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ANALYSIS OF SWITCHGRASS LARGE SQAURE BALE PRODUCTION AND HANDLING PARAMATERS

A Thesis In

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by

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Abstract

Large square bales currently hold great potential for harvesting and storing switchgrass biomass energy feedstocks. Producing, transporting, and storing large square bales have many advantages over both small square bale and round bale counterparts as well as other possible harvest methods. These advantages stem from the high capacity of the machines and both storage and transportation characteristics of the bales. To optimize the logistics of switchgrass as a biomass feedstock, the characteristics of harvesting switchgrass with a large square baler must be well understood. Parameters that effect switchgrass large square bale production and handling logistics are the focus of this research.

A New Holland large square baler was used to harvest switchgrass biomass in May of 2010. The biomass had been cut with a discbine the previous fall and left to overwinter on the ground in order to create a spring harvest situation. The large square baler was able to produce bales that approached 200 kg/m^3 at 12% (w.b.) moisture content. Fuel consumption of the tractor that powered the baler did not significantly change when different bale density setting were applied to the baler. However, the efficiency of the baler was found to be heavily dependent on windrow density and consistency. The square bale handling capabilities were then studied at a commercial farm to determine the benefits of producing denser bales in terms of labor and energy costs.

Lab scale compression tests were performed to analysis the effects of harvest time and moisture content on switchgrass large square bale production. For the switchgrass samples compressed at various moisture contents, no statistical differences in the specific energy required for compression were found when only the dry matter bulk density was considered. The spring harvested samples were found to require more energy to compact than the fall harvested samples, mainly due to a decrease in the leaf to stem ratio caused by the biomass overwintering in the field.

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Chapter 1 - Introduction

Large square bales currently hold great potential for harvesting biomass feedstocks. Producing, transporting, and storing large square bales have many advantages over both small square bale and round bale counterparts. These advantages stem from the high capacity of large square balers and both storage and transportation characteristics of the bales. Biomass in the form of large square bales is already employed in co-firing plants to produce electricity (Prochnow, 2009). Biomass large square bales are also a viable cellulosic feedstock for future ethanol production. As the U.S. transitions to more sustainable forms of energy, optimization of all components of energy consumption in the production of biomass is vital so that these feedstocks can compete in the energy market.

Recent interest in renewable energy has been spurred by the dwindling supply of oil and the negative impacts oil has on the environment. While oil demands are expected to increase by 57% from 2004 to 2030, forecasters speculate that maximum oil production has already peaked and will continue to decline (Jessup, 2009). This decline will need to be offset with alternatives such as renewable fuels from biomass. The Department of Energy recently conducted a study that determined the United States has the potential to harvest 1.37 billion tons of biomass from forest and agricultural sources (DOE, 2008). The U.S. Energy Independence Act of 2007 mandates that the country needs to produce 21 billion gallons of renewable fuel a year from feedstocks other than those used in starch-based ethanol (DOE, 2008). This mandate will create a great demand for the biomass identified in the DOE study. Biomass feedstocks will need to be harvested, transported, and stored with both existing and new technologies.

Large square balers can be immediately put to use supplying biomass feedstocks in the form of dense bales. Machinery, transportation, and storage for large square bales in agricultural markets already exist. The benefits of a large square baler are based on the ability of the baler to produce bales that are uniformly square-shaped and of considerable density. Newer large square balers have a pre-compression chamber that compresses the material before bringing the material up into the bale chamber. The bale chamber consists of hydraulically-loaded panels. The result of these features is a dense, uniform bale that other baler styles are incapable of producing (Afzalinia, 2008).

The largest challenges in biomass logistics are the transportation and storage costs. Current transportation costs are as high as $.25 per km per Mg (Sokhansanj, 2009). Storage costs are usually greater than $15 per Mg (Kumar and Ileleji, 2009). These costs become substantial when mass quantities of biomass must be transported and stored. Maximizing the transportation and storage efficiency through densification is critical. Using a large square baler to produce high-density bales reduces handling, storage, and transportation costs to an extent. Biomass harvested in the form of large square bales can be compacted over a range of bulk densities, based on the limits of the large square baler used. Bale compression is also an option after the bales are produced. Identification of the relationship between costs of increasing the density of bales and savings incurred during transportation and storage due to the increased densities are necessary to further enable the optimization of large square bale use. This relationship can be acquired by comparing different bale densities in terms of energy and all other associated costs. After the relationship between bale density and energy consumption in bale production is developed, optimal bale densities for different scenarios can be determined.

Biomass feedstocks for bioenergy plants can be harvested from a variety of biological sources in both agricultural and forest settings. Agricultural sources include residues left from a primary crop and dedicated energy crops such as switchgrass and miscanthus. Switchgrass is currently the most promising dedicated energy crop in the United States. The grass is native to North America and grows well in most regions east of the Rocky Mountains. Average yields of up 20 Mg per hectare have been realized at many locations across the United States (Kumarappan 2009). Currently the grass is grown on Conservation Reserve Program land for wildlife enhancement and erosion control. Since the grass grows well on marginal land, in the future switchgrass could be planted on a large portion of land that is currently idle due to infertility (Sarath et al., 2008). Switchgrass biomass will be the focus of the proposed research due to the potential it holds as a leading bioenergy feedstock in the future.

Large square balers that currently accommodate forage crop harvest can be readily utilized in biomass harvest (Sokhansanj, 2009). However, harvesting biomass feedstocks involves creating a product with a whole different set of logistical requirements than traditional agricultural commodities. The challenge in the future is to overcome these logistical barriers with new knowledge and technology. Many unknowns exist with large square balers and their ability to harvest biomass crops, such as switchgrass, that are just starting to be grown on a commercial scale. Parameters for switchgrass harvest with a large square baler such as material capacity, efficiency, and bale density need to be documented. The focus of the proposed research is to address these unknowns, which will improve the logistics of using large square bales in renewable energy applications.

Chapter 2 - Literature Review

This literature review examines the research progress related to harvest, storage, and transportation of agriculturally-derived biomass crops used as energy feedstocks. The emphasis of the review is the logistics involved in the harvest, storage and transportation of biomass. The needs of various bioenergy plants are first discussed followed by an assessment of the sum of the logistics involved in supplying biomass to these plants. These logistics include crop type, harvest, transportation, and storage. Bulk density of biomass is one of the main focuses of this review. The role bulk density plays in each area of logistics will be evaluated and discussed individually.

2.1 Biomass as an energy feedstock

While most bioenergy production methods from herbaceous materials are not yet economical, government policy is helping to drive new innovation and technology in the field. The U.S. Energy Independence Act of 2007 has laid out a roadmap for future renewable fuel production (DOE, 2008). The Act mandates that by 2022, the United States will need to be producing 36 billion gallons of renewable fuel per year. Of the 36 billion gallons, starch-based ethanol production will be capped at 15 billion gallons. This means that 21 billion gallons will need to come from new sources, including 16 billion gallons from either biochemical or thermochemical processes (DOE, 2008).

The feedstocks for these 16 billion gallons will be primarily comprised of agricultural residues, energy crops, and forest residues. While agricultural and forest resources are immediately available to various degrees, a steady supply of energy crops will have to be produced as they become economically feasible. The DOE in conjunction with the USDA recently analyzed the nation's biomass resources and released the "Billion Ton Study" in 2005

(DOE, 2008). The study states that about 1.3 billion dry tons of biomass could be harvested annually in a sustainable manner. Based on projected advances in biorefinery technology, this volume of biomass has the potential to displace 30 percent of the current gasoline consumption in the United States (Kumarappan, 2009). While 1.3 billion tons of biomass production and harvest may someday be possible, the infrastructure to support a system of this magnitude first needs to be built (Jessup, 2009).

Advanced biofuels technologies stem from two different pathways, biochemical conversion and thermochemical conversion. Both of these conversion methods have the ability to use many different forms of biomass as feedstocks. Biochemical conversion is the method used to produce cellulosic ethanol. In biochemical conversion, the lignocellulose contained in the cell well must be broken down into simple sugars with either enzyme or acid pre-treatment. These sugars are then fermented in a similar fashion as corn starch is fermented in corn ethanol production. The key to advancing this technology is to find cost effective methods of pre-treating the material and efficiently isolating the fermentable sugars. Cellulosic ethanol is still in the research and development stage and will remain in this position until the product can economically compete with gasoline (Ruan, 2008).

Thermochemical conversion involves either gasification or pyrolysis, both of which can be applied on almost any type of biomass. Gasification is the production of synthesis gas from biomass using heat. The synthesis gas can then used to produce a variety of different biofuels. Pyrolysis also involves applying heat to biomass, but in a low oxygen environment. Pyrolysis occurs at a lower temperature then gasification and produces a liquid fuel that is then further refined. Thermochemical conversion currently requires very large facilities to be economically competitive. However, efforts are underway to develop smaller plants that process 200 to 500 tons of biomass per day (DOE, 2008). A plant of this size would greatly reduce the logistical burden of providing a year round supply of biomass necessary for a larger scale plant.

Biomass derived from grass land is currently being used as an energy feedstock in direct combustion application to generate heat and power. The production and processing of biomass used in a combustion application is handled largely in the same manner as hay and forages (Prochnow, 2009). The crops are mowed, windrowed, and baled with standard farm machinery that is commonly used in forage production. These biomass crops are typically baled at 10%-20% moisture content to facilitate conventional storage methods, decrease dry matter losses and increase the heating value of the fuel when it reaches the plant.

The types of bales produced for combustion are normally either round bales or large square bales made from common agricultural machinery. Different methods of utilizing the biomass fuel include stand-alone biomass combustion or co-firing the grass biomass with traditional fuels such as coal or peat. The biomass bales are collected in the field and then transported to the plant by flat bed trucks. Some plants can fire an entire bale without any preprocessing. However, it is usually necessary to slice the bales or grind them into finer particles. Other options include pelleting or briquetting the biomass prior to firing (Prochnow, 2009).

Harvest and transportation are the most expensive and energy intensive processes in the production of biomass feedstocks. However, these costs can be substantially reduced through improvements in the logistics of biomass harvest, transport, and storage (Searcy, 2007). At current production costs, the use of agricultural biomass in thermochemical, biochemical, and combustion plants would need to be subsidized to create economic incentive for producers. However, many nonmarket values of these biomass feedstocks, including ecological, environmental, and rural economic benefits, make feedstock economically comparable to fossil fuels (Jessup, 2009). Demand for biomass feedstocks will stimulate rural economics by creating new sources of income for farmers. Ecological and environmental benefits are discussed in later sections. Beyond these nonmarket values, any improvements in the logistics of the feedstocks will significantly help make them a feasible renewable energy option.

2.2 Types of energy crops

The most potential for biomass harvest lies in agriculture residues, dedicated energy crops, and forestry residues. Since the focus of this review is biomass from agricultural systems, forestry residues will not be discussed in detail. Agricultural residues consist of residues that are left over from the production of food and fiber for human and livestock consumption. These residues are abundant in most kinds of agricultural systems. Dedicated energy crops have not been produced on a large scale to date. These are crops that are primarily grown as a biomass energy feedstock.

The most prevalent agriculture residues in the United States come from corn and other cereal crops. Many factors play a role in the amount of biomass that will be obtained from these sources as future demand for biomass feedstocks increases. These residues cannot be considered merely a waste product of intensive agriculture given that they play several important roles in modern agriculture. Residue left in the field serves as a fertilizer to future crops as well as soil cover that aids in preventing erosion. When residues are taken from the field, they are most often used in livestock production. Only excess residue left over after meeting the soil conservation and livestock demands should be made available as a biomass feedstock. The price of this feedstock will then need to compensate for harvest and transportation costs of the residue as well as lost fertilizer value (Kumarappan, 2009).

Dedicated energy crops can include several different types of biomass ranging form forest resources to crops from agriculture to even algae. For agricultural crops, the focus has been on high-yielding perennial grasses (Jessup, 2009). Switchgrass and miscanthus are often cited as the most promising of these grasses. Both are C4 warm season plants that have the ability to grow in hot arid conditions.

Switchgrass, being native to North America, has been of particular interest in the United States. Switchgrass is native to almost anywhere in the United States as seen in Figure 2.1. Since switchgrass is a perennial, the management intensity is greatly reduced after proper establishment. Switchgrass is a perennial crop that can grow for years without the need for replanting. Herbicide applications are usually necessary the year of establishment but if a healthy stand is established herbicide applications are minimal the following years. Switchgrass also has many soil and wildlife enhancing attributes that have initiated its establishment on Conservation Reserve Program (CRP) land (McLaughlin and Kszos, 2005). Ground nesting birds use the grass as a nesting habitat during the summer months. Switchgrass roots can penetrate over 40 cm into the ground. These roots sequester large amounts of carbon dioxide from the air while building the organic matter in the soil. The best management practices for switchgrass have been intensively studied in the past few years (McLaughlin and Kszos, 2005). Many variables including establishment practices, fertilizer rates, and harvest windows are still under discussion and may vary from region to region.

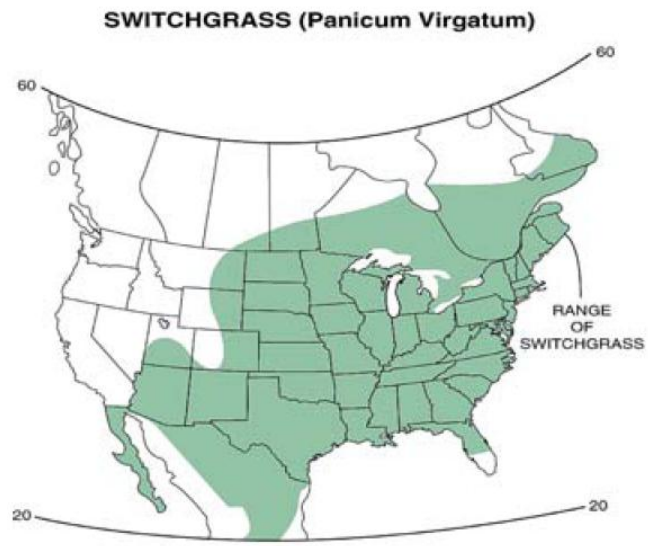

Figure 2.1: Native range of switchgrass in North America (Sarath et al., 2008).

The goal of growing switchgrass for a biomass feedstock is to maximize the dry matter yield of the grass. Switchgrass yields have proven to be the highest when the crop is harvested in fall after anthesis. Multiple harvests per year result in decreased cumulative yields and decreased stand thickness (Sanderson, 2008). A one-pass harvest system results in the least dry matter losses during harvest (Sarath et al., 2008). However, a one pass system does not always produce the most economical product for the end user. Switchgrass yields have been reported to range from 10 Mg/ha up to 20 Mg/ha depending largely on growing conditions and nutrient availability. The farmgate price of switchgrass in terms of cellulosic ethanol has been estimated at $.17/L (Sarath et al., 2008). This figure does not take into account the cost acquired from transportation and storage logistics.

Figure 2.2 breaks down the estimated tons of biomass available as a function of price. MSW is an acronym for municipal solid wastes. Agricultural residues are shown to currently be the cheapest of the groups evaluated and are readily available. The price at which dedicated energy crops become available is strikingly higher than the price at which agricultural residues become available. The difference in price is due to the fact that dedicated energy crops have to exceed the opportunity costs of conventional crops to be profitable. Agricultural residues do not have to compete with opportunity costs since they are byproducts of some other type of agricultural production.

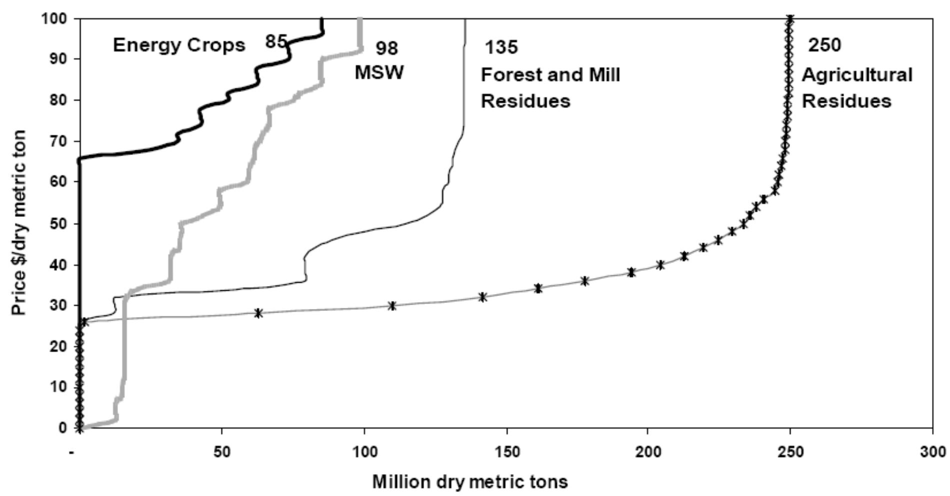

Figure 2.2: Tons of biomass available in the United States verses price (Kumarappan, 2009).

2.3 Bioenergy plant size

Most agricultural biomass sources are fairly remote from the major population centers, which are key locations where the most demand for energy is found. A major goal of biomass logistics is to determine the best location and size for a plant that will produce energy from biomass. Biomass typically has a low bulk density and therefore a low energy density, making it expensive to handle and transport. Valid arguments have been made that biomass energy plants should be kept at the farm level to avoid the high transportation costs of biomass (Ruan, 2008). The energy dense product from these plants will be much more economical to handle, transport, and store. However, advanced biofuel plants are very capital intensive and economies of scale must be taken into consideration (Alfonso, 2009).

Carolan et al. (2007) documented popular projected plant sizes as found in current research. Optimal plant size will ultimately depend on developing technologies, biomass availability, and crop yields. 2,000 to 10,000 dry Mg of biomass per day is the range of plant sizes currently under investigation. Three optimal sizes based on short, middle, and long term analysis of technology development have been speculated (Hamelinck, 2005). This research specifies 2000 Mg, 5000 Mg, and 10000 Mg of biomass per day will be appropriate for plants built in 5 years, 10 to 15 years, and greater than 20 years respectively.

2.4 Biomass harvest methods

Current harvest systems that can immediately be implemented to harvest biomass have all been specifically designed to produce a product most appropriate for agricultural use. While the harvest demands of a biomass energy feedstock product are different from that of a product used in agriculture, the current harvesting technologies are suitable for these new demands. Recently, one pass harvest systems in agriculture have become more popular as have transportation of large loads that reduce the number of trips in and out of the field. However, due to high moisture contents often resulting from one pass systems, multiple pass systems are often preferred for biomass harvest (Sokhansanj, 2009).

Harvesting agricultural crops in the form of baled material is currently one of the most effective harvest methods for transporting the material off the farm. The most common type of bale in the United States is the round bale, which varies in size but is typically 1.5 m tall and 1.8 m in diameter. The advantage of these bales is their ability to shed rain water when properly stored outdoors. However, the shape of the round bale makes handling, transportation, and storage of the bale inefficient compared to a large square bale. Round bales were specifically designed for use on the farm where the bale was produced. Efficient systems for transporting these type of bales over-the-road have not been developed (Cundiff, 2008)

Large square bales are increasing in popularity across the United States due to recent advances in large square baler technology. Large square balers produce a bale that is as large as 1.2 m x 1.2 m x 2.4 m in size. Models that produce smaller square bales have the ability to produce a more dense bale (Sokhansanj, 2009). Cundiff and Marsh (1996) found that large square bale densities of 200 kg/m^3 can be achieved with modern large square balers. This value is considerably higher than the density they were able to achieve with a round baler, which was around 140 kg/m^3. Large square bales have been shown to harvest crops cheaper then round balers on a per dry Mg basis (Cundiff and Marsh, 1996). Although the shape of the square bale has many advantages over round bales, large square bales cannot be stored outside in wet climates unless wrapped in a plastic film. However, when stored properly, large square bales preserve the crop better than round bales (Sokhansanj and Turhollow, 2004). The other downside to large square balers is a high initial equipment cost as compared to round balers.

The production of both kinds of bales involves a multiple pass system. Because the biomass must be left in the field to dry to desirable moisture content, mowing is typically accomplished with a machine that also conditions the crop by cracking the stems to reduce the dry-down time. Following mowing, a rake is used to gather the crop into a swath that not only helps to facilitate drying, but windrows the crop so that it can be picked up by the baler. Balers are implements that are pulled behind a tractor in the field. Sokhansanj et al. (2009) comment that self-propelled large square balers are currently being designed. Bale collection is typically performed by loading the bales onto a flatbed truck with a front-end bale grabber. Automatic bale collectors for large square bales are also available and have the advantage of being able to both retrieve and stack the large square bales.

Forage harvesters that chop materials are another possible biomass harvest option. Wet chop is typically produced for animal feed and has been limited to on-the-farm use. Typically a multiple pass system is necessary for biomass crops where a crop is cut and allowed to dry to some extent before harvest. However, one pass harvest can be implemented with crops such as corn. Wet chop typically has to be ensiled to avoid dry matter losses. While wet chop has become the best harvest method for use on the farm, the high moisture content of the material makes it costly to transport. Also, the high moisture content may not be desirable to the end user in bioenergy production. Worley et al. (1996) found that silage produced from wet chop is not competitive with dry hay in terms of cellulosic feedstocks.

Dry chop is similar to wet chop except dry chop biomass is typically harvested with a moisture content below 15%. This harvest system requires the same multiple pass operations as baled hay. Due to the low moisture content of dry chop, the material does not have to be ensiled. However, the material has a bulk density that is under half that of baled herbaceous biomass. The material must also be stored out of the rain since chopped material will not shed water. Although dry chopped herbaceous biomass may be of benefit to the end user, the characteristics of the material currently make chopped material hard to justify in terms of storage, handling, and transportation (Sokhansanj, 2009).

2.5 Transportation of biomass

Unless the biomass feedstock is used directly on the farm, transportation and handling are unavoidable. Transportation options are mainly limited to truck, rail, and, to a lesser extent, barge or pipeline. Truck transport of biomass is by far the most accessible and well developed. To analyze the transportation costs, both the distance variable costs and the distance fixed costs must be taken into account. Distance variable costs are based solely on the distance over which the biomass must be transported. Distance fixed costs will depend on the costs of handling different forms of biomass. As biomass is transported over a longer distance, the distance fixed costs of the process will decrease in proportion to the distance variable costs (Searcy, 2007).

Biomass transportation costs by truck are currently determined by the total mass of the material being transported, regardless of the actual dry matter mass of the load. The moisture content of any type of biomass is going to play a large role in the overall cost to transport the material. Due to the low bulk density of typical biomass feedstocks, volume becomes the limiting factor in most types of transportation. The most efficient biomass to transport would have a low moisture content and be dense enough to exceed the mass limitations of the transportation vehicle before just exceeding the volume limitations. Therefore, when optimizing biomass logistics one must take into account the expected moisture content of the biomass as well as the bulk density of the product. Lowering the moisture content as well as raising the bulk density of biomass after harvest are energy and capital intensive processes. The ideal farm gate biomass product for transportation would have a moisture content that is as low as feasibly possible, while having a bulk density that is just sufficient enough so that volume is no longer the limiting factor in the amount if material that can be loaded on the vehicle (Searcy, 2007). Generalizations of optimal bulk densities based on weight restrictions for various types of transportation can be seen in Table 2.1 (Kalminski, 1989).

Table 2.1: Optimal material density for various shipping modes (Kalminski, 1989).

Shipping Mode	Optimal Density (kg/m^3)
Semi Truck	256
Rail	320-480
Container	640-800

The other transportation types suitable for biomass besides truck transport include barge, rail, and pipeline systems. These three options obviously have specific infrastructure requirements and are not available everywhere. The pipeline option involves using water and chopped biomass to create a slurry that can be pumped as a liquid. This option is still hypothetical and has only been applied to wood chips (Sokhansanj, 2009). As seen from Figure 2.3, barge and rail transportation are cheaper than truck transportation over long distances. Truck transportation is most economical under a distance of 100 km. To implement rail and barge transportation, a combination of transportation methods will be needed. A combination of different transportation types applied to the same material will also increase the handling charges. The types of transportation noted here will need to be optimized for different situations depending on distance and availability.

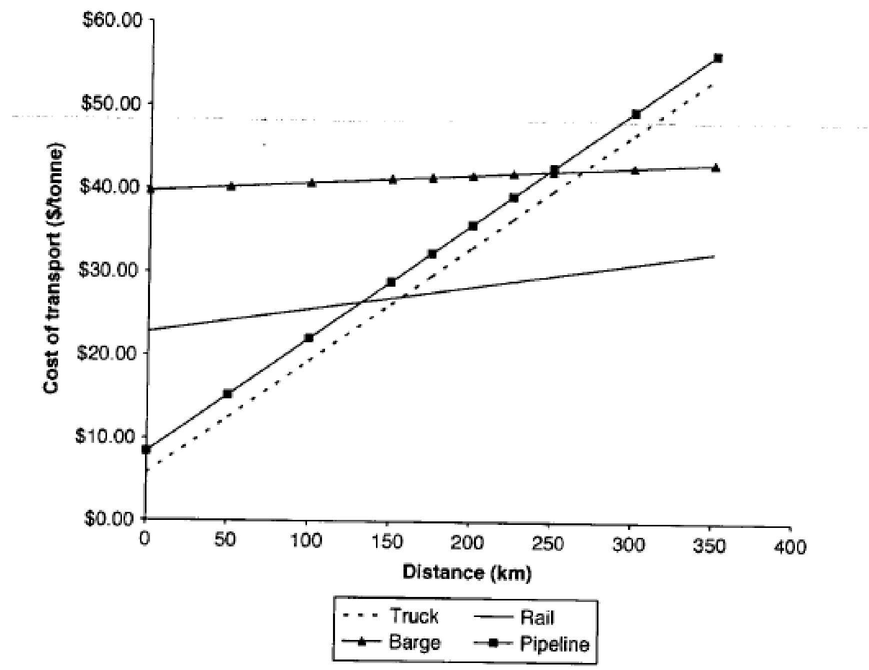

Figure 2.3: Transportation cost as a function of distance (Sokhansanj, 2009).

2.6 Storage of biomass

A large percentage of biomass will need to be stored for periods of time before the material can be processed at a bioenergy plant. Storage is necessary since biomass can not be produced throughout the year and bioenergy plants require a steady source of feedstock. Storage of biomass outside and uncovered is acceptable and economical in some climates across the United States, however in many areas significant losses will be incurred from storage that lacks any type of covering. Biomass stockpiled uncovered is frequently set on crushed stone. The crushed stone reduces dry matter losses, forms a base for equipment operation, and is not overly expensive (Cundiff and Marsh, 1996). In wetter climates, biomass must often be stored under roof or at least under a tarp to prevent dry matter losses due to rotting and to maintain low moisture contents. Bulk density of biomass stored inside becomes of great importance since space is often limited and valuable. Generally, the higher the bulk density, the more efficiently the storage space is used.

Kumar and Ileleji (2009) analyzed the costs associated with large square bale storage under roof. The results were based on a bale density of 150 kg/m^3. These costs are stated in dollars per Mg and are universal for all crops with a bale density of 150 kg/m^3. Storage costs can be expected to decrease with increased bale density and vice versa. The storage facility held ten days worth of bales that were stacked six high. Half the ground space inside the building was assumed to be left open for access to the bales. The results of the analysis are seen in Table 2.2. The costs were based on both the building costs and handling costs. Telehandlers were used for handling. Because the bulk density of the bales was held constant, there is no indication of the impact bulk density has on the storage costs.

Table 2.2: Storage requirements and costs for large square bales with a density of 150 kg/m^3 (Kumar and Ileleji, 2009).

Plant Capacity (Million Gallons per Year)	Inventory Required (Mg)	Area of Storage Site (m^2)	Number of Telehandlers	Storage Costs ($/Mg)
40	15873	35000	1	16.23
60	23810	53000	2	18.9
100	39683	88000	3	17.83
150	47620	105000	4	18.8
200	79366	175000	5	16.23

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2.7 Significance of biomass bulk density

Bulk density is one of the most important characteristics of biomass feedstocks. Bulk density has a direct influence on many attributes that determine the cost of delivered biomass feedstock to the refinery (Lam et al., 2008). Biomass densification is vital to increasing bulk density and therefore reducing transportation and handling costs. Densification processes such as compression baling can increase the bulk density of a material to one-fifth of the loose bulk density by decreasing both inter-particle and intra-particle voids (Van Pelt, 2003).

Densification processes use pressure that is applied directly to biomass and are fairly energy intensive. A power model as seen in equation 2.1 has been used to demonstrate the mathematical relationship between bulk density and pressure.

Equation 2.1: Bulk density power curve equation

$$\boldsymbol{\gamma = k(p^n)}$$

Where: γ = bulk density (kg/m^3)
k = constant
p = pressure (kPa)
n = exponential constant

The constants n and k are specific to each material and must be determined with compression testing. A general model used to describe biomass compression is kg/m^3 = 205(mPa)$^{.278}$. A graphic representation of Kalminski's model can be seen in Figure 2.4. Based on this model, to double the bulk density of biomass, approximately twelve times more pressure is required. To more accurately describe biomass compression, models must be developed that are specific to each different crop, particle size, and moisture content.

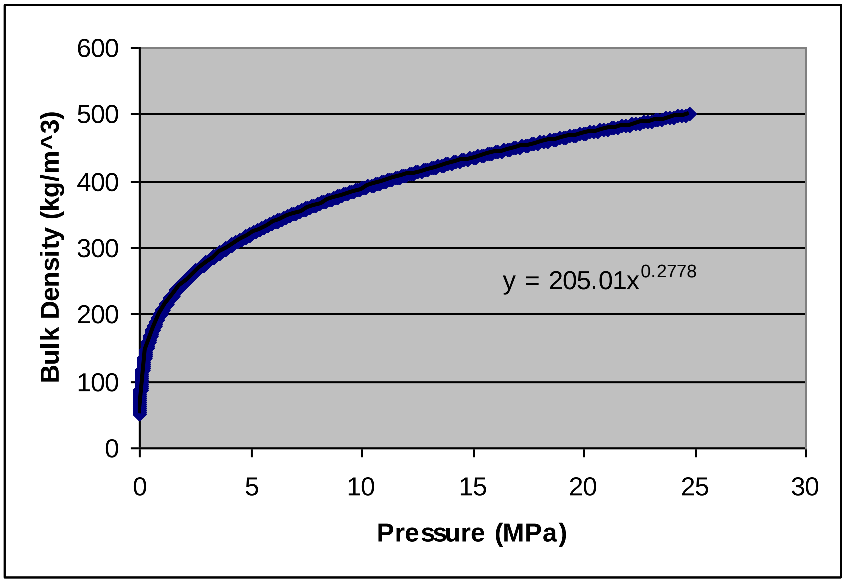

Figure 2.4: Bulk density vs. pressure universal model to describe biomass compression (Kalminski, 1989).

The model in Figure 2.4 is a generalization; the actual relationship will vary depending on the type of material, moisture contents, and partial size. Biomass with a greater percentage of leaf matter will compress easier than stalk material (Van Pelt, 2003). Heating biomass before and during compression has been shown to reduce the pressure needed to achieve desired bulk densities (Kalminski, 1989). Moisture is a major variable that has a great effect on pressure density relationship of biomass. High moisture contents tend to decrease the friction of biomass particles rubbing against each other during compression. The moisture content of biomass increases, the pressure required to achieve a desired wet bulk density will decrease (Van Pelt, 2003).

The bulk density of most plant biomass in loose, uncompressed form is well below 100 kg/m^3 (Sokhansanj, 2004). To increase the bulk density beyond these values, mechanical force is required. The bulk density of switchgrass harvested using various methods can be seen in Table

2.3. Densification after harvest involves recompression to achieve higher densities. Forming pellets, cubes, or briquettes are current options. These options require grinding the biomass into fine particles and applying pressures greater than 100 MPa (Kaliyan and Morey, 2006). The results of these biomass densification techniques used on switchgrass can also be seen in Table 2.3.

Table 2.3: Density achieved from various harvest and densification techniques for switchgrass (Sokhansanj, 2009).

Form of biomass	Shape and size characteristics	Density (kg/m^3)
Chopped biomass	20-40 mm long	60-80
Ground particles	1.5 mm loose fill	120
Baled biomass	Round or large squares	140-180
Ground particles	1.5 mm pack fill with tapping	200
Briquettes	32 mm diameter x 25 mm thick	350
Cubes	33 mm x 33 mm cross section	400
Pellets	6.24 m diameter	500-700

Bale compression outside of the field currently holds a niche market for specialty agricultural forage markets. Several manufacturers currently sell bale compressors that slice large square bales into smaller sections and further compress the sections using hydraulic rams. Manufacturers such as Steffen Hay Inc. claim a bulk density of up to 500 kg/m^3 can be achieved with their product (Steffen Systems, 2009). The output of these machines is typically a small bale around 35kg that is often stacked in shipping containers (Hierden, 1999). The machines are mostly used for international forage shipping logistics due to the current high costs of compression. Current compression costs average around $30 per ton (Miles, 2008). However, modifications to bale compressor designs could make the machines feasible for use in a biomass supply industry.

2.8 State of the art of switchgrass large square bale production and densification

Due to both economic and political drivers, biofuels derived from biomass resources are slated to soon meet a significant percentage of the nation's fuel demand. Energy production from direct combustion of biomass is also on the rise as the U.S. economy transitions from coal and other fossil fuels to renewable sources of energy. Over a billion tons of biomass are available for energy production annually in the United States. Searcy (2007) as well as many others, have emphasized the great need to develop the logistics necessary to harvest, transport, and store large quantities of biomass. The challenges of economically producing biomass are complex problems that will need to be solved using a combination of old and new technology.

Switchgrass, being native to much of the United States, has been identified as the most promising dedicated energy crop for various types of bioenergy plants. Established stands of switchgrass produce high yields of dry matter year after year without the need for intensive management practices. Switchgrass can be grown on marginal land that is not suitable for other crops. The plant is rather drought tolerant and does require large fertilizer inputs.

While a variety of harvest methods can be applied to switchgrass, dry large package bales are currently the most convenient harvest method when transportation and storage are necessary. Large square bales are a type of large package bale gaining popularity across the U.S. due to recent advances in large square baler technology. Large square bales make the most efficient use of transportation and storage space based on the nature of their shape. Kumar and Ileleji (2009) have hypothesized that large square bales will be a significant harvest method for energy crops across much of the United States.

Large square bale density can be controlled at the time of production, as well as after production. Large square balers have a wide range of density settings to choose from in the field. Densification options after bale production include compression, pelleting, cubing, and brisquetting. Pelleting, cubing, and brisquetting are energy intensive processes that may not need to be performed on all switchgrass feedstocks. When switchgrass in the form of large square bales is a satisfactory product for the end user, the density of the bales becomes a significant factor in the logistics production, transportation, handling, and storage of large square bales.

Sokhansanj (2009) has quantified the cost of various forms of transportation for biomass feedstocks. Similarly, Kumar and Ileleji (2009) have quantified the handling and storage costs for large square bales at a bioenergy plant. However, in both of these evaluations the density of the biomass is held constant. No indication of the benefits of increasing density from the initial assumed value is given. Increasing the density of large square bales will have both costs and rewards that play a valuable role in logistics and economics.

Kalminski (1989) stated that biomass compression could be simulated with a power model that predicts bulks density as a function of pressure. However, the model does not take into account biomass type, particle size, or moisture content. Further research is needed to accurately quantify the pressures and energy required to compress switchgrass in order to transform it into a viable energy feedstock.

Chapter 3 - Goals, objectives, and hypothesis

Densification is a fundamental process that is vital to the production of biomass feedstocks. Densification increases the bulk density of biomass, which is necessary to harvest, transport, and store a product that is an economically feasible biomass energy feedstock. Current herbaceous biomass harvest methods produce either chopped loose materials or bales. The literature review recognized baled material as the most readily available form of biomass suitable for current off the farm storage and transportation methods. Of the different types of agriculturally-derived biomass available, switchgrass is recognized as holding the greatest potential as a dedicated energy crop in the United States.

The goal of this research is to determine the parameters associated with switchgrass large square bale production and handling.

The objectives associated with the goal statement were as follows:

1. Measure the energy consumption, material capacity, and efficiency of a large square baler while producing switchgrass bales of various densities.

2. Examine bale handling and transportation material capacities on a commercial scale.

3. Determine the effect moisture content and harvest time on the efficiency of large square bale production.

Hypothesis 1: The first hypothesis deals with a large square baler test in a switchgrass field. Bales will be produced at different densities by incrementally increasing the density setting of the baler. The change in fuel use will be recorded to determine if there is any extra energy requirements associated with increasing the bale density.

H_o = Increasing bale density does not have a significant effect on the fuel consumption of the tractor used to operate the large square baler.

H_a = Increasing bale density does have a significant effect on the fuel consumption of the tractor used to operate the large square baler.

Hypothesis 2: Hypothesis two deals with the effects of variable moisture contents on the specific energy requirements of densification. The lab scale compression tests will be used to test the following:

H_o = Moisture content in switchgrass has no effect on the specific energy requirements to reach a certain dry matter bulk density

H_a = The higher the moisture content of switchgrass, the lower the specific energy required to reach a certain dry matter bulk density.

Hypothesis 3: Hypothesis three tests if there is a difference in the specific energy requirements for densification of fall and spring harvested switchgrass. Although the large square baler will only be used on spring harvested switchgrass, this test will provide insight as to how the large square baler would behave in a fall harvest situation.

H_o = The fall and spring harvested switchgrass samples have the same specific energy requirements for compression.

H_a = The fall and spring harvested switchgrass samples have different specific energy requirements for compression.

Chapter 4 - Methodology

The methodology section lays out the experimental design that is formulated to answer the hypotheses. The experimental design is broken down into the four phases listed below:

Phase I: Switchgrass large square bale production field test

Phase II: Examine large square bale handling and transportation efficiencies.

Phase III: Switchgrass laboratory compression testing.

Phase IV: Data analysis and hypothesis testing.

Phase one entails producing large square bales at Ernst Conservation Seeds in Meadville, PA. This phase will focus on determining the field capacity, efficiency, and density capabilities of a large square baler when used to harvest switchgrass. Phase two examines the rate at which large square bales can be gathered, transported to a storage location and put into storage under roof at a large commercial farm. Phase three involves laboratory compression testing of various samples of switchgrass. The goal of the laboratory testing is to determine the effects of moisture content and harvest time on the mechanical force required to compress the switchgrass. In phase four, the data collected from both the field and laboratory tests will be analyzed and used in hypothesis testing. Figure 4.1 is a flow chart used to visually describe the experimental design and arrangement of the four phases.

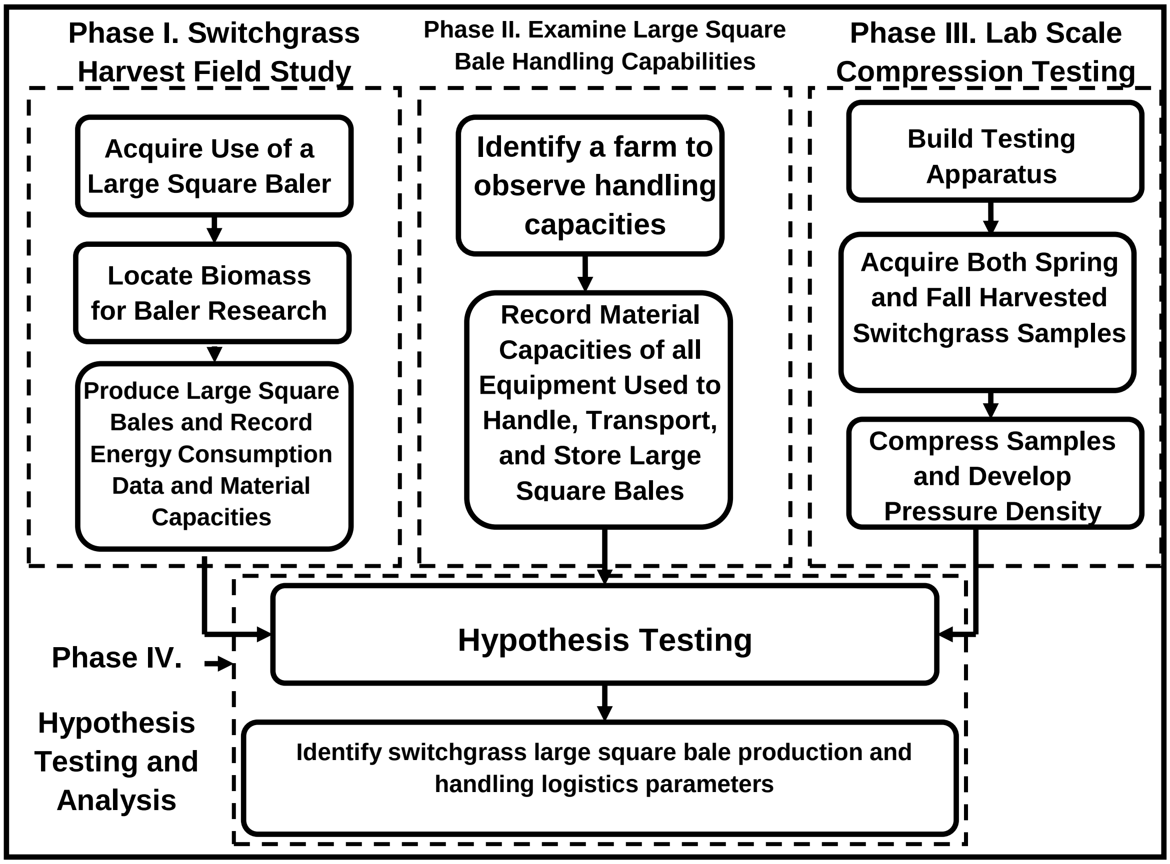

Figure 4.1: Methods Flow Chart

Chapter 5 – Large Square Baler Field Test

5.1 Materials and Methods

The experimental field was located at Ernst Conservation Seeds Inc., Meadville, PA. This seed company grows roughly 3000 acres of switchgrass per year for seed production. The seeds are harvested in the fall and the biomass is typically baled in the spring due to fall time constraints. All the biomass is currently baled as round bales. Round bales are the preferred harvest method since they shed water well, allowing them to be stored outside, uncovered. Average biomass yields for the switchgrass fields in previous years were reported to be 4.5Mg/ha (wet matter). When the switchgrass is baled in the spring, a majority of the bales are processed through a tub grinder and used for dairy bedding. The bales are transported to local dairy farms throughout the year and ground on site. The ground up switchgrass can be as much as three times as absorbent by volume compared to traditional materials (Arnett, 2010). A small percentage of the bales are ground and pressed into briquettes. Allowing the biomass to overwinter on the ground causes it to shatter more easily and decreases the energy requirements of the grinding processes (Arnett, 2010). For this field study, large square bales were produced on a field that would be normally harvested with a round baler. The large square bales were left at the farm where they will be ground for either dairy bedding or briquettes. Unlike the round bales, the large square bales needed to be stored under roof until their final utilization.

5.1.1 Switchgrass Field

The field is currently used as a continuous switchgrass field for seed production. This particular field was planted in “Cave-in-Rock” switchgrass and had been in continuous production for five years. The switchgrass is allowed to grow throughout the entire growing season until anthesis. The seeds are then harvested when field and weather conditions permit, normally in October or November. The field was harvested with a combine using a stripper head to strip the seeds from the top of the plant. No biomass was removed from the field during seed harvesting. After seed harvest, the field was mowed in November with a 3.66 m swath discbine and the biomass overwintered on the ground.

The field was approximately ten hectares in size. The yield of the field varied greatly. The average yield for this field test was 2.42 Mg of dry matter per hectare at 12.5% (w.b.). This yield is considered low compared to yield results from other studies. The low yield can be attributed to the fact that the grower is only interested in seed production and not biomass. The switchgrass population in the field was fairly low and fertilizer had not been applied to stand in previous years. Yield also varied greatly from one section of the field to another. The yield difference is partially due to the fact that this single ten hectare field had been managed as several smaller fields before switchgrass establishment. Each of the former fields had different pH and nutrient levels.

5.1.2 Tractor and Baler

The tractor and baler were both provided by CNH. An experienced field test engineer from CNH operated the baler during the experiment. The tractor used was a Case Puma 210 diesel tractor which had the capability of producing 142 kW PTO power. The baler was a New Holland BB9080 Rotor Cutter large square baler. This particular baler requires 112 kW minimum PTO power. The baler was equipped with a rotor cutter at the pickup head but was not engaged during baling. The end dimensions of the bales produced were 1.20 m x 0.90 m. Bale length was set at 2.44m (8ft).

The baler had a pre-compression chamber where a bale flake was formed before being loaded in the bale chamber by stuffer forks. The pace at which the flakes are fed into the bale chamber is determined by the rate the material was gathered by the pickup tines. The speed of the tractor was varied based on windrow size in order to maintain one stuffer stroke per plunger stoke. At this feed rate a consistent and uniformly dense bale is produced. The stuffer trip leaver was adjusted so that the flake size in the finished bale would be approximately 70 mm at the first and lowest density setting used. No further adjustment was made to the stuffer trip lever. The higher density setting resulted in thinner flake due to the greater compression force applied to the same volume of switchgrass.

Figure 5.1: Tractor and Baler

5.1.2 Other materials

A bale scale was used to weigh all the bales produced in the field. The scale had been checked for accuracy prior to all field tests. The bales were collected one at a time with a skid loader, weighed, and set at the edge of the field. Fuel measurements were taken by measuring the weight of a five gallon fuel container before and after topping off the fuel tank of the tractor. A

GPS Trimble unit was mounted on the baler and the GPS data was collected on a computer in the tractor cab. All bales were probed with a forage sampler to provide several samples for moisture analysis.

5.2 Experimental Design and Test Procedures

Measurements taken during the field test include bale weight, volume, and moisture content. The distance traveled by the tractor as well as the time spent baling was recorded. Fuel consumption was measured by topping off the fuel tank with a fuel container and measuring the difference in container weight. Yield was determined from the sum of the weights of the bales that were harvested over a given area of land. The baler was operated at several different density settings to measure differences in energy consumption. The baler and tractor were operated as they would be in commercial operation.

Modern large square balers are designed to produce bales of constant density by keeping the load on the plunger constant. The baler identifies bale density as a percentage of the maximum load that can be applied to the plunger. Resistance from hydraulically loaded panels that form the bale chute is continuously varied to keep the load on the plunger constant. This percentage of plunger load will create different bale densities for every crop based on the properties of the crop. An initial goal was to produce bales at 40%, 70%, and 100% of the maximum load. However, several problems arose over the course of the baling process. At 100% plunger load, the bales exerted too much force on the strings, causing them to tear. A string with a higher tensile strength would need to be used for this density setting in switchgrass. After determining the string did not have enough tensile strength for the maximum bale density, the bales were formed at 40%, 60%, and 80% of the maximum plunger load. During the 60% plunger load sample, the ISOBUS connection to the baler was interrupted, causing an interruption in the density control system. Bales were produced at very low densities following the interruption. After fixing the problem, several bales from the sample needed to be produced to allow the bale density to stabilize, resulting in inconsistent densities. Due to this malfunction, the data from the 60% plunger load sample had to be discarded.

The field was raked the morning prior to baling. Tandem roller bar rakes were used to rake the switchgrass from a 7.5 meter swath into one windrow. The 7.5 meter swath was chosen in order to form windrows that were properly sized for the baler. However, due to varying yield throughout the field, the windrows varied considerably in size and density.

The field was divided into three sections of windrows that each contained six windrows. Each section was assigned one density setting. A subsample consisted of all the biomass that resulted from baling one windrow, turning once in the headland and baling another parallel windrow of equal length. Each subsample contained two windrows to balance effects of the field slope. All bales were marked according to which sample and subsample they belonged. The number of bales produced in each subsample varied depending on the amount of biomass in the subsample's two windrows. At the end of each subsample, the fraction of an untied bale in the chute was manually tied off to mark the start of a new subsample. The identification of the bales in each subsample allowed the biomass from each subsample to be weighed. Bales were not manually ejected at the end of each subsample so that a steady and continuous flow of material through the baler could be maintained.

Figure 5.2 shows the actual GPS data from the three subsamples while producing bales at 40% of the plunger load capacity. Each individual color line as shown in Figure 5.2 indicates one sample from the 40% plunger load data. The other density treatments were baled in a similar fashion. The GPS data, which provided the exact length of each sample, was collected while the baler was in operation. A time stamp was included with each GPS data point. The time stamp was used to calculate the exact time the baler spent in operation for each subsample. When the tractor reached the end of each subsample, it was immediately shut off and fuel consumption measurements were taken. The bales remained in the field until baling operations were completed. The bales were then collected, weighed, and measured to determine the cumulative mass and volume of the biomass baled in each sample. A forage sampler was used to obtain samples of the biomass for moisture content analysis.

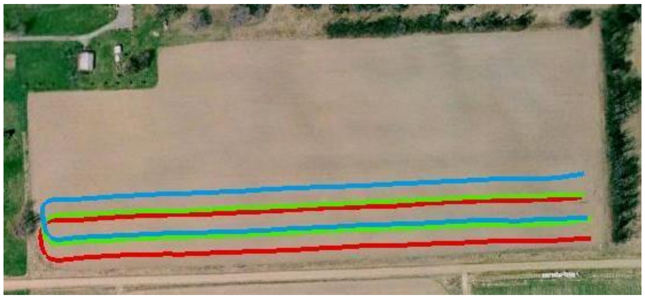

Figure 5.2: GPS data showing the three samples from the 40% plunger load capacity setting.

5.3 Results and Discussion

5.3.1 Measured Results from Field Test

Table 5.1 lists the measurements taken in the field during the study. The plunger load column identifies the two samples which each represents one plunger load setting. The 60% plunger load setting is not shown due to the problems encountered when baling that sample. The length column is the total length of windrow baled in each sample as determined from the GPS data. The mass and volume are the sum of the measurements taken from all the bales made in each sample, including the fractional bale. Three or more full length bales and one bale of fractional length were produced in each subsample depending on the amount of biomass in each subsample. Fuel consumption and time are also given for each sample. All mass values represent the total wet matter. Average moisture content for all of the bales was 12.5% (w.b.).

Table 5.2 shows that the yield difference between areas of the field is dramatically different. The northern side of the field yielded significantly more than the southern side where the material was baled at 40% of the plunger load capacity. Great variation in switchgrass yields has been documented in other switchgrass research plots. Switchgrass yield can vary greatly based on soil parameters. Yields at specific locations within a 4.8 hectare field ranged from less than 3 Mg per hectare to greater than 20 Mg per hectare. These yield differences were primarily attributed to differences in soil fertility and pH (Di Virgilio et al., 2007). Given the fact that the switchgrass field used in the field study was managed as several separate fields in the past, the changes in the yield are not surprising.

Table 5.1: Field Measurements

Plunger Load (sample)	Subsample	Subsample Length (m)	Mass Baled (kg at 12.5% w.b.)	Total Volume of bales (m^3)	Fuel Consumption (L)	Time (sec)
40%	1	780	1200	8.59	2.224	439
	2	800	1185	7.96	2.250	356
	3	780	1177	7.90	2.115	408
80%	1	780	2172	12.51	2.445	533
	2	600	1494	8.09	2.042	456
	3	580	1431	7.74	1.927	412

Table 5.2: Calculated Results (Calculated results derived from the data in Table 5.1).

Plunger Load	40%	80%
Average Yield (Mg/Hectare)	2.06	3.53
Average Ground Speed (km/h)	7.45	5.29
Average Bale Density (kg/m^3)	145.8	181.1
Average Fuel Consumption (L/h)	19.90	16.49
Average Material Capacity (Mg/h)	10.75	12.99
Average Fuel Consumption (L/Mg)	1.85	1.28

The biomass yield averages as a whole for each sample at Ernst were much lower than switchgrass's potential due to a combination of minimal inputs and spring harvest. These yields are representative of what can be expected when fertilizer is not applied to switchgrass in this particular soil type. The yields also would have been substantially higher if the field had been harvested in the fall as opposed to the spring. Typically, fall harvest losses will be around 20% spring harvest losses can greater than 40%. (Adler et al., 2006). When the switchgrass overwinters before harvest, a greater percentage of the biomass becomes unrecoverable by mowers, rakes, and balers. This decrease in yield is partially dependent on snowfall over the winter. Up to 90% of the yield reduction from fall to spring was due to harvest losses from material that was not picked up by the baler, the other 10% in yield reduction was from decreased tiller weight (Adler et al., 2006).

Since all the windrows were raked from a 7.5 meter wide strip, the greater yielding sections of the field resulted in greater windrow thickness. Consequently, the tractor did not have to be driven as fast in the heavier windrow to load the baler to capacity. This decrease in speed by an average of 2.16 km/h from the 40% sample to the 80% dramatically increased the efficiency of the baling process. The baler was able to process more material per hour since the operator did not have to drive at excessive speeds and the heavier windrows were more uniform in thickness. The decrease in tractor speed caused fuel consumption per hour to decrease by 17%. Because of the decrease in fuel consumption and the increase in the processing rate, the fuel use in terms of L/Mg of switchgrass decreased by 31%. After increasing the density, the tractor was expected to use more energy to process the same amount of material, resulting in greater fuel consumption. The energy transmitted through the PTO most likely did increase in order to produce the denser bales since more force was applied to each plunger stroke. However this increase in the energy requirement to create a denser bale was outweighed by a decrease in energy requirement due to driving slower through the field while gathering the switchgrass at a faster rate.

5.3.3 Discussion on baler field efficiency

The field efficiency of the baler can be determined by dividing the actual material capacity by the theoretical material capacity. Equation 5.1 was used to calculate the theoretical material capacity of large square balers.

Equation 5.1: Baler Theoretical Field Material Capacity (Srivastava, et al., 2006)

$$m_f = \frac{d_c w_c \delta_s \rho_c \omega_c}{60}$$

Where m_f = material capacity or material feed rate, kg/s

d_c = depth of bale chamber, m

w_c = width of bale chamber, m

δ_s = thickness of each compressed slice in the bale, m

ρ_c = density of the bale, kg/m^3

ω_c = plunger speed at rated PTO speed, strokes per minute

Table 5.3 lists the value for each variable in equation 5.1. The bale chamber depth ($\boldsymbol{d_c}$), bale chamber width ($\boldsymbol{w_c}$) and plunger speed ($\boldsymbol{\omega_c}$) remained constant for each density setting. Bale density ($\boldsymbol{\rho_c}$) increased due to an increased plunger load setting. An increase in bale density caused a decrease in the flake width ($\boldsymbol{\delta_s}$). These parameters are either measured or provided by the manufacture.

Table 5.3: Variables for different windrow samples

Variable	40% Maximum Plunger Load	80% Maximum Plunger Load
$\boldsymbol{d_c}$	.9 meters	.9 meters
$\boldsymbol{w_c}$	1.2 meters	1.2 meters
$\boldsymbol{\delta_s}$	.07 meters	.056 meters
$\boldsymbol{\rho_c}$	146 kg/m^3	181 kg/m^3
$\boldsymbol{\omega_c}$	42 stokes per minute	42 stokes per minute

When bales were produced at the 40% plunger load density setting, the baler produced bales with 0.07m wide f*l*akes and bale densities that averaged 146 kg/m^3. These parameters resulted in a theoretical material capacity of 7.73kg/s or 27.83 Mg/h. The average actual material capacity stated in Table 5.2 for the 40% plunger load setting is 10.75Mg/h. The field efficiency is calculated as actual material capacity divided by theoretical material capacity. At the 40% plunger load setting the field efficiency is 39%. At the 80% plunger load setting the bale density increased but the flakes contained the same amount of material because no adjustment was made to the stuffer trip lever and the volume of material in each flake remained the same. The density of the bales increased but the flake width decreased, resulting in a theoretical material capacity remained the same at 27.83 Mg/h. The actual material capacity for the 80% plunger load setting from Table 5.2 is 12.99 Mg/h. The field efficiency for the 80% plunger load setting increased to 47%.

With this particular baler the theoretical material capacity is limited by the size of the flake injected into the bale chamber. The baler can be adjusted to produce different flake sizes. Optimal flake size varies for different crops. The operator's manual for the baler recommends that the finished flake size average 70 mm for straw like materials. Increasing the flake size beyond 70 mm results in less plunger strokes per Mg of biomass, causing decreased bale density and uniformity. Smaller flakes will result in denser bales but the material capacity will decrease. The baler cannot be expected to reach theoretical material capacity for any extended periods of time due to variations in windrow thickness and time delays. When operating near theoretical field capacity, slight increases in the feed rate can cause the pickup head on the baler to jam or shear bolt failure within the pickup head drive line.

5.3.3 Bale Density

The density of the bales created from the two different treatments was quite different. By increasing the plunger load by 40% there was a 26% increase in bale density. 100% of the plunger load capacity was not used in the experiment due to problems with bale strings tearing due to insufficient tensile strength. However, test data indicated that the baler would have been theoretically able to produce switchgrass bales that approach 200 kg/m^3 at 12.5% (w.b.) moisture content if string with a higher tensile strength was used. Moisture content, which is known to affect bale formation, will be unique in every situation. The moisture content of switchgrass had various effects on biomass densification which is discussed in Chapter 7.

5.4 Conclusions and hypothesis testing

The actual material capacity is dependent on how well the operator is able to adequately feed the baler with material from the windrow. In this field test the operator attempted to feed the baler at one stuffer stroke per plunger stroke. At this feed rate, a new flake in the bale would be formed with every plunger stroke and the actual material capacity would approach the theoretical material capacity. The best material capacity achieved was only 47% of the theoretical material capacity. Part of the loss in capacity was due to the single 180 degree turn in the head land for each sample. The tractor spent several seconds turning between each windrow. However, the turns in the headland cannot account for all the loss in efficiency. The operator did his best to run the baler as efficiently as possible but was not able to consistently load the baler to capacity. The inability of the operator to properly feed the baler stems from light and inconstant windrows. Inconstant windrow densities cause the operator to have to constantly vary the speed of the baler. This creates difficulties maintaining a consistent and adequate feed rate. Although windrows were merged with a parallel bar rake prior to the baling, windrows were very light at some points that the operator could not maintain a speed high enough to feed the baler at or near it maximum capacity.

This study indicated that actual material capacity of the baler significantly affected machine fuel consumption. There was a 31% decrease in the fuel consumption per Mg in the 80% plunger load sample as compared to the 40% plunger load samples. This decrease in fuel consumption partly resulted from the increase in actual material capacity of the baler. The closer the baler was operated to theoretical material capacity, the more fuel efficient the whole process became. In this particular study, a 21% increase in the actual material capacity accounted for a majority of 31% decrease in fuel usage per Mg. This increase in actual material capacity and decrease in fuel usage between the two density settings can be directly attributed to a thicker and more consistent windrow in 80% plunger load setting samples. Since the material was fed into the baler at a faster pace in the 80% plunger load sample, the plunger and other major moving components of the baler were able to produce bales at a faster rate while requiring only a marginal increase in power.

The thick and consistent windrows in the 80% plunger load treatment meant that the tractor did not have to be driven as fast to properly load the baler. By decreasing the speed of the tractor by an average of 2.16 km/h, the operator had the ability to considerably increase the efficiency of producing bales. This 2.16 km/h decrease in the ground speed of the tractor and baler was also a component that helped result in the 31% decrease in fuel use per Mg. The greater the speed of the tractor and the baler, the greater the power requirements to maintain that speed were. The field speed of the tractor and baler was within or below the typical field speed of 6.5-13 km/h for a large square baler reported in ASAE standard 497.4. However the field efficiency did not reach the typical range of 70-90% as reported in the same standard due to problems with windrow consistency, causing an inability to provide a high enough material feed rate throughout the field test.

It is unclear how much extra power was used to increase the density of the bales from 146kg/m^3 to 181kg/m^3. However, it is clear that the actual material capacity and travel speed of the tractor and baler had a much greater effect on the energy requirements than the density setting of the baler. Since the ground speed and actual material capacity are directly correlated to the quality of the windrow, raking an appropriately-sized and consistent windrow is the most important component in improving the efficiency of the baler. Hypothesis one was stated as follows:

H_o = Increasing bale density does not have a significant effect on the fuel consumption of the tractor used to operate the large square baler.

H_a = Increasing bale density does have a significant effect on the fuel consumption of the tractor used to operate the large square baler.

Based on the results of the field study, there was not a perceptible increase in fuel consumption as bale density was increased and the null hypothesis could not be rejected. Any increases in fuel consumption caused by increasing bale density were marginalized by the effects of other less controllable factors such as the actual material capacity and ground speed. Although the null hypothesis could not be rejected in this instance, the unanticipated results of the study provide valuable insight into other important aspects of large square baler efficiency such as the affects of ground speed and windrow size.

This baler theoretically has the ability to produce spring harvested switchgrass bales that approach 200 kg/m^3. Bale density is a critical aspect of large square bale logistics. As discussed in the literature review, transportation methods for large square bales are restricted by volume. By increasing bale density, more dry matter can be transported per unit of volume available in transportation. For over the road transportation, the volume available on a flatbed trailer restricts the maximum number of .9m x 1.2m x 2.44m size bales that can be loaded on a flatbed semi-trailer to a current maximum of 42. Aluminum flatbed trailers coupled with a day cab truck can carry a maximum net weight of 20 to 25 Mg before exceeding the maximum gross weight of 36.3 Mg. At 200 kg/m^3 a flatbed trailer can be loaded with a net weight of 22.1 Mg. This net weight approaches the maximum net weight that can be hauled by many aluminum flatbed trailer and truck combinations. For steel flatbed trailers, 22.1 Mg may be greater than the maximum allowable net weight. If the bales produced in the field study at the 80% plunger load setting and a density of 181kg/m^3 were loaded on a flatbed trailer, the net load would be marginally limited by volume depending on truck and trailer configuration. However, for both rail and container shipping, net load would still be greatly limited by volume.

Chapter 6 – Bale Handling and Transportation Logistics: A Case Study

6.1 Description of the farm

Jaindl Farms in Allentown, Pennsylvania was chosen to study the logistics of handling large square bales. Jaindl Farms raises approximately 750,000 turkeys every year. 4000 hectares of crop land are used to grow the raw materials needed to feed and maintain the livestock raised on the farm. The farm uses a large square baler to bale wheat straw left in the fields after grain harvest in early July. The large square bales of straw are used for bedding in the turkey houses. Because of the wet climate in Pennsylvania, all of the bales must be collected after baling and stored under roof in a timely fashion to prevent rain from dampening the bales.

Jaindl Farms bales and stores around 650 hectares of wheat straw per year, producing 4600 to 4800 bales that measure .9m x 1.2m x 2.44m. Most of the baling is done in fields that range from 20 to 60 hectares in size. The bales all need to be transported several kilometers, depending on the field location, for storage. The baling usually starts in early July. Fifteen to thirty days are necessary from the time bale production starts until all the bales are stored under roof. The amount of days needed to perform these operations is largely depended on weather conditions. If little or no rain falls in early July, all operations can be completed in as fast as two weeks. Although the farm is not producing switchgrass bales, the logistical requirements are the same as what can be expected from similar acreages of switchgrass.

6.2 Equipment

The equipment used in large square bale production, handling, and in-field transportation was determined by the farm to be the most efficient for their particular situation. The straw was all raked with a Kuhn twin rotary rake model GA 6002. The rake was used to form uniform and evenly spaced windrows from the straw that had been expelled by the combines. If the straw was rained on before baling, the rake was also needed to fluff the straw so that it would dry properly. The swath the rake covered was adjustable. The operator adjusted the swath of the rake in order to form windrows of proper size. The maximum swath or working width of the rake was 5.8 meters. The rake was pulled by a John Deere 7820 tractor that had 115.6 kW PTO power. The rake requires a minimum of 30 kW PTO power. The tractor used to power the rake was extensively oversized. The oversized tractor was used due to availability; a smaller tractor would greatly improve fuel efficiency.

A New Holland model BB960A large square baler was used to bale all 650 hectares of wheat straw. A John Deere 8330 tractor with 168 kW PTO power was used to run the baler. The baler calls for a minimum of 90 kW of PTO power. However the extra power and weight of the tractor were necessary to properly handle the baler on fields with steep inclines. The baler was fitted with a Hoelscher bale accumulator that trailed behind the baler. The bale accumulator accumulated two large square bales at the back to the bale chamber and simultaneously dumped these bales onto the ground in a parallel configuration. The accumulator required hydraulic power from the tractor and added slightly to the power requirements of the baler. The baler was typically run from 11:00 am to 7:00 pm. When weather conditions were optimal, a maximum of approximately 350 bales could be produced in a day. Time restrictions on baling were based on the dew burning off in the morning and setting in the night.

A compact wheel loader was used to load the bales onto trucks with 2.44 m x 7.32 m flatbeds. All loading was performed in the field. Unloading at the storage facility was preformed with a second wheel loader. The wheel loaders were fitted with Hoelscher grapples that lift the bale from the top. The grapples, which were matched to the accumulator, had the ability to pick up two bales at a time. Three flatbed trucks were used to transport the straw bales back to storage site. This size truck was well suited for the specific farm conditions. The trucks were able to get in and out of the field easily and adequately maneuver around the storage facility. All of the trucks had the same 2.44 m x 7.32 m bed and a 17 bale capacity.

All of the bales were moved to a storage facility that was 3 to 8 kilometers away, depending on field location. The farm's large square bale handling capabilities accurately portray how switchgrass bales would be collected and transported to a satellite storage facility. Semi trailers would not necessarily be needed to pick bales up at farms and transport them a short distance to a storage facility. The trucks with only a 7.32 m long bed were able to drive through the field to each set of two bales, eliminating the need to further accumulate the bales. For a storage facility 3 kilometers away, three trucks carrying 17 bales per load were needed to haul away the bales at the same or greater pace then bales were produced by the baler.

Figure 6.1: Large square baler, bale handler, and truck

6.3 Labor

The operation included one man operating the baler, two men operating the two wheel loaders and two truck drivers. The baler ran continuously throughout the day with the exception of a lunch break. Since no bales were left out in the field over night, the bales were collected at about the same pace as they were produced. A truck driver would bring the truck into the field and drive up to each set of two bales. The wheel loader operator would follow the truck through the field and load the bales two at a time. When the truck was full the driver would exit the field and head toward the storage facility. The trucks were loaded in an interlocking manner and the bales were not strapped down. Disregarding the straps greatly saved time and increased efficiency. Because there were three trucks and two truck drivers, a driver was not present while the truck was unloaded. The driver of the fully loaded truck would drive into the storage facility and park the truck to be unloaded. By the time this truck arrived with a full load of straw, the previous truck to arrive at the site would be empty. This process was repeated in a cycle, with minor delays from a driver waiting for a truck to be unloaded.

6.4 Results and Discussion

A 30 hectare field of wheat straw was observed. The field yielded 3.20 Mg of straw wet matter biomass per hectare. The field was rectangular shaped with no slopes greater than 3%. The field was raked, baled, and all the bales were put into storage in one day. While this field is significantly larger than the switchgrass field baled at Ernst Conservation Seeds, many conditions that effect baler performance were similar. Both fields were approximately 610 meters in length, resulting equipment in both fields spending equal amount of time per windrow operating in the headlands. In addition, both the switchgrass and the wheat fields did not contain any slopes greater than 3%. Both fields yielded a similar amount of wet matter biomass with the switchgrass field at 3.53 Mg/ha and wheat straw field at 3.20 Mg/ha.

The field was raked with the twin rotary rake at a field capacity of 8 hectares per hour. The raking started at 10:30 am and finished in 3.75 hours. The average speed of the rake was 12 km/h which was a speed chosen based on field conditions. At this rate, the rake was able to process approximately 26 Mg of material per hour.

Baling in the field was started at approximately 11:00 am. The baler was set to produce 2.44 meter (8ft) bales that averaged 306 kg of wet matter. This resulted in an average bale density of 116 kg/m^3. The bale density was kept low so that the bales would break apart easily to spread for turkey bedding. Increasing the density of straw bales beyond 120 kg/m^3 results in higher permanent deformation and causes the straw to cake together. At this density, 310 bales were produced from the field in 7.5 hours. The actual material capacity of the baler was 13 Mg of wet matter per hour at a ground speed of 11 km/h, resulting in an average of 43 bales per hour.

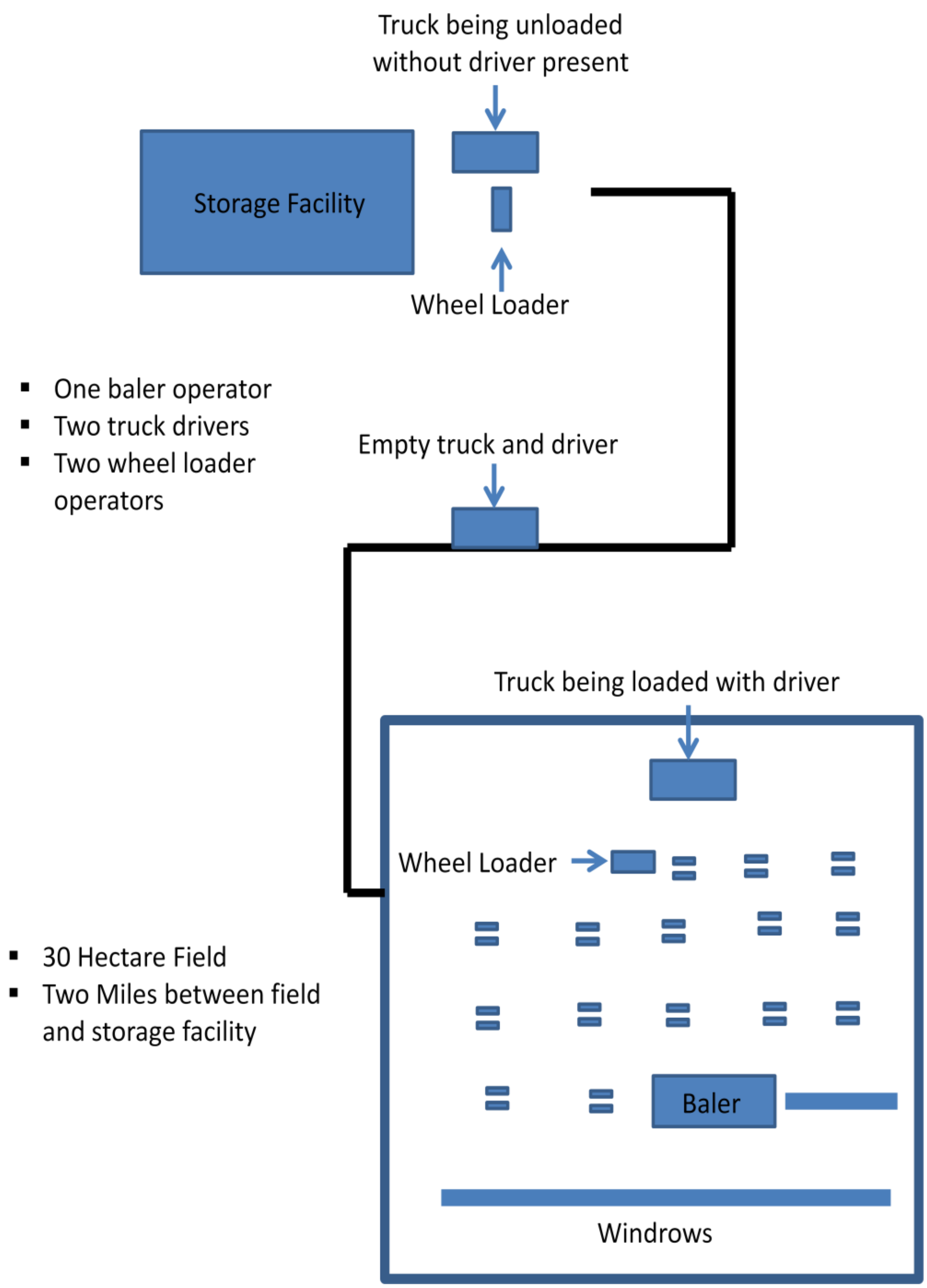

Figure 6.2: Schematic of Field and Storage Operations

Loading the bales on trucks was performed in two different ways. If there was not a truck present in the field, the wheel loader operator would accumulate the bales onto stacks. When a truck did arrive, the truck would pull up to the stack and the bales would be loaded. If there were trucks available, each truck would drive through the field to each set of two bales left by the baler. The wheel loader would follow and immediately load the bales. When the bales were unloaded into storage the truck was stationary while wheel loader operator drove in and out of a pole barn. Bales were stored in an open ended pole barn. The barn was high enough to stack the bales three layers high. Unloading times varied slightly with how far the bales had to be driven into the pole barn to be stored. Like the wheel loader in the field, the wheel loader at the storage facility was capable of handling two bales at all times.

Material capacity data was recorded of each piece of equipment over the course of approximately nine hours from the time the tractor and rake started to operate in the field at 10:30 am until all bales were placed in storage at 7:30 pm. For comparison purposes all material capacities are presented in terms of bales per hour in Figure 6.3. Material capacity in terms of tons per hour will be depended on bale density.

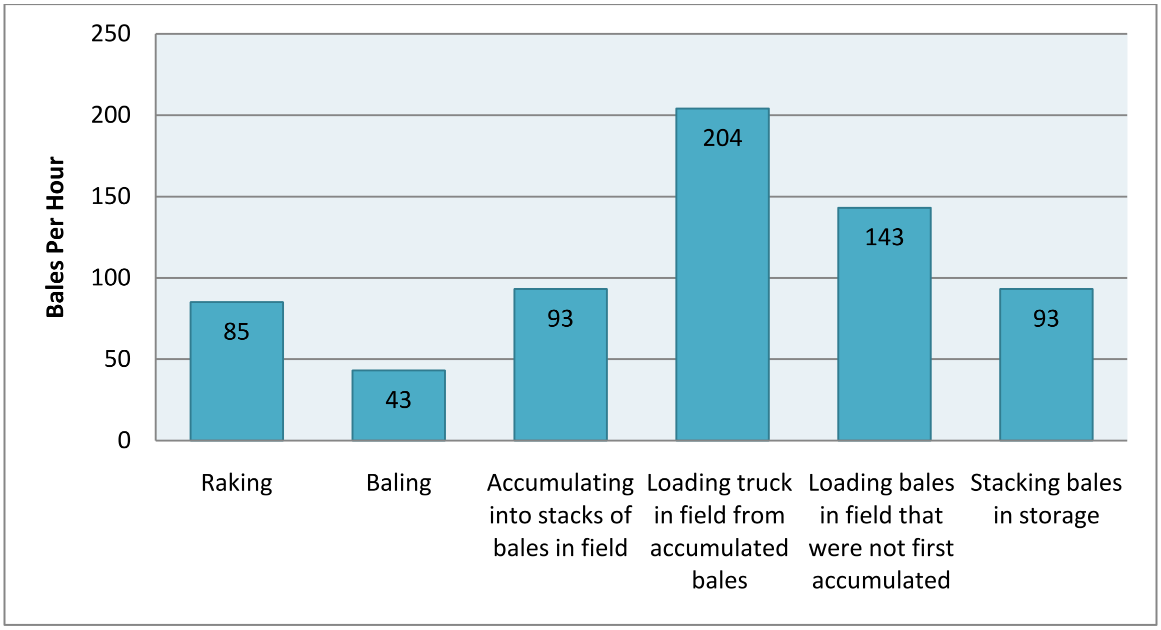

Figure 6.3: Material capacity in terms of bales per hour for raking, baling, and handling operations

Figure 6.3 shows that the baler had a much lower material capacity than any other operations that took place simultaneously. The bale accumulator attached to the baler and paired with the wheel loader grabbles roughly doubled the pace at which the bales could be loaded and unloaded as compared to handling one bale at a time. This resulted in idle handling equipment at many points throughout the day. The bales could be loaded onto a truck from a stack the fastest but required that the bales must be accumulated first. The combination of time required to accumulate bales into a stack and then load bales from that accumulation was slower than if the bales were loaded directly onto the trucks without any prior accumulation. Accumulating in the field was most likely performed to keep the wheel loader and operator from sitting idle when a truck was not present.

The large square bale field test focused only on the baling aspect of switchgrass large square bale logistics. However, the only major difference between bales produced in switchgrass field study and this logistics case study was bale density. The large square balers used in both studies were New Holland Models that made bales with a 900mm x 1200mm end section. The bales at both farms were made at the same length. The baler used in the switchgrass study was a slightly newer model than the baler used in the field study but they mechanically function exactly the same. The switchgrass does not have exactly the same biological properties as the straw but have many similarities. The similarities between the switchgrass and straw are evident in the fact that both balers had an average material capacity of approximately 13 Mg (wet) per hour for each material. By using the densities of the bales to convert material capacity in bales per hour into Mg/hr for each operation, the rate at which the switchgrass from the large square baler field study can be theoretically gathered, transported, and put into storage was calculated. Table 6.1 compares these operations for both farms in terms of Mg per hour.

Table 6.1: Comparison of material capacities for different operations and densities

Operation	Mg Per Hour Straw ($116\ kg/m^3$ wet matter)	Mg Per Hour Switchgrass ($180\ kg/m^3$ wet matter)
Raking	25.9	28.6
Baling	13.0	13.0
Accumulating bales on stacks	28.5	44.0
Loading truck from accumulated bales	62.4	96.7
Loading bales that were not first accumulated	43.77	67.8
Stacking bales in storage	28.5	44.0

The rake had constant field capacity of 8 ha/hr. Therefore the material capacity of the rake increased with an increase in yield in the switchgrass field as compared to the straw field. The maximum material capacity of both balers was 13 kg/m^3. The baler in the straw field did not create as dense of a bale and therefore produced more bales for any given amount of material. The bottom five operations in table 6.1 illustrate the increased rate at which the material can be handled due to an increase in bale density. The switchgrass bales were produced 55% more dense than the straw bales. This would results in a 55% increase in the rate at which the material from the field could be loaded, transported, and put into storage. The amount of extra energy used to pick up and transport the heavier bales is marginal. Over the long term, the denser bales would result in roughly a 55% decrease in fuel consumption and labor to move the same amount of material for each of the five operations.

6.5 Conclusions

The logistics of handling and transporting large square bales and the equipment used were unique in this particular bale production system . It is important to note that the bales could be handled and transported at more than twice the rate at which the bales were produced. This was due in part to the ability of the wheel loaders to handle two bales at a time. If the wheel loaders could only handle one bale at a time, the loading and unloading rates would be 50% less. The field wheel loader had the most idling time. Based on the pace of bale collection in this field, two balers could be operated at the same time and the wheel loaders would still be able to keep pace with the baler. The addition of another baler and either three more trucks or trucks with larger capacities would double daily bale production, transportation and storage capacities. Currently a maximum of 350 bales can be handled in one day. A second baler could bring production above 700 bales per day.

By comparing material capacities of the machines in both bales per hour and tons per hour, the of bale density became significant. Every percent increase in bale density corresponds to a percent increase in the material capacity of the wheel loaders and trucks. Bales produced for the turkey farm were kept at a low density so that the quality of the straw as a bedding material would not be negatively affected. In a biomass scenario, it would be advantageous to produce bales as dense as possible in order to minimize costs incurred from handling, transportation, and storage.

In both the switchgrass field and the straw field, the balers were found to have an actual material capacity of 13 Mg/h. When the actual material capacity of the baler is known, the capacities necessary for wheel loaders and other equipment needed to meet the logistical needs of other large square bale operations can be calculated. The number of wheel loaders needed will be determined by baler material capacity and bale density. Transportation requirements will be a function of the cycle time from field to storage facility and back. The rate at which bales need to be loaded and unloaded as well as the distance between the field and storage can be used to determine the size and number of trucks needed.

Chapter 7 – Lab Scale Compression Test on Switchgrass Samples of Various Moisture Contents

7.1 Background Information

Moisture content greatly effects large square bale production (Mohsenin 1970). The moisture content at time of harvest must not exceed 18% to 22% (w.b.) for dry harvest, depending on the crop. Moisture contents above this threshold will experience dry matter loses and fire danger from both high respiration rates within the cells of the biomass and mold growth. Low moisture content at time of harvest cause dry matter losses from shattering. Moisture content is known to have a large effect on bale density (Kalminski 1989). Typically, small increases in moisture content cause large increases in bale density if baler setting remains contents. The goal this compression test was to determine if increasing the moisture content decreases the energy needed for compression due to decreased friction between biomass particles.

7.2 Switchgrass Sample Collection

Switchgrass used in the compression tests was collected from a demonstration plot at the Penn State agronomy farm in Rock Springs, Pennsylvania. The switchgrass was a Cave-in-Rock cultivar. This is the same cultivar that was harvested with a large square baler during the earlier field study as described in Chapter 5. To mimic a fall harvest situation, the switchgrass was cut and collected manually, leaving three to four inches of stubble. The grass was immediately taken back to the Agricultural Engineering building to begin testing. The switchgrass was harvested in late September after growth had stopped. The moisture content of standing switchgrass decreases dramatically after the first killing frost. Switchgrass harvest in the fall for biomass is typically done after a killing frost in order to make use of the ability of the biomass to dry down while standing and take advantage of nutrient leaching back into the soil. The switchgrass samples collected for the compression testing were cut prior to the first fall frost in order obtain a higher moisture content 48% (w.b.). Subsequent moisture contents were obtain by allowing the switchgrass to dry over time.

7.3 Instrumentation and Measurements

A compression test stand located in the Agricultural and Biological Engineering Building was used to compress the switchgrass samples. This compression stand is a product made by Cooper Instruments and Systems. The compression stand is capable of producing 89000 N of compression force through the use of two vertical hydraulically actuated cylinders that oppose each other as seen in Figure 7.1. These two cylinders can be operated individually. The stroke of these two cylinders was 20.36cm. For the compression tests in this study, only the top cylinder that extends downward was used. The maximum extension speed of the top and bottom cylinder is 2.84 cm/sec.

Figure 7.1: Compression stand

The stand was equipped to display displacement and vertical force. A load cell on the rod end of the cylinder measured force while displacement was measured with a linear potentiometer. The stand originally came from the manufacturer with only digital readouts of force and displacement. No data logging capabilities were present on the machine as it arrived from the manufacture. A data logger provided by the Agricultural and Biological Engineering department was used to collect and store force and displacement measurements over time. For the force measurements, the data logger was connected to the load cell on the machine. The load cell was then calibrated using a proving ring. To gather displacement data, a cable extension transducer was mounted on the compression stand. The cable extension transducer consisted of a potentiometer that measured the distance between the plunger head and a fixed point on the stand. The data logger was able to store time, displacement, and force over the course of each tests. Sampling rate was 16 per second.

To perform the compression tests, a steel compression chamber and a plunger head were manufactured. Preliminary compression tests on switchgrass determined the pressure needed to reach a final density of 500 kg/m^3 was approximately 3400 kPa. Since 89000 N of force were available from the stand, the maximum area over which the compression force could be applied to was .0262 m^2. The steel chamber was built with a square 16 cm x 16 cm open end, resulting in a .0256 m^2 area over which the compression force would be applied. The depth of the chamber was limited to 20.32 due to the stroke of the top cylinder. A plunger head, which applied the compression force to the sample, was made of aluminum. The dimensions of the plunger head were slightly smaller than the opening of the compression chamber to avoid contact between the plunger head and chamber during compression.

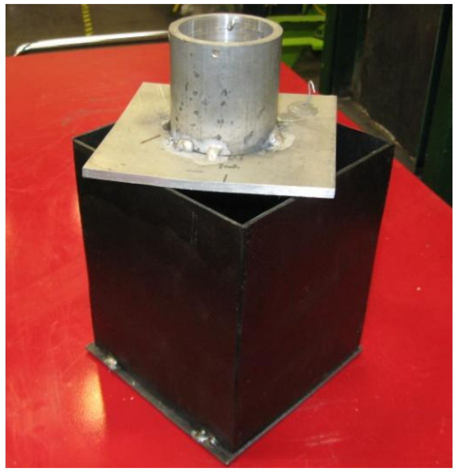

Figure 7.2: Plunger head and compression chamber

7.4 Experimental Design

To achieve several different levels of moisture contents, the switchgrass harvested at the Penn State agronomy farm was spread out inside the departmental building and allowed to dry. Compression tests were performed approximately every twelve hours over the course of four drying days. Seven different moisture contents were expected. The first set of tests occurred right after the switchgrass was harvested in order to evaluate the high level of moisture content. For the last set of tests, the switchgrass samples were dried in an oven to reach moisture contents lower than what was possible with naturally-dried samples. The first day the humidity averaged 30% and the grass dried down 18%. Drying rates for the rest of the three days varied with changes in humidity and temperature.

All the switchgrass used in the testing was manually cut to lengths just under 16cm so that the grass could be horizontally oriented in the chamber. The stems and leaves of each switchgrass tiller were all cut just before each test into similar lengths in order to maintain the same ratio of stems and leaves found in the field for every test. While the grass was all horizontally oriented during compression, the stems and leaves were not all perfectly parallel. This orientation was intended to mimic the way switchgrass would be oriented by stuffer forks in the bale chamber of a large square baler. The cut switchgrass was manually loaded in to the chamber until an initial bulk density of 70 kg/m^3 was achieved. The chamber was then placed under the plunger and force was applied until the bulk density in the chamber exceeded 500 kg/m^3. Three replications were performed at each moisture content level. After each replication all the switchgrass was removed from the chamber, placed in a plastic bag, and weighed to determine the mass of the sample in this replication. A new sample was then loaded into the chamber for the next replication. After all the replications for any particular moisture content were completed, samples from each replication were placed in paper bags and used for moisture analysis. ASABE standards were used in the moisture analysis and all results are reported on a wet basis. Microsoft Excel was used to fit one power curve all the data points from the three replications at each moisture content. The curves were fitted to all the data points from an initial bulk density of 70 kg/m^3 to 350 kg/m^3 on both a wet and dry basis.

7.5 Results and Discussion

The force values for all the data were converted to pressures in kilopascals using the surface area of the plunger. To calculate bulk density, the displacement values were used to calculate the volume of the switchgrass in the chamber that corresponded to each pressure value. The mass of the switchgrass sample in each replication was then divided by the volume values to determine the bulk density for every force and displacement data point collected during the compression stroke of the cylinder.

7.5.1 Fitting Curves to the Pressure Density Relationships

The relationship between measured pressures and bulk densities can be described with a power curve. An example of a power curve used in the data analysis can be seen in Figure 7.3. Excel was used to fit a power curve to the data points from different moisture contents. The equations that describe the curves are derived from a power curve line of best fit over the data points from the three separate replications preformed on each moisture content.

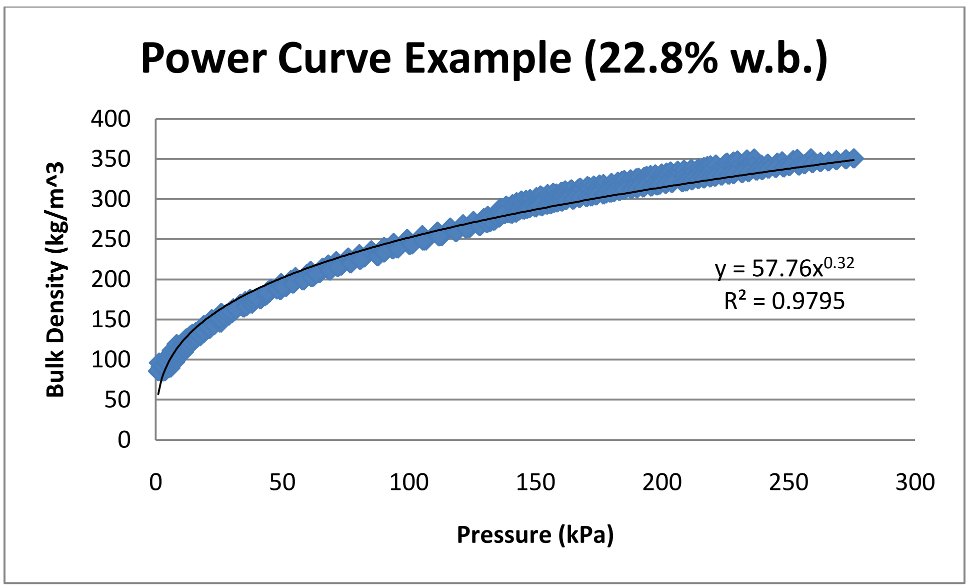

Figure 7.3: Power Curve Example

The power curves for the dry matter bulk density are described in Equation 7.1 and shown in Table 7.1.

Equation 7.1: Dry matter bulk density power curve equation

$$\gamma_{dry} = k(p^n)$$

Where: γ_{dry} = dry matter bulk density (kg/m^3)
k = constant
p = pressure (kPa)
n = exponential constant

Table 7.1: Power Curve Parameters for dry matter bulk density

Moisture Content (% w.b.)	Coefficient (k)	Exponential Constant (n)	R^2
4.74	42.93	0.334	0.95
12.60	34.19	0.374	0.99
20.56	32.59	0.380	0.99
22.80	42.39	0.332	0.90
22.83	45.37	0.326	0.99
31.40	38.53	0.372	0.98
48.80	38.19	0.343	0.92

The power curves for the wet bulk densities are described in Equation 7.2 and the constants are given in Table 7.2.

Equation 7.2: Wet bulk density power curve equation

$$\boldsymbol{\gamma_{wet} = k(p^n)}$$

Where: γ_{wet} = wet bulk density (kg/m^3)
k = constant
p = pressure (kPa)
n = exponential constant

Table 7.2: Power Curve Parameters for wet matter bulk density

Moisture Content (% w.b.)	Coefficient (k)	Exponential Constant (n)	R^2
4.74	44.92	0.334	0.96
12.60	54.82	0.301	0.97
20.56	46.86	0.352	0.98
22.80	57.75	0.320	0.97
22.83	47.39	0.367	0.96
31.40	63.00	0.331	0.88
48.80	79.32	0.303	0.91

Exponential constants for all moisture levels are near constant. K values are an indication of how much pressure is required to compress the material. Smaller k values for the dry bulk density curves mean more pressure was needed to increase the bulk density of the material as compared to the wet matter bulk density curves. All of the k values for the wet bulk density are higher because less pressure was needed to reach any particular density value as compared to the dry matter bulk density pressures. At any point during the compression stroke, the wet matter bulk density was higher than the dry matter bulk density due to the inclusion of water mass in the wet matter bulk density value.7.5.2 Specific Energy Requirements

The equations describe the compression process. Further analysis of the equations with integration can determine the specific energy requirements of compression at each moisture content. The specific energy values can be compared to one another to determine the best how much energy for compression is necessary relative to the other samples. The power curve equations that describe the compression process do not indicate how much energy is consumed during the compression process. By inverting the power curve Equations 7.1 and 7.2 and integrating with respect to pressure, the specific energy requirement of each compression test in kJ/kg can be calculated over a desired range of denities. This integration is illustrated in equation 7.3 (Van Pelt, 2003)

Equation 7.3: Integration of power curve

$$\int_0^p \frac{1}{k(p^n)} dp = specific\ energy\ requirment\ (\frac{kJ}{kg})$$

The inverted power curve needs to be integrated from a start pressure to a final pressure. At the start of these compression tests, no force was being applied to switchgrass, making the lower bound of the integration zero. To find the specific energy required to compress the sample to the density of 350 kg/m^3, the pressure required to reach 350kg/m^3 is used as an upper bound of the integration. All the pressures required to produce density 350 kg/m^3 are given for both dry matter bulk densities and wet matter bulk densities in tables 7.3 and 7.4.

Table 7.3: Specific energy requirements to reach 350 kg/m^3 dry matter bulk density

Moisture (% w.b.)	Pressure to reach 350 kg/m^3 (kPa)	Specific Energy Requirement (kJ/kg)
4.74	529.14	2.27
12.60	501.49	2.29
20.56	512.33	2.36
22.80	576.27	2.47
22.83	519.93	2.36
31.40	372.52	1.70
48.80	638.28	2.34

Table 7.4: Specific energy requirements to reach 350 kg/m^3 wet matter bulk density

Moisture (% w.b.)	Pressure to reach 350 kg/m^3 (kPa)	Specific Energy Requirement (kJ/kg)
4.74	461.09	1.98
12.60	466.27	1.91
20.56	302.53	1.33
22.80	278.84	1.17
22.83	229.60	1.04
31.40	175.80	0.75
48.80	133.31	0.55

The specific energy requirements given in Tables 7.3 and 7.4 are an average of the three replications preformed at each moisture content. A liner regression was performed on the relationship between the specific energy requirements and the moisture content to examine the correlation between these two variables. One regression was performed on both the dry matter and wet matter bulk density relationships (Fig. 7.3). Similar with the power curve constants, the data points represent an average of the three replications at each moisture content.

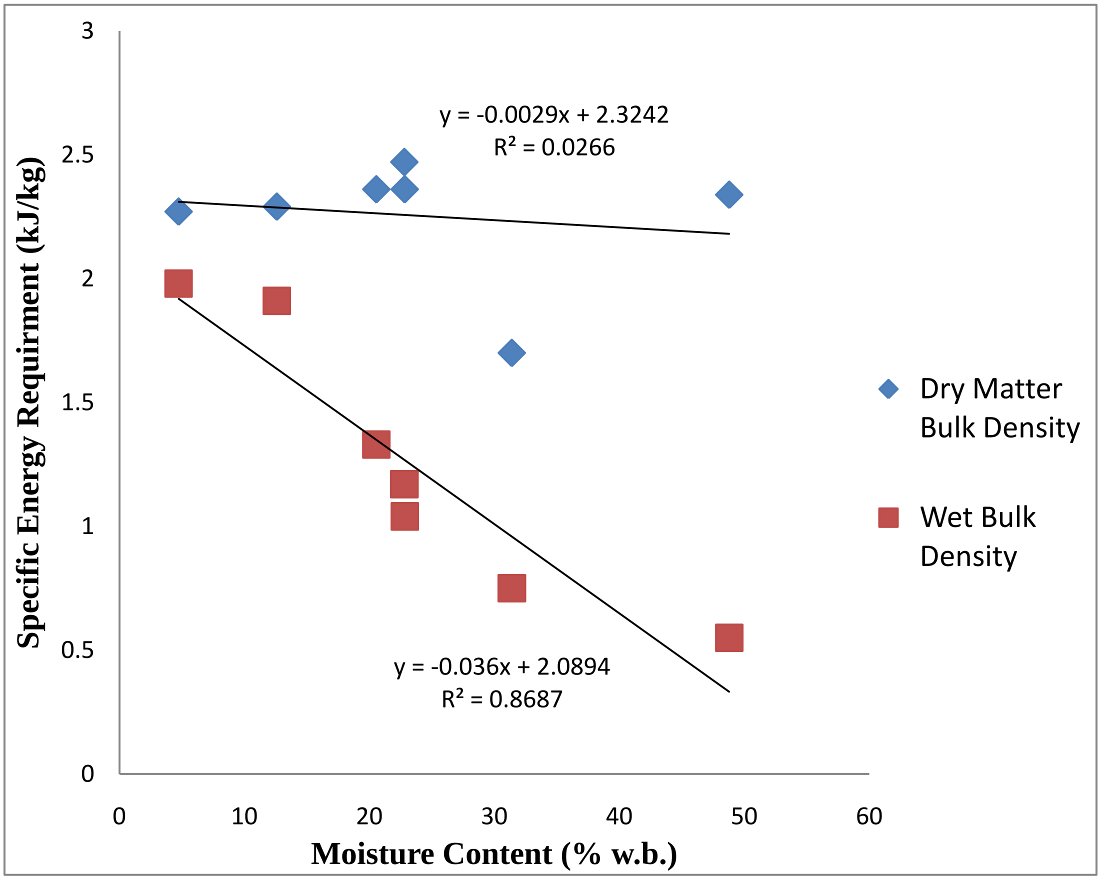

Figure 7.4: Moisture content verse specific energy requirement

When only the dry matter content was used to calculate the specific energy, no correlation between the moisture content and the specific energy requirements for compression was found (Fig. 7.3). The dry matter specific energy requirements appear to neither decrease nor increase with an increase in moisture content. The wet matter specific energy requirements, however, clearly decreased when increasing the moisture content. This correlation indicates that when considered on a wet basis, increased moisture content decreased the energy required for compression. When the compression process is analyzed on a dry basis, there was no correlation between the moisture content and the specific energy requirement for compression.

7.6 Conclusion and hypothesis testing

Figure 7.3 indicates that the moisture content of the switchgrass did not have a significant effect on the energy needed to compress it. When the density of the switchgrass was calculated in terms of dry matter, the wettest sample required roughly as much energy for compression as the driest one. With the wet matter bulk density, there was a dramatic decrease in the energy needed to compress the switchgrass with an increase in moisture content. This decrease in energy requirements could be attributed to the fact that increasing the moisture content increased the wet bulk density regardless of the pressures applied to the material. The wet bulk density value at the start of each compression test directly correlated to its moisture content. Higher moisture contents resulted in higher wet bulk densities before any force was applied to the material. A wet bulk density of 350 kg/m^3 was achieved with less volume reduction within the chamber as moisture content increased.

Hypothesis two stated the following:

H_o = Moisture content in switchgrass has no effect on the specific energy requirements to reach a certain dry matter bulk density

H_a = The higher the moisture content of switchgrass, the lower the specific energy required to reach a certain dry matter bulk density.

This hypothesis pertained to the dry matter bulk density correlation as shown in Figure 7.2. Based on an R^2 value of .03, there was not a statistically significant relationship found between the moisture content and the specific energy requirement to reach the density of 350 kg/m^3. In this instance the null hypothesis was not rejected and it could be concluded that moisture content either had no effects on densification requirements when only dry matter bulk density was considered, or the effects could not be measured using this equipment.

Chapter 8 – Lab Scale Compression Test on Samples of Fall and Spring Harvested Switchgrass

8.1 Background Information

Switchgrass biomass is typically harvested either in the fall after a killing frost or in the spring before new growth emerges. These two harvest times are least damaging to stand persistence. The difference in the properties of fall and spring harvested switchgrass has been documented by Adler et. al (2006). These property differences include changes in leaf and stem composition and chemical changes. The goal of these compression tests was to determine any changes occur in the energy requirements of compression for the two different harvest times.

8.2 Spring Harvested Switchgrass Collection

Samples of switchgrass from the Ernst field where the large square baler research was conducted were collected for compression tests. These samples represented spring harvested switchgrass. The samples tested in Chapter 7 represented the fall harvested switchgrass. The switchgrass from the spring harvest were tested in the same manner as the samples in Chapter 7. Both the switchgrass in the baling field test and agronomy farm were a Cave-in-Rock variety. The only difference between the samples from the different farms was the time of harvest. The switchgrass from the field study was cut in November, overwintered on the ground, and baled in early May. The samples taken from the baling test field were stored inside and then compressed in September. Moisture content was constant for all fall harvest samples. The compression test stand and the compression chamber, plunger, data acquisition system were the same as used in Chapter 7. The switchgrass samples from the agronomy farm were harvested in September while the plants were still actively growing and were compressed immediately as described in Chapter 7.

8.3 Results

The switchgrass from spring harvest was compressed to examine the impact of harvest season on the specific energy requirements of compression. The spring switchgrass was compressed in three replications to quantify compression force and density relationships; which were represented with power curves. All of the power curves in the spring switchgrass compression test have significantly lower k values compared to fall harvested switchgrass. This indicated that the spring harvested switchgrass was much harder to compress than the fall harvested switchgrass. To statistically prove that the switchgrass from the spring harvest did require more energy to compress, the specific energy requirements were calculated from the curves of compression force-displacement and compared to the same energy requirements from the fall harvested switchgrass. Since the compression testing of the various moisture contents determined there was no difference in the energy requirements to compress the switchgrass when only the dry matter was considered, both the fall and spring harvested tested were compared in terms of dry matter. This comparison can be seen in Table 8.1

Table 8.1: Specific energy requirements to reach 350 kg/m^3 for both the Agronomy Farm and Ernst switchgrass in terms of dry matter bulk density.

Source	Moisture (% w.b.)	Pressure to reach 350 kg/m^3 (kPa)	Specific Energy Requirement (kJ/kg)
Fall Harvest	4.74	529.14	2.27
	12.60	501.49	2.29
	20.56	512.33	2.36
	22.80	576.27	2.47
	22.83	519.93	2.36
	31.40	372.52	1.70
	48.80	638.28	2.34
Spring Harvest	7.29	1237.29	5.66
	7.29	1504.38	6.50
	7.29	1174.87	5.32

8.4 Hypothesis Testing

The specific energy requirements of the spring and fall harvest data were first both found to be normally distributed. Then an unpaired two sample t test was performed on the following hypothesis:

H_o = The fall and spring harvested switchgrass samples have the same specific energy requirements for compression.

H_a = The fall and spring harvested switchgrass samples have the different specific energy requirements for compression.

The t test was used to compare the values for the specific energy requirements of compression for both the fall and spring samples to determine if there is a statistical difference between these two sets of values. The t test which is listed in Appendix A resulted in a p-value of .01 or 1%. This p-value indicates that there is a 1% percent chance that the null hypothesis is correct and that one can be 99% confident the alternative hypothesis was correct. Given this low p-value, the null hypothesis is rejected and the alternative hypothesis is concluded. Since the specific energy requirements for the spring harvested switchgrass were all larger than the values for the fall harvested switchgrass, one can conclude that the spring harvested switchgrass requires more energy to compress to any given bulk density.

8.5 Discussion

The increase in specific energy requirements of the spring harvested switchgrass are attributed to the fact that the switchgrass was mowed and laid on ground for an entire winter. This caused both physical and chemical changes. The largest change occurred was in the stalk to leaf ratio of the switchgrass. Mechanically harvesting switchgrass causes greater mass loss in leaves than stalks. When the switchgrass overwinters on the ground the leaves tend to become disjointed from the stalk and settle close to the ground. The leaves eventually degrade or settle and become unattainable for the harvest equipment. Research in Canada has shown that there was approximately a 66% reduction in leaves in the composition the spring harvested switchgrass as compared to fall harvested switchgrass (REAP-Canada, 2008). The reduction in leaf matter is primarily responsible for the reduction in yield that occurs when the switchgrass was harvested in the spring, as discussed earlier. This resulted in spring harvested biomass that contained a much lower percentage of leaves than the biomass obtained from the agronomy farm in the fall. The greater the percentage of stalks in herbaceous biomass, the harder the material becomes to compress (Van Pelt, 2003). Chemical changes caused the stems to become brittle and less pliable and also have an impact on the compression process.

8.6 Comparison of Compression Tests and Large Square Baler Field Test

The specific energy requirements of the spring harvested switchgrass derived in the lab were a scaled version of the energy requirements for compression within the large square baler that was used in the switchgrass field study. The switchgrass samples from the field study were collected from the field windrows right before baling. The collected switchgrass were stored indoor and its moisture content dried down to 7.29% (w.b) from 12.5% (w.b) at harvest when conducting laboratory compression test. Based on the findings in Section 7.3, when only the dry matter was considered, the specific energy requirements of compression was the same regardless of moisture contents. The average wet matter bulk density of the field switchgrass bales was 180 kg/m^3; and it was 157.5 kg/m^3d for dry matter bulk density . Based on the equations developed for the spring harvested switchgrass, the average specific energy requirement to reach a bulk density of 157.5 kg/m^3 of dry matter was 1.42 kJ/kg. The baler used 1.46 L/Mg DM of diesel fuel at the same bulk density. This fuel consumption rate converts to 52.4 kJ/kg, based on the lower heating value of diesel fuel.

Based on the specific energy requirements calculated, only about 2.7% of the energy consumed by the tractor and baler was used to compress the switchgrass to the same bulk density in the lab tests. The largest percentage of the energy was lost in the form of heat rejection due the inefficiencies of internal combustion engines. Typically, approximately 70 to 75% of energy in the fuel was rejected as heat by the engine (Srivastava et al., 2006). The rest of the energy is converted into mechanical power. The overall mechanical efficiency of a traditional tractor transmission is 83% (ASAE, 2006).. The output power is used to drive the tractor and implement attached to the tractor. Typically, the best tractive efficiency of off-road vehicles is between 70 to 75% (Goering, et al., 2006). After transmission and tractive losses, the power left over is used to power the baler through a mechanical drive line. Power is also lost due to friction and mechanical inefficiencies within the baler.

Since the actual material capacity of the large square baler used in the large square baler field test has been determined in Section 5.3 , the power allocated by the tractor to bale compression can be determined using equation 8.1 (Srivastava, et al., 2006).

Equation 8.1: Power used in bale compression

$$P = m_f E_c$$

Where P = Power needed for bale compression

m_f = material capacity in (kg/s)

E_c= specific energy requirement of compression (kJ/kg)

The maximum measured actual material capacity of the baler in dry matter was 3.16 kg/s and the specific energy requirement of compression to reach a dry matter bulk density of 157.5 kg/m^3 was 1.42 kJ/kg. Based on these data, 4.5 kW of power were needed for bale compression within the baler. Since the tractor PTO power was 142 kW, only 3.2% of the PTO power was needed purely for compression. However, compression of switchgrass in a large square baler is a cyclical process since the plunger impacted the bale that was being formed 44 times per minute at the rated 1000 PTO rpm. The speed at which the plunger moves created high impact forces. This speed also requires a great amount of power over a relatively short period within each stroke while requiring relatively zero power through the rest of the stroke when the plunger is not in contact with the bale. Due to these spikes in load to the baler driveline, the baler requires a large amount of power in short bursts. If the compression process were constant like in the lab compression tests, the power needed for compression of a bale would be closer to the stated values.

8.7 Comparison of Compression Tests and Large Square Bale Compressors

In the year previous to the switchgrass field study, several large square bales were made with the same large square baler in the same farm, and then bales were transported to Heidel Hollow farm in Allentown, PA to be compressed with a commercial hay bale compressor (Brownell, 2010). The compressor at this facility compresses and slices large square bale into approximately 24 individual 35 kg bales that are considerably denser than the original large square bale. The switchgrass bales of 900mm x 1200mm end dimensions are first hydraulically cut into three slices that have end dimensions of 900mm x 400mm. At this point, each slice was compressed into higher density bales and tied with plastic twine. The compressed bales are then cut once more into cubes that have 450mm x 400mm end dimensions.

All operations of the bale compressor are preformed using hydraulics. One diesel power unit rated at 185kW was used to drive a hydraulic pump. The hydraulic the pump was then used to power the various operations of the compressor. Compression was accomplished mainly with a large hydraulic cylinder, which used the most power of any of the operations. Other smaller cylinders were used to move the original and compressed bale. Fuel flow meters were installed in line with the send and return lines to the engine to measure the instantaneous fuel consumption while the bales were compressed.

Nine bales at 14.1% moisture content (w.b.) were processed with this bale compressor. The dry matter bulk density of the bales was increased from 140 kg/m^3 to 248 kg/m^3. Measured results indicated that the average of 2.21 L/Mg (wet matter) were used. This was converted to a specific energy requirement of 79.3 KJ/kg to run the compressor. The specific energy requirements to increase the dry matter bulk density from 140 kg/m^3 to 248 kg/m^3 in the lab were 2.03 KJ/kg.

In this instance the compressor used about 2.6% of the energy consumed by the engine to compress the switchgrass bales. While the lab-scale compression tests may not be a suitable simulation of the compression process that takes place in the large square bale compressor. It is evident that like the baler, the compressor used very small percentage of the energy fuel consumed to compress the bales. The large square bale compressor used 2.6% of the energy consumed for compression while the large square baler used 2.7% of the energy it consumed for compression. In the case of the compressor, the rest of the energy was used in other processes or given off as waste heat. The power unit for the compressor ran at full RPM at all times while the actual compression stroke took only a few seconds. The slicing operation of the compressor also required tremendous energy. Also, all operations of the compressor ran off hydraulic power, which had inherent inefficiencies.

Chapter 9 – Conclusions and Recommendations

The large square baler field test examined the ability of a modern large square baler to produce bales of switchgrass in a spring harvest situation. The study found that bale density can range from 100 kg/m^3 to 200 kg/m^3 at an average moisture content of 12.5% (wb). This range of densities is based on the density control settings on the baler. There was no measureable increase in fuel consumption with an increase in the bale density settings. Depending on the transportation vehicle, a density of 200 kg/m^3 may adequately load a flatbed truck and trailer to the maximum legal over the road weight limit. Based on these findings, large square bales would not need further densification for short distance truck and trailer transport. However, these densities would not be very economical for rail or cargo ship transportation.

The field efficiency of the baler depended greatly on the speed of the tractor and baler as well as the rate the material was feed into the baler. Decreasing the speed of the baler due to denser windrows had a very positive effect on the field efficiency of the baling process as well as the actual material capacity of the baler. Proper windrow density can be achieved by raking crops in to a windrow from appropriate sized swaths. Further research should be conducted to optimize windrow density according to baler capacity.

The bale handling and transportation case study at Jaindl Farms can be considered state of the art at this time. Data from the research can be used illustrate the rate at which bales can be gather and transported to a storage facility. The single large square baler at the farm was found to be the limiting factor in the logistics of the operation. By using wheel loaders that handle two bales at a time, the bales could be collected, transported, and stored at roughly twice the rate that the baler produced bales. The baler at Jaindl's farm and the baler used at Ernst both had a maximum actual material capacity of around 13 Mg/h. While the rate at which bales can be gathered, transported, and stored remains constant for different operations, the density of the bales can vary. The Jaindl Farms field study shows that for every percent increase in bale density there is an equal percent decrease in the labor and energy requirements to gather, transport, and store any particular amount of dry matter harvested.

The lab scale compression tests were used to quantify the energy requirements needed for switchgrass compression. The tests found that the moisture content of the switchgrass did not have any effect on the energy required to compress the switchgrass when only the dry matter bulk density is taken into account. The wetter switchgrass could be compressed to a higher wet bulk density for any given pressure only because of the moisture contained in the biomass. When baling switchgrass, the dry matter bulk density of the bales will not be influenced by the moisture content. Bales of higher moisture content will have a higher wet bulk density due to the increased water content and possibly changes in the frictional coefficient between the bale and the bale chamber that causes the plunger to unintentionally exert more force on the bale as it is being formed.

The time of the year that switchgrass is harvested will have a great impact on the yield of a switchgrass field as well as the characteristics of the biomass. Other research has found that there is a substantial yield loss if the switchgrass is harvested in the spring. This yield loss is mostly attributed to biomass that becomes unrecoverable. Most importantly there is a decrease in leaf content. The lab scale compression test of spring and fall switchgrass showed that the decrease in leaf matter caused the spring harvested switchgrass to be much harder to compress as opposed to the fall harvested switchgrass. Switchgrass fields harvested in the fall will not only yield more dry matter, but will also have the ability to be formed into denser large square bales.

The main objective of both large square balers and bale compressors is to form a dense product that can be easily handled and transported. However, based in the specific energy requirements calculated from the lab compression tests, it is clear that very little of the raw energy consumed by large square balers and bale compressors is actually needed for densification. There is great room for improvement with both of these machines in terms of efficiency. The large square baler inefficiencies stem from the repetitive motion of the plunger which creates high impact forces and cyclical spikes in power requirements. The greatest energy losses for both machines come from the use of internal combustion engines which are inherently inefficient. Use of electric motors for the stationary bale compressor would greatly enhance the efficiency of the machine.

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Appendix

Two-Sample T-Test and CI: Spring Harvest, Fall Harvest

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Two-sample T for Spring Harvest vs Fall Harvest

                N   Mean  StDev  SE Mean
Spring Harvest  3  5.827  0.607     0.35
Fall Harvest    7  2.256  0.253    0.096


Difference = mu (Spring Harvest) - mu (Fall Harvest)
Estimate for difference:  3.571
95% CI for difference:  (2.007, 5.135)
T-Test of difference = 0 (vs not =): T-Value = 9.82  P-Value = 0.010  DF = 2
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