtered out of the miscanthus pile as mentioned before. This allowed for initial calibration of the baler. Parameters such as side wall pressure and bale lengths were adjusted to increase bale densities. Two miscanthus bales, one of each conditioning type, were made as an initial test. Once the baler was set up and adjusted properly, both conditioned and unconditioned crop were laid into a windrow. The baler was then used to make bales of each type. The tractor pulling the baler was operated at a speed of approximately 2.4 kilometers per hour because of the high amount of material and the need to produce bales with the highest bale density possible. Three separate baling tests were completed on different days. The first baling test used the entire initial amount of conditioned and unconditioned crop prepared while the two subsequent tests used the remaining amount of available crop.

5.2 Results and Discussion

The preliminary smooth steel roll conditioning test, utilizing a lawn roller and additional suitcase weights, did not result in an acceptable level of quality-of-conditioning. An acceptable level of quality-of-conditioning can be defined as a visual change in the stalk shape which is seen when compared to the normal round shape of unconditioned miscanthus stalks for the entire length of the miscanthus piece. The lawn roller, when used on one single stalk of miscanthus, would break the stalk fibers across the entire length of the crop after the additional suitcase weights were added. However, when the lawn roller was pulled over multiple stalks of miscanthus at one time, the quality-of-conditioning was extremely poor. Because of the inconsistent stalk diameter of miscanthus between pieces as well as the tapering stalk diameter from the bottom to the top within a single piece of miscanthus, it was very difficult to achieve an acceptable level of quality-of-conditioning when the roller was pulled over more than one miscanthus piece at a time. A usable amount of miscanthus that would be considered conditioned properly, for example 10 small square bales of crop, was not able to be obtained and therefore the lawn roller smooth steel roll testing was stopped from further testing.

In the second steel roll test, a commercial Sakai double drum asphalt roller was used to condition miscanthus. This asphalt roller was a self-propelled roller and was selected because the machine weight was between 10 and 14 times heavier than the lawn roller. However, once the miscanthus was put into a small pile and the roller was driven over the pile, the quality-of-conditioning was still unacceptable. When compared to the lawn roller, the asphalt roller performed a more complete conditioning of the miscanthus but still not at an acceptable level. To quantify the level of quality-of-conditioning and quantity of miscanthus that could be considered acceptable, measurements were made. Once the miscanthus was run over with the roller for either one or two passes, it was examined at each of the internode sections. A node for miscanthus is the knuckle-like area. A typical piece of miscanthus, used in this testing, had between 8 and 10 internode sections. To look at the quality-of-conditioning, each piece of miscanthus was examined for breakage in each internode section. The initial breakage of the miscanthus stalk outer fibers then results in the miscanthus being flattened which was considered conditioned. Table 5.2 shows the results of the number of pieces and how they were classified.

Table 5.2- Smooth steel roll conditioning results.

		After One Pass with Sakai Roller	After Two Passes with Sakai Roller
1 or 0 un-flattened internodes	Number of pieces	86	57
	Mass (kg)	1.77	1.24
	% of total mass tested	71.08%	74.70%
2 or more un-flattened Internodes	Number of pieces	33	20
	Mass (kg)	0.72	0.42
	% of total mass Tested	28.92%	25.30%

When examining an individual miscanthus piece, if one or zero internodes unbroken and un-flattened was found, then the piece was classified as conditioned properly because the majority of the crop's stalk was changed by the roller. If two or more sections were left unbroken and not flattened, then the piece was classified as not conditioned properly because not enough of the crop's stalk was changed by the roller. By examining the mass of the miscanthus that was classified in these ways, approximately 71 percent of the miscanthus conditioned with one pass of the roller was properly conditioned, while the remaining 29 percent was not. Two passes with the roller resulted in 75 and 25 percent respectively. Figure 5.4 shows miscanthus conditioned with the Sakai roller.

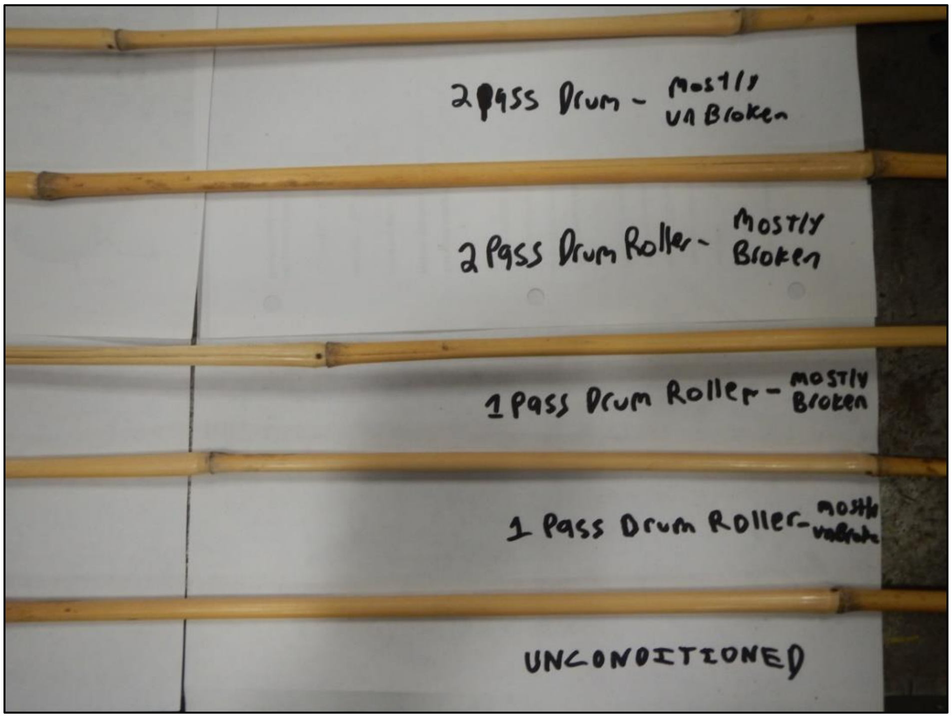

Figure 5.4 - Miscanthus conditioned with Sakai double drum roller.

After the smooth steel roll tests, the crimp conditioning table was used to crimp condition miscanthus. The crimp conditioning table was used to produce enough crimp-conditioned crop to make bales for bale compression testing. The miscanthus was fed into the table in small handfuls and each piece was fully conditioned as it exited the table, yielding an extremely high quality-of-conditioning. The crimp conditioning rolls also resulted in full length pieces being shortened into much smaller lengths of multiple pieces, upon exiting the table top crimper. Of a random sample of 20 full length miscanthus pieces, the longest piece after being conditioned with the crimp conditioner was 0.9 meters long. Only 12 percent of the miscanthus pieces were above 0.5 meters long after crimp conditioning therefore 88 percent of the pieces were shorter than 0.5 meters long after conditioning. This means that most of the conditioned pieces are similar in length to the unconditioned pieces that were cut to a 0.4 meter length. Figure 5.5 shows a typical piece of miscanthus after it was crimp conditioned.

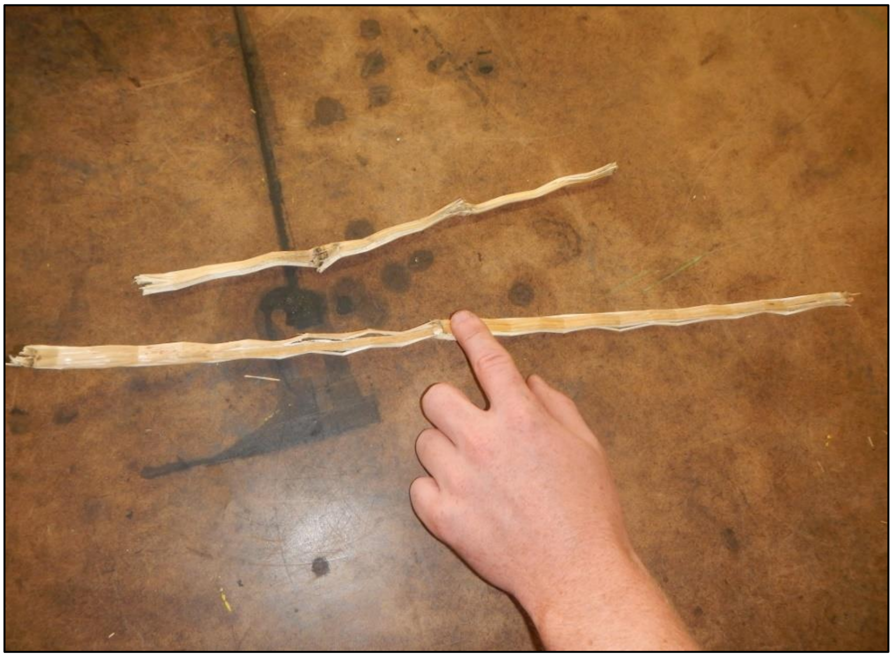

Figure 5.5 - Crimp conditioned miscanthus.

The initial baling test yielded 10 bales from crimp conditioned crop and 6 bales from the 0.4 meter length unconditioned crop. A second baling test yielded an additional 6 conditioned bales and 7 unconditioned bales. By using the entire available crop, a total of 16 conditioned bales and 16 unconditioned bales were made. It was confirmed that miscanthus can be baled with a New Holland 575 small square baler and the pickup head of the baler is able to operate properly when the miscanthus was conditioned with the table top crimper or when it was cut to approximately 0.4 meter lengths and placed into a windrow. The New Holland 575 baler failed to bale full length miscanthus crop as issues arise with not only the pickup head of the baler but also with the stuffer forks as well. The average small square bale density after baling for the conditioned bales was 94 $kg/m^3 \pm 7.3\ kg/m^3$ and the average unconditioned bale density was 89 $kg/m^3 \pm 7.6\ kg/m^3$.

5.3 Conclusions

The objective of the steel roll tests was to not only determine if smooth steel rolls can condition miscanthus in a way that simply flattens the stalk along its length and not bend or crimp it in any way, but also to condition enough miscanthus so that it could be used for subsequent baling and bale compression testing and comparisons. The lawn roller minimally conditioned the miscanthus if multiple pieces were conditioned at one time, making this method extremely impractical. Therefore the lawn roller method was not a viable option for this purpose and no further tests were carried out. Typical current production rollers have some type of fins or lugs in order to aid in crop feeding; another reason why further lawn roller testing was eliminated. However, the double drum asphalt roller also did not provide an acceptable level of conditioning for enough pieces of miscanthus to warrant conditioning more miscanthus and producing small square bales. The Sakai asphalt roller conditioned more crop to an acceptable level than the lawn roller, however even at two passes with the roller, 25 percent of the miscanthus pieces remained insufficiently conditioned. Therefore, the asphalt roller method was also eliminated and the crimp conditioning method was the only method used to condition miscanthus for comparisons to unconditioned crop when baling and compressing bales.

The purpose of both the steel and crimp conditioning tests was to see the change in the stalk properties of miscanthus when compared to unconditioned crop. As discussed, miscanthus is an extremely stiff and long crop. If the stalk can be broken, flattened and or crimped, the miscanthus is no longer stiff and can be molded into a different shape much easier. This is important when baling miscanthus. Although the smooth steel roll conditioning method was unsuccessful, the crimp conditioning method was successful and produced conditioned miscanthus that was less stiff and easily bendable when compared to unconditioned miscanthus. This can be examined by seeing that the conditioned miscanthus cab be bent into any shape or angle and will remain there until it is bent back. The unconditioned miscanthus when bent will bounce back as soon as the bending force is removed.

The crimp conditioning method also sufficiently conditioned nearly every piece that was fed through and fully changed the crop's structural property. This could not be said about the steel roll conditioning as some pieces were left untouched and unconditioned. The crimp conditioner not only produces a shorter length crop but also greatly changes the shape and strength properties of the miscanthus pieces, which aids in the ability of the small square baler to pick up and bale the conditioned crop.

Both the crimp conditioned and unconditioned miscanthus pieces were baled using the same small square baler. The baler was able to pick up, feed and form a small square bale although the bale densities were less than traditional hay and forage crops. The unconditioned miscanthus was also harder to cut the side of the bale, as what happens when it is formed in the bale chamber, than the conditioned crop. This was observed when the baler was being operated and the knife door would open and close to form the sides of the small square bales. Smoother cut end sides of the small square bales were observed with the conditioned crop, than when compared to the unconditioned crop.

It was unclear if the smooth steel roll conditioning changed the bending properties and strength of miscanthus, when compared to unconditioned miscanthus. This was not quantified or examined because the steel roll conditioning methods did not produce an acceptable quality-of-conditioning at a large enough quantity. In a situation where miscanthus is in a field and still has its leaves attached, it is unclear whether the leaves could be conditioned and if they would be able to be baled with the miscanthus stalks; or if the leaves would become part of the mass that is lost during the harvest process. The energy consumed during the conditioning process was also unable to be measured. Therefore, additional tests to quantify this energy should be complete so as to determine the full energy balance during the process. Finally, subsequent bale compression tests were completed to quantify the benefits of conditioning miscanthus, when compared to unconditioned crop, to determine if conditioning can increase bale density.

Chapter 6 – Miscanthus Small Square Bale Compression

After the miscanthus conditioning and baling study, the bale compression study could begin. This section discusses the materials, methods and experimental design procedures to provide some background information and describe the testing. Subsequently, the results, discussions, conclusions and hypothesis testing are described.

6.1 Materials and Methods

The next phase of research was the compression of small square bales of miscanthus of two types; crimp conditioned miscanthus, from here on referred to as conditioned miscanthus, and unconditioned crop, which was cut to 0.4 meter lengths. A lab scale bale compressor, developed by Hofstetter (2011), was used to compress the small square bales of miscanthus. A description of the bale compressor and some additional modifications made since Hofstetter's work will be discussed.

The bale compressor is located in the Agricultural and Biological Engineering department on the main campus at The Pennsylvania State University. The bale compressor chamber in which the bales are placed can accommodate only small square bales with a standard width of 0.36 meters and depth of 0.46 meters. The maximum bale length that can be used is 0.86 meters. Figure 6.1 shows the bale compressor and the terminology used to identify the different faces of a bale for discussion purposes.

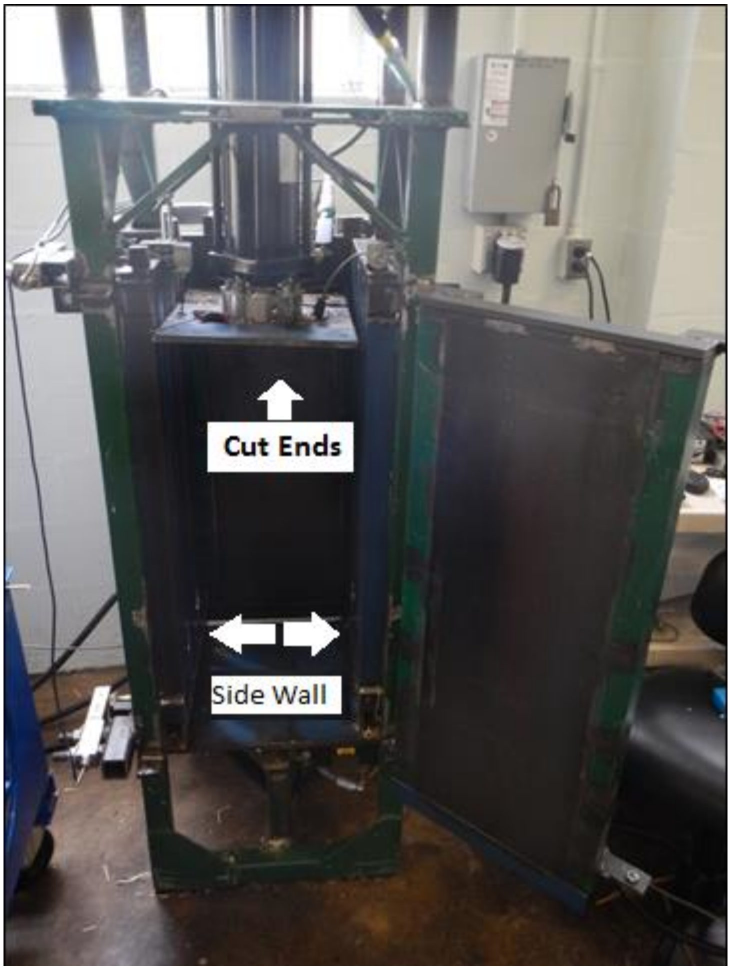

Figure 6.1 - Small square bale, bale compressor.

The bale compressor frame consists of the bale chamber, in which the bale is inserted, and also a hydraulic cylinder and compression plate. The hydraulic cylinder has a cylinder bore diameter of 0.13 meters and a max stroke length of 0.6 meters. If a small square bale with a length of 0.86 meters is inserted into the compression chamber, the maximum volume reduction that can be obtained as a result of the cylinders stroke length is 70 percent. The cylinder is rated at a maximum pressure of 20684 kPa and max load of 2600 kN. Hofstetter's (2011) work examined the structural properties of the frame to ensure that the frame can sustain the resulting forces and stresses during the bale compression process.

The bale compressor is hydraulically powered by a stand-alone hydraulic power pack, with a maximum hydraulic flow rate of 90 liters per minute and 24,130 kPa from the variable displacement hydraulic pump. The relief pressure was set at 20,680 kPa and the variable displacement pump was set to maintain 17,236 kPa. The power pack uses a three-phase, 208 volt electrical supply. A solenoid controlled directional control valve was used to direct flow to either the cap-end or rod-end of the hydraulic cylinder to either extend or retract the cylinder respectively. Pressure gauges and pressure transducers were used at each end of the cylinder to monitor hydraulic pressures throughout the compression process. A flow control valve was also located at both the cap end and rod end of the cylinder and was used to control both the extension and retraction speeds of the cylinder in a meter-out function. The extension and retraction speeds for these tests were set at 0.05 meters per second, under a no load situation. A simple speed test was completed to ensure the proper setting on the flow control valve was used. To achieve this speed, the flow rate from the hydraulic power pack is 38 liters per min.

In order to quantify the bale compression process, several measurement devices and data logging equipment were used. The vertical compressive force on the small square bales was measured using a load cell (Transducer Techniques model lpu-50k). This load cell was mounted to the compressive plate and the hydraulic cylinder and is the same load cell used by Hofstetter (2011) in his study. A potentiometer (Celesco model spl-25) was used to measure the vertical position of the compressive plate and its distance from the fully retracted position. This measurement device allows for the calculation of initial bale length, compressed bale length and the instantaneous position of the plate, at any point during the compression process. Beam load cells (Omegadyne model 296522sk) were used to measure the sidewall and cut end forces. Four load cells, one at each corner, were used on one of the cut end faces of the compression chamber. An additional four load cells were used at the four corners on one of the sidewall faces of the compression chamber. With these four load cells, the forces can be combined into one sidewall or one cut end force. Using four load cells was an accurate method of seeing changes in the total force, however, the exact location of the force or the distributed load profile cannot be determined. The usefulness of this data lies with knowing the maximum force and designing the sidewall or cut end bale chamber walls accordingly. For comparison purposes between conditioned and unconditioned crop, as well as successive compressions and different crops, the maximum force values are sufficient, without an exact known location.

To connect and obtain all the data from the measurement devices, a Campbell Scientific CR3000 data logger was used to collect the data as well as control the solenoid directional control valve, which operates the hydraulic cylinder with a Campbell Scientific Loggernet program. A manual start/stop/retract switch box wired into the data logger was used so that the operator could control the cylinder operation. The code for the Loggernet program, written in CRbasic code, controlled the operation of the cylinder and integrated the switchbox with the solenoid directional control valve. The data logger records a new data point every 0.15 seconds. The program also controlled the compression process which will be discussed further in later sections.

A bale scale was used to weigh the small square bales before and after compression, and also to measure the mass loss during the loading, compression and unloading processes. The wet basis moisture content of the bales at the time of compression was measured by obtaining samples from the bales and drying them in an oven for 24 hours at approximately 105 degrees Celsius. The mass of the sample into and out of the oven was recorded so that the percent moisture could be calculated.

6.2 Experimental Design and Testing Procedure

A complete bale compression cycle consists of an extension segment, a holding segment and a retraction segment, which obtained its name corresponding to what the cylinder is doing throughout the compression cycle. The cycle began once the data logging equipment and Loggernet program were running, and the hydraulic power pack was powered on. Before the extension segment, the cylinder was manually extended until the plate reached the top of the uncompressed bale, so that the initial bale length was recorded. After the extension segment was begun, by pressing the start switch, the cylinder moved from the initial position at the top of the uncompressed bale downward, while compressing the bale. From this point forward, the Loggernet program completely controlled the cylinder operations during the bale compression cycle, with no further manual controls being needed.

Once the cylinder reached the desired extension, in this case 0.58 meters, the cylinder stopped and the compression plate was held in its vertical position. The holding time during the bale compression cycle was defined as the amount of time that the compression plate was held in the fully extended position, with the bale being held at its smallest bale length or the highest possible volume reduction. This was the time between the cylinder extension and retraction segments. Once the desired holding time was reached, the cylinder retracted to its initial position. Once this occurred, the bale was allowed to bounce back for one minute. The bounce back is a relaxation of the biological materials in which the bale continues to get longer in length over a period of time, when the compressive force on the bale is removed. By keeping the compressive plate at full retraction for one min, the bale was allowed to fully relax and bounce back. Through experimental tests, it was found that the bale would bounce back no further after 45 seconds and therefore one minute was chosen. After this bounce back time, the cylinder was manually extended, to just reach the top of the bale. This provided a compressed bale length for future analysis purposes.

The bale compression tests consisted of two different conditioning types, namely conditioned miscanthus and unconditioned miscanthus, at two different holding times. This resulted in four different experimental treatments. Each bale that was compressed was a replication; therefore the number of bales compressed in each treatment was the number of replications completed. The first conditioning and baling test resulted in 10 conditioned bales and six unconditioned bales. These bales were compressed at a hold time of 2.5 minutes. The second conditioning and baling test resulted in six conditioned bales and seven unconditioned bales. These bales were compressed at a hold time of 5 seconds. A final test that produced six unconditioned bales with a hold time of 2.5 min was completed to consume all available miscanthus. Although it was desired to finish with the same number of bales in each treatment, the amount of crop available was less than desired and was exhausted sooner than expected. Figure 6.2 shows the treatments completed while table 6.1 shows the total number of bales produced and compressed in each treatment. The switchgrass tests will be explained further in the switchgrass section; however, these are included in table 6.1 and figure 6.2.

Table 6.1 - Total number of bales tested.

Crop Type	Hold Time [sec]	Number of Bales Tested
Fall Switchgrass	5	8
	30	6
	60	6
	150	6
Spring Switchgrass	5	6
	30	6
	60	6
	150	6
Conditioned Miscanthus	5	6
	150	10
Unconditioned Miscanthus	5	10
	150	7

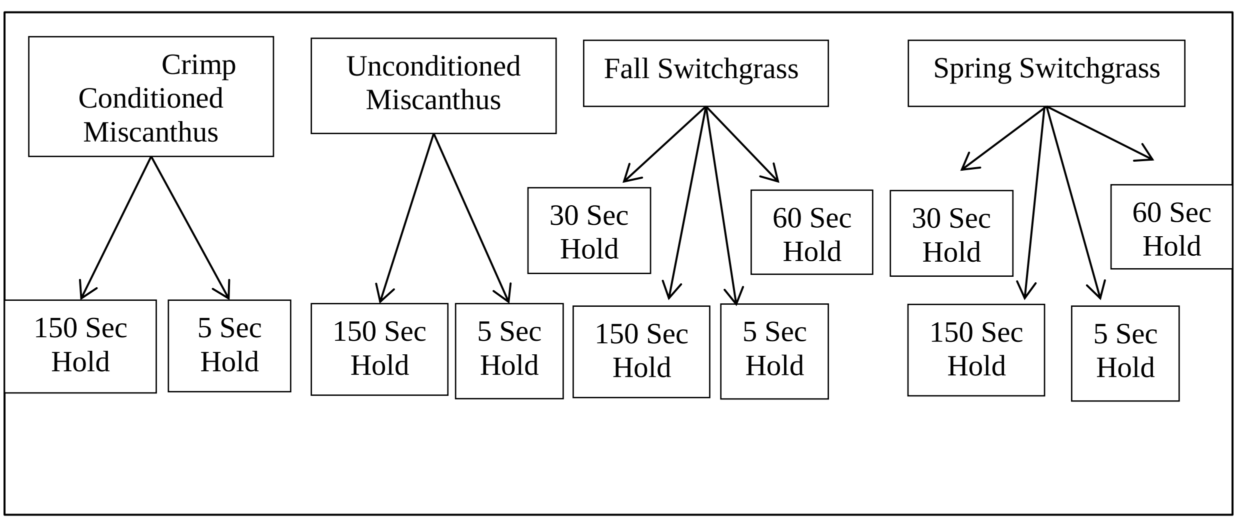

Figure 6.2 - Compression treatment diagram.

Within each bale of miscanthus, four complete compression cycles were completed. This was completed to examine the effects of multiple compressions on the subsequent forces and energy required to compress small square bales of miscanthus. Once a bale was loaded into the chamber, it went through the extension, holding and retraction segments and then was allowed to bounce back. The bale was then compressed again for a total of four complete cycles. Separate data logging files were taken for each complete cycle. Once the fourth cycle was completed, a new bale was loaded and compressed. Below is a detailed outline of the compression process.

1. Record initial bale weight
2. Load bale into the bale chamber
3. Extend the compression plate down to the very top of the bale
4. Start the data collection with CR3000 datalogger
5. Begin compression cycle by pushing the start button switch
6. Once the cylinder has extended, held and retracted, begin a timer for one min
7. Once the timer has reached one min and the bale has relaxed, manually extend the plate to the top of the bale to measure final relaxed bale length
8. Shut off data logger and collect the data
9. Repeat steps one through eight for the subsequent cycles
10. Remove the bale from the bale chamber
11. Record final bale weight
12. Collect losses on the ground to ensure mass is balanced
13. Collect a moisture sample and record the mass
14. Place moisture sample into the dryer and remove and weigh after 24 hours

6.3 Data Processing

After collecting data from the Loggernet program, Excel was used to import and begin processing the compression cycle data. A separate file for each compression cycle was collected, and therefore was processed individually. Each data file was named according to the type of conditioning, holding time, bale number and cycle number. Within a single data file from the data logger, several measurements were recorded.

1. Time (seconds)

2. Cylinder displacement (inches)
3. Main compressive force
4. Sidewall forces one through four
5. Cut end forces one through four
6. Moving key (shows what step of the cycle each data point is in)

Several macros in excel were developed to import, format and calculate several values for further analysis. The use of macros helped ensure that each data file was processed in the same way; to aid in consistency and decrease processing time. The only manual inputs to the results spreadsheet required were the bale weight and moisture content. Moisture content was measured and used in all calculations by using the corresponding bale's dry mass, so as to remove any variations in the results due to moisture content. At the completion of the macro sequence, all the desired calculations and values were found in both metric and English units. A sample results spreadsheet can be seen in Appendix A.

The results were categorized into four categories: summary information, compression information, holding time information and density analysis. The summary information section contains the initial mass, final mass, mass loss, and dry mass calculation, by using the measured moisture content for the particular bale. The summary section also includes the initial, final, compressed and relaxed bale lengths, as found from the potentiometer readings in the raw data file, by using the moving key to identify when the cylinder reaches these lengths. The compressed bale length is the length of the bale, once the compression cycle has reached the holding phase; the relaxed bale length is length of the bale after it has been allowed to relax for one minute after the retraction phase of the compression cycle. As a function of these bale lengths, along with bale mass and the standard small square bale width and depth, the initial, compressed and relaxed bale volumes and densities were calculated. The volume reduction between the initial and compressed volumes, as well as the density increase, was also calculated.

The compression information section contains calculations and values for only the time that the cylinder is extending and the bale is being compressed. For the vertical compressive force, sidewall forces and cut end forces, the maximum, minimum and average forces were calculated. The distance traveled during the compression cycle, as well as the time taken to do so, produced an average compression speed which varied slightly between bales. In addition, the peak power, energy consumption and specific energy were also calculated.

Peak power during the compression cycle was defined as the maximum power consumption when each instantaneous power value was compared. The instantaneous power equation can be seen in equation 9 in Appendix B, where the instantaneous force (F) is the main compressive force at a particular data point, d is the distance travelled by the compressive plate from the previous data point to the current data point, and Δt is the time between data points which was 0.15 seconds.

Energy consumption was found by using equation 10 in Appendix B; integrating force and displacement with respect to time. Energy was calculated for the compression segment, only while the cylinder was moving downward and compressing the bale. The force on the compression plate was d multiplied by the displacement distance from the potentiometer. The trapezoidal method for numerical integration was used to calculate the accumulated energy for the compression process. To minimize the effects of variances in bale weights, the specific energy, shown in equation 11 in Appendix B, was found by taking the energy from the compression segment and dividing by the dry mass of the bale.

The holding information section of the results section shows the time in which the bale was held in the fully compressed length, as well as the maximum, minimum and average compressive, sidewall and cut end forces. The final section of the compression results is the density analysis section. After each bale was compressed, the initial and compressed bale densities were examined for overlaps. In order to compare the forces, pressure, power and energy consumption between bales, a common density range was selected so that each bale was compared in the same way, to minimize the effects of differences in bale weights, initial volumes or densities. The common range between each bale which was selected was 107-180 kg/m^3. Although this range was used to eliminate variance between bales, the full compression range was used in some analyses as well. The density analysis section of the results includes maximum, minimum and average compressive force as well as peak power, energy consumption and specific energy.

6.4 Results and Discussion

The first set of results obtained was the summary data of all of the bales used. The average dry weight of the conditioned miscanthus bales was 11.33 ± 1.08 Kg while the unconditioned miscanthus bale weight was 10.29 ± 1.28 Kg. This is much less than the average weight of other crops, for example alfalfa and switchgrass, which can be upwards of 20 Kg in weight. The average moisture for all the miscanthus bales was 12.18 % ± 1.96 %, and did not statistically change when the conditioned crop was compared with the unconditioned crop. By knowing the moisture percentage, on a wet basis, the dry weight of the bales was used in further calculations. Although the weight of the conditioned miscanthus bales was slightly heavier than the unconditioned miscanthus bales, this did not consider the length of the bales, which also varied slightly and does not consider the length of the bales.

6.4.1 Initial Compression Cycle Evaluation

In order to evaluate bale densities, the benefits of conditioning miscanthus before baling, as compared to unconditioned miscanthus, were examined by compressing the bales using the lab scale bale compressor. The weight of each bale used was recorded as well as the initial and compressed bale densities. From this, the corresponding volume reduction and density increase was calculated. Table 6.2 shows the summary values for the first complete compression cycle. The final row in the table tests for a difference in means between the total conditioned miscanthus and total unconditioned miscanthus bales, using an analysis of variance (ANOVA) at a confidence level of 95%. Therefore, any p-values less than 0.05 are statistically significant. The bolded values have statistically different means.

Table 6.2 - Miscanthus compression, cycle one summary.

	Hold Time	Dry Weight	Volume Reduction	Initial Bale Density	Compressed Bale Density	Density Increase	Percent Moisture
Average Values	sec.	Kg	%	Kg/ m^3	Kg/ m^3	Kg/ m^3	% D.B.
Conditioned	5	11.60	61.12	98.66	253.90	155.24	10.67
Unconditioned	5	11.35	60.83	95.47	244.78	149.31	11.13
Conditioned	150	11.17	62.69	91.22	245.94	154.71	11.45
Unconditioned	150	9.47	58.66	85.61	207.30	122.53	14.37
Conditioned	total	11.33	62.10	94.01	248.92	154.91	11.16
Unconditioned	total	10.29	59.61	89.93	224.17	134.24	12.95
ANOVA P-value		**0.019**	**0.030**	0.133	**0.009**	**0.009**	0.304

From table 6.2 it can be seen that the average dry weight of the conditioned small square bales was slightly higher than that of the unconditioned bales, directly after baling. The initial bale density of the conditioned bales is also slightly higher than that of the unconditioned bales, but not statistically different. This is a result of the unconditioned bales being slightly shorter, because the small square baler used to make the bales was able to pack the conditioned bales tighter. The compressed bale density is the density of the bale once it is in the fully compressed state of the first compression cycle. The conditioned bales were able to be compressed tighter and reach a statistically higher compressed bale density (24.75 Kg/ m^3) as well as a higher density increase (20.67 Kg/ m^3) and volume reduction (2.5 %) .

6.4.2 Energy, Specific Energy and Power

During the compression process, the energy, specific energy and power were calculated from the measurements taken. As seen in table 6.2, there are slight differences in bale weights, compressed densities and density increases. This could skew the results for compressive force, peak power and energy requirements. In order to compare conditioned miscanthus and unconditioned miscanthus bales and reduce the slight differences in bale length and weight, a common density range was used in which each bale was compared over that range only. This is because initial and final densities are different between each bale, thus a common density range was selected for comparisons. Table 6.3 shows the average values for the compressive force, peak power, energy and specific energy for both the conditioned and unconditioned miscanthus bales, across the 107-180 Kg/m^3 common density range for the first compression cycle. Specific energy, another method of eliminating the differences seen in the forces and energy caused by using bales with slightly different initial densities and weights, is also shown.

Table 6.3 - Miscanthus compression summary values, over a common density range.

Average Compression Data Over the Common Density Range (107-180 Kg/m^3)				
	Peak Compressive Force	Peak Power	Energy	Specific Energy
Average Values	N	kW	kJ	kJ/Kg
Conditioned Bales	7,549.03	1.00	1.91	0.17
Unconditioned Bales	12,003.94	1.41	2.79	0.27
ANOVA P-Value	**0.00**	**0.00**	**0.00**	**0.00**

From table 6.3, we can see that the averages for conditioned miscanthus are less than that for unconditioned miscanthus, for each of the four parameters examined. All of the p-values from the ANOVA testing are less than 0.05 and therefore we can conclude that they are statistically different. The average compression force is approximately 6,000 N less for the conditioned miscanthus, than the unconditioned miscanthus. This is extremely beneficial because it can decrease excess wear on machines and possibly require smaller sized machine components. The peak power during the compression process is directly related to the maximum force seen during this time. Similar to the average compression force, the average peak power is significantly less for the conditioned miscanthus bales, as compared to the unconditioned miscanthus bales.

In order to further examine the differences during the compression process, the energy and specific energy were examined. The energy and specific energy calculations utilize each data point collected during the compression process and integrates the area under the force vs. displacement curve, with respect to time, during the common density range. Therefore, this calculation is influenced much less by one individual force recorded and uses each data point to sum the total area under the curve for the total compression cycle energy. The energy and specific energy is a more accurate comparison than simply average force or even peak power because it uses the entire process in calculation. As seen in table 6.3, both the energy and specific energy during the compression process is significantly less for conditioned miscanthus than unconditioned miscanthus.

Although the common density range was used to more accurately compare the conditioning types during the compression cycle, the compressive force, peak power, energy and specific energy was also calculated for each bale during the individual density range. Table 6.4 shows the averages for each individual bale's entire density range.

Table 6.4 - Miscanthus compression summary values, over the full density range.

Average Compression Data Over Each Bale's Full Density Range				
	Peak Compressive Force	Peak Power	Energy	Specific Energy
Average Values	N	KW	KJ	KJ/Kg
Conditioned Bales	14,603.75	2.51	6.21	0.54
Unconditioned Bales	15,851.65	2.33	6.20	0.58
ANOVA P-Value	0.527	0.374	0.982	0.482

This analysis disregards the differences in initial bale density and final bale density between bales, as well as the differing bale weights and volume reductions. Although the specific energy alleviates some of these differences, by showing the energy for the entire bale compression per unit mass, the amount of change in mass is not enough to show a difference for the full density range. The ANOVA p-values are all statistically insignificant, which explains there is not a difference in means for this data, over the entire compression range. This justifies the reason for looking at the parameters shown in the table, over a common density range, because a stronger conclusion can be obtained. The conditioned miscanthus, although it consumes much less energy and has lower forces at a common density range, is closer to equal to the unconditioned miscanthus when looking at the full bale compression for each individual bale. This is believed to be because the conditioned bales have more mass and are compressed to a statistically higher compressed bale density.

To help understand the compression process in the bale compressor for one cycle, figure 6.3 shows the relationship between compressive force and time. The secondary axis shows the coding for the cycle segment that is used to show the cylinder extension, holding, retraction and resting or unused data segments. The force greatly increases during the extension segment, which is coded with a “1” on the secondary axis. During the holding segment, the force exponentially decreases, which is coded with a “0” on the secondary axis. This is because the compression plate is not moving and the materials are beginning to relax and push less on the plate while beginning to stick together more easily. Finally the force drops to zero during the retraction phase, which is coded with a “2” on the secondary axis. The coded variable “3” indicates the prep time in between cycles when no useful data is being obtained.

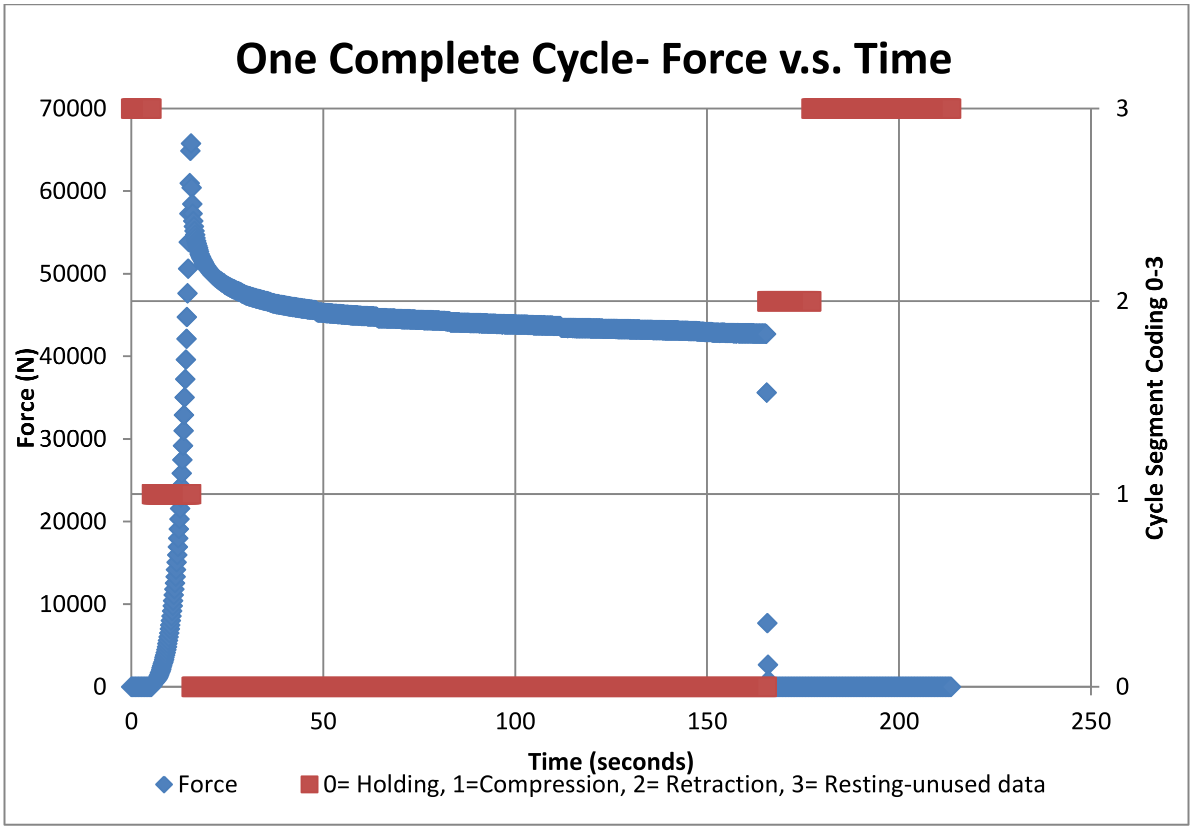

Figure 6.3 - Force and time relationship for one complete cycle.

The energy during the compression cycle, as reported so far, has been for the first compression cycle, for each bale, as it is the most representative of the true small square bale making process in field operations. However, especially with a large square baler, multiple compression cycles in which the bale is packed tighter by subsequent compression forces, is more realistic. The benefit of examining the energies across multiple compression segments was that by the end of cycle four, any slight variation due to differences in biological materials is more likely to be eliminated. That is, by if some chance, a few individual pieces of miscanthus within the bale were not compressed fully in cycle one, by cycle four they are more likely to be fully compressed and would contribute to the total energy consumed.

In this testing, each bale completed four complete compression cycles. Figure 6.4 shows the specific energy for each compression cycle and also shows the total specific energies for the four cycles combined, which is found by looking at the top line value of the bar chart because the graph bars are stacked from cycle one through cycle four and are additive..

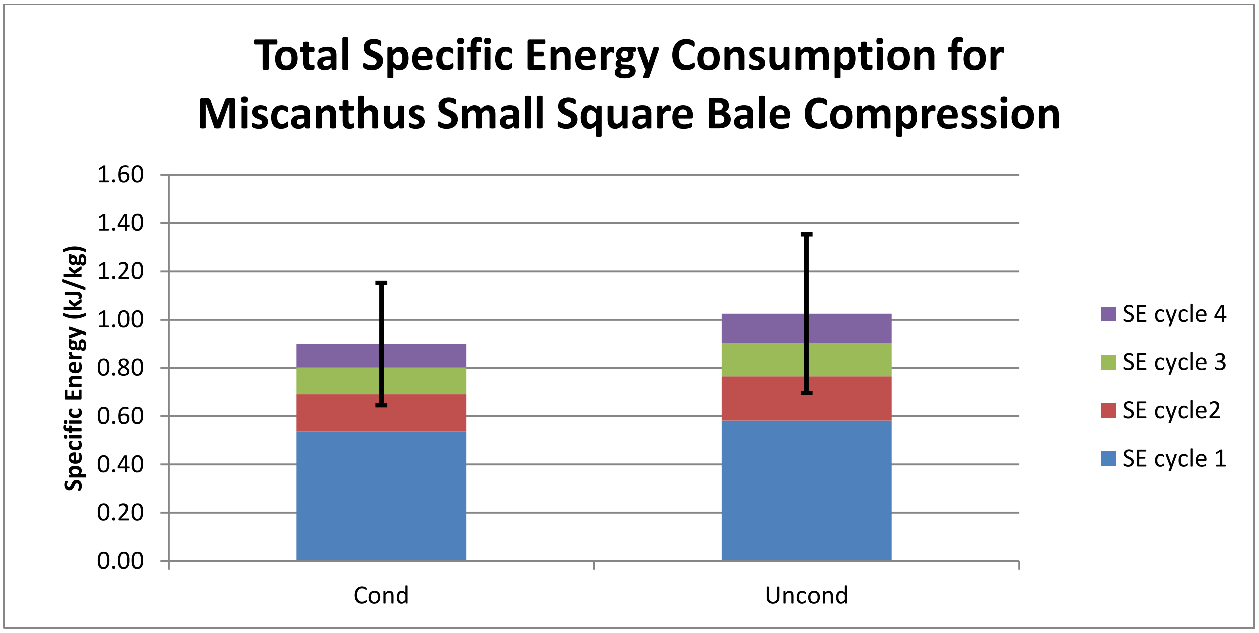

Figure 6.4 - Total specific energy consumption for miscanthus.

For subsequent cycle analyses where all four cycles are compared, it is extremely difficult to evaluate cycles 2-4 over the same density range, therefore the data will be presented for the entire compression range. In this case, for the same density range, unconditioned miscanthus has statistically higher values then conditioned miscanthus and as the whole range is used, the conditioned miscanthus values become higher because of their higher initial and compressed densities as well as initial bale weight.

When looking at the specific energy during the successive compression cycles, it can be seen that the specific energy greatly decreases from cycle one to cycle two and continues to decrease in the third and fourth compressions; however, at a slower rate. After the first compression cycle, the crop fibers are broken and more flexible, which results in much less specific energy consumption over a shorter time. Miscanthus bales inherently contain a large amount of air. This is because of the individual pieces for ability of being stacked and packed together and is seen in the low bale densities that were obtained. In addition, after the first compression, the bale length is shorter which results in a shorter compression time and smaller specific energy value because energy is calculated by integrating with respect to time. When the total specific energy summed across all four cycles is examined, it can be seen that the average for the conditioned miscanthus bales (0.17 ± 0.04 KJ/Kg) is less than that of the unconditioned miscanthus bales (0.27 ±0.04 KJ/Kg).

As mentioned, drawing conclusions when using the entire compression density range can be skewed because the conditioned miscanthus bales begin to proceed toward being equal to the unconditioned miscanthus bale values. Nevertheless, in this case using the full density range, a slightly decreased total energy consumption is still seen for conditioned miscanthus bales although it is not a statistically significant difference. Comparing the energy values for each subsequent cycle over a common density range would help prove this and could make the conclusion statistically significant. This analysis could not be done in our case, because the small square baler cannot produce a large enough common density range.

6.4.3 Bale Relaxation

For both the conditioned and unconditioned miscanthus bales, the amount of relaxation after each cycle was measured and analyzed. The bale was allowed to relax for one minute, after a complete cycle was finished, and then the relaxed bale length was recorded. After this measurement, the next successive cycle was begun. The amount of bale relaxation can vary between different crops, because it is a function of crop properties such as the stiffness, wall thickness and Poisons ratio. The purpose of this study was to examine if conditioning miscanthus, in a way that significantly alters the structural shape and property of the crop, would result in a decreased amount of relaxation. Two different holding times (the amount of time the cylinder is held in the fully extended position before retraction begins) was also used to examine the effect of holding time on bale relaxation.

The percent volume reduction for the relaxed bale lengths of both conditioning methods as well as both holding times can be seen in figure 6.5. Table 6.5 shows the values of the percent volume reduction that corresponds to the graph for further comparison purposes in subsequent sections of this thesis. The relaxed bale volume uses the relaxed bale length, as measured once the bale was allowed to relax, and/or bounce back for one minute. The percent volume reduction is the percentage of the initial bale volume that was reduced or eliminated, as a result of the bale compression cycle, by knowing the relaxed bale volume. Therefore, a higher percent volume reduction results in a smaller bale which is beneficial and can be related to decreased transportation costs. A high volume reduction also means that there is less pressure and force placed on the new strings used to tie off the bale in its compressed state. The percent volume reduction calculation removes the effect of varying initial bale lengths, after the bale was baled with a small square baler, and allows conclusions to be drawn by essentially normalizing the results.

Table 6.5 - Miscanthus relaxed bale percent volume reduction.

	Relaxed Bale Percent Volume Reduction Cycle 1	Relaxed Bale Percent Volume Reduction Cycle 2	Relaxed Bale Percent Volume Reduction Cycle 3	Relaxed Bale Percent Volume Reduction Cycle 4
	% of Initial Bale Volume	% of Initial Bale Volume	% of Initial Bale Volume	% of Initial Bale Volume
Unconditioned- 5 sec hold (purple)	25.02	28.14	28.17	29.76
Conditioned- 5 sec hold (Green)	30.33	33.34	34.26	35.00
Unconditioned- 150 sec hold (Red)	27.09	29.53	30.96	32.25
Conditioned- 150 sec hold (Blue)	39.22	41.37	43.74	42.85

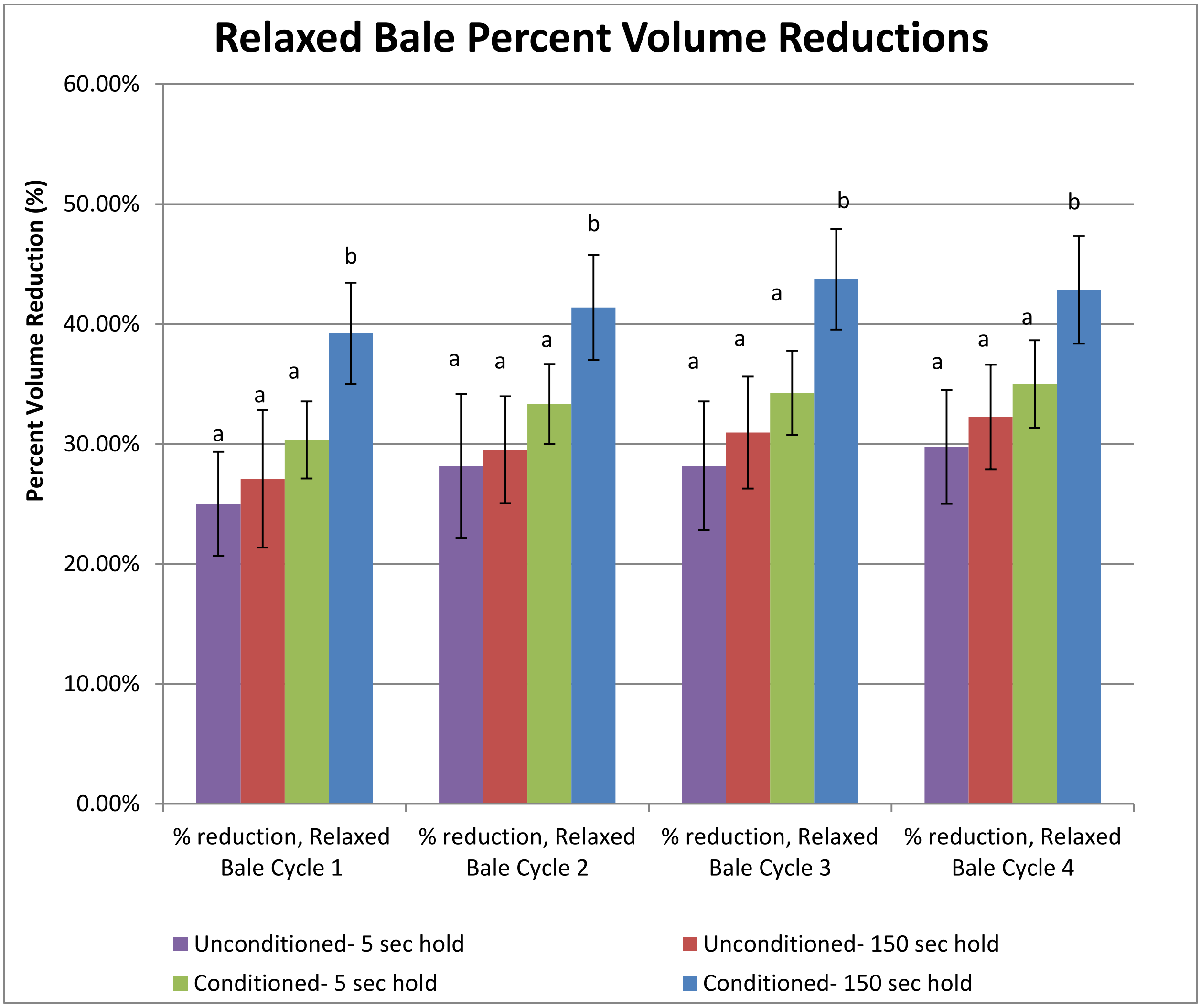

Figure 6.5 - Miscanthus relaxed bale percent volume reductions.

From figure 6.5, two analyses can be completed; the first being the examination of the relaxed bale percent volume reduction when the hold time is held constant and the second comparing the conditioned miscanthus bales to the unconditioned miscanthus. The second analysis is holding the conditioning type constant and comparing the difference in percent volume reduction, due to holding time. In figure 6.5, different letters above the bars indicate statistical differences.

When the holding time is held constant, the results show that for a holding time of 150 seconds, the conditioned miscanthus bales achieve an approximately 10% higher average relaxed bale percent volume reduction than the unconditioned miscanthus bales. This was statistically confirmed with an ANOVA analysis.

For a hold time of 5 seconds, the conditioned miscanthus bales achieve an approximately 5% higher average relaxed bale percent volume reduction than the unconditioned bales. By completing an ANOVA analysis, this was not statically different, at a 95% confidence interval. However, additional testing and lowering the confidence interval could result in a significant result, at a hold time of 5 sec. This explains that for miscanthus, the longer the bale is held in the fully compressed length and position, the relaxation distance will be shorter and the percent volume reduction will be higher. This is intuitive because the longer the bale is in the fully compressed form, the crop fibers are held under higher force for longer. This allows for the bale to stay together easier when the load is removed, and thus a shorter relaxed bale length is achieved.

When the type of conditioning is held constant and conditioned bales are examined, the 150 second holding time resulted in an average 8% increase in relaxed bale percent volume reduction as compared to the five second hold time. The ANOVA test concludes that the means are statistically different and the 150 second holding time results in a higher relaxed bale volume. For unconditioned bales, the 150 second holding time resulted in an average 3% increase in relaxed bale volume as compared to the five second hold time and the ANOVA test cannot statistically conclude that there is an increase in relaxed bale percent volume reduction.

The conditioned miscanthus bales have a greater potential for increased relaxed bale percent volumes reduction, as compared to unconditioned miscanthus bales. The relaxed bale percent volume reduction can also be compared from compression cycle one thru compression cycle four, for each bale. As each successive compression is completed, the relaxed bale percent volume reduction is increased and therefore the relaxed bale length is shorter as additional compression cycles are completed. The increase for conditioned bales from cycle one to cycle four is on average 4.5% where unconditioned bales is on average 2.8%. The amount of increase from cycle one to cycle four is statistically similar regardless of hold time, although, the initial and ending percent volume reductions themselves are different. Therefore, to conclude, the benefits of completing successive compressions for conditioned miscanthus will be greater than that for unconditioned miscanthus.

Examining the bale relaxation, by means of the relaxed bale percent volume reduction, is important in understanding the benefits that conditioning miscanthus can provide. Often times, when bales of agricultural materials are made, there is tension on the strings used to tie off the bales. The material's desire to bounce back and relax is the cause of the tension on the string or twine. This tension can result in bales breaking or changing shape, due to the string or twine breaking or moving. When breaking happens after a bale has been stacked in a wagon or in a barn, the stack of bales can fall over. This can be a costly, time-consuming and dangerous problem for farmers. For miscanthus, an increase in percent volume reduction was, on average, 10 percent higher for conditioned miscanthus with respect to unconditioned miscanthus. In addition, the average difference in relaxed bale length between conditioning types was approximately 0.4 m with the unconditioned miscanthus bales being longer. Unconditioned bales of miscanthus are more likely to place additional tension on bale strings or twine and cause breakage, because these bales want to relax and bounce back significantly further than conditioned bales. Conditioned bales of miscanthus compress and stay compressed significantly easier than unconditioned miscanthus bales.

6.4.4 Complete Cycle and Further Holding Times Analysis

For miscanthus bales that were conditioned and unconditioned, two different holding times were used to examine the effects of holding time between the extension (compression) and retraction phases. As discussed on section 6.4.3, holding time has a significant effect on the relaxation distance or the amount of bounce-back after the compression plate is retracted. Additionally, there are effects of holding times that can be seen when examining all four compression cycles, which were completed for the same small square bale. The successive compression cycles, the cycles after the first compression cycle, are affected most by the holding time.

In order to understand the effect of successive compressions, another graph showing the relationship between force and displacement was made. Figure 6.6 shows cycles one through four, with respect to displacement, for one conditioned bale. In this case, the displacement is measured from the top of the bale compression chamber. Therefore zero displacement corresponds to a bale length of 0.8 meters, while fully compressed would correspond to 0.2 meters respectively. The horizontal axis in the figure shows displacement from zero (cylinder fully retracted) to 0.6, which is the fully extended compressive plate displacement. From the figure, the trend that shows the maximum force decreasing for subsequent compressions can be seen, along with the decreased area under each curve for subsequent compressions; this is the amount of energy consumed during each cycle. The first compression cycle consumes the most energy and contains the highest peak force value.

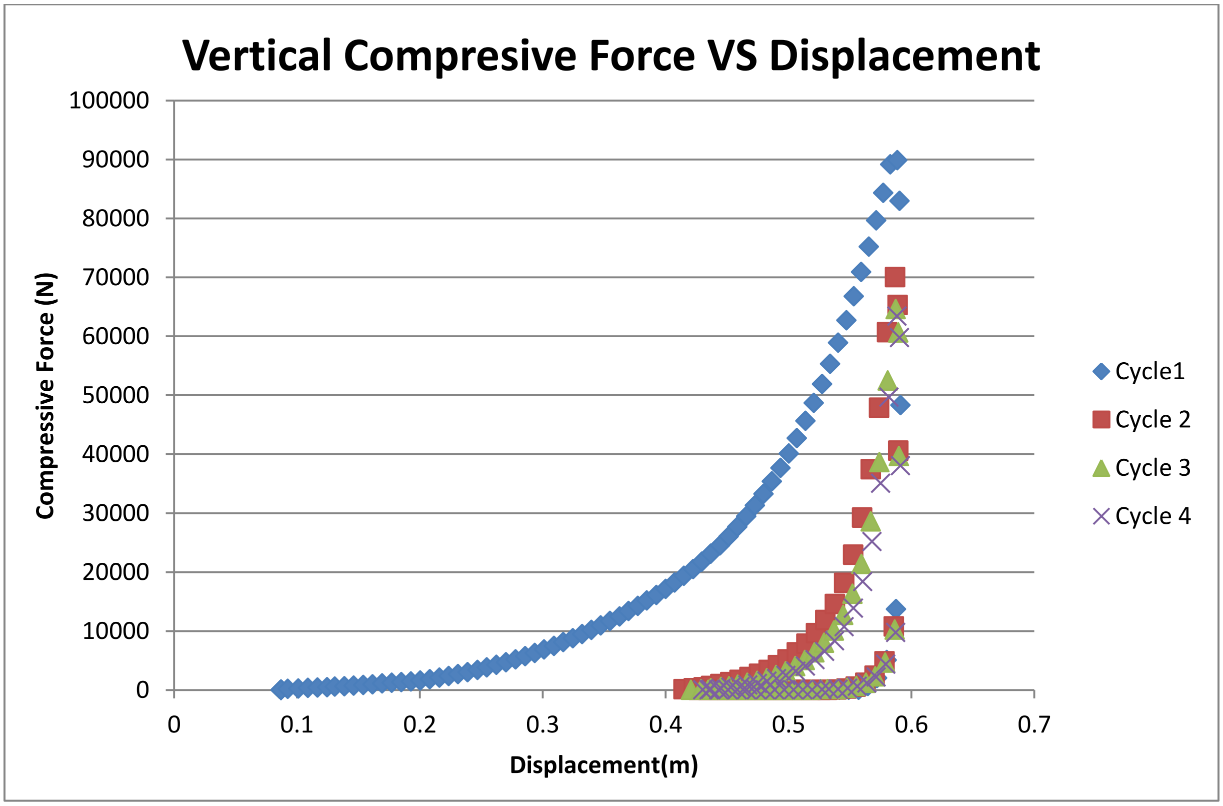

Figure 6.6 - Force and displacement relationship for one conditioned miscanthus bale.

Figure 6.7 shows the relationship between force and time. In this figure, each cycle is shown along with the holding time. During the holding and retraction segments, the forces are decreasing exponentially from a maximum value, which is seen as the bale reaches its fully compressed length, until the compression plate is removed from contact with the bale. It is interesting to see that during the holding period, while the plate is not moving, there was a stress relaxation where the forces decreased instead of remaining relatively constant throughout the entire holding segment. A similar exponential decrease in each of the four cycles holding periods is seen, although the magnitudes of the forces are different in each of the four cycles.

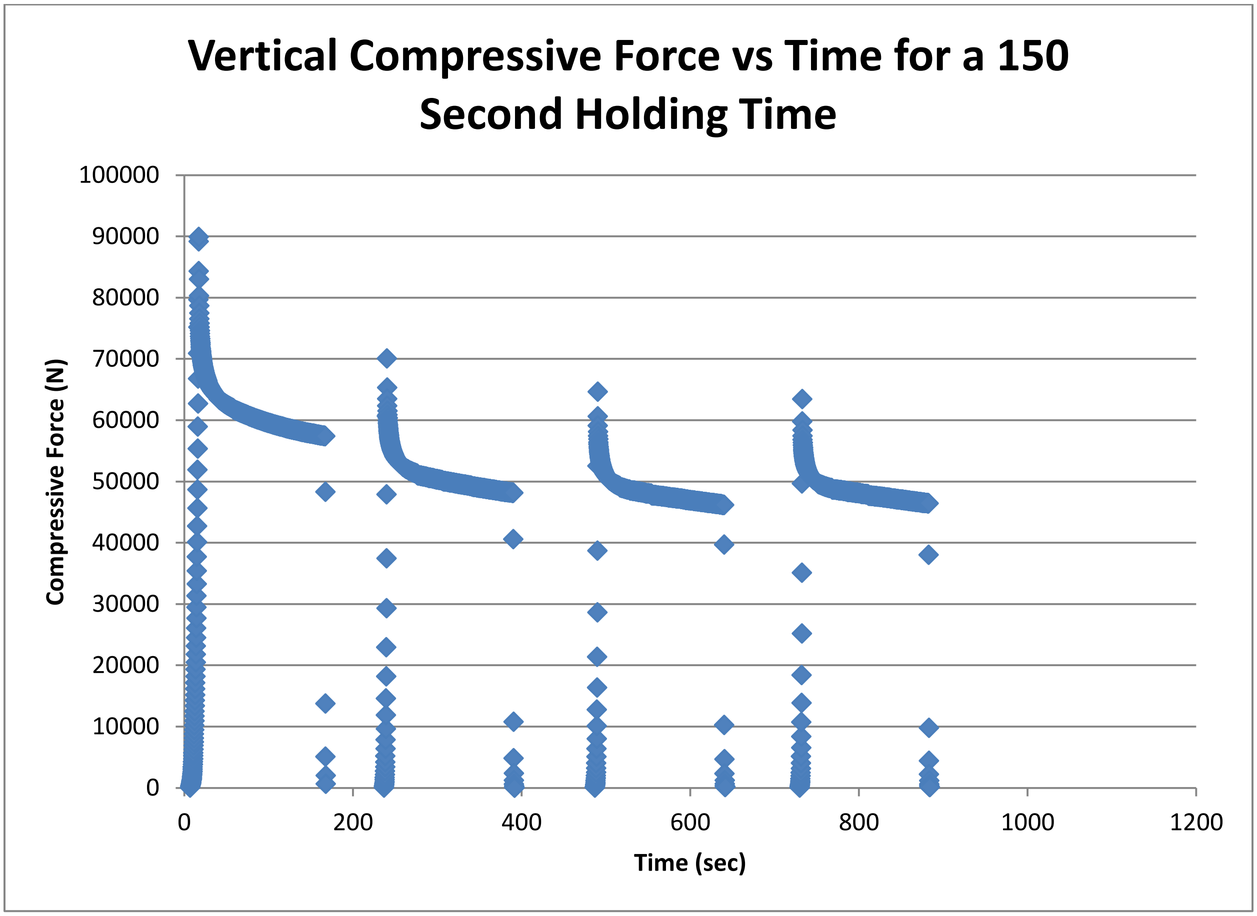

Figure 6.7 - Force and time relationship for one miscanthus bale compression full cycle.

In figure 6.8, the peak power and specific energy analyses for a conditioned bale are used to compare, evaluate and examine successive compression cycles for miscanthus bales. The figure compares each of the four compression cycles to show the relationship between subsequent cycles. Both conditioned and unconditioned miscanthus compression result in a similar pattern in which the subsequent cycle values decrease as more compressions are completed.

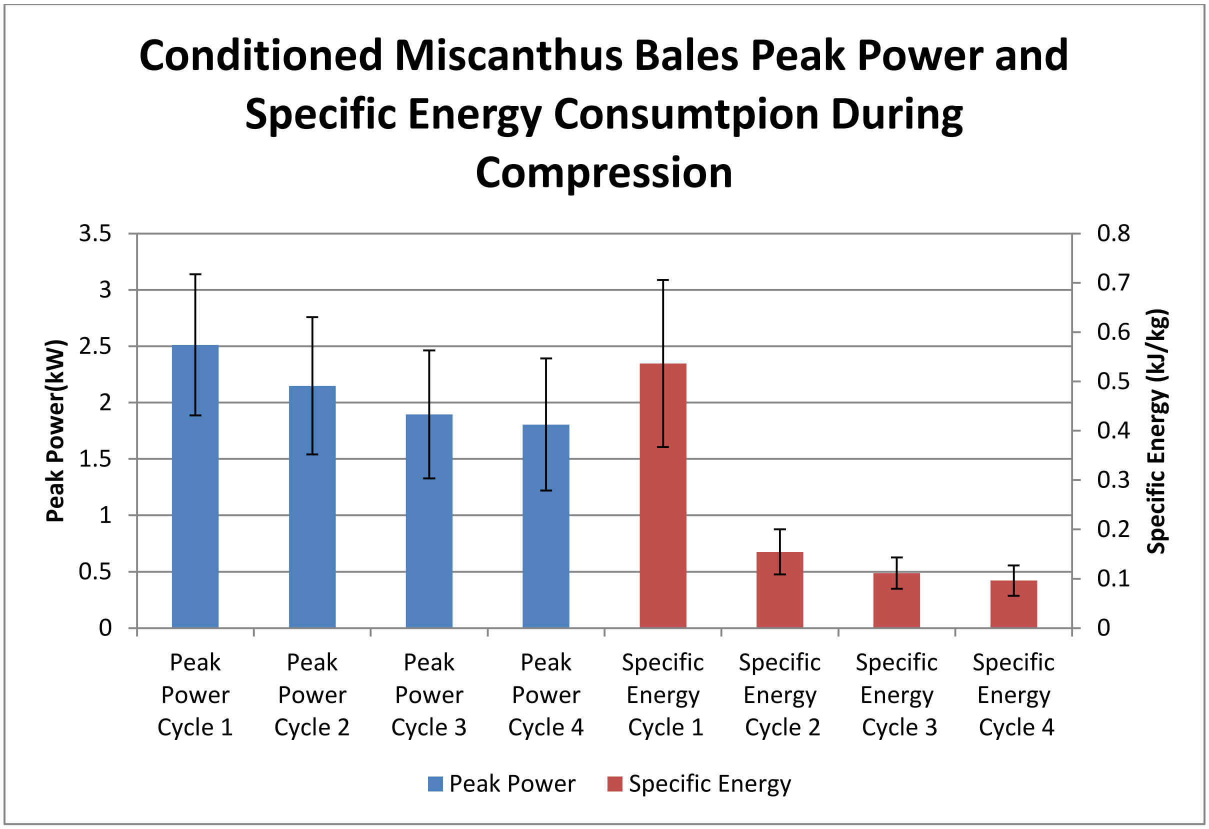

Figure 6.8 - Peak power and specific energy for conditioned miscanthus bales.

For peak power, a steady decrease can be seen from cycle one to cycle four. The unconditioned miscanthus bales show the same pattern as the conditioned bales. A dramatic drop is seen between the specific energy for cycle one with respect to cycle two. This is likely because of the longer compression time required for cycle one. The second compression traveled approximately 60 % of the distance that the first cycle did because the bales will relax to about 40 percent of the initial height. This, along with the decreased forces with respect to cycle one, results in a much sharper drop off between cycle one and two for specific energy. However, the decrease from cycle two through four is comparatively small.

As mentioned before, another key parameter in the miscanthus testing was holding time. Figure 6.9 shows the effects of holding time on the peak power and specific energy consumption, by examining all four compression cycles for a conditioned bale. In this case, each parameter was evaluated by taking each successive cycle value as a percentage of the value for cycle one. For example, peak power cycle two, as a percentage of cycle one, is the average peak power for cycle two divided by the average peak power for cycle one for an individual bale. This method of analysis removes differences in individual bales caused by higher bale weights and initial densities for cycle one. The average across all bales is then shown in the graph. This also removes some variation due to different density ranges during compression.

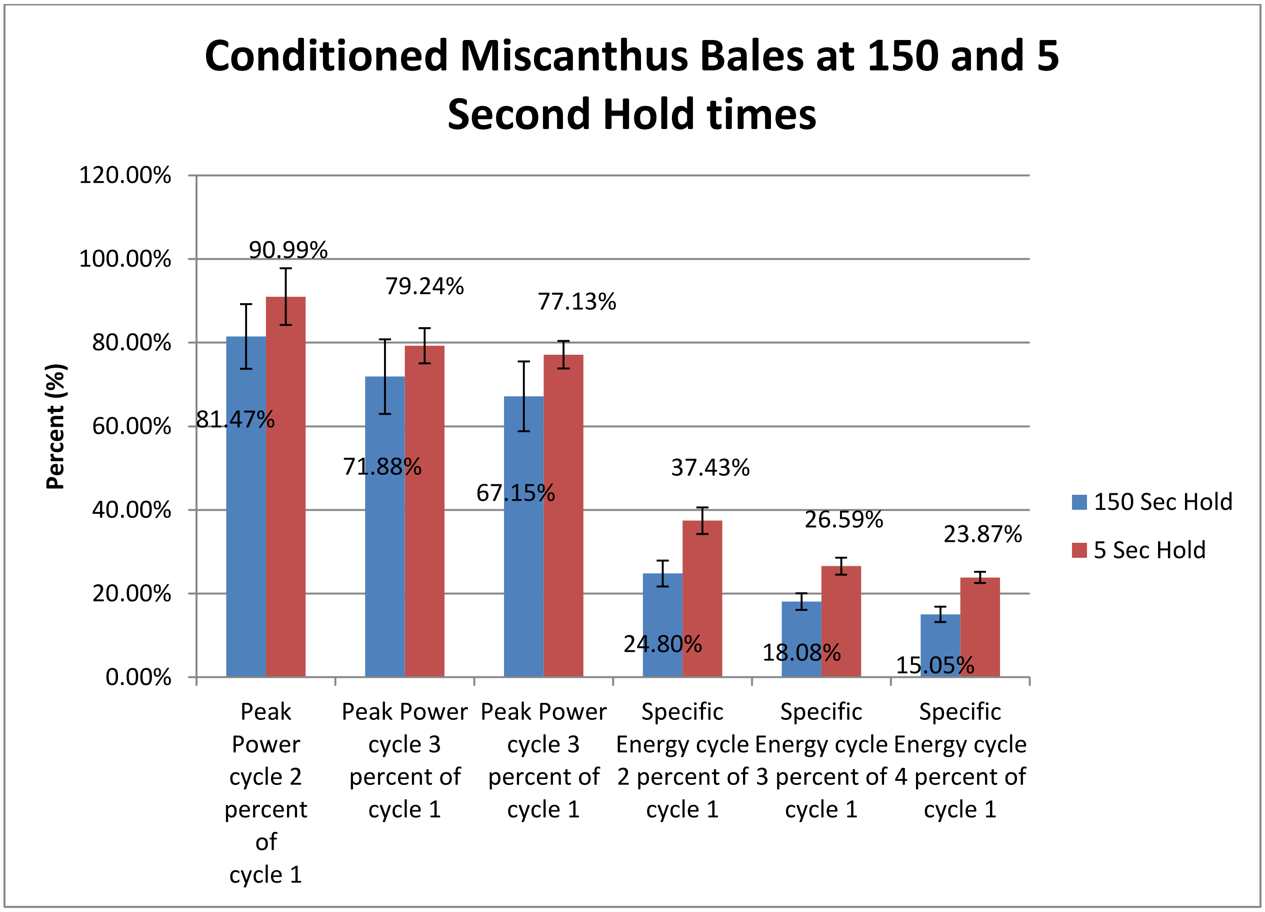

Figure 6.9 - Holding time comparison for conditioned miscanthus.

Table 6.6 - Conditioned miscanthus peak power and specific energy ANOVA results for a difference between 150 and 5 second holding times.

	Peak Power cycle 2 percent of cycle 1	Peak Power cycle 3 percent of cycle 1	Peak Power cycle 4 percent of cycle 1	Specific Energy cycle 2 percent of cycle 1	Specific Energy cycle 3 percent of cycle 1	Specific Energy cycle 4 percent of cycle 1
ANOVA P-VALUE	0.026	0.080	0.015	0.000	0.000	0.000

From figure 6.9, it can be seen that the longer hold time (150 seconds) results in lower average peak power and specific energy (as a percentage of cycle one) for the subsequent cycles, as compared to a shorter (five seconds) hold time. A lower percentage on the vertical axis represents a greater decrease in the amount of power or specific energy required, with respect to the first cycle, and higher percentages are closer to the value of the first cycle. An ANOVA summary found in table 6.6, showing the p-values, shows that the means, when testing for a difference between 150 and 5 second holding times in one cycle, are statistically different.

In this analysis, we can see that the successive compressions cost less in terms of force, power and energy for the longer holding time, when compared to the shorter hold time; this shows the benefit of longer holding times. Increased holding time does not require any additional power input, other than the no load operating power consumed by the hydraulic system, because the hydraulic cylinder is locked by the directional control valve. This means that no additional energy is consumed by the compression plate when holding for 150 seconds as compared to five seconds. Because longer holding times decrease the cost of subsequent compressions, as compared to shorter holding times, the other benefits of longer holding times such as bale relaxation become more favorable.

6.4.5 Sidewall vs. Cut End Forces Comparison

The compressive force placed on the bale by the plate attached to the hydraulic cylinder in the bale compressor is the largest force during the bale compression process and also consumes the most energy. However, the bale places a reactionary force on the sidewall and cut end sides of the bale compressor chamber, as a result of the compressive force and the volume reduction process. These forces are critical to machine design because, in a baler, these walls help form the bale and must be able to withstand the reactionary forces during the bale making process. During the miscanthus bale compression process, the sidewall and cut end forces were examined so that they could be compared and analyzed as well as related to the bale forming process within the baler.

The first analysis compared the differences in the average sidewall and cut end forces, during the entire compression cycle for both conditioned and unconditioned miscanthus to determine which force is greater and the magnitude of the difference. For miscanthus, the average cut end force was greater than the sidewall force for all bales tested, regardless if conditioning was used. Figure 6.10 and 6.11 show the relationship between sidewall and cut end forces for both conditioned and unconditioned miscanthus.

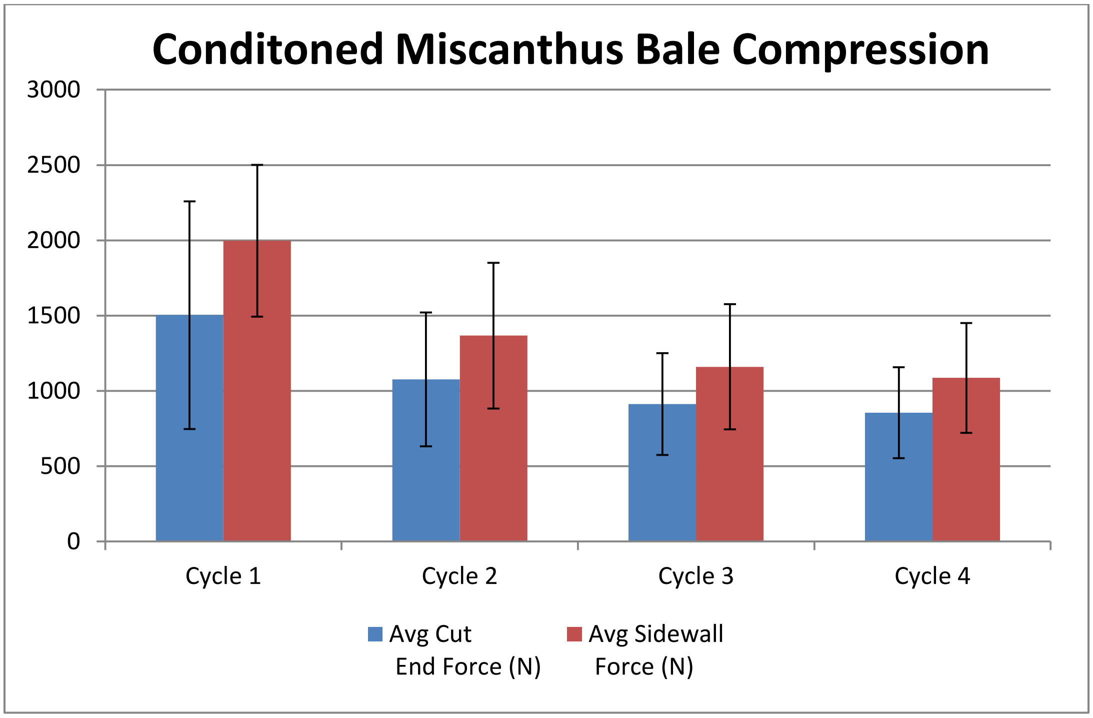

Figure 6.10 - Sidewall and cut end forces for conditioned miscanthus.

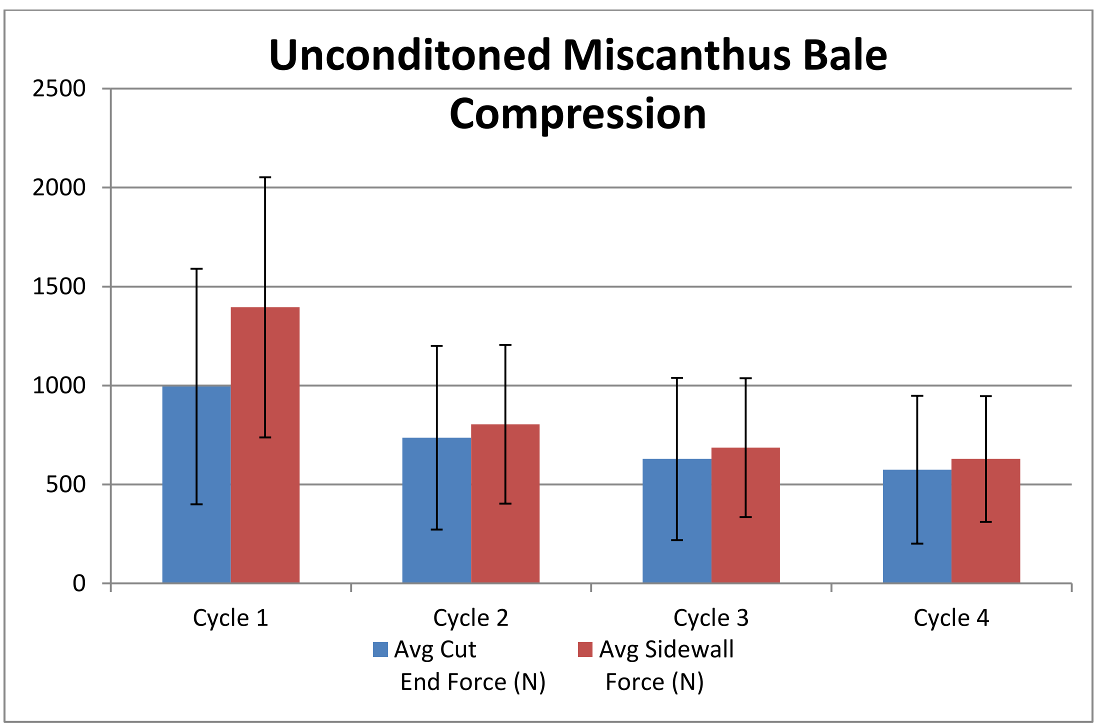

Figure 6.11 - Sidewall and cut end forces for unconditioned miscanthus.

The magnitude of the difference varied depending upon the type of conditioning and the cycle number. For cycle one, both the conditioned crop and unconditioned crop show an average cut end force that is approximately 75 percent of the sidewall force. For cycles two through four of conditioned miscanthus bales, the average cut end force is approximately 78 percent of the sidewall force. However, for unconditioned miscanthus, cycles two through four show average cut end forces that are approximately 94 percent of the sidewall forces. Again, we see that unconditioned miscanthus performs more poorly than conditioned miscanthus in terms of reduced forces. In addition, the conditioned miscanthus results are statistically significant whereas the unconditioned miscanthus results are not statistically significant when comparing the differences between sidewall and cut end forces.

It is unclear whether the bale chamber in a baler will produce a similar relationship between cut end and sidewall forces with respect to the main compressive force. However, this analysis completed in a bale compressor can provide initial data for the relationship for miscanthus and further studies should be completed.

6.4.6 Density and Pressure Relationship

The density versus pressure relationship was examined for all miscanthus bales, including both conditioned and unconditioned miscanthus. The instantaneous density was calculated by using the measured mass of the bale, as well as the position of the cylinder and chamber dimensions, to calculate the volume. In addition to the instantaneous density values throughout the compression cycle, the instantaneous force on the compression plate was used to calculate the pressure on the top of the bale by knowing the standard small square bale compression chamber dimensions. This produced a pressure versus density relationship for the duration of the compression cycle, for each bale.

Previous work completed by Hofstetter (2011) evaluated several equations and found that an equation developed by Faborode and O’Callaghan (1986) best predicted the pressure during compression for four biomass crops tested; corn stover, indiangrass, switchgrass and wheat straw. Hofstetter used nonlinear regression to evaluate the fit of the data for each bale to the developed equation. In this study, the Faborode and O'Callaghan (1986) equation was evaluated with pressure and density data for miscanthus and the differences between conditioned and unconditioned bales were examined. An example of the density versus pressure relationship for a conditioned miscanthus bale can be seen in figure 6.12.

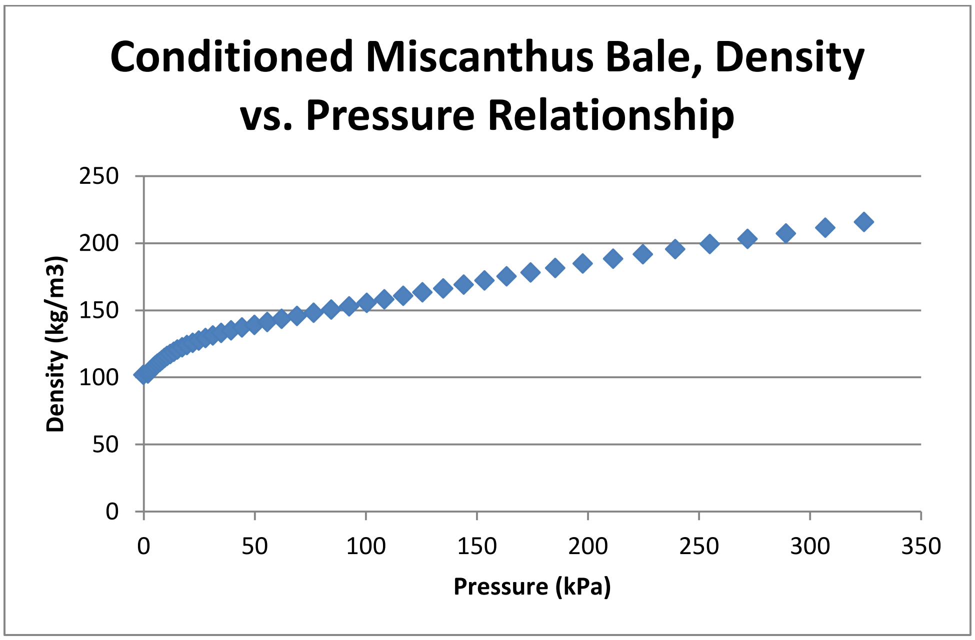

Figure 6.12 - Density and pressure relationship for miscanthus bale compression.

The instantaneous pressure and density data collected from each individual bale was used with the initial bale density in a nonlinear regression analysis; the regression was completed using the Faborode and O'Callaghan (1986) equation, shown below, to determine the regression coefficients for both conditioned and unconditioned miscanthus separately.

Equation 1 - Faborode and O'Callaghan equation.

$$\gamma = \gamma_0 \left[\frac{ln\left(\frac{P}{\gamma_0\left(\frac{A}{B}\right)} + 1\right)}{B} + 1 \right]$$

Where: γ= instantaneous density [Kg/m^3]

γ_0 = initial bale density [Kg/m^3]

P = instantaneous pressure [kPa]

A = regression coefficient [m^2/s^2]

B =regression coefficient [(Kg/m^3) / (Kg/m^3)]

Only the data for the compression segment from cycle one was used for the regression. Table 6.7 shows the average regression equation coefficients (A and B) for conditioned and unconditioned bales, which were found by completing a regression analysis for each bale. The average standard error is also shown for both of the regression coefficients. The coefficients for conditioned bales when, compared to unconditioned bales, were found to be different through examination of the coefficients and the respective standard errors.

Table 6.7 – Miscanthus pressure vs. density regression coefficients.

Bale Type	Avg. Initial Bale Density	A	Standard Error (A)	B	Standard Error (B)
	Kg/m^3	m^2/s^2		(Kg/m^3) / (Kg/m^3)	
Conditioned	94.04	0.691	0.024	1.446	0.050
Unconditioned	88.01	0.9519	0.083	1.365	0.134

The two instantaneous density equations using the average regression coefficients from table 6.7 were graphed against the respective conditioned and unconditioned miscanthus raw instantaneous pressure and density values. This allows for the additional examination of how the raw data fits the model suggested by Faborode and O'Callaghan (1986), using the coefficients found in this regression analysis.

Figure 6.13 shows the conditioned data, while figure 6.14 shows the unconditioned data respectively.

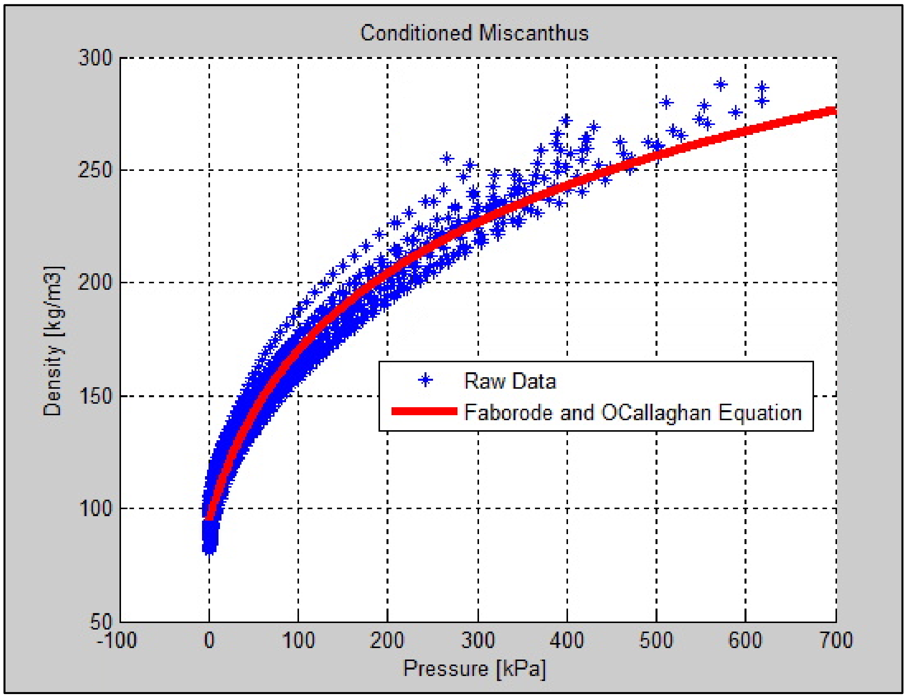

Figure 6.13 - Conditioned miscanthus pressure and density relationship.

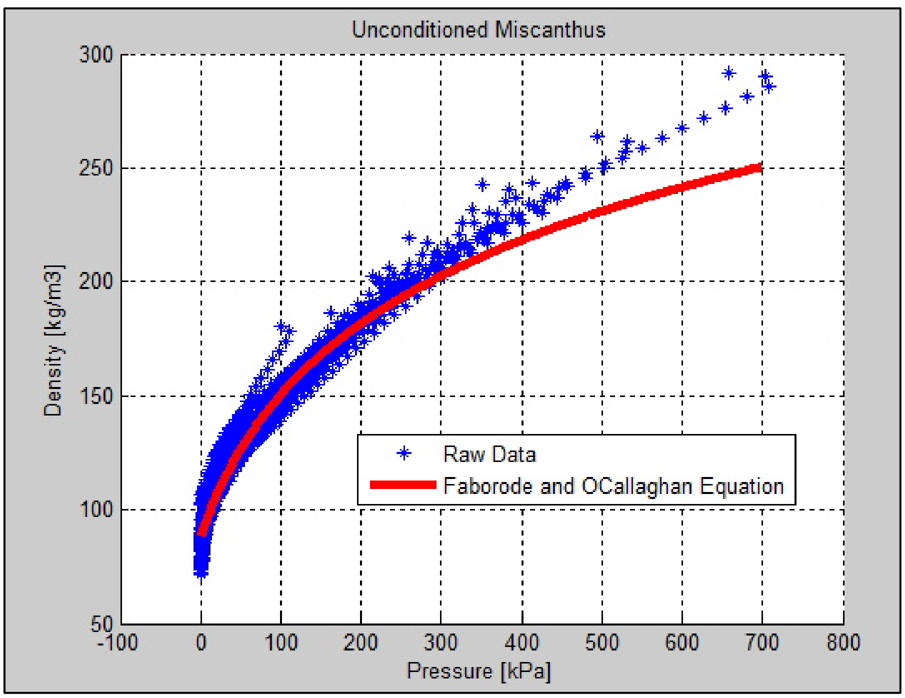

Figure 6.14 - Unconditioned miscanthus pressure and density relationship.

From Figures 6.13 and 6.14 the Faborode and O'Callaghan equation can be seen in relationship to the raw data collected. For the miscanthus bales in this study, the Faborode and O'Callaghan (1986) equation sufficiently models the relationship between density and pressure, during the small square bale compression process. The model is slightly more accurate at predicting the relationship between density and pressure for conditioned miscanthus, as compared to unconditioned miscanthus. This can be seen by visually examining the graph and the goodness of fit. In addition, the RMSE for the model fit of the raw data for the conditioned bales is 7.06 Kg/m3 while the unconditioned bale data is 12.02 Kg/m3 respectively. This also shows a slightly more accurate model of the raw data for the conditioned miscanthus.

It is believed that the conditioned miscanthus bales more accurately fit the modeled equation because the conditioned miscanthus is the most similar to the other crops in which this equation was developed and used with. Conditioned miscanthus is most similar in terms of the stiffness, pliability and the ability to be packed to the other crops that have been used with this equation. The reason why the unconditioned miscanthus data is a poorer fit with the model equation is because it differs in these areas. The pressure and density relationship for conditioned miscanthus follows the Faborode and O'Callaghan equation for pressures up to approximately 500 kPA and at densities higher than this, there is an insufficient number of data points to confirm that the relationship holds true at higher pressures. For unconditioned miscanthus, the Faborode and O'Callaghan is followed only up approximately 300 kPA. After this, there is insufficient number of data points to confirm that the relationship holds true at higher pressures.

By evaluating both the conditioned and unconditioned miscanthus bales together, we can see the overall density and pressure relationship for miscanthus. In figure 6.15 every instantaneous pressure and density is plotted. There is some overlap between the two conditioning methods but the higher initial density can be easily seen. At the upper end of the pressure and density curve, the higher densities for conditioned crops can also be seen.

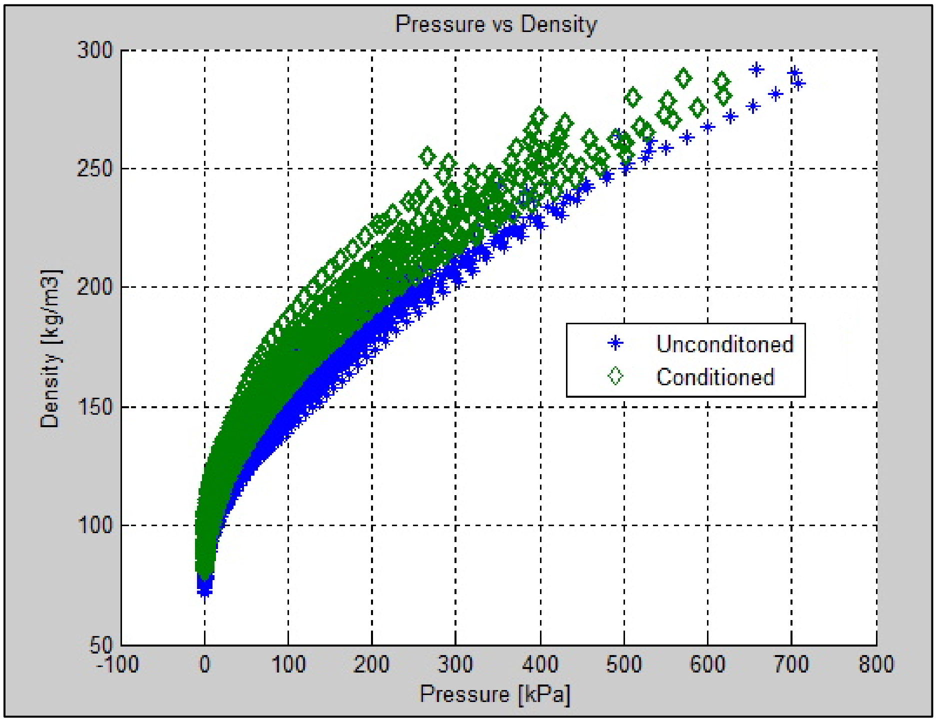

Figure 6.15 - Miscanthus pressure and density instantaneous values.

Figure 6.16 shows the regression lines for both the conditioned and unconditioned crop, as developed from the model equation. In this graph, the differences between conditioned and unconditioned miscanthus, in terms of the pressure and density relationship, can be seen. The conditioned miscanthus curve is always above the unconditioned miscanthus curve, for the bales tested using the model equation that was developed by Faborode and O'Callaghan (1986). For example, at a common compression pressure of 300 kPa, the predicted density of conditioned miscanthus bales is approximately 20 Kg/m^3 (10 %) higher than unconditioned miscanthus bales. This also shows that higher densities can be achieved for conditioned miscanthus bales, when compared to unconditioned bales when evaluating at a constant pressure value. Likewise, at a common density value, the pressure and correlated forces are higher for unconditioned miscanthus bales than conditioned miscanthus bales.

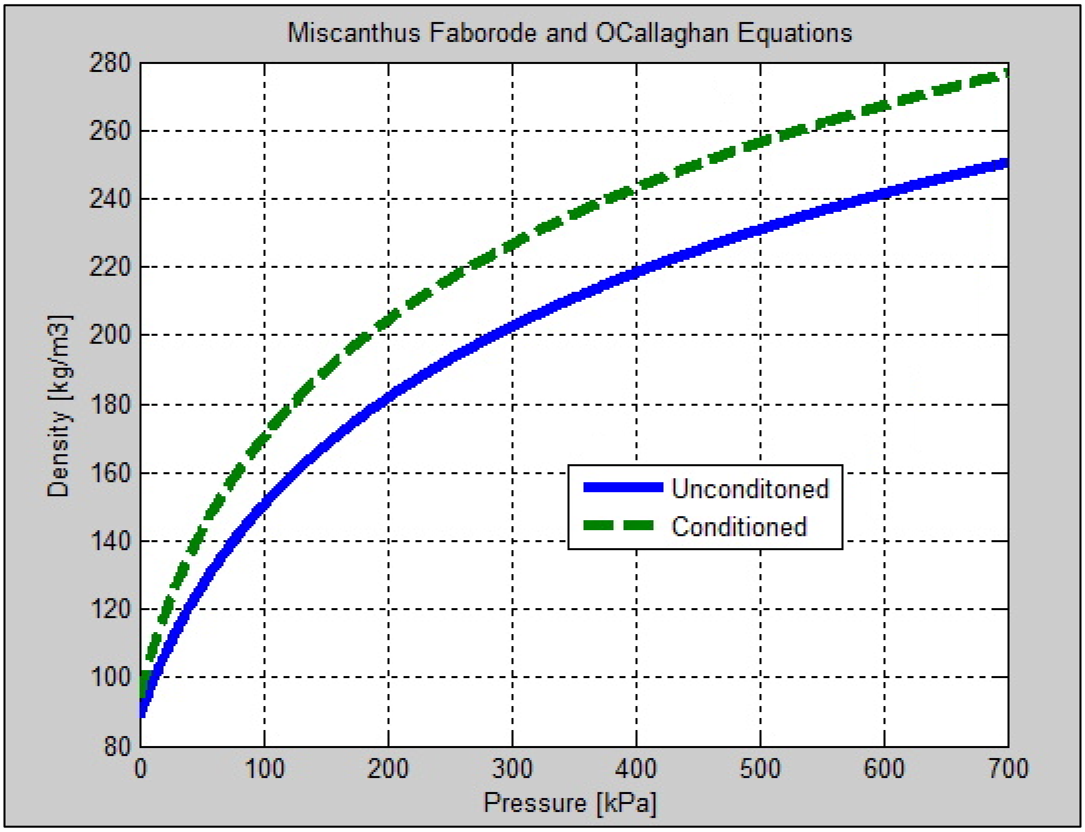

Figure 6.16 - Conditioned and unconditioned miscanthus model equations.

6.5 Hypothesis Testing Miscanthus Compression Conclusions

From the miscanthus compression testing, several conclusions can be made from the results that explain the bale compression process, as well as comparing the crimp conditioning method with unconditioned crop by compressing small square bales of miscanthus. Although bale compression is slightly different than the bale making process in a baler, it is related and the conclusions found in these tests can be preliminary research for examining the baling process in a full-scale large square baler.

6.5.1 Hypothesis Testing

The first hypothesis focused on comparing miscanthus conditioned with a crimp conditioner to unconditioned miscanthus. The specific energy consumed during the first cycle of the bale compression process was used to evaluate the effect of conditioning. The results were compared over the common density range of 107-180 Kg/m^3. The hypothesis was stated as follows:

Ho = The mean specific energy consumption of crimp conditioned miscanthus and unconditioned miscanthus, over a common density range of 107-180 Kg/m^3, is statistically equal during the small square bale compression process.

Ha = The mean specific energy consumption of crimp conditioned miscanthus and unconditioned miscanthus, over a common density range of 107-180 Kg/m^3, is not statistically equal during the small square bale compression process.

From the first compression cycle of both conditioned and unconditioned miscanthus bales, the specific energy was calculated over the common density range for each bale. Using an analysis of variance statistical test, the means of the specific energy for the conditioned and unconditioned miscanthus were statistically tested. The result of the test was a P-value of 0.00, and therefore the null hypothesis can be rejected at a confidence level of 95%. By examining the interval plot and confidence intervals, the mean specific energy consumption of crimp conditioned miscanthus is statistically less than that of the unconditioned miscanthus, during the bale compression process. This explains that the bale compression process for miscanthus can consume significantly less specific energy if the crop's mechanical properties are altered by a crimp conditioning method as compared to unconditioned miscanthus.

The second hypothesis focused on examining crimp conditioned miscanthus, and the results of two different holding times during the compression process. Conditioned miscanthus bales were compressed with either a holding time of five seconds or 150 seconds, and the relaxed bale percent volume reduction was calculated. The percent volume reduction was calculated by using the bale volume after the compression cycle was finished and the bale was allowed to relax for one minute along with knowing the initial bale volume. The second hypothesis was stated as follows:

Ho = The mean relaxed small square bale percent volume reduction for crimp conditioned miscanthus, for a hold time of 150 seconds as compared to a five second hold time, after the first compression cycle is statistically equal.

Ha = The mean relaxed small square bale percent volume reduction for crimp conditioned miscanthus, for a hold time of 150 seconds as compared to a five second hold time, after the first compression cycle is not statistically equal.

The relaxed bale percent volume reduction was calculated for the first compression cycle for crimp conditioned small square bales of miscanthus, and an analysis of variance test was completed. The mean of the relaxed bale percent volume reductions for a five second hold time was statistically lower than that of a 150 second hold time. The result of the test was a P-value of 0.00 and therefore the null hypothesis can be rejected at a confidence level of 95%. By examining the interval plot and confidence intervals, the mean relaxed small square bale percent volume reduction for crimp conditioned miscanthus is statistically higher for a 150 second compression cycle hold time than a five second hold time. This explains that the 150 second holding time, during which the bale is held in the fully compressed position and at its highest compressed bale density, results in a higher relaxed bale percent volume reduction than a 5 second holding time. A greater relaxed bale percent volume reduction is a result of the small square bale having a smaller relaxation distance.

6.5.2 Overall Miscanthus Compression Conclusions

The primary conclusion of the miscanthus bale compression testing relates to the type of conditioning method that was used prior to baling and the comparison of the effects from this conditioning method with unconditioned miscanthus. With a small square baler, a statistically higher initial bale weight, compressed bale density, density increase and volume reduction during the first compression cycle was found for the conditioned miscanthus with respect to the unconditioned miscanthus. This is extremely important because higher bale densities are related to decreased transportation and logistics costs.

When the first compression cycle of both conditioned and unconditioned miscanthus was evaluated over a common density range, the maximum compressive force, peak power, energy and specific energy during this process was statistically less for the conditioned miscanthus than that of the unconditioned miscanthus. When the entire density range for each individual bale is used, a possible wrong conclusion can be obtained because the differences in initial and final bale densities, as a result of bale weight and bale lengths, were not accounted for. However, even under all full density range analysis, the conditioned bales result in slightly decreased average maximum force, peak power energy and specific energy although the results are not statistically significant. Similarly, when the energy is totaled across the four compression cycles for each bale and averaged, there is not enough statistical evidence to prove that conditioned bales consume less energy than unconditioned bales although the average value is less for conditioned miscanthus. Further testing with bales of a more constant density range could change this result and should be compared over a common density range as well.

When examining the four complete bale compression cycles together for conditioned small square bales, it can be seen that the specific energy and peak power requirement for both conditioned and unconditioned miscanthus decreases on average approximately 75 percent between cycle one and cycle two and 25 percent between cycle two and three. The decrease between cycle three and the fourth and final cycle is minimal. For a 150 second holding time, as compared to a five second holding time, the maximum compressive force, peak power, energy and specific energy requirements are significantly decreased. For conditioned miscanthus this is a statistically significant decrease while for unconditioned miscanthus the average value is decreased, although it is not statistically significantly decreased.

The relaxed bale percent volume reductions, as a percentage of the initial bale volume, for each individual bale were examined for each conditioning type as well as the two different holding times between the extension and retraction segments of the cycle. The results showed that conditioned miscanthus can achieve a statistically significant increased relaxed bale percent volume reduction for a hold time 150 seconds when compared to a hold time of only 5 seconds. Unconditioned miscanthus can result in a higher average relaxed bale percent volume reduction for a hold time of 150 seconds, as compared to a five second hold time, although it is not significant at a 95 % confidence interval. Therefore, the 150 second hold time is more useful when trying to increase the relaxed bale percent volume reduction and decreasing the bales ability to relax and bounce back after compression, especially for conditioned miscanthus.

The pressure and density relationship developed by Faborode and O'Callaghan (1986), and used by Hofstetter (2011), was used in this testing as a model regression equation and was used to fit and model the pressure versus density for the bale compression process. It was found that the equation accurately fit the data for both conditioned and unconditioned miscanthus; however, the regression coefficients differ depending on the conditioning type. The RMSE error from the regression equation analysis was approximately 7.06 Kg/m3 and 12.02 Kg/m3 for the conditioned and unconditioned miscanthus bales respectively. The conditioned miscanthus behaves more similarly to the model equation than unconditioned miscanthus, because it is more pliable and the crop properties are most similar to the other crops that were used and tested with the Faborode and O'Callaghan (1986) model equation.

The bale compressor was used to evaluate the effects of conditioning by simulating the baling process. Although the bale compressor uses an already formed bale, a correlation can be made to the actual forces, power and energy consumed during the baling process. A direct equation or function relating the values from the bale compressor to the values in a baler is unknown; however, the benefits seen during the compression process, such as decreased energy consumption, could also be seen in a baler under field conditions. Future testing should be completed to further evaluate the effects of conditioning in a large square baler.

Chapter 7 – Switchgrass Compression Testing

Although the switchgrass testing was completed before the miscanthus testing in time, it is discussed afterwards so as to compare the results to the main research focus, which is miscanthus. The switchgrass studies, which used both spring and fall harvested switchgrass, are compared and then also compared with the miscanthus bales as a larger group.

7.1 Materials, Methods and Design

The next phase of the research was to examine the bale compression process with switchgrass by comparing the compressive force, energy and specific energy, as well as the effect of holding time for switchgrass and miscanthus. The switchgrass used in this study was taken from a farm in Julian PA in both a spring and fall harvest in 2012. For switchgrass only, the results of the compression study were compared for both a fall and spring harvest to quantify any differences as a result of harvest time.

The process used for the switchgrass bale compression process was as similar as possible to that of the miscanthus compression. The same small square bale compressor was used and the same technique of completing four compression cycles for one individual switchgrass bale was used. For switchgrass, four different holding times were used to evaluate the effect of hold time for switchgrass. For the miscanthus bales, the amount of crop was limited so only the shortest and longest hold times (5 seconds and 150 seconds respectively) were used, while the switchgrass tests also consisted of a 30 second and 60 second holding time additionally. Figure 6.2, shown previously, showed the different treatments used for the switchgrass testing in addition to those for the miscanthus testing.

The methods used to quantify the switchgrass bale compression process were identical to those used in the miscanthus bale compression process. The same process of weighing the bale, completing the compression cycles and measuring the moisture was identical. The same data acquisition and processing was used, and the equations used to calculate the power and energy were the same. With the switchgrass bales, a greater initial bale density was seen than miscanthus because the small square baller can pack switchgrass much tighter than miscanthus. Because of this, the switchgrass bales were evaluated for two common density ranges. The first common density range was the same range used for the miscanthus bales to allow for comparison between crops. The second common density range was only used for switchgrass. This range was selected by using the highest initial density as well as the lowest final density for all switchgrass bales. This common density range was used several times, for example, to examine the differences in forces and energy between fall and spring harvested switchgrass.

7.2 Results and Discussion

The results of the switchgrass testing are summarized in this section. Comparisons between fall and spring switchgrass were made, as well as switchgrass was compared to miscanthus, both conditioned and unconditioned. These comparisons were intended to show the differences and similarities between the two crops for the purpose of understanding the behavior of each crop and aid in the selection of a particular biomass crop for bioenergy production.

7.2.1 Initial Compression Cycle Evaluation

The number of switchgrass bales that were tested is shown in table 7.1, for both the fall and spring harvested bales. Included in the table are the conditioned and unconditioned miscanthus bales for comparison purposes. Also, for several other switchgrass bale compression results, the miscanthus results were used for comparison purposes. Table 7.1 also shows the number of bales that were tested and at which holding time. Because the switchgrass testing was completed first, and more crop was available than miscanthus crop, two additional hold times (30 and 60 seconds respectively) were completed.

Table 7.1 - Number of bales used during compression testing.

Crop Type	Hold Time [seconds]	Number of Bales Tested
Fall Switchgrass	5	8
	30	6
	60	6
	150	6
Spring Switchgrass	5	6
	30	6
	60	6
	150	6
Conditioned Miscanthus	5	6
	150	10
Unconditioned Miscanthus	5	10
	150	7

The initial results of the compression testing for switchgrass can be seen in table 7.2 and a comparison with switchgrass is shown. The average weight of the fall switchgrass bales was statistically heavier than the spring bales and this can be explained by the effects of over-wintering. The volume reduction from the first compression cycle is slightly, but statistically, higher for the spring bales than the fall bales which also is an expected result from overwintering. The moisture content is statistically higher in the fall (12.25 % d.b.) than the spring (9.5 % d.b.) and this can be expected because the spring switchgrass had been allowed to overwinter. When comparing switchgrass to miscanthus, the main statistical differences are seen in the dry bale weight and initial bale length. In the terms of volume reductions, unconditioned miscanthus bales are statistically lower than both of the switchgrass bale types however the conditioned miscanthus bales are not statistically lower. When percent moisture is examined, the spring switchgrass is the only statistically lower percent moisture with the remaining three types being statistically the same.

Table 7.2 – First compression cycle results, comparison between switchgrass and miscanthus.

Average Values	**Dry Weight**	**Volume Reduction**	**Initial Bale Length**	**Percent Moisture**
Units	*Kg*	*%*	*m*	*% D.B.*
Fall Switchgrass	18.50	63.34	0.86	12.25
Spring Switchgrass	15.87	66.86	0.86	9.50
Conditioned Miscanthus	11.33	62.10	0.74	11.16
Unconditioned Miscanthus	10.29	59.61	0.70	12.95

Similar to the miscanthus compression testing, a density analysis is exremely important. The density analysis from the miscanthus testing was used for comparison to the switchgrass bales, while an addition comparison between the spring switchgrass bales and fall bales was made. Figure 7.1 shows the initial, compressed and relaxed bale densities, as well as the denisty increase, for conditoned and unconditoned miscanthus along with the fall and spring switchgrass bales. Differing letters above the bars show a statisitcally significant difference in means from ANOVA testing. However, the letters are only used within one density type and are not connected to another density column in anyway.

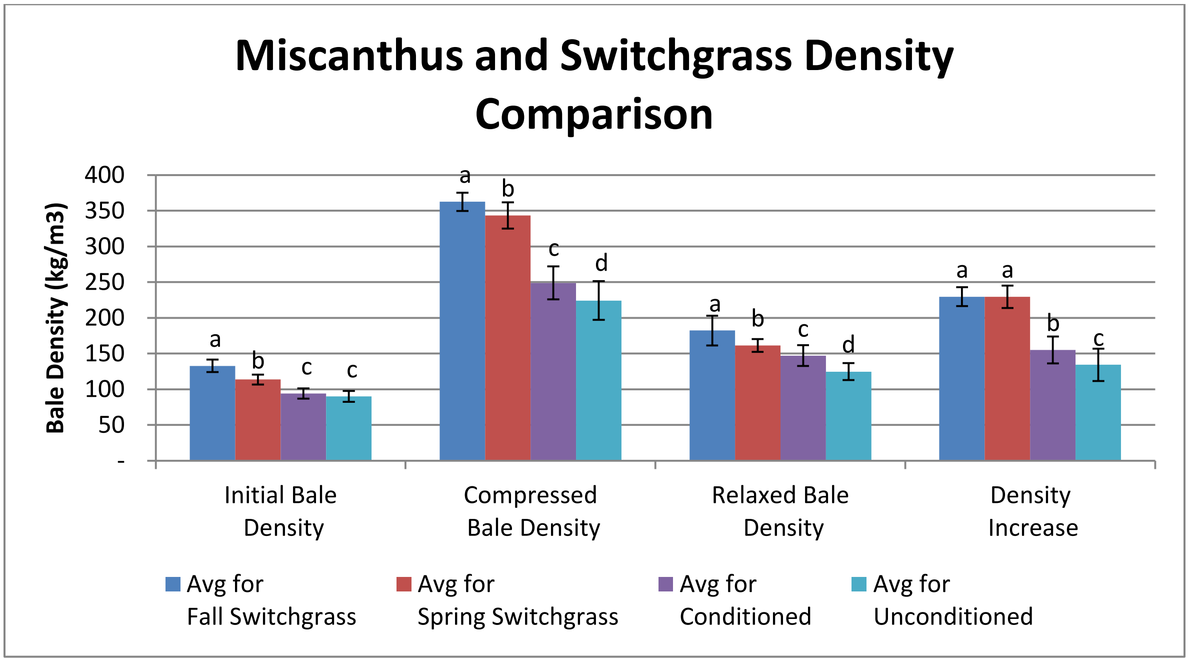

Figure 7.1 - Switchgrass and miscanthus density comparison.

The initial small square bale densities, for both conditioning types of miscanthus bales, are statistically less than the initial densities for both types of switchgrass bales. When only analyzing switchgrass bales, the fall switchgrass initial densities were statistically higher than that of the spring bales. Initial bale densities are related to the ability of the small square baler to produce a bale and pack as much crop as possible. Variation in baler configurations, settings and models can affect the initial density. When evaluating compressed bale densities, we can see that both switchgrass bale types achieve a statistically higher density than both types of miscanthus bales, which is a result of much higher initial bale weights and the ability to compress the switchgrass crop tighter to remove air between the individual crop pieces during the compression process. When comparing compressed densities between fall and spring switchgrass, the fall bales achieved a statistically higher compressed small square baled density.

When the bale is allowed to relax and the relaxed bale density is measured, a higher relaxed bale density is seen for switchgrass with respect to miscanthus but this is co-related to higher compressed bale densities as well. Similarly, the fall switchgrass is more favorable than spring harvested switchgrass because statistically higher relaxed bale densities can be obtained. Perhaps the most interesting finding from the density analysis is the density increase obtained during the compression process. For both spring and fall switchgrass, the density increase is statistically equal; whereas, with miscanthus, a higher density increase can be obtained through conditioning the crop. Increased bale densities are important when trying to decrease the harvesting and transportation logistical costs of a biomass harvesting operations.

7.2.2 Energy, Specific Energy and Power

In addition to examining the densities from the compression process, for both switchgrass and miscanthus bales, the forces, power and specific energy consumption analyses were also examined. Table 7.3 shows the summary data for theses parameters for both the fall and spring switchgrass bale compressions, during the first compression cycle. Similar to miscanthus bale compression, a common density range was selected to include every bale tested and examine measureable parameters over the same density range to eliminate differences in initial bale weights, lengths and densities. For the switchgrass compression, the density range used was 149-307 Kg/m^3. This range is much wider than the miscanthus bales because of the higher initial bale weights, longer bale lengths and less variation between spring and fall bales as compared to the density difference between conditioned and unconditioned miscanthus.

Table 7.3 - Switchgrass compression summary values, over a common density range.

Switchgrass Small Square Bale Compression (Over a Common Density Range of 149-307 Kg/m3)				
Average Values	Peak Compressive Force	Peak Power	Energy	Specific Energy
Units	N	kW	kJ	kJ/Kg
Fall Switchgrass	48,599	3.88	16.68	0.91
Spring Switchgrass	59,118	3.92	16.83	1.07
ANOVA P-value	**0.003**	0.473	0.741	**0.00**

When the fall and spring switchgrass bales are considered, there are some slight differences between parameters as well as some statistically significant differences as well. The spring switchgrass resulted in a statistically higher average compressive force and specific energy consumption (10,519 N and 0.16 kJ/Kg respectively). The spring switchgrass peak power and compression energy consumption is slightly higher (0.04 kW and 0.12 kJ respectively), but not statistically higher. This shows a similar pattern previously found by other researchers, in which spring harvested crop has higher forces, power and energy consumption although the exact explanation as to why is still unknown. However, these results can partially be explained by lower moisture contents in the spring and the effects of over wintering.

To be able to compare the forces, power and energy consumption between switchgrass and miscanthus, the switchgrass compression was also examined over the same miscanthus common density range of 107-180 Kg/m^3(table 7.4).

Table 7.4 - Switchgrass and miscanthus compression analysis, over a common density.

Miscanthus vs. Switchgrass Small Square Bale Compression (Over a Common Density Range of 107-180 Kg/m^3)				
Average Values	Peak Compressive Force	Peak Power	Energy	Specific Energy
Units	N	kW	kJ	kJ/Kg
Fall Switchgrass	4,846.64	0.80	1.23	0.07
Spring Switchgrass	6,269.97	1.06	1.93	0.12
Conditioned Miscanthus	7,549.03	1.00	1.91	0.17
Unconditioned Miscanthus	12,003.94	1.41	2.79	0.27

When a common density range is used to compare switchgrass and miscanthus the difficulty of compressing miscanthus can be seen. As discussed in the miscanthus analysis, unconditioned miscanthus is significantly harder to compress than conditioned miscanthus. The average compressive force for each crop and bale type combination was all statistically different. The small square bales of both switchgrass types are statistically less than that of both miscanthus types with unconditioned miscanthus bales being the highest and fall switchgrass the lowest.

The peak power and energy values show the same pattern in which the spring switchgrass and conditioned miscanthus are not statistically different, however the fall switchgrass, being the lowest value, is statistically different than unconditioned miscanthus which is the highest values. This indicates that conditioned miscanthus, at least for peak power and energy consumption, is closer to the switchgrass consumption values as compared to unconditioned miscanthus which is statistically higher.

Because specific energy accounts for differences in mass between bales tested, this is the most accurate calculation. The specific energy during compression of unconditioned miscanthus is 75 percent higher than the specific energy consumption of fall switchgrass while conditioned miscanthus is 59 percent higher than fall switchgrass. When the miscanthus results are compared to spring switchgrass, unconditioned miscanthus is 56 percent higher while conditioned miscanthus is only 30 percent higher, thus showing that conditioning miscanthus can greatly reduce the specific energy requirements closer to the switchgrass requirements.

7.2.3 Bale Relaxation

Similar to the miscanthus compression testing, the switchgrass relaxed bale volumes were measured to evaluate the effect of different holding times and the ability of the compression process to keep the bale compressed when it is allowed to relax afterward the cylinder is removed. For switchgrass, four different hold times were evaluated. Table 7.5 shows the results of the relaxed bale percent volume reduction study for switchgrass.

Table 7.5 - Switchgrass relaxed bale percent volume reductions.

Hold Time	Relaxed Bale Percent Volume Reduction Cycle 1	Relaxed Bale Percent Volume Reduction Cycle 2	Relaxed Bale Percent Volume Reduction Cycle 3	Relaxed Bale Percent Volume Reduction Cycle 4	Relaxed Bale Percent Increase from cycle 1 to cycle 4
[Sec]	% of initial bale volume	% of initial bale volume	% of initial bale volume	% of initial bale volume	%
150	29.17	33.64	36.14	36.85	7.67
60	28.86	33.87	35.89	37.55	8.69
30	28.30	32.25	34.53	35.84	7.54
5	25.50	33.27	34.94	36.03	10.53

From examining the results of the switchgrass relaxation tests, switchgrass is similar to miscanthus in terms of the pattern of the data with respect to cycle number and holding times. The trend is that the longer the holding time is during the compression cycle, a greater relaxed bale volume can be obtained. However, the switchgrass holding time analysis is not nearly as statistically significant as the miscanthus analysis was. A greater relaxed bale volume is important because the cause of a higher volume is less bale relaxation and a shorter bale length in the compression chamber, when the bale is allowed to bounce back as far in length as it can. Increased relaxed bale volume reductions can help improve small square bales in the ability to retain their shape as well as places less stress on the twine that holds the bale together. The bales with a higher relaxed bale volume reduction do not want to relax as much as a lower relaxed bale volume reduction and places less strain on the strings holding the bale together.

When the percent volume reduction is examined for one particular hold time and examined from cycle one through to cycle four, an increase can be seen. The last column in table 7.5 shows the average percent volume reduction increase from cycle one to cycle four for the individual bales. The average across all hold times is approximately 8.6%. This, similar to miscanthus, shows that the more successive compressions completed helps increased the relaxed bale volume reductions and, if no mass is lost, the density will also be increased as well. The five second holding time had the largest increase from cycle one through four which means the benefits of successive compressions are greater for short hold times. Similarly, the 150 second had the lowest increase from cycle one through four; however the overall percent volume reduction is still higher for the hold time of 150 seconds.

By examining the switchgrass data for relaxed volume percent reduction and knowing that amount of miscanthus was limited for testing purposes, the 150 and 5 second hold times were selected for the miscanthus testing. As mentioned, the relaxed bale volume was measured after the bale was allowed to relax for one minute after a compression cycle. Figures 7.2 and 7.3 show the relaxed bale percent volume reduction for both miscanthus and switchgrass for five and 150 second hold times respectively.

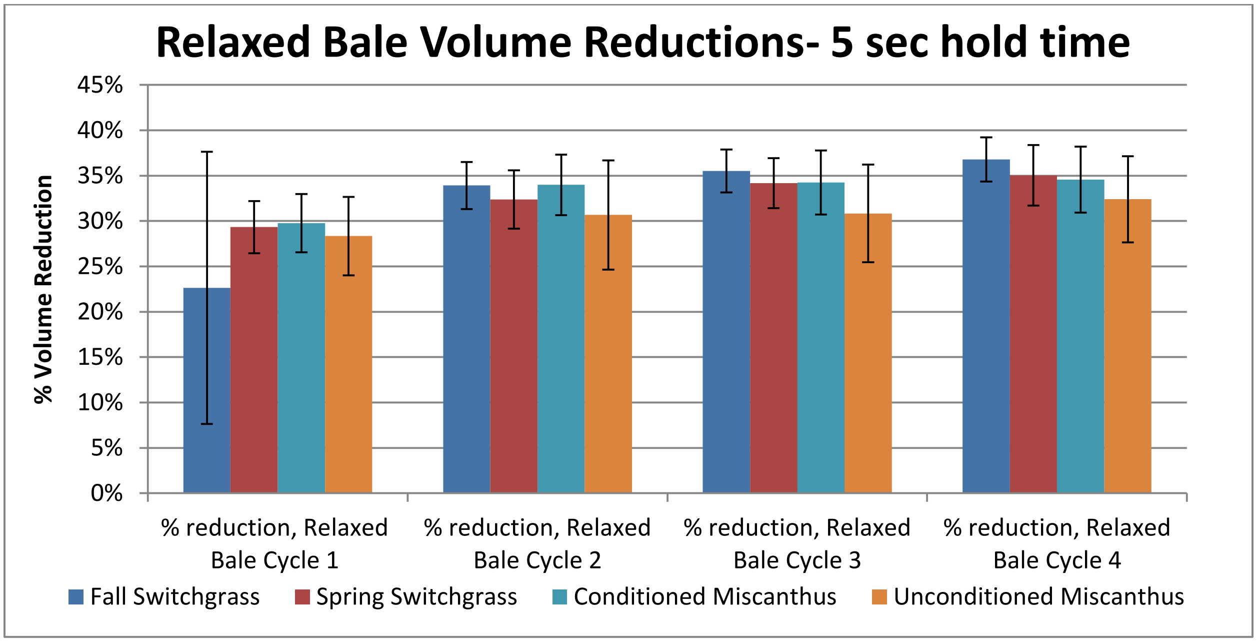

Figure 7.2 – Miscanthus and switchgrass relaxed bale percent volume reductions for a 5 second holding time.

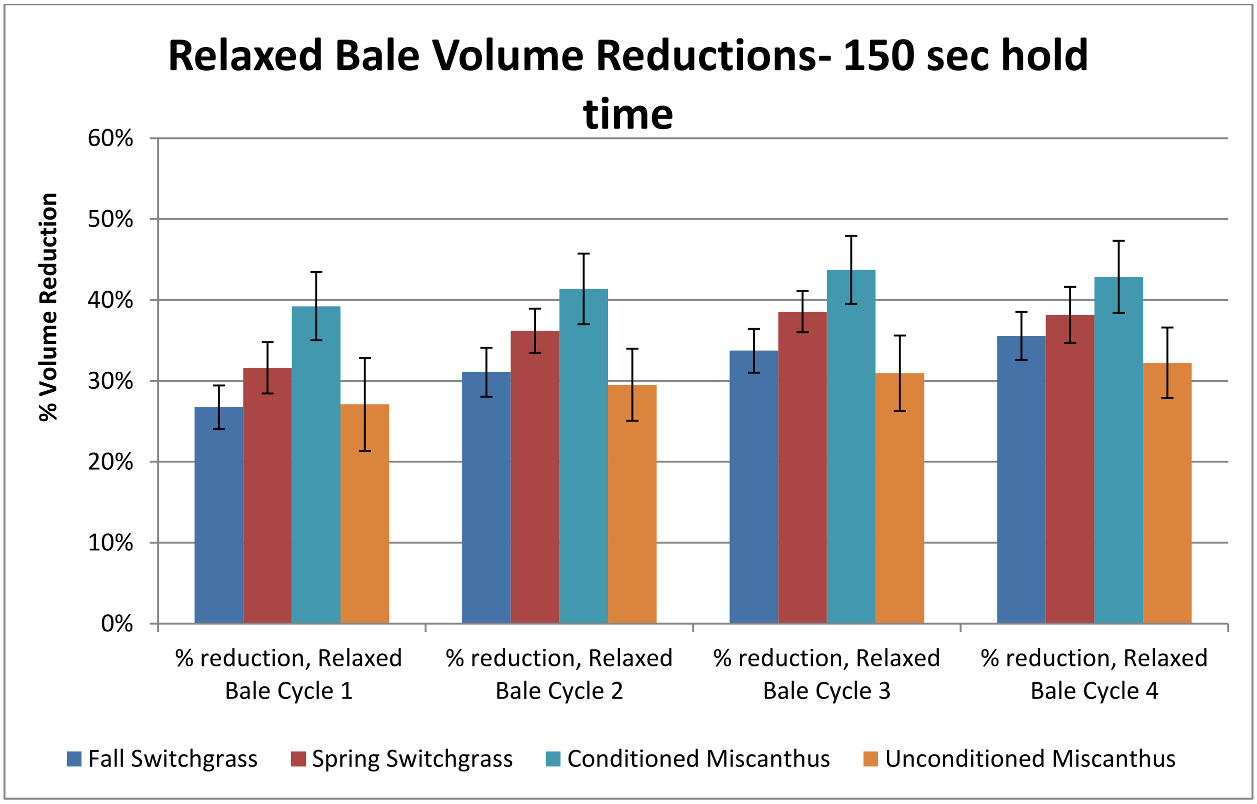

Figure 7.3 – Miscanthus and switchgrass relaxed bale percent volume reductions for a 150 second holding time.

Both types of miscanthus, conditioned and unconditioned, were compared to both types of switchgrass, fall and spring harvested, all together. In figure 7.2 we can see the results of the five second holding time. Although there are some minor trends in the averages, statistically we can see no difference in the mean relaxed bale percent volume reductions between the four crop types. However, for a longer holding time of 150 seconds, as seen in figure 7.3, we can see a trend with statistically different relaxed bale volume reductions.

For a 150 second holding time, the bales were held under a higher force for a longer period of time which helped allow them to relax less after the compression plate is removed and the retraction phase is completed. In addition, the longer holding time allowed the difference between different crops, harvesting time, conditioning etc. to be seen. In figure 7.3, a statistically significant consistent trend was seen for the different crops across cycles one through three. The highest relaxed bale percent volume reduction was the conditioned miscanthus and, in decreasing order from highest to lowest, was the spring switchgrass, fall switchgrass and finally unconditioned miscanthus. Cycle four shows a slight difference where the fall and spring bales are not significant at a 95 % confidence level; however they do follow the same trend in which the average for the spring bales is higher than the fall. This is the only statistically insignificant difference in figure 7.3; all other comparisons are statistically different.

A higher relaxed bale volume reduction means that after the bale is compressed and allowed to relax to whatever volume it can, the percent volume reduction is still greater than other bales, which is desired because this shows that the higher percent volume reduction bales want to stay compressed together on their own and less additional energy is required to keep it at a certain compressed density. This can be related to less stress on the bale twine holding the bale together and less broken bales.

7.2.4 Complete Cycle and Further Holding Time Analysis

For the miscanthus bale compression process, the specific energy consumption for the first compression cycle, as well as the subsequent cycles, was shown and totaled to see the distribution of the total compression energy as a function of cycle number. Figure 7.4 shows this analysis for switchgrass and miscanthus together. A similar pattern to miscanthus is seen for switchgrass where the first cycle accounts for approximately 50 percent of the total specific energy consumed, while the three subsequent cycles account for the remaining 50 percent of the total specific energy. The total energy consumed for the fall switchgrass is statistically higher than that of the spring switchgrass harvested small square bales.

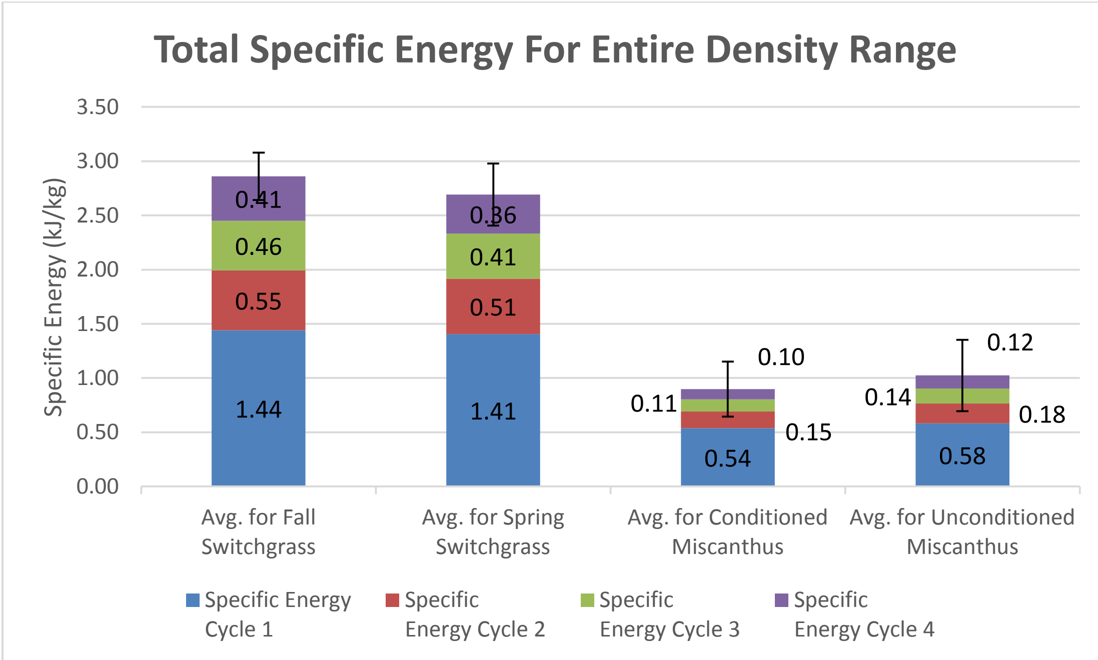

Figure 7.4 - Miscanthus and switchgrass specific energy comparisons.

In figure 7.4 we can see that the total specific energy requirement for switchgrass is greater than that of miscanthus. Although specific energy does consider the mass of the bales, this analysis calculates the energy for the entire compression cycle for each of the four cycles for every bale. As mentioned earlier, to accurately compare energies, they must be compared over a common density range. For example, the average compressed density for switchgrass bales is 350 Kg/m3 while the average for miscanthus is 250 Kg/m3. This explains the large difference in total specific energy consumption for switchgrass as compared to miscanthus over the full compression cycle. Further testing and developments that could produce bales of miscanthus with a higher compressed density would decrease this difference.

In table 7.4, when the switchgrass and miscanthus were compared over the same density range, a higher specific energy consumption for miscanthus is seen. However, the common density analysis could only be completed for the first compression cycle because the small square bales did not have a large enough common density range during subsequent compressions. Because of this, figure 7.4 is shown for the entire density range.

For miscanthus, a decreasing trend of peak power with respect to subsequent cycles was seen and can be explained by the large amount of air in the bales and the stiffness of the crop with less of an ability to be compressed together. For switchgrass, a slightly different pattern can be seen. Figure 7.5 shows the peak power with respect to cycle number for conditioned miscanthus and fall switchgrass. For simplification, the unconditioned miscanthus is not shown; however, unconditioned miscanthus follows the same trend as conditioned.

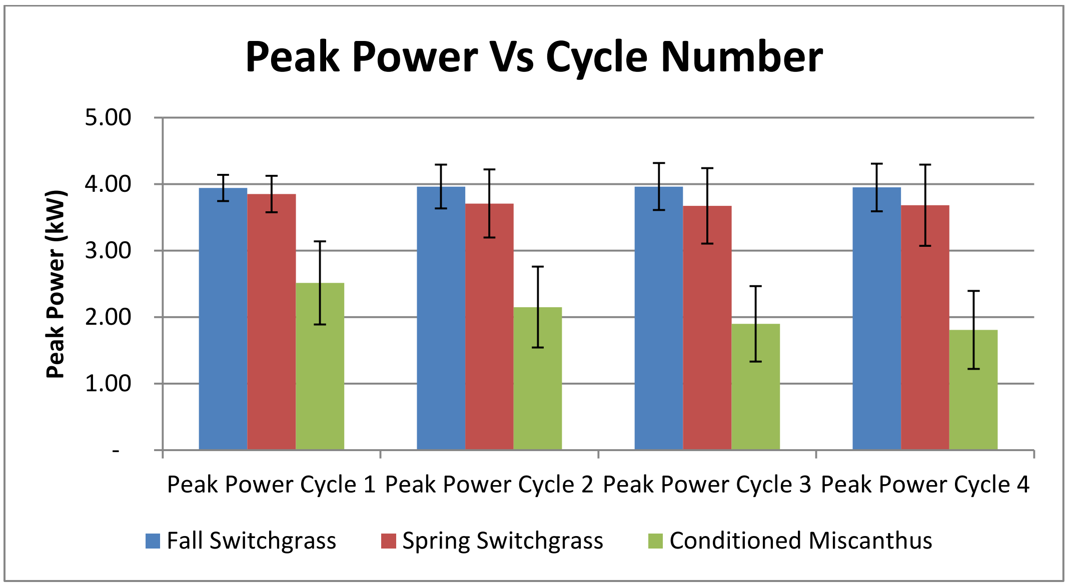

Figure 7.5 - Switchgrass and miscanthus peak power consumptions.

The fall switchgrass pattern does not show a steady decrease in peak power with respect to subsequent cycles like the conditioned miscanthus, and unconditioned miscanthus which is not shown, does. This could be explained by the small square baler's ability to form the switchgrass bales with a higher density and higher bale weight, and therefore in the bale compression process, the peak power to compress miscanthus is statistically constant from cycle one through four for fall switchgrass bales. The spring switchgrass, although not statistically significant, shows a comparable trend to miscanthus in which the peak power decreases slightly from cycle one through four and this is related to the fact that both the spring switchgrass and miscanthus were allowed to overwinter and harvested in the spring.

Once again, the peak power for switchgrass is higher than that of miscanthus. However, this data is across the entire density range rather than the common density range to examine the trends across the four cycles. If the miscanthus bales had a higher and similar density to switchgrass, the magnitude of the results can then be compared. Figure 7.6 shows the results of comparing the specific energy and cycle number between switchgrass and miscanthus.

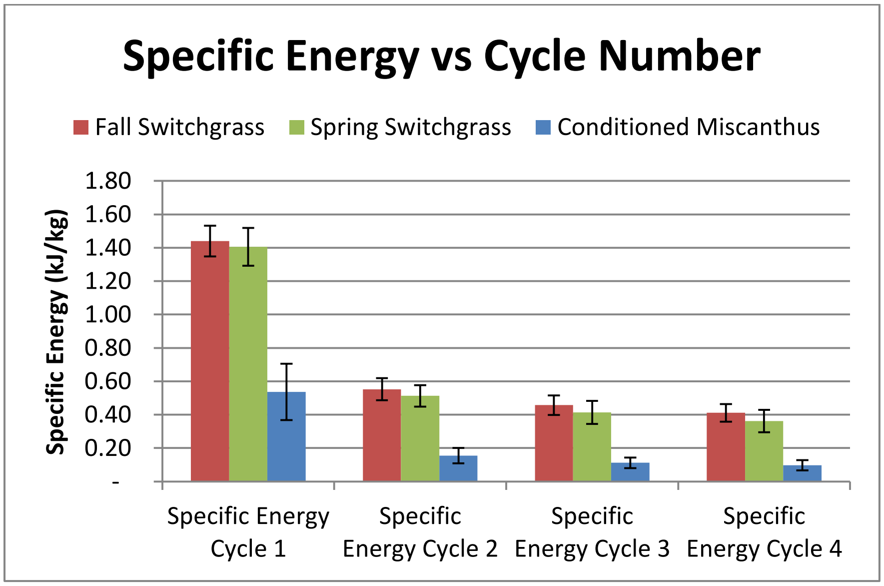

Figure 7.6 - Switchgrass and miscanthus specific energy and cycle number relationships.

Similar to miscanthus, switchgrass shows a similar trend when looking at the specific energy consumption during the compression cycle, with respect to cycle number. From figure 7.6, the largest drop in specific energy for all crops is between cycle one and two, while the drop between the subsequent cycles are significantly less. For cycle two, the percent decrease from cycle one for both fall and spring switchgrass is on average 62% while conditioned miscanthus is 72% respectively. For the subsequent cycles, the energy begins to drop more consistently for switchgrass, while miscanthus is decreased very quickly in cycles one and two and begins to level off in cycles three and four. This is believed to be a result of the stiffness of miscanthus and the smoothness of the stalks in which once the bale is compressed in cycle one and two, the crop will not pack together any tighter. Baling in the fall when leaves are still on the miscanthus plants may effect this result.

To examine the effects of different holding times on switchgrass, the specific energy of cycles two through four was taken as a percentage of cycle one for each individual bale to determine if different hold times can statistically decrease the amount of specific energy required compress the bales for each subsequent cycle (figure 7.7).

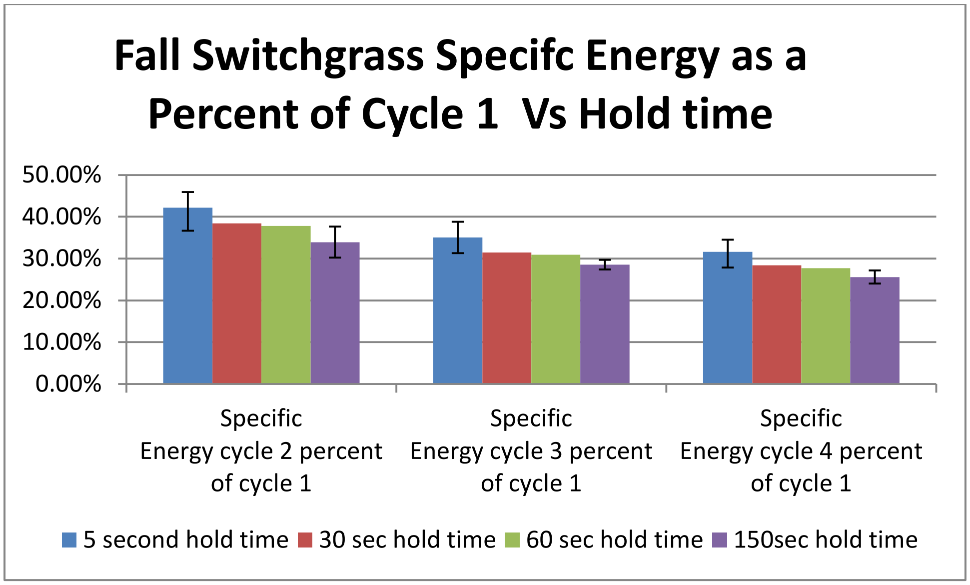

Figure 7.7 - Fall switchgrass specific energy and successive compression relationships.

An analysis of variance was completed and the result showed a statically decreased specific energy requirement with a 95 % confidence from a hold time of 5 seconds to a hold time of 150 seconds for each of the three subsequent cycles as a percentage of cycle one (figure 7.7). However, the results were not statistically decreased for the holding times in-between five and 150 seconds. In other words, to obtain statistically decreased results, the analysis must compare the five second hold time to the 150 second hold time only for these results. Additional holding times greater than 150 seconds should be examined to more accurately evaluate the trend.

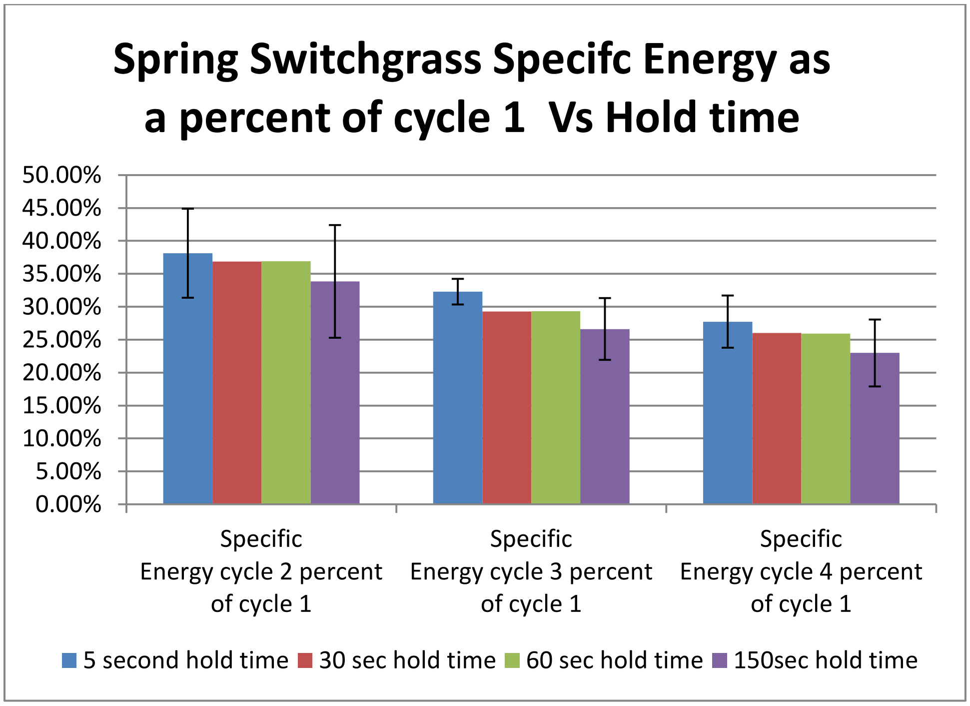

Figure 7.8 - Spring switchgrass specific energy and successive compression relationships.

The same analysis was completed for the spring switchgrass bales, and the analysis of variance at a 95 % confidence level resulted in finding that the specific energy as a percent of cycle 1 was not statically decreased between the 5 and 150 seconds. However an average decrease can be seen. These results are shown in figure 7.8. This completed the switchgrass testing and the comparison to miscanthus.

7.3 Hypothesis Testing and Conclusions

With the addition of the switchgrass testing, conclusions can be made about switchgrass bale compression alone as well as comparing miscanthus to switchgrass during the compression process. These conclusions will be presented and the third and final hypothesis of this research will be tested.

7.3.1 Hypothesis Testing

The final hypothesis focused on comparing miscanthus to switchgrass. The specific energy used during the bale compression process was used to compare the different crop types. The results were compared over a common density range for normalization purposes. The hypothesis was stated as follows:

H_o = The mean specific energy consumptions of crimp conditioned miscanthus, unconditioned miscanthus, spring harvested switchgrass and fall harvested switchgrass, over a common density range, are statistically equal during the small square bale compression process.

H_a = One of the mean specific energy consumptions of crimp conditioned miscanthus, unconditioned miscanthus, spring switchgrass and fall switchgrass, over a common density range, is not statistically equal during the small square bale compression process.

The specific energy consumption during the first compression test for each type of crop was processed using an analysis of variance statistical analysis with a confidence level of 99 percent, which resulted in a P-value of 0.00 therefore concluding that at least one mean is different. By examining the confidence intervals for each of the crop types, it can be seen that all of the crop types and harvesting/processing methods are statistically different. It can be concluded that the unconditioned miscanthus requires the highest specific energy consumption and followed by, in decreasing order, conditioned miscanthus, spring switchgrass and fall switchgrass.

7.3.2 Switchgrass Conclusions

After the switchgrass small square bale compression process, several conclusions can be made. Firstly, the moisture content of the fall bales was higher than that of the spring bales, due to harvest time and overwintering effects. Similarly, the bale weight was higher in the fall than in the spring because of the higher moisture content. A higher moisture content and bale weight in the fall than the spring as well as a statistically equal initial bale length between fall and spring resulted in a higher initial and compressed bale density in the fall than the spring. However, the spring bales were able to obtain a higher relaxed bale percent volume reduction than the fall bales which is believed to be a result of the moisture content. Although the fall bales had a higher compressed bale volume, the fall bales wanted to relax more and bounce back further. Because the relaxed bale volume was taken as a percent of the initial bale volume, the explanation for this can began to be explained by the differences in densities and moisture content. This can cause the bale to relax more and decrease the relaxed bale percent volume reduction.

A switchgrass small square bale common density range of 149-307 Kg/m3 during the compression cycle was used to compare the fall harvested bales to the spring harvested bales. The fall bales were found to have statistically less compressive force and specific energy consumption, over the common density range, than the spring bales. The peak power and energy consumption was not found to have statistically different average values between the fall and spring harvested bales. Therefore, in this study, the spring switchgrass bales are both easier to compress in terms of force and power and consume less energy than the fall harvested bales.

For switchgrass, four different holding times were evaluated during the compression process. The bales were divided and processed at a five, 30, 60 or 150 second holding time between the compression plate extension and retraction phases in the bale compressor. Through examination, it was found that the 150 second holding time statistically decreased the specific energy consumption, when compared to the specific energy consumption of the five second holding time for the fall switchgrass bales. For the spring bales, although the mean values were not statistically different at a 95 % confidence level, they did show a similar trend to that of the fall bales. The difference in specific energy for 30 and 60 second holding times fell in between and also followed the deceasing specific energy consumption trend as holding time was increased. This is similar for other parameters such as compressive force and peak power for example. In addition, the relaxed bale percent volume reduction is most affected, and statistically higher, for the 150 second holding time, when compared to the five second holding time. Therefore, we can conclude that a longer holding time is most beneficial and will decrease the energy consumption, peak power value, and compressive forces as well as maximizing relaxed bale percent volume reductions.

7.3.3 Miscanthus and Switchgrass Comparison Conclusions

The benefit and reason for compressing switchgrass small square bales was to compare the process and results to the miscanthus process and results. Switchgrass production has occurred for longer, as a biomass crop, than miscanthus and therefore, to understand how to increase the amount of miscanthus produced for biomass production, it was important to compare the similarities and differences between these two crops.

From the initial compression cycle and the small square bale production process, miscanthus and switchgrass can be compared. The dry matter bale weight of switchgrass is on average 8 Kg higher than miscanthus. Similarly, the initial bale length (bale length produced by the small square baler) was on average 0.12 m longer and is a result of the small square baler's ability to pack the switchgrass better than miscanthus. The percent volume reduction during the first compression cycle was statistically equal for conditioned miscanthus when compared to fall and spring switchgrass however the unconditioned miscanthus volume reduction is statistically less than the other three bale types.

By knowing the initial bale length and bale weight relationship between miscanthus and switchgrass, the initial bale density and compressed bale density were statistically higher for switchgrass by 40 and 140 percent on average respectively. This was between the highest bale type (fall switchgrass) and the lowest (unconditioned miscanthus) bale type. The conditioned miscanthus and spring switchgrass are the two bale types that fell in the middle. Perhaps the most interesting comparison was the first compression cycle density increase, which subtracts the compressed bale density from the initial density. For switchgrass, the density increase was statistically equal between fall and spring where the density increase was statistically different for miscanthus in which the conditioned miscanthus was significantly higher than the unconditioned miscanthus. Once again this explained the benefit that quality conditioning of miscanthus could have over unconditioned miscanthus.

When the spring and fall switchgrass was compared to conditioned and unconditioned miscanthus all together, over a common density range of 107-202 Kg/m^3, the results showed that the fall switchgrass bale compression resulted in the lowest compressive force, peak power, energy and specific energy consumption while unconditioned miscanthus was the highest. The differences are also statically proven at a 95 percent confidence level. Also, from lowest to highest, the spring switchgrass and conditioned miscanthus average values fell in-between. Conditioned miscanthus, although it was still on average higher than switchgrass for these parameters, was much closer to equal than the unconditioned miscanthus was to the switchgrass values; once again showing the benefit of conditioned miscanthus. The difficultness in the ability to compress unconditioned small square bales of miscanthus has been documented and compared to conditioned miscanthus as well as fall and spring switchgrass.

When the effect of different holding times, 150 seconds and 5 seconds, were examined for the relaxed bale percent volume reduction for all four bale types, a conclusion can be made. The five second holding time did not show a statistical difference between any of the crop types. However, the 150 sec hold time did show a significant difference, in which the conditioned bales resulted in the highest percent volume reduction, followed by in decreasing order the spring switchgrass, fall switchgrass and unconditioned miscanthus bales.

Chapter 8 – Overall Conclusions and Recommendations

8.1 Conclusions

The miscanthus conditioning tests consisted of both a smooth steel roll conditioning system as well as a crimp conditioning method, in order to prepare miscanthus for baling with an altered crop property. The smooth steel roll testing was found to be ineffective because an acceptable level of quality of conditioning was not achieved and, after conditioning, a significant percentage of the miscanthus stalks were unaffected. Therefore the lab-built crimp conditioning method, which is similar to current production steel rolls with some differences, was used to condition enough miscanthus to make 16 small square bales for compression testing. After being conditioned with a crimp conditioner, the miscanthus was formed into an accordion shape which allowed it to be formed into another shape more easily which is much more difficult to do with unconditioned miscanthus.

Along with the conditioned miscanthus, enough unconditioned miscanthus was also used to make 16 small square bales. The unconditioned miscanthus crop was directly mowed in the field and then cut into approximately 0.4 meter lengths. From the small square bale making process, it was found that that the conditioned miscanthus was formed into bales with higher densities and weights as compared to unconditioned miscanthus. Full length unconditioned miscanthus pieces were unable to be baled in a small square baler because the stalks could not be fed into the compression chamber by the bale forks. When examined over a common density range, conditioned miscanthus experiences a statistically less maximum compressive force and consumes statistically less peak power, energy and specific energy than unconditioned miscanthus, during the bale compression process. The bale compression process was used to simulate the actual bale making process in order to quantify and evaluate the benefit that conditioning could have on bale densities, energy consumption and peak power and force. A higher relaxed bale percent volume reduction was achieved with conditioned miscanthus, which results from the bale bouncing back or relaxing less and placing less stress on the bale twine and increasing the ability of the bale to retain its shape.

Three successive compression cycles were completed after the first compression cycle for each individual bale, to examine the effects on the forces, power, and energy and percent volume reduction. It was found that the decrease in the forces, energy and power between cycle one and two was the largest decrease whereas cycles three and four saw a minimal decrease. The relaxed bale percent volume reduction increased from cycle one to cycle four. Two different holding times (150 and 5 seconds) were evaluated between the compression plate extension and retraction phases of one complete compression cycle. The results showed that the longer holding time (150 seconds) decreased the maximum compressive force and energy consumption for subsequent compression cycles and less bounce back or relaxation occurred at longer holding times.

Switchgrass bales harvested in both the fall and spring were compressed for comparison purposes to miscanthus. The switchgrass bales were able to achieve a higher initial and compressed bale density because of an increased initial bale weight. When the switchgrass and miscanthus bales were examined over a common density range, the unconditioned bales averaged over twice as much specific energy consumption and maximum compressive force than the switchgrass bales. However, the conditioned bales were only slightly higher than the switchgrass bales; thus showing the importance of conditioning miscanthus. A comparison over a common density range for switchgrass and miscanthus small square bale compression has now been completed.

8.2 Recommendations

The bale compression process has shown that conditioning miscanthus can be beneficial when compared to unconditioned miscanthus. From this study, a quality conditioning system resulted in decreased energy consumption during the bale compression process. In addition, conditioning can increase bale density and ultimately decrease harvesting and transportation costs. Future studies should be completed to see if the same decreases can be seen inside a baler during field conditions. Additional field testing should be completed to examine different types of conditioning methods and bale densities produced, as well as the energy consumed in a field harvesting situation, with the goal of determining a conditioning method which maximizes the achievable bale density and minimizes the requirements to do so. The energy consumed during the conditioning process should be calculated and compared to the energy saved during the bale production and compression processes.

Although a small square baler was used to make bales of miscanthus in this study so that the small square bale compressor could be use, a small square baler may not be suitable for most miscanthus harvesting operations. This is because, with unconditioned crop, miscanthus cannot be fed into the bale chamber effectively by the bale forks. However, if the crop was conditioned and became more flexible, then the baler forks could begin to become more effective at picking up the miscanthus and baling it. In addition, the bale densities produced by the small square baler are rather low, when compared to other crops such as switchgrass. For this reason, either a large square baler or round baler could be more efficient. Further testing with a large square baler or round baler should be completed.

In addition to conditioning type research, further examination of the successive compression and holding time analyses should be completed. The benefits of holding time and successive compressions were seen in a bale compression chamber, where holding time can be specifically controlled. However, inside a conventional baler, these parameters are less likely to be able to be controlled. However, if a bale could be held under a compressive force for a longer time in a baler, the relaxation distance for example could be decreased. In a large square baler, successive flakes of crop are added to previous stacks until the bale reaches a desired length. At this time the bale is tied off and removed from the bale chamber. The successive flake addition process could behave similar to the successive compressions examined in this study; however due to varying field travel speeds and crop feeding rates this is an area for further examination. Further development of a new conditioning system that could be interchanged into a current production mower/conditioner that achieves a higher quality of conditioning should be considered. However this should only occur if the market for miscanthus, as a biomass crop, vastly increases and the research, design and development of a new conditioning system is economically viable.

Conditioning miscanthus shows decreased energy consumption during the bale compression process, along with decreased maximum required forces and peak power. This is largely beneficial for energy conservation, decreased wear on machines and machine component sizing. The bale compression process is related to the bale making process within the baler in field situations and provides justification for why a small square baler was used for quantification purposes. However, the cost of conditioning miscanthus, that is the energy spent in turning the rolls to condition the crop, has not been able to be quantified and therefore a total energy analysis has not yet been completed. Although some energy is consumed during the conditioning process, if bales can be made with less energy and a higher final bale density can be obtained, cheaper transportation costs could outweigh the energy cost of conditioning miscanthus and further examination is warranted for confirmation.

References

1. Afzalinia, S., M. Roberge. 2008. Modeling of pressure distribution inside the compression chamber of a large square baler. *Transactions of the ASAB*E 51(4): 1143-1152.

2. Cundiff, J., and R. Grisso. 2011. Comparison of bale operations for smaller production fields in the southeast. ASABE Paper No: 1110922. St. Joseph, Mich.: ASABE.

3. Brownell, D. 2009. Analysis of biomass harvest, handling and computer modeling. MS thesis. University Park, PA: The Pennsylvania State University, Department of Agricultural and Biological Engineering.

4. Buchanan, G. 2008. Energy issues series--from field to biorefinery. *Engineering & Technology for a Sustainable World* 15:5–7.

5. Buchanan, G., J. A. Dunn, J. R. Fischer, S. R. Johnson and J. A. Finnell. 2008. Biomass feedstocks: Opportunities to increase biofuels. In *Energy Issue Series* 15(2): 7-8.

6. Groothuis, M., and A. Womac. 2012. Bulk-format switchgrass harvest system logistics. ASABE Paper No: 121337867. St. Joseph, Mich.: ASABE.

7. Hofstetter, D., and J. Liu. 2011. Power requirement and energy consumption of bale compression. ASABE Paper No: 1111266. St. Joseph, Mich.: ASABE.

8. Hofstetter, D. 2011. Compression of baled cellulosic biomass feedstocks. MS thesis. University Park, PA: The Pennsylvania State University, Department of Agricultural and Biological Engineering.

9. Ileleji, K. 2007. Transportation logistics of biomass for industrial fuel and energy enterprises. *7th Annual Conference on Renewable Energy from Organics Recycling.* Indianapolis, IN.: University of Purdue.

10. Kemmerer, B. 2011. Analysis of switchgrass large square bale production and handling parameters. MS thesis. University Park, PA: The Pennsylvania State University, Department of Agricultural and Biological Engineering.

11. Kitani, O. 1999. Part 1.3 Biomass Resources. *CIGR Handbook of Agricultural Engineering, Volume V: Energy and Biomass Engineering.* 6-11. St. Joseph, Michigan: American Society of Agricultural Engineers.

12. Liu, J., R. Grisso and J. Cundiff. 2013. Harvest systems and analysis for herbaceous biomass. In *Biomass Now-Cultivation and Utilization*. 458. Naples, FL.: InTech.

13. Liu, Q., S.K. Mathanker, Q. Zhang and A.C. Hansen. 2012. Biomechanical properties of miscanthus stems. *Transactions of the ASAB*E 55(4): 1125-1131.

14. Ma, S., and S.R. Eckhoff. 2012. Economy of scale for biomass refineries: Commodity vs. contract pricing, area utilization factor and energy crops. *Transactions of the ASAB*E 55(2): 599-607.

15. Ma, S., and S.R. Eckhoff. 2014. Economy of scale for biomass refineries: Bulk densities, transportation cost, and producer incentives. *Transactions of the ASAB*E 57(1): 85-91.

16. Miao, Z., J. Phillips, T. Grift and S. Mathanker. 2012. Determination of energy requirements for densifying miscanthus and switchgrass feedstock with a medium-scaled compressor. ASABE Paper No: 121338481. St. Joseph, Mich.: ASABE.

17. Perlack, B. 2007. Availability of biomass feedstocks in the Appalachian region. In *Appalachian Woody Biomass to Ethanol Conference*. 1-36. Charleston, WV.: West Virginia Division of Energy.

18. Perlack, R.D, and B. J. Stokes. 2011. U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts industry. Oak Ridge, TN.: U.S. Depeartment of Energy.

19. Remoue, T. 2007. Modeling and validation of crop feeding in a large square baler. MS thesis. Saskatoon, Saskatchewan: University of Saskatchewan, Department of Agricultural and Bioresource Engineering.

20. Shastri, Y.N., A. C. Hansen, L. F. Rodrigguez and K. C. Ting. 2010. Optimization of miscanthus harvesting and handling as an energy crop. Transactions of the ASABE 3(1): 37-69.

21. Shinners, K. J., G. Boettcher, R. Muck, P. Weimer and M. Casler. 2010. Harvest and storage of two perennial grasses as biomass feedstocks. *Transactions of the ASABE* 53(2): 359-370.

22. Shinners, K. J., R.J. Straub, R.L. Huhnke and D.J. Undersander. 1995. Harvest and Storage losses with mid-size rectangular bales. *Applied Engineering in Agriculture* 12(2): 167-173.

23. Shinners, K., J. Wuest, J. Cudoc and M. Herzmann. 2006. Intensive conditioning of alfalfa: drying rate and leaf loss. ASABE Paper No: 061051. St. Joseph, Mich.: ASABE.

24. Taylor, R. K. 1992. Mechanically conditioning alfalfa hay. In *Farm Machinery and Equipment.* MF-989. Stillwater, OK.: Oklahoma State University.

25. Ting, K.C. 2009. Engineering solutions for biomass feedstock production. *Engineering & Technology for a Sustainable World* 16:12–13.

26. USDOE Bioenergy Technologies Office. 2013. *About the Bioenergy Technologies Office: Growing America's Energy Future by Replacing the Whole Barrel of Oil*. Washington, D.C.: U.S. Department of Energy. Available at http://www1.eere.energy.gov/bioenergy/about.html Accessed 14 October 2013.

27. Womac, A., W. Hart, V. Bitra and T. Kraus. 2012. Biomass harvesting of high-yield low-moisture switchgrass: Equipment performance and moisture relations. Applied Engineering in Agriculture 28(6): 775-786.

Appendix

Appendix A – Sample Bale Compression Result Page

Initial Information				
Initial Mass	24.94	lbm	11.31	kg
Final Mass	24.66	lbm	11.19	kg
Mass Losses	0.26	lbm	0.12	kg
Moisture Content	9.89	% w.b.	9.89	% w.b.
Dry Mass	22.47	lbm	10.19	kg
Initial Bale Length	25.56	in	0.65	m
Compressed Bale Length	10.89	in	0.28	m
Relaxed Bale Length	17.76	in	0.45	m
Relaxation Distance	6.87	in	0.17	m
Initial Bale Volume	6,441.12	in^3	0.11	m^3
Compressed Bale Volume	2,744.28	in^3	0.04	m^3
Relaxed Bale Volume	4,475.52	in^3	0.07	m^3
Volume Reduction	57.39	%	57.39	%
Initial Bale Density	0.003489	lbm/in^3	96.57676	kg/m^3
Compressed Bale Density	0.008189	lbm/in^3	226.676	kg/m^3
Relaxed Bale Density	0.005021	lbm/in^3	138.9922	kg/m^3
Density Increase	0.0047	kg/m^3	130.0993	

Density Analysis				
Max Bottom Force	3894.273	lbf	17322.59	N
Min Bottom Force	131.6792	lbf	585.7382	N
Average Bottom Force	1296.288	lbf	5766.176	N
Peak Power	1.140747	HP	0.850655	kW
Energy	11743.08	in-lbf	1.32679	kJ
Specific Energy	522.5315	in-lbf/lbm	0.130157	kJ/kg

Compression Information				
Max Bottom Force	8,561.55	lbf	38,083.65	N
Min Bottom Force	17.07	lbf	75.93	N
Avg Bottom Force	2,156.13	lbf	9,590.92	N
Max Sidewall Force	707.73	lbf	3,148.12	N
Min Sidewall Force	1.32	lbf	5.89	N
Avg Sidewall Force	165.10	lbf	734.38	N
Max Cut End Force	1,091.05	lbf	4,853.23	N
Min Cut End Force	2.84	lbf	12.63	N
Avg Cut End Force	339.74	lbf	1,511.22	N
Distance Traveled	14.66	in	0.37	m
Time Traveled	7.35	s	7.35	s
Compression Speed	1.99	in/s	0.05	m/s
Peak Power	2.37	HP	1.77	kW
Energy	28,963.46	in-lbf	3.27	kJ
Specific Energy	1,288.79	in-lbf/lbm	0.32	kJ/kg

Holding Information				
Max Bottom Force	7,720.27	lbf	34341.45	N
Min Bottom Force	4,381.98	lbf	19491.997	N
Average Bottom Forc	5,864.50	lbf	26086.575	N
Max Sidewall Force	725.30	lbf	3226.2773	N
Min Sidewall Force	613.96	lbf	2731.0168	N
Average Sidewall For	631.15	lbf	2807.5097	N
Max Cut End Force	1,080.65	lbf	4806.9662	N
Min Cut End Force	917.33	lbf	4080.4827	N
Average Cut End Forc	942.12	lbf	4190.7415	N
Hold Time	150	s	150	s

Appendix B – Equation List

Equation 1

$$DM = \left(1 - (MC)\right) * (M)$$

Where DM= Dry Mass, Kg

MC = % moisture

M = initial bale mass, Kg

Equation 2

$$MC = \frac{(m_{in} - m_{out})}{m_{in}}$$

Where MC = % moisture

m_{in} = mass of sample into the oven, g

m_{out} = mass of sample out of the oven, g

Equation 3

$$R = RBL - CBL$$

Where R = bale relaxation distance, m

RBL = relaxed bale length, m

CBL = compressed bale length

Equation 4

$$V = l * w * d$$

Where V = bale volume, m3

l = bale length, m

w = bale width, m

d = bale depth, m

-For bale length, if compressed bale length is used, the volume would be the compressed volume. This equation can be used for initial, compressed and relaxed bale volumes.

Equation 5

$$VR = \left[\frac{(IBV - CBV)}{IBV}\right] * 100$$

Where VR = percent volume reduction, %

IBV = initial bale volume, m3

CBV = compressed bale volume, m3

Equation 6

$$BD = \frac{DM}{BV}$$

Where BD= Bale Density, Kg/m3

DM= Dry Mass, Kg

BV = bale volume, m3

-For bale density, if compressed bale volume is used, the density would be the compressed density. This equation can be used for initial, compressed and relaxed bale densities

Equation 7

$$D = CBD - RBD$$

Where D = Density increase, Kg/m3

CBD = Compressed bale density, Kg/m3

IBD = Initial bale density, Kg/m3

Equation 8

$$s = \frac{(IBL - CBL)}{t}$$

Where s= average compression speed, m/s

IBL= initial bale length, m

CBL = compressed bale length, m

t= time of compression segment, s

Equation 9

$$P = \frac{(F * TD)}{\Delta t}$$

Where P= Power, W

F= Compressive Force, N

TD = distance traveled, m

t= time taken for the distance traveled, s

Equation 10

$$E = \int F * D \;\; dt$$

Where E= Energy consumption, J

D= displacement, m

t= time, s

Equation 11

$$SE = \frac{E}{m}$$

Where SE= Specific Energy, kJ/Kg

m= bale mass, Kg

E= Energy consumption, kJ

Appendix C – Statistical Testing

Table 6.2 - Miscanthus compression cycle 1 summary

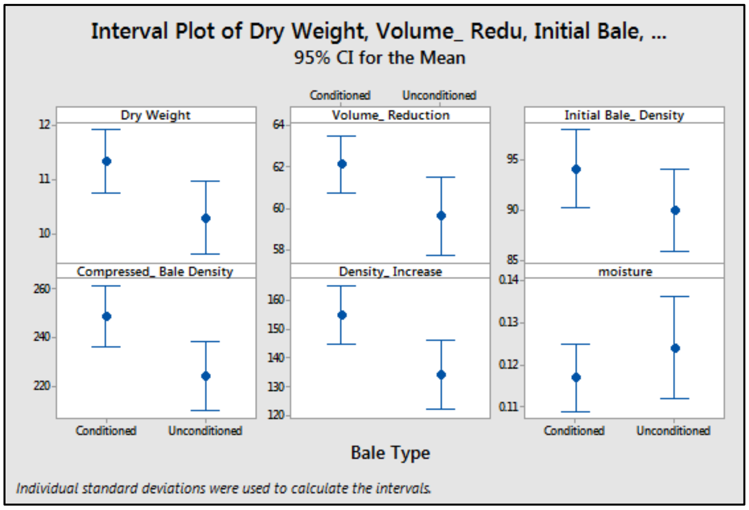

Table 6.3 - Miscanthus common density range compression summary

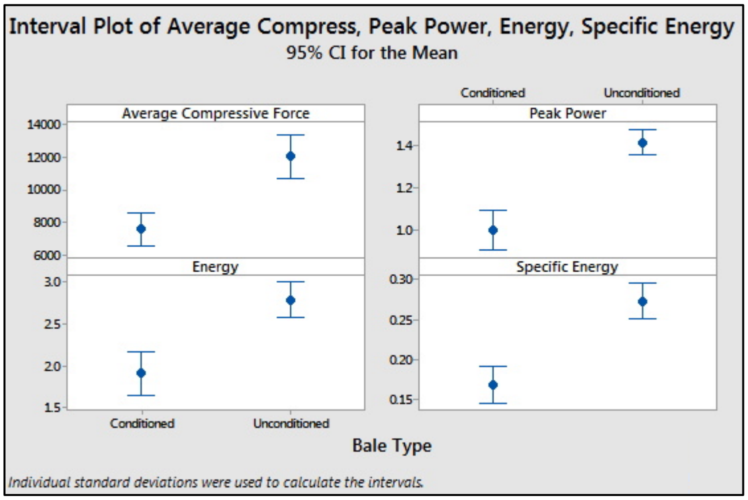

Table 6.4 - Miscanthus compression over full density range for each bale

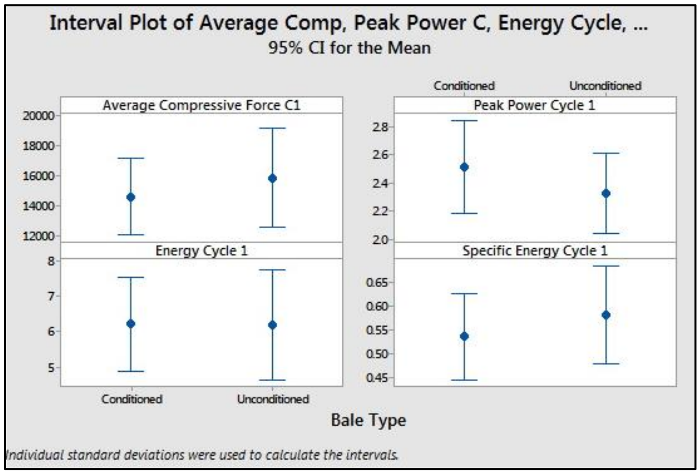

Figure 6.4 - Total specific energy consumption for miscanthus

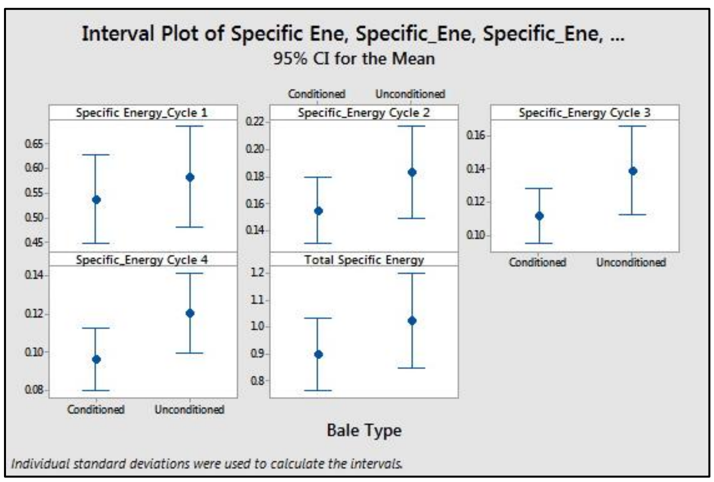

Figure 6.5 - Miscanthus relaxed bale percent volume reduction

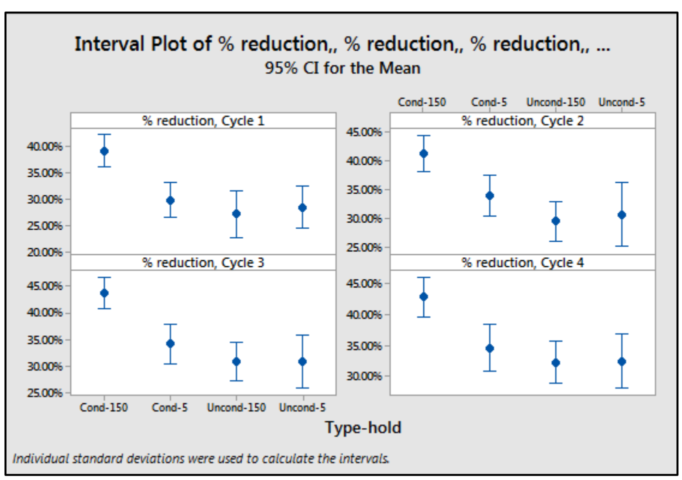

Figure 6.9 - Hold time comparison for conditioned miscanthus

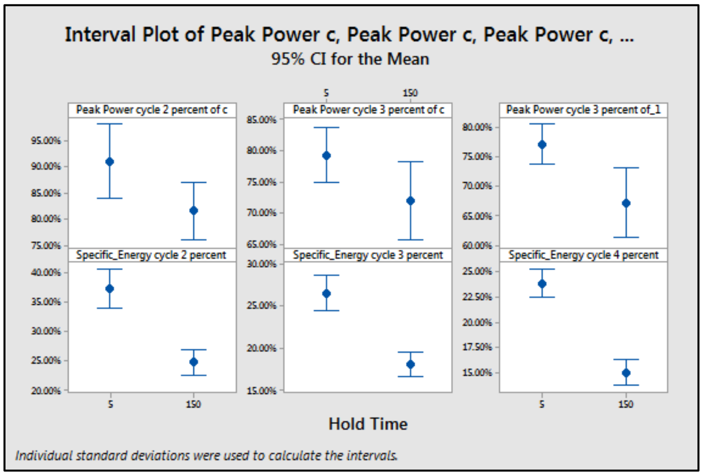

Table 7.2 - Initial compression cycle results comparison for switchgrass and miscanthus

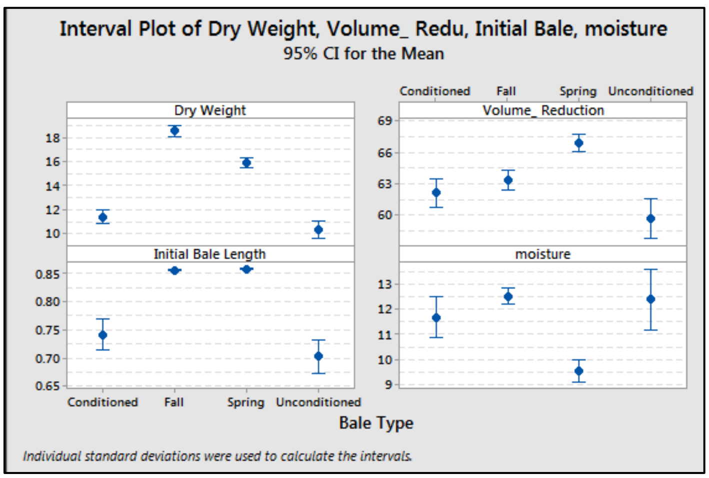

Figure 7.1 - Switchgrass and miscanthus density comparison

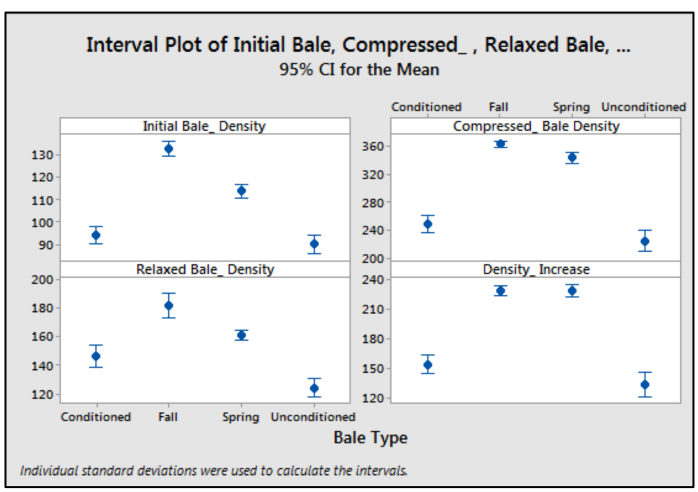

Table 7.3 - Switchgrass common density range analysis

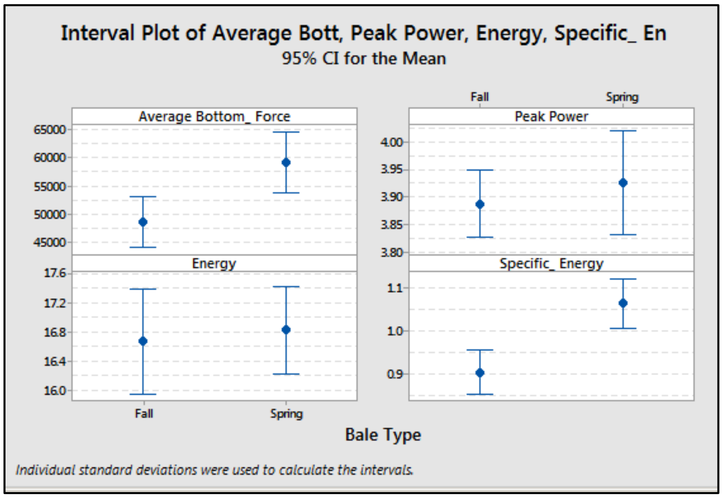

Table 7.4 - Switchgrass and miscanthus common density range analysis

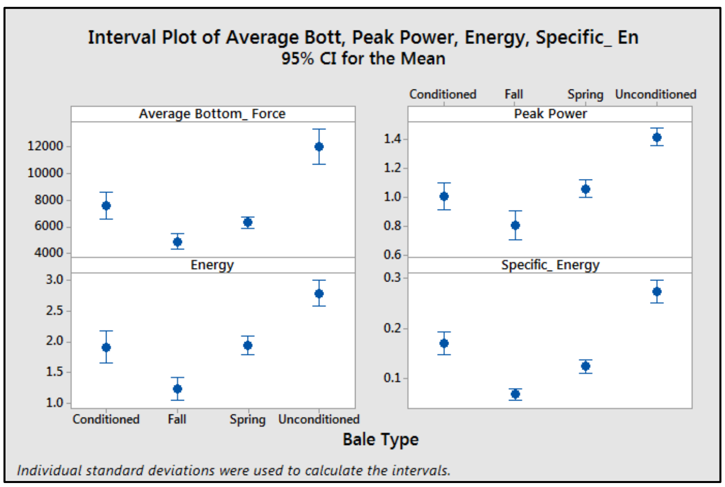

Table 7.5 - Switchgrass relaxed bale percent volume reduction

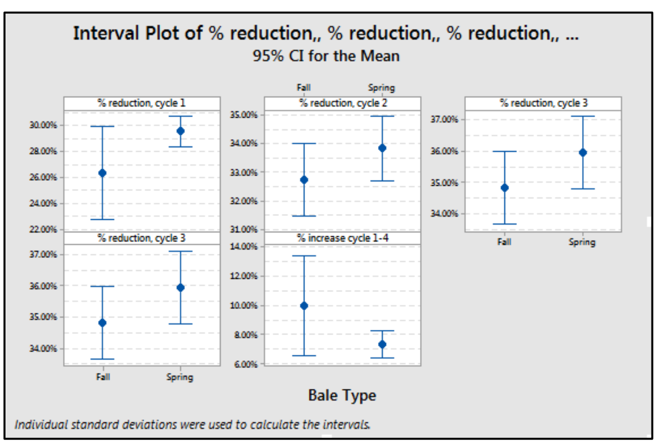

Figure 7.2 - Miscanthus and switchgrass relaxed Bale % volume reduction for 5 second hold time

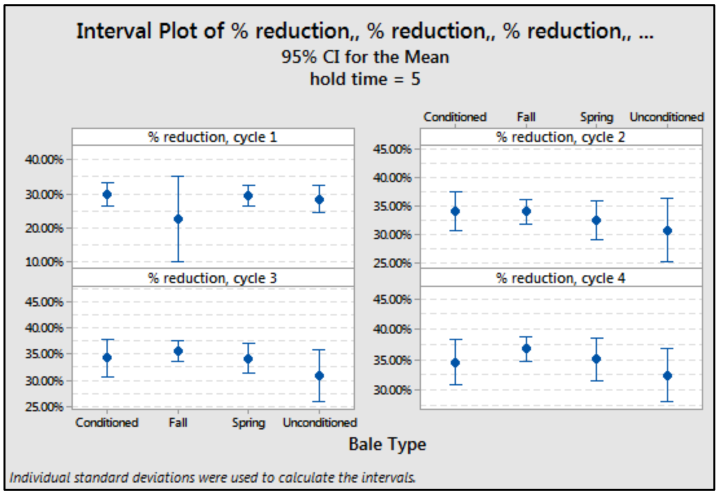

Figure 7.3 - Miscanthus and switchgrass relaxed bale % volume reduction for 150 second hold time

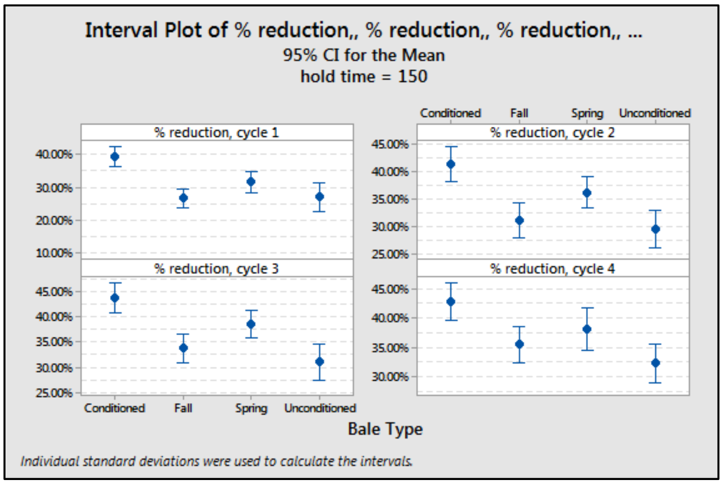

Figure 7.4 - Miscanthus and switchgrass specific energy comparison

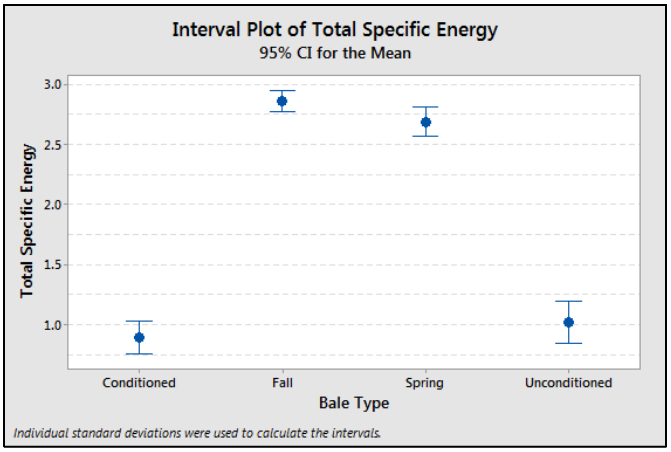

Figure 7.5 - Switchgrass and miscanthus peak power consumption

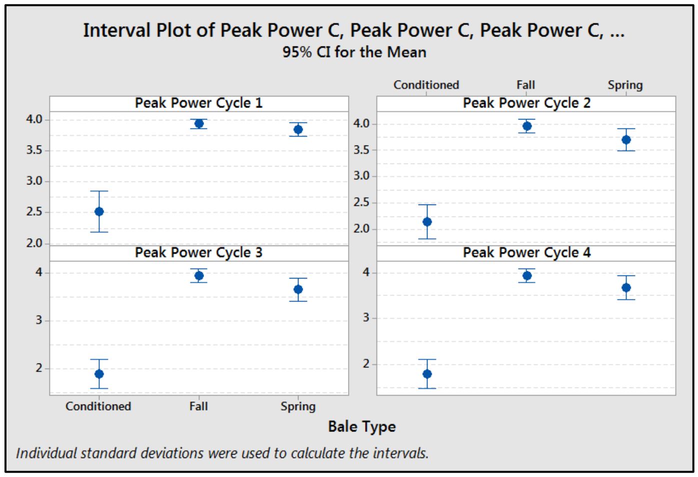

Figure 7.7 - Fall switchgrass specific energy vs. successive compression analysis

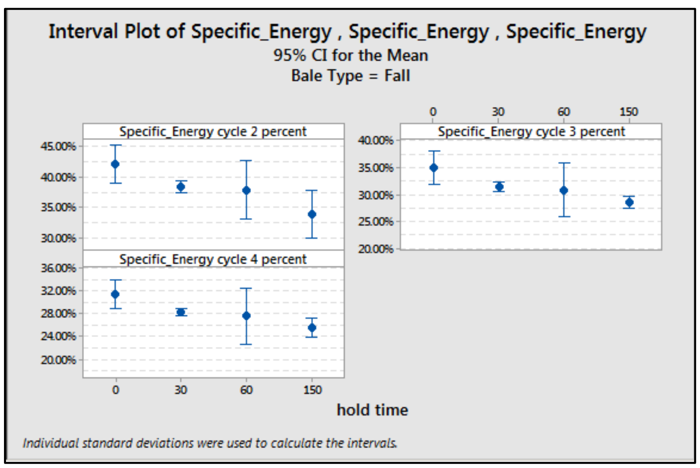

Figure 7.8 - Spring switchgrass specific energy vs. successive compression analysis