SWITCHGRASS HARVEST TIMING & HARVEST/STORAGE METHOD INFLUENCE QUANTITY, QUALITY & SUSTAINABILITY ASPECTS OF A LIGNOCELLULOSIC ETHANOL PRODUCTION SYSTEM IN THE NORTHERN CORN BELT/GREAT LAKES REGION

By

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ABSTRACT

SWITCHGRASS HARVEST TIMING & HARVEST/STORAGE METHOD INFLUENCE QUANTITY, QUALITY & SUSTAINABILITY ASPECTS OF A LIGNOCELLULOSIC ETHANOL PRODUCTION SYSTEM IN THE NORTHERN CORN BELT/GREAT LAKES REGION

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A three year field study was conducted to help develop agronomic suggestions on how to create an economically viable and sustainable switchgrass crop production phase of a lignocellulosic ethanol production system, in the Northern Corn Belt/Great Lakes region, that facilitates the procurement, storage, and delivery of a high quantity of high quality lignocellulosic feedstock. An early fall chop/ensile harvest scenario may maximize harvest yield, facilitate a more timely harvest, not affect winter hardiness, and potentially be most profitable for growers. Successive early fall harvests may significantly reduce both feedstock cellulose and lignin contents, however theoretical ethanol yields indicated that an early fall harvest did not significantly impact potential ethanol yield. An early fall harvest resulted in a significantly higher glucose hydrolysis yield, which suggests that an early fall harvest timing may be most conducive to increasing enzymatic hydrolysis efficiency. Life cycle assessment suggested that an early fall chop/ensile harvest scenario throughout the ten year lifetime of a dedicated switchgrass bioenergy stand in this region may minimize environmental impacts while also potentially being the most economically sustainable option for a grower. Insignificant reductions in feedstock ash content during the fall or between harvest/storage methods suggested increased grower flexibility to choose an appropriate region-specific harvest management strategy without compromising the potential for cofiring in energy production.

Dedicated to my wife, Lauren Nicole Hoxie

Your love, humor, and endless support throughout my graduate program helped make all this possible. I love you.

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INTRODUCTION

As energy demands in the world continue to grow and available fossil fuel energy declines, the pursuit of developing alternative sources of economically viable and renewable energy will become increasingly critical to national energy policies. One of the largest sectors in energy use is the transportation sector. Transportation has largely relied upon the availability of energy dense liquid transportation fuels such as gasoline and diesel. Scientists and policy makers have suggested that ethanol should be the predominant renewable, liquid energy substitute to liquid fossil fuels. Most ethanol used in the transportation sector has been produced from the fermentation of corn grain. Unfortunately, corn grain ethanol is not a long-term solution. Available farmland can supply no more than ten percent of the world's current liquid energy demand (Huber and Dale, 2009). Increased demand for corn grain has also increased the price of animal feed, subsequently increasing the cost of certain foods, and has led to the food versus fuel debate. Additionally, the net energy gain from corn ethanol production is low and is nowhere near a sustainable level. This has fueled the desire to develop a more sustainable renewable energy production system.

Renewable alternative energy production needs to be developed towards sustainability. Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations (U.S. Environmental Protection Agency website, 2013).

The quest to develop more sustainable, carbon-neutral, and renewable sources of liquid transportation fuels that promote energy independence and climate security has become one of the top energy priorities in the United States. In response to this demand, current scientific research has focused on developing sustainable systems that produce ethanol from lignocellulosic plant material. Lignocellulosic material is largely comprised of plant cell wall material that is made up of a complex network of polymers (notably cellulose) that can be broken down into fermentable monosaccharides. These monosaccharides are then fermented into ethanol. This form of ethanol has been aptly named cellulosic ethanol. The Energy Independence and Security Act of 2007 (EISA) calls for the Renewable Fuels Standard (RFS) to be increased to 36 billion gallons of renewable fuels by 2022, of which 16 billion gallons must be derived from lignocellulosic feedstocks. Additionally, the Food, Conservation and Energy Act of 2008 (2008 U.S. Farm Bill), contains provisions that authorize payments to producers in an effort to support and expand production of cellulosic ethanol. Cellulosic ethanol is a viable fossil fuel alternative because it is renewable, can lead to a reduced dependence on foreign oil, and is compatible with existing automobile standards (Mitchell et al., 2008). However, to meet this potential, a sustainable lignocellulosic ethanol production system must be established first.

The current proposed lignocellulosic ethanol production system is a made up of complex phases: 1. Crop production; 2. Pretreatment; 3. Enzymatic hydrolysis; 4. Fermentation; and 5. Distillation. Crop production consists of the production of various lignocellulosic plant biomasses that can be used to produce ethanol, the harvest of that plant biomass, the storage of that biomass prior to ethanol conversion, and the delivery of that biomass to a pretreatment facility. Pretreatment is a necessary step that alters the structure of cellulosic biomass to make it less recalcitrant to enzymatic hydrolysis (Mosier et al., 2005). Pretreatment will most likely be done at Regional Biomass Processing Depots (RBPDs), which are strategically distributed facilities that procure, pre-process/pre-treat and densify biomass into stable intermediate products that are compatible with existing bulk commodity logistical systems (Eranki et al., 2011). This densified material would then be transported to larger, centralized ethanol conversion facilities where enzymatic hydrolysis, fermentation, and distillation would occur. Enzymatic hydrolysis consists of exposing enzymes to pretreated cellulosic biomass in order to convert the carbohydrate polymers (cellulose and hemicellulose) into a hydrolysate liquor of fermentable sugars (glucose and xylose) (Mosier et al., 2005). Fermentation consists of incorporating yeast (*S. cerevisiae*) into the hydrolysate in order to ferment the monosaccharide sugars to ethanol. Distillation is the final step where ethanol is purified and is transported to market. The research presented in this study will predominantly be focused within the crop production phase of a lignocellulosic ethanol production system located in the Northern Corn Belt/Great Lakes Region.

A proper crop production phase, that facilitates the procurement, storage, and delivery of a high quantity of high quality lignocellulosic material, needs to be examined and developed within the framework of the pillars of sustainability: economics, society, and environment. In terms of economics, lignocellulosic crop production needs to be profitable to growers. Not only is it crucial for growers to produce high yields of cellulosic feedstock and obtain reasonable prices for their crop, it is also equally important that growers are able to adopt these production practices without having inhibiting upfront costs (Sokhansanj et al., 2009; Parrish et al., 1999). In terms of society, crop production of lignocellulosic feedstocks cannot largely be produced on arable land that could otherwise be used to produce more food for the ever growing world population (Robertson et al., 2008). Dedicated stands of cellulosic biomass will need to be grown on land less suitable for food production. Additionally, an emerging cellulosic ethanol industry proposes to help stimulate rural economies by aiding in job creation, which in turn promotes societal well-being. In terms of environment, cellulosic feedstock production, unlike the carbon-positive use of fossil fuels that promotes climate change, has the potential to become a carbon-neutral system. Research has already suggested that certain lignocellulosic feedstock production systems (such as switchgrass production) have the potential to not only supply carbon-neutral energy, but can also reduce atmospheric carbon levels through carbon dioxide sequestration (Ma et al., 2000). Additionally, certain biomass feedstock production systems have been shown to improve upon environmental concerns such as greenhouse gas emissions, eutrophication of bodies of water, soil erosion, and soil nutrient depletion.

Switchgrass (*Panicum virgatum* L.), a native, warm-season, perennial grass, has been selected as a model herbaceous perennial crop for cellulosic ethanol production by the U.S. Department of Energy (DOE) (U.S. Department of Energy, 2011). Since switchgrass is native to the Great Lakes Region, pesticide application is generally not needed because switchgrass is already well adapted to the regional insect and disease pressures. Perenniality is a highly desirable characteristic for a lignocellulosic crop because perennial crops, like switchgrass, do not have to be established each year. Therefore, they provide an economic benefit to the grower and require fewer energy inputs relative to annual crops. This in turn helps improve the overall net energy balance of the fuel production system (Hill, 2007). Since tillage is not required for most of a switchgrass stand's lifetime, carbon sequestration is more likely to occur, which in turn contributes to soil organic carbon and improves soil quality overall (Robertson and Swinton, 2005). Perenniality also means that switchgrass recycles its nutrients for subsequent years during senescence via translocation to its rootstocks and the soil. This in turn reduces nutrient export from the field and lowers the fertilizer requirements and energy requirements associated with fertilizer production and application (Muir et al., 2001). Reduced nitrogen application combined with better nitrogen use efficiency reduces the potential for eutrophication caused by excessive nitrate runoff (Carpenter et al., 1998) and the potential for nitrous oxide to contribute to greenhouse gas emissions (Mosier et al., 1998).

Since lignocellulosic ethanol production systems will most likely have to be localized in order to be sustainable (Eranki et al., 2011), region-specific agronomic information of crop production is needed in order to inform local growers and ethanol producers with the best crop management suggestions; this is especially true in the Northern Corn Belt/Great Lakes region. A proper crop production phase is one that facilitates the procurement, storage, and delivery of a high quantity of high quality lignocellulosic material. Additionally, lignocellulosic crop production needs to be economically profitable for a grower while also being environmentally sustainable. While switchgrass stand establishment has been studied in the Northern Corn Belt/Great Lakes region, less is known on how harvest variables affect procurement, storage, and delivery of switchgrass feedstock. The two major variables that affect procurement, storage, and delivery of switchgrass are harvest timing and harvest/storage method. Region-specific information on how harvest timing and harvest/storage method affect procurement, storage, and delivery of switchgrass feedstock is needed.

Objectives of the Study

The major objective of the overall study was to develop agronomic suggestions on how to create an economically viable and sustainable switchgrass crop production phase of a lignocellulosic ethanol production system, in the Northern Corn Belt/Great Lakes region, that facilitates the procurement, storage, and delivery of a high quantity of high quality lignocellulosic feedstock. The study focused on how harvest timing and harvest/storage method influenced these crop production aspects. These crop production aspects can be examined in three aspects: quantity, quality, and sustainability.

In regards to a crop production quantity aspect, a study was conducted that evaluated how harvest timing and harvest/storage method affected switchgrass harvest yield. The study also evaluated spring survivability, soil nutrient levels, and biomass ash content to determine how long term survivability of a switchgrass stand may be compromised.

In regards to a crop production quality aspect, a study was conducted that evaluated how harvest timing and harvest/storage method affected switchgrass feedstock quality. The study not only examined how these variables affected the switchgrass cell wall compositional profile but also examined how these variables affected the enzymatic digestibility of the biomass.

In regards to a crop production sustainability aspect, a life cycle assessment was conducted that evaluated how harvest timing and harvest/storage method affected environmental impacts at the crop production level. The study also examined how these two variables affect grower profitability.

CHAPTER 1

SWITCHGRASS HARVEST YIELD RESPONSE TO HARVEST TIMING AND TWO HARVEST/ STORAGE METHODS OF A BIOENERGY CROPPING SYSTEM IN THE GREAT LAKES REGION

Abstract: Less than ideal conditions during a late fall harvest timing in the Northern Corn Belt/Great Lakes region do not facilitate proper field drying of switchgrass prior to baling. In order for a cellulosic ethanol production system to be feasible, a region specific switchgrass biomass harvest system that facilitates timely harvest for farmers, maximizes harvest yield, minimizes dry matter storage loss, and maximizes switchgrass winter hardiness needs to be developed. This study investigated the effects of harvest timing and harvest/storage method on switchgrass yield, stand frequency, and soil nutrients. Harvest yield results suggested that yield is maximized during an early fall harvest timing using a direct chopping and ensiling harvest/storage method. Short-term stand frequency data and soil nutrient analysis suggested that switchgrass winter hardiness and spring survivability were not compromised at this stage in the switchgrass stand's lifetime. Overall, the data support a hypothesis that harvest during the early fall with a direct chopping and ensiling harvest/storage method will not affect winter hardiness, will facilitate timely harvest, will maximize harvest yield, and will potentially be most profitable for farmers in the Northern Corn Belt/Great Lakes region.

INTRODUCTION

Switchgrass (*Panicum virgatum* L.) was identified as a potential energy crop by the U.S. Department of Energy's Biomass Feedstock Development Program. Breeding programs since the 1930s by the USDA and additional scientists have produced a multitude of cultivars that are specifically suited to most areas of the United States, including the Midwestern Great Lakes region. The best suited switchgrass varieties to the Great Lakes region are the upland ecotype varieties, including 'Cave-In-Rock', due to their adapted winter hardiness. Switchgrass is widely considered to be the model perennial grass for bioenergy production (U.S. Department of Energy, 2011).

Switchgrass has great potential as a bioenergy crop for multiple reasons including: reliable productivity across a wide geographical range, suitability for marginal quality land, drought resistance, relatively low yearly inputs during and after stand establishment, low potential for invasiveness, few major insect or disease pests, and other positive environmental attributes including carbon sequestration, soil conservation, and wildlife habitat (Wright and Turhollow, 2010; U.S. Department of Energy, 2011). However, the greatest potential drawback of switchgrass is farmer profitability relative to existing crop alternatives. Switchgrass requires a lengthy establishment period of two to three years. So, successful stand establishment during the seeding year is mandatory for an economically viable bioenergy production system (Perrin et al., 2008). A reliable switchgrass harvest yield will help ensure farmer profitability and an economically viable bioenergy production system, but losses due to harvest and storage management have largely been under studied and raise several potential problems in the Northern Corn Belt/Great Lakes region that could potentially undercut the viability of a bioenergy production system in this area of the United States. Recovering high biomass yields is a top priority for switchgrass lignocellulosic feedstock production regardless of the efficiency of downstream processes. The quantity of recoverable lignocellulosic biomass produced per unit area determines the potential energy production capacity and the amount of land required to produce the feedstock that will be converted into cellulosic biofuel (McKendry, 2002).

It has been generally concluded that switchgrass would be harvested during the late fall or early spring harvest season, after a killing freeze causes frost-induced rupturing of cell walls which helps facilitate environmental washing of nutrients back to the soil (U.S. Department of Energy, 2011; Mooney et al., 2012). Additionally, it has also been generally assumed that baling will be the primary harvest/storage method for biomass feedstock (Mooney et al., 2012; Sanderson et al., 1997; Monti et al., 2009; Shinners et al., 2010; Khanchi et al., 2010, U.S. Department of Energy, 2011). Unfortunately, weather conditions associated with the late fall harvest season in the Northern Corn Belt/Great Lakes region are typically not conducive to field drying biomass to a level dry enough to facilitate proper bale storage. Additionally, the unpredictable and typically more extreme weather conditions during the late fall harvest season, in this region, do not provide harvest flexibility for farmers and could contribute to greater in-field physical losses via leaf shattering and contribute to further metabolic losses by facilitating decomposition during storage (Schroeder, 2013). Proper storage of biomass will be a crucial step in a cellulosic ethanol production system due to a year-round demand for biomass feedstock and an unavoidable processing time bottleneck at biorefineries (Digman et al., 2010; Mooney et al., 2012). Storage will help preserve both quantity and quality of biomass prior to ethanol conversion. Both harvest timing and harvest and storage management need further Great Lakes region-specific investigation.

Biomass handling and storage management is predominantly determined by biomass moisture content (Schroeder, 2013). In a switchgrass energy crop production system, it is assumed that the biomass will be cut and left in the field to dry to proper moisture content suitable for baling; otherwise, high moisture content within a bale will contribute to substantial microbial growth and subsequent dry matter loss. However, the biomass can undergo both physical and chemical loss if weather conditions are not ideal during the in-field drying period. Additionally, the biomass can further undergo physical loss during the baling process because collecting and wrapping the biomass, when it is dry and brittle, can cause excessive shattering, which further leads to yield reduction (Schroeder, 2013).

One potential solution to avoiding the potential harvest losses associated with a baling system is to treat the biomass as a silage crop (Digman et al., 2010; Schroeder, 2013). Treating switchgrass as a silage crop requires a completely different harvest and storage management system. Compared to a baling system, which is a low moisture content storage method, treating switchgrass as a silage crop requires an ensiling process, a high moisture content storage method. Ensiling is a method where biomass is stored compacted into covered piles or silos to ensure minimal light and oxygen exposure. The biomass then undergoes a fermentation process that helps preserve the quality of the biomass by lowering its pH due to the production of lactic acid. There are potentially many benefits to treating switchgrass as a silage crop. First, there are minimal harvest losses when biomass is harvested as silage because it is directly chopped and immediately collected in the field. Second, there is greater harvest timing flexibility for farmers because direct chopping and ensilage storage is less dependent on periods of rain-free weather prior to biomass collection (Schroeder, 2013). Additionally, chopping and ensiling is a one pass harvest system (compared to baling which requires multiple passes in order to collect the biomass), it increases product uniformity, it potentially improves feedstock susceptibility to enzymatic hydrolysis, and it potentially helps reduce the risk of fire (Richard et al., 2001; Shinners et al., 2007). However, there are potential disadvantages. The fermentation process during ensiling causes some dry matter loss due to aerobic and anaerobic digestion of the biomass. Additionally, ensiling at too low of a moisture content can lead to excessive heating and mold growth and can even run the risk of self-combustion (Schroeder, 2013).

A direct chopping and silage storage method may prove to be a more viable alternative to protect switchgrass harvest yields compared to a baling system in the Northern Corn Belt/Great Lakes region. Region-specific harvest timing and harvest/storage issues could lead to problems that potentially undercut the viability of a bioenergy production system in this area of the United States. Harvest loss due to harvest and storage management has largely been under studied, especially in regards to ensiling of biomass dedicated to bioenergy production. In order to ensure farmer profitability and an environmentally sustainable and economically viable bioenergy production system in this region, research is needed to evaluate how harvest timing and harvest/storage methods affect recoverable biomass yield and stand survivability.

Objective of Study

The objectives of this study were to: 1. Investigate the effect of harvest timing and harvest/storage method on switchgrass yield; and 2. Develop a switchgrass biomass harvest system for the Northern Corn Belt/Great Lakes region that facilitates timely harvest for farmers, maximizes harvest yield, minimizes dry matter storage loss, and maximizes switchgrass winter hardiness.

MATERIALS AND METHODS

Site Description and Experimental Design

Switchgrass Stand Establishment

Beginning in the fall of 2006, a field experiment site was established at the Michigan State University Agronomy Research Farm in East Lansing, Michigan (42°42’52” N 84°27’57” W). Soils consisted predominantly of Capac loam (USDA Web Soil Survey). The site was conditioned using a conventional chisel plow tillage system in the fall of 2006 and was further conditioned twice over with a field cultivator in the spring of 2007 to ensure a flat, weed-free seed bed. The upland switchgrass cultivar ‘Cave-In-Rock’ was then seeded at a rate of 9 kg ha^{-1} using a double roller seeder (Brillion, Brillion Iron Works, WI) to about a 1.25 cm depth. The switchgrass was allowed to establish for three years. The switchgrass was cut and removed during the establishment years once senescence and a killing frost (-2.2 °C) had occurred to allow mineral nutrients to return to the root crowns and soil. Stand frequency was not taken at the onset of the study after three establishment years, but visual evidence showed a full complete stand with at least a 40% stand frequency (Vogel et al., 2001).

Weed Control

Weed control was most important during the establishment phase because broad leaf weeds and grasses could out-compete switchgrass seedlings if not controlled (Parrish et al., 1999). Weeds were controlled during the establishment phase with a tank mixture of S-metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl] acetamide) and atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) at rates of 1.3 and 1.8 kg ha^{-1}, respectively. Weeds were not chemically controlled after the establishment phase was completed.

Fertilization & Nutrient Management

Due to potential weed competitiveness during switchgrass establishment, the site was not fertilized during the establishment year. The site was fertilized with granular urea (46-0-0 NPK) at a rate of 78.5 kg N ha^{-1} during the spring green-up in the years after the first establishment year.

Description of Study Variables

Variable #1: Harvest Timing

Four harvest timings were identified in order to observe how various harvest timings throughout the harvest period in the Northern Corn Belt/Great Lakes region affect switchgrass harvest yield, storage loss, stand frequency, and soil nutrient content. Table 1, below, outlines the four harvest timings and their specific details.

Timing	Time of Year	Description & Pros/Cons
Early Fall Harvest	Early September to Late September	Immediately following seeding and peak biomass production. Prior to major translocation of nutrients to root crowns. High moisture content (> 50%). Ideal biomass for ensiling. Potential weather impact on harvest yield is low. Low nutrient translocation to the root crown could impact winter hardiness and subsequent spring survival rates.
Mid Fall Harvest	Early October to Late October	Plant senescence has begun. Translocation of nutrients to root crowns begins. Mid-level moisture content (35-50%). Marginally ideal biomass for ensiling. Potential weather impact on harvest yield is slight. Winter hardiness and spring survival is potentially compromised. Timing coincides with corn and soybean harvest in the region, which is not timely for farmers.
Late Fall Harvest	Early November to Late November	2 weeks after a killing frost (-2.2 °C). Frost-induced rupturing of cell walls. Mediated translocation of nutrients to root crowns and soil occurs. Low moisture content (20-35%). Not ideal for ensiling. Unpredictable weather not ideal for drying time required for baling. Potential weather impact on harvest yield is moderate. Increased frequency of extreme weather could compromise harvest yield. Winter hardiness and spring survival is not compromised.
Spring (Over-winter) Harvest	Mid March to Mid April	Environmental washing of a majority of the remaining mineral nutrients to the soil due to winter precipitation. Low moisture content (< 10%). Ideal for baling. Too dry for ensiling. Potential weather impact on harvest yield is high. Spring survival is not compromised.

Table 1. Harvest timing descriptions, benefits and potential issues. These harvest timings are specific to the Northern Corn Belt/Great Lakes region.

Variable #2: Harvest/Storage Method

Two general harvest/storage methods are suitable for collection of switchgrass biomass. Investigation of these harvest/storage methods served to provide new insights into optimizing the feedstock production end of a cellulosic ethanol production system in the Northern Corn

Belt/Great Lakes region. Table 2, below, outlines the two harvest/storage methods and describes the specific details, benefits, and issues associated with each method.

Method	Description	Pros/Cons
Cut/Bale	Biomass is cut into windrows and allowed to dry to a proper moisture content suitable for bale storage (< 20%). Biomass is turned to allow even drying. Then it is round or square baled and stored covered or uncovered until further processing.	This harvest and storage method is ideal for biomass with low moisture content. It is a multiple-pass harvest system, requiring more harvest management input. Impact on harvest yield is potentially high due to physical and mechanical loss when drying and handling the biomass. Potential for storage loss due to aerobic and anaerobic respiration is low due low moisture content storage conditions, especially if stored isolated from weather events.
Chop/Ensile	Biomass is directly chopped with a forage harvester at high moisture content (> 50%). It is blown directly into a silage cart and immediately compacted in piles or bunker silos and allowed to ensile. It is kept covered until further processing.	This harvest and storage method is ideal for biomass with high moisture content. It is a one pass harvest system that requires relatively less harvest management input. Impact on harvest yield due to physical and mechanical loss is low. Potential for storage loss due to aerobic and anaerobic respiration is high due to high moisture content storage conditions.

Table 2. Harvest/storage method variable descriptions, benefits, and potential issues.

Experimental Design

In the spring of 2010, the experimental design was marked off within the established switchgrass field. The experimental design was a randomized complete block design (RCBD) with four replications (blocks). The main plot variable was harvest timing. The sub-plot variable was harvest/storage method. The sub-plot variable could not be randomized within the main plots because the chop/ensile harvest system requires a minimum 3.66 m wide harvest clearance, whereas the sub-plots were only 3.05 m wide. See figure 1, below, for a complete visual description of the experimental design.

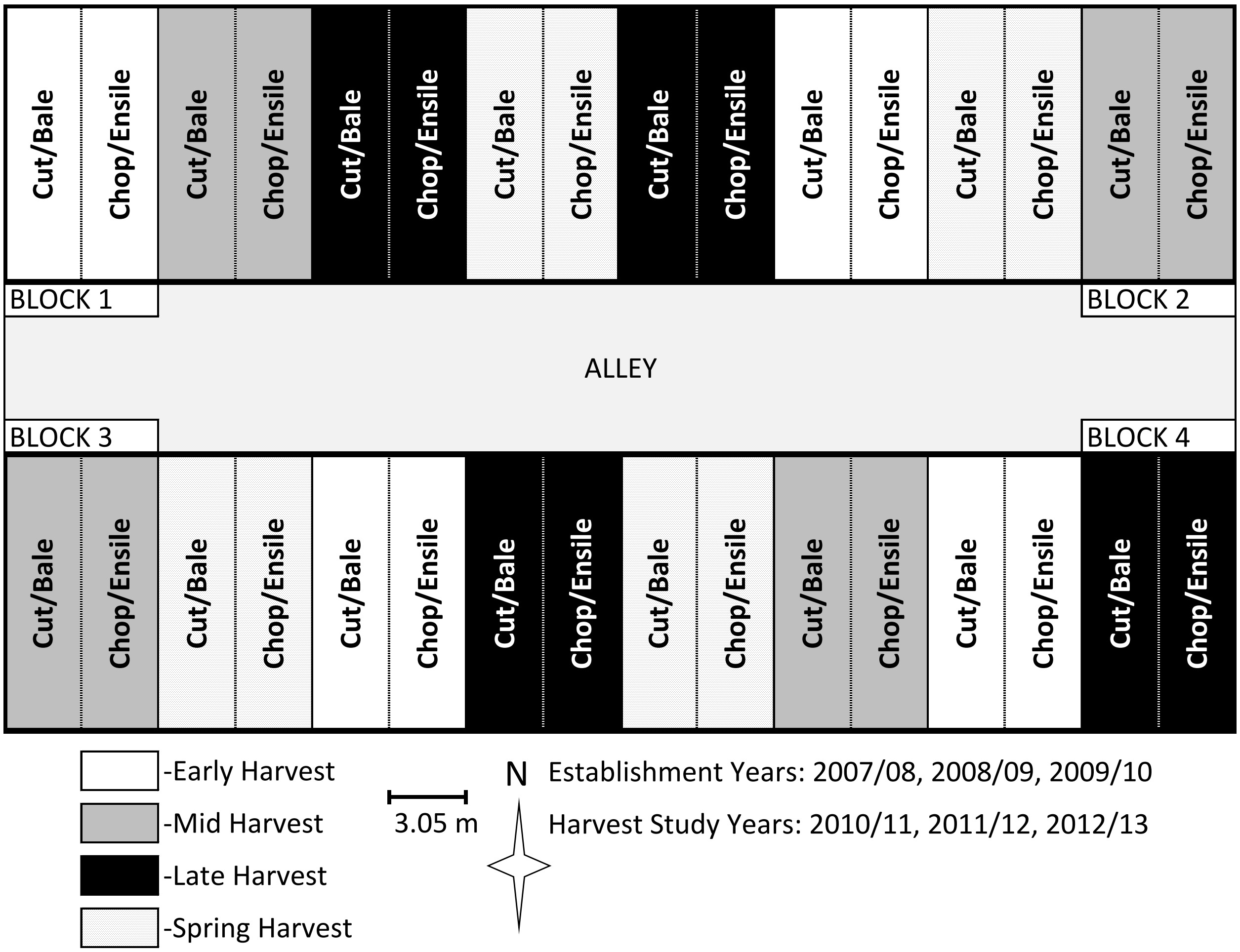

Figure 1. Switchgrass harvest management study site experimental design. Sub-plots were 3.05 m x 12.20 m. A 7.62 m wide alley ran down the center of the site. The total dimensions of the site were 32.0 m x 48.8 m (0.156 ha). The site was located at 42°42’52” N 84°27’57” W.

Harvest Yield & Storage

When weather permitted, the sub-plots were harvested within each main plot according to their harvest/storage method during the harvest timings.

The cut/bale sub-plots were harvested using a custom built plot windrower (Swift Machine and Welding Ltd., Swift Current, SK, Canada) with a 1.52 m wide cutter head, set at an 18 cm cutting height, to cut the switchgrass into two windrows. Because of the small plot size, the biomass was hand raked into one windrow and was inverted as needed over the course of about two weeks to ensure even drying. Once the biomass reached the proper baling moisture content (< 20%) each sub-plot biomass was individually baled with a John Deere 7830 tractor equipped with a John Deere 582 round baler (Deere & Company, Moline, Illinois). Due to baler mechanical issues during the early and mid fall harvest timings in 2012, each sub-plot had to be baled with a John Deere 7830 tractor equipped with a John Deere 338 small square baler. The mass of each bale was recorded. Bale moisture content was recorded by drying samples in a forced-air oven at 66 °C until a constant mass was achieved. Harvest yield was reported as dry kg ha^{-1}. The bales were stored indoors for six months without any disturbance. The six month mass was recorded for each bale. The bales were then sampled. The samples were dried and their moisture content was recorded using the same method just described.

The chop/ensile sub-plots were harvested with a Hesston 7650 forage harvester (Hesston Co., Hesston, Kansas) equipped with a 3.66 m wide chopper head set at an 18 cm cutting height that was modified for plot research with the addition of a weigh bin for sub-plot harvest yield determination. The sub-plot mass was recorded and the harvest yield was reported as dry kg ha^{-1}. The chopped biomass was immediately sampled. A fraction of the sample was used to determine biomass moisture content by drying the fraction in a forced-air oven at 66 °C until a constant mass was achieved. The remaining fraction was simulation ensiled at its harvest moisture content. A known mass of biomass was packed into a food vacuum bag and was evacuated of its air to simulate ensiling conditions. The vacuum bags were stored indoors for six months without any disturbance. After six months, the vacuum bags were unsealed and the silage moisture content was recorded.

Storage Loss

Storage loss was calculated in order to evaluate how harvest storage method impacted dry matter yield. Storage loss due to baling was calculated as the percent difference between the zero month bale dry mass and the six month bale dry mass. Storage loss due to ensiling was calculated as the percent difference between the zero month silage dry mass and the six month silage dry mass.

Stand Frequency

Switchgrass stand frequency was recorded on June 4, 2013 during spring green-up. Recording stand frequency provided a way to evaluate how harvest timing has impacted winter hardiness and spring survival rates. Stand frequency was evaluated using the grid method developed by Vogel and Masters (2001). A 0.75 X 0.75 m frequency grid, comprised of 25 cells (each 225 cm^2) was flipped end-to-end in a randomly chosen place within each sub-plot until a total of 100 cells were observed for the presence or absence of switchgrass. The stand frequency was recorded as the number of observed cells with a positive switchgrass presence out of 100 observed cells.

Soil Nutrient Content

Soil samples were taken on September 11, 2013. Soil samples were obtained to a depth of 22.9 cm using a soil core sampler. Four samples were randomly taken across each main plot, making sure that two samples were taken from each sub-plot. The soil samples were then sent to the Michigan State University Soil and Plant Nutrient Laboratory for soil nutrient testing.

Statistical Analysis

Data were analyzed using PROC MIXED in SAS 9.2 (2009, SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was conducted to measure the treatment effects on harvest yield, harvest moisture content, bale and ensile storage loss, stand frequency, and soil nutrient content. Harvest year, harvest timing and harvest/storage method were treated as fixed effects while blocking was considered to be a random effect. Initially, harvest year was assumed to be a random effect, but upon evaluation, harvest year had obvious non-random effects, due to major yearly precipitation differences, and was chosen to be treated as a fixed effect. Regardless, this change had no effect on the ANOVA results. Normality of the residuals and homogeneity of variances were evaluated by examining normal probability plots and box plots. Fisher's protected least significant difference (LSD) multiple comparison procedure was used for mean separation when ANOVA was significant (Saxton, 1998). Results were reported as statistically significant at $\alpha = 0.05$.

RESULTS & DISCUSSION

Climatological Summary

Mean monthly air temperatures in East Lansing did not vary considerably between the study years, but they tended to be higher compared to the monthly mean over the last 30 years, especially during the switchgrass growth phase (table 3). Every monthly temperature mean, for all three study years during the switchgrass growth phase, was higher compared to the monthly 30 year average. The first killing frost (-2.2 °C) dates for the 2010/11, 2011/12, and 2012/13 study years were: November 1, October 28, and November 4, respectively.

Cropping Phase	Month	Total Precipitation			30-yr Avg	Mean Temperature			30-yr Avg
		'10/'11	'11/'12	'12/'13		'10/'11	'11/'12	'12/'13	
Growth Phase	May	10.4	14.6	6.2	8.5	15.9	15.0	16.8	13.9
	June	10.0	4.0	2.7	8.9	20.4	19.8	20.3	19.4
	July	4.4	13.0	3.7	7.2	23.2	24.1	24.4	21.6
	August	1.4	7.8	5.3	8.2	22.5	21.0	20.8	20.6
Fall Harvest Phase	September	8.9	6.7	5.5	8.9	16.3	15.9	16.3	16.3
	October	3.6	7.5	9.2	6.4	11.5	10.7	10.1	9.8
	November	4.2	6.2	0.8	7.1	4.6	6.0	3.3	3.8
Over-Wintering Phase	December	1.4	5.2	3.2	4.8	-4.1	0.3	0.9	-2.5
	January	0.7	3.2	6.9	4.2	-6.8	-1.9	-3.1	-5.1
	February	1.9	2.2	2.3	3.7	-4.6	-1.0	-4.2	-3.8
Spring Harvest Phase	March	6.4	5.9	1.7	5.2	0.4	9.4	-0.5	1.3
	April	11.6	4.4	16.5	7.7	7.4	8.3	6.5	8.2

Table 3. Monthly precipitation (cm) and mean temperatures (°C) during the study years compared to the 30-year means (1981-2010). The 30-year averages were obtained from NOAA. Weather data were obtained via the Michigan State University Enviro-Weather website (figure 28). The station was located 0.9 km away at the Hancock Turfgrass Research Center.

The 2010/11 and 2012/12 study years tended to be drier, while the 2011/12 study year tended to be average when compared to the 30-year mean (table 4). The 2010/11 study year was 19.9% drier and 2012/13 was 20.8% drier compared to the 30 year mean, while 2011/12 was essentially the same (0.1% drier). Additionally, the total precipitation during the switchgrass growth phase during the 2010/11 and 2012/13 study years was considerably lower (20.2% and 45.7%, respectively) while during the 2011/12 study year was considerably higher (20.0%) compared to the 30-year mean (table 4). The 2010/11 study year tended to be wet during May and June and drier during July and August compared to the 30-year means (table 3). However, these late drought stresses did not seem to have an effect on harvest yield. The 2011/12 study year tended to be significantly wetter during May and July, significantly drier in June, and average during August compared to the 30-year means (table 3). Finally, 2012/13 displayed very severe drought conditions throughout the growth phase (May-August). Each month was significantly drier compared to the 30-year means (table 3). Drought related stress responses were observed for this study year.

	Total Precipitation			30-yr Average
	2010/11	2011/12	2012/13	
Total Growth Phase Precipitation	26.2	39.4	17.9	32.9
Total Yearly Precipitation	64.7	80.7	64.0	80.8

Table 4. Total growth phase (May-August) and yearly (May-April) precipitation (cm) during the study years compared to the 30-year means (1981-2010). Weather data were obtained via the Michigan State University Enviro-Weather website (figure 28). The station was located 0.9 km away at the Hancock Turfgrass Research Center. The 30-year averages were obtained from NOAA.

Harvest Dates

Figure 2, below, displays the harvest dates across the three study years along with daily weather data.

A.)

Month	Day	Timing	Study Year														
			2010/2011					2011/2012					2012/2013				
			Weather			Method		Weather			Method		Weather			Method	
			P	H	L	C/B	C/E	P	H	L	C/B	C/E	P	H	L	C/B	C/E
SEPTEMBER	9	Early Fall Harvest		19	10			0.84	25	15				22	9		
	10			20	6			0.10	26	16				23	5		
	11		1.14	16	11				25	14				26	11		
	12			23	13				28	15				28	13		
	13			25	11				25	12			0.51	26	13		
	14			21	9			0.41	19	7			0.91	21	11		
	15			22	5				15	4				23	5		
	16		3.40	19	12				15	2				25	9		
	17			19	11				18	8			0.03	24	10		
	18		0.97	19	12				21	7			0.48	18	6		
	19			22	11			1.85	19	13			0.03	18	4		
	20			19	13			0.03	22	8			0.15	20	9		
	21		0.38	30	15				24	11			0.41	20	6		
	22			25	16				20	10			0.15	15	7		
	23			30	16				18	11			0.15	13	5		
	24		0.03	27	14				18	7			0.03	17	3		
	25			15	9			0.05	21	10			0.05	20	10		
	26			14	6			1.55	21	10			0.03	22	10		
	27		0.08	16	6			0.23	19	7				18	8		
	28		0.36	17	10				17	11				21	8		
	29			22	4			0.89	17	10				22	5		
	30		0.03	22	9			0.33	11	4				18	7		
OCTOBER	1	Mid Fall Harvest		20	7				12	3				19	2		
	2		0.71	12	6				17	2				21	11		
	3			13	3				20	6				18	13		
	4			15	2				23	3			0.23	24	12		
	5			19	0				25	5			0.03	15	7		
	6			21	4				28	6				8	4		
	7			21	7			0.33	26	7				8	2		
	8			25	5			0.03	27	10				12	-1		

Figure 2. Timelines of harvest events for study years 2010/11, 2011/12, & 2012/13. A.) Early fall harvest timing events; B.) Mid fall harvest timing events; C.) Late fall timing events; D.) Spring harvest timing events. P- precipitation (cm); H- daily high temperature (°C); L- daily low temperature (°C); C/B- cut/bale harvest/storage method; C/E- chop/ensile harvest/storage method. Weather data were collected at the nearby Hancock Turfgrass Research Center.

Figure 2 (cont'd).
B.)

Month	Day	Timing	Study Year 2010/2011 Weather P	H	L	Method C/B	C/E	2011/2012 Weather P	H	L	Method C/B	C/E	2012/2013 Weather P	H	L	Method C/B	C/E
OCTOBER	13	Mid Fall Harvest	1.24	15	8			0.81	18	11			2.13	17	0		
	14			17	6			0.08	15	9			0.94	21	11		
	15		0.08	16	6			0.13	13	7			0.03	11	7		
	16			17	1			0.03	15	8				16	0		
	17			16	5				14	6			0.69	23	12		
	18			14	7			0.15	12	3			0.94	15	6		
	19			14	0			2.16	9	6			0.30	11	5		
	20		0.69	18	4			2.44	8	5			0.15	13	6		
	21		0.03	10	2				8	2				17	0		
	22			14	-2				15	-1			1.47	21	4		
	23			17	8				18	3			0.56	18	15		
	24		0.03	22	11			0.71	15	4				25	14		
	25		0.43	22	14			0.03	19	3				24	14		
	26		0.38	19	12				14	6			0.15	21	5		
	27			18	11				9	3				11	1		
	28			11	5				10	-3				8	0		
	29			10	4			0.36	11	0				6	1		
	30			15	4				10	-4			0.89	4	0		
	31			10	0				10	1			0.05	5	1		
NOV	1	Late Fall		11	-5				15	-1				9	2		
	2			10	-5				19	6				6	1		
	3			7	-6				12	4				3	-1		

Figure 2 (cont'd).
C.)

Month	Day	Timing	Study Year														
			2010/2011					2011/2012					2012/2013				
			Weather			Method		Weather			Method		Weather			Method	
			P	H	L	C/B	C/E	P	H	L	C/B	C/E	P	H	L	C/B	C/E
NOVEMBER	9	Late Fall Harvest		16	1			0.58	17	3				14	-1		
	10			14	1			0.08	5	-1				17	8		
	11			18	2				5	-1				20	12		
	12			21	2				15	1			0.74	16	-1		
	13		0.33	17	3			0.10	18	11				1	-5		
	14			10	2			0.05	12	4				5	-7		
	15			11	2				15	-1				7	-6		
	16		0.18	9	-3				9	-2				12	-6		
	17		0.18	11	4				1	-5				12	-5		
	18			5	0				8	-6				13	0		
	19			7	-3				12	4				13	-3		
	20			7	-1				14	1				14	1		
	21			15	0				8	-2				13	-2		
	22		1.85	16	14			1.19	3	-3			0.05	16	5		
	23			15	-2			0.05	10	0			0.05	12	-1		
	24		0.08	3	-6				7	1				-1	-2		
	25		0.89	6	-3				15	5				2	-4		
	26			0	-4			0.08	16	8				0	-2		
	27			2	-3			0.91	13	1				2	-6		
	28			5	-5			0.08	2	0				4	-4		
	29			10	-3			2.34	3	-2				9	-2		
	30		0.69	13	-1			0.46	3	-6				5	1		

Figure 2 (cont'd).
D.)

Month	Day	Timing	Study Year														
			2010/2011					2011/2012					2012/2013				
			Weather			Method		Weather			Method		Weather			Method	
			P	H	L	C/B	C/E	P	H	L	C/B	C/E	P	H	L	C/B	C/E
MARCH	14	Spring Harvest		6	-3				26	1				4	-7		
	15		0.08	7	-3				26	15			0.15	3	-1		
	16		0.08	13	1				26	9				0	-5		
	17			20	6				25	11				-1	-8		
	18			17	4				22	11			0.23	1	-7		
	19			9	-2				26	11				1	-7		
	20		1.65	7	-1				27	12				-3	-10		
	21		0.58	9	4				30	12				-1	-10		
	22		0.81	6	0			1.55	30	12				3	-4		
	23		0.64	1	-4			0.94	19	12				0	-5		
	24		0.03	-1	-7				14	10				2	-6		
	25			-1	-9				22	7				3	-2		
	26			0	-9				7	-2				5	-1		
	27			2	-9				13	-3				7	-1		
	28			3	-8				16	6				10	-2		
	29			6	-7				7	0				12	-4		
	30			7	-7			0.79	3	-2				13	-4		
	31			9	-7				6	0			0.08	13	3		
APRIL	1			9	-6				12	1				3	-5		
	2		0.03	7	-2				14	0				4	-7		
	3		0.46	7	-3			0.48	17	3				6	-5		
	4		0.03	15	3				16	2				13	-4		
	5			8	-1				8	1				9	0		

Harvest Yield

Harvest yields were reported as dry kg ha-1 (figure 3). See table 18 for the raw data. Harvest moisture contents were reported as the percent of switchgrass mass at the time of harvest (figure 4). Statistical difference between harvest yields due to a three way interaction among year, harvest timing, and harvest/storage method (P = 0.0165) was observed (figure 3).

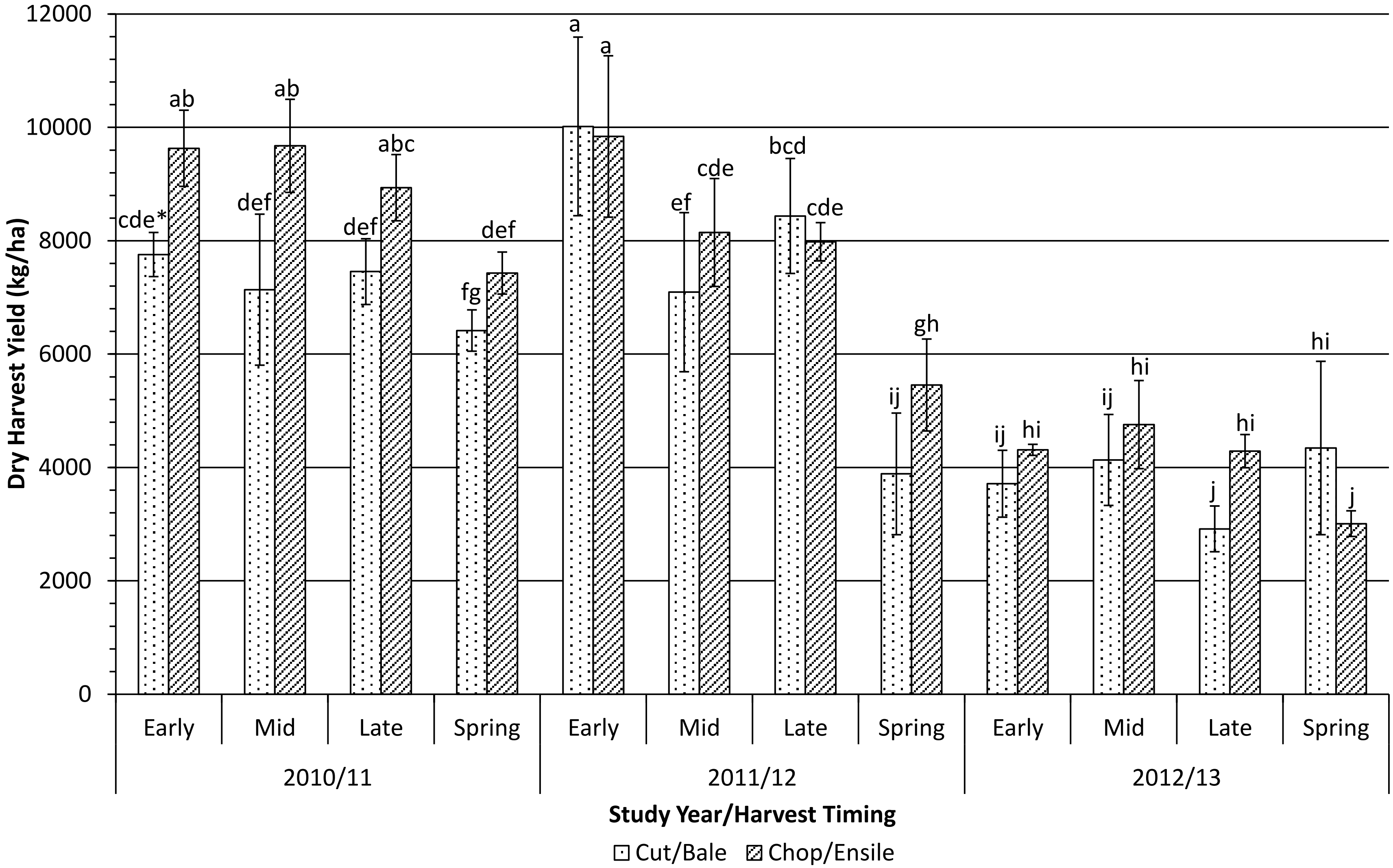

Figure 3. Switchgrass dry harvest yields. Harvest yields are reported as dry kg ha^{-1}. Error bars represent one standard deviation from the harvest yield mean. *Harvest yields with the same letter(s) are not statistically different (α = 0.05). See table 18 for the raw data.

The most significant differences between cut/bale and chop/ensile harvest yields were observed during the 2010/11 study year. For every harvest timing except for spring, the cut/bale harvest yields were significantly less than the chop/ensile yields (figure 3). Additionally, for both harvest/storage methods, harvest yields were not statistically different among the three fall harvest timings. The spring chop/ensile harvest yield was statistically less than the fall harvest yields, whereas the spring cut/bale harvest yield was only statistically different from the early cut/bale harvest yield. Overall, the 2010/11 harvest year suggested that a chop/ensile harvest system was favorable in terms of maximizing harvestable dry matter, whereas timing did not play a crucial role. However, it was important to note that there was a slight decrease in mean harvest yield later into the harvest season. The 2010/11 year also suggested that a spring harvest was not favorable in terms of harvestable dry biomass regardless of the harvest/storage method used.

For the 2011/12 study year, the cut/bale and chop/ensile harvest yields were statistically the same for all the harvest timings except for the spring (figure 3). Both cut/bale and chop/ensile harvest yields for the mid and late fall timings were statistically less than the early fall harvest yields. Furthermore, the spring harvest yields were both statistically less than all three fall harvest timing yields. Overall, the 2011/12 harvest year suggested that an early fall harvest timing was favorable in terms of maximizing harvestable dry matter, whereas harvest/storage method did not play a crucial role. The 2011/12 year also suggested that a spring harvest was not favorable in terms of harvestable dry biomass regardless of the harvest/storage method used.

The 2012/13 study year showed that harvest/storage method did not have substantial impact on harvest yields during the early and mid fall harvest timings (figure 3). Statistical difference in harvest yields was present during the two later harvest timings. The cut/bale harvest yield was significantly less than the chop ensile harvest yield during the late fall harvest timing. The opposite was found during the spring harvest. Overall, the 2012/13 study year suggested that an early or mid fall harvest timing potentially prevented harvest loss associated with the different harvest/storage methods. However, it was important to note that the cut/bale harvest yield means tended to be slightly less than the chop/ensile harvest yield means.

The most significant observation during the 2012/13 season was how the drought conditions during the growth phase of the switchgrass (figure 3) had a significant impact on the total harvestable biomass during the harvest phase. Almost every harvest yield was significantly less than all the other harvest yields for both the 2010/11 and 2011/12 study years. This observation made it evident that drought resistant characteristics of switchgrass only protected potential harvest yields to a point. Beyond that point, the switchgrass shifted to a survival mode instead of continuing to add above ground biomass during extreme drought. However, the switchgrass did perform well under mild drought conditions during the 2010/11 study year (table 4). Most harvest yields were statistically the same or even higher than harvest yields during the 2011/12 study year (figure 3), which had above average rainfall during the growth phase (table 4).

Early and mid fall harvest timings provided more predictable windows of low precipitation (figure 2a), which allowed proper drying times for cut biomass prior to baling.

Most bale moisture contents were around or below the target moisture content of 20% (figure 4). One exception was during the mid fall harvest timing in 2012. Although the biomass was at proper moisture content when it was baled, it underwent the longest drying period of the whole study because of unexpected rain that lasted for days (figure 2a). The bale moisture contents at harvest were more variable during the late fall harvest. During the late fall harvest in 2011, there were high amounts of precipitation predicted later that week (figure 2a). It was decided that the biomass needed to be baled right away to avoid a total crop loss. Unfortunately, this meant that the biomass needed to be baled at a moisture content higher than 30%, which made it prone to excessive heating and mold growth (Schroeder, 2013). The spring harvest moisture contents were so dry (figure 4) that they contributed to excessive shattering when the biomass was being collected and wrapped by the baler. Biomass brittleness was so severe during the spring timings that it caused baler mechanical issues in which the biomass would not properly bale. The bales had to be counted as lost. Overall, baling was ideal in the early and mid fall harvest timings because these timings provided excellent drying periods prior to baling. Baling was less ideal during the late fall due to increased weather unpredictability that threatened proper biomass drying. Baling was not ideal during the spring harvests because excessive biomass dryness contributed to yield loss via excessive biomass shattering (Sanderson et al., 1997) and baler mechanical issues.

Moisture Content

Statistical difference between harvest moisture contents due to a three way interaction among year, harvest timing, and harvest/storage method ($P = < 0.0001$) was observed (figure 4).

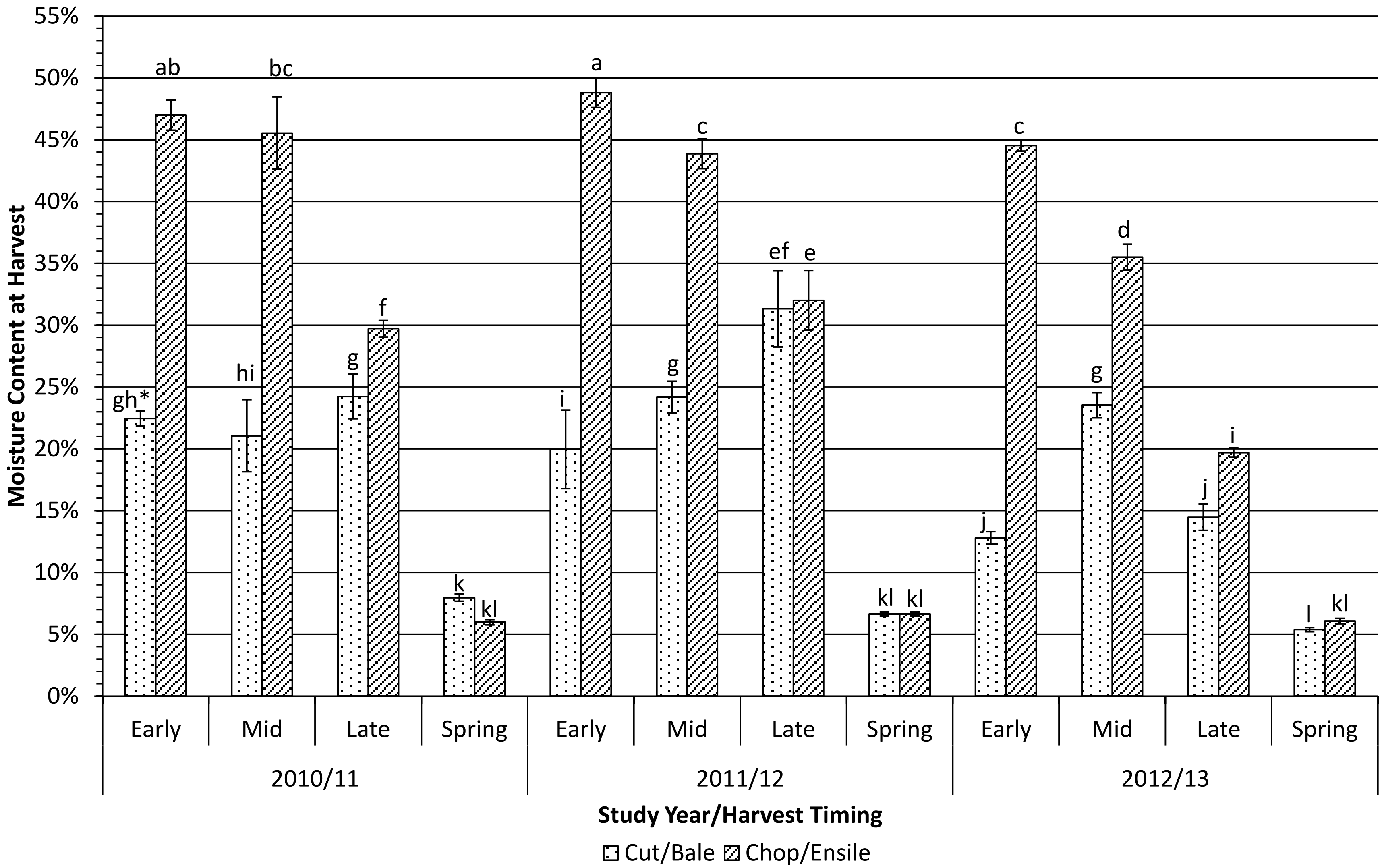

Figure 4. Moisture content of biomass at harvest. Moisture content is reported as percent wet mass of total mass at the time of biomass removal. Error bars represent one standard deviation from the harvest moisture content mean. *Moisture contents with the same letter(s) are not statistically different (α = 0.05). See table 18 for the raw data.

Biomass moisture contents were ideal for ensiling during the early and mid fall harvest timings. Biomass was around 45-50% moisture content (figure 4), except during the 2012 mid fall harvest due to the drought conditions of 2012. Biomass moisture contents during the late fall harvest were not ideal for ensiling because they were within the danger zone of excessive microbial growth and heating (Schroeder, 2013). Moisture contents during the spring harvest were too low for an ensiling process because an adequate amount of moisture was needed in order to properly pack the biomass into piles and to allow fermentation to occur in order to preserve the biomass. Overall, ensiling was ideal during both the early and mid fall harvest timings because the biomass was at a moisture content suitable for an ensiling process. Ensiling was not ideal during both the late fall and spring harvest timings because the biomass moisture content was too low to support an ensiling process.

Baling and ensiling were not favored during both the late fall and spring harvest timings. However, baling and ensiling were favored during both the early and mid fall harvest timings. Since harvest yields for both baling and ensiling had a significant decrease between the early and mid fall harvest timings during the 2011 study year, it was suggested that the early fall harvest timing helped ensure maximum biomass recovery. Since baling harvest yields were significantly less than the ensiling harvest yields for both the early and mid fall harvest timings during the 2010 study year, it was suggested that a direct chopping and ensiling harvest/storage method helped ensure maximum biomass recovery. Overall, it was suggested that using a direct chopping and ensiling harvest/storage method, during an early fall harvest timing, over the course of a switchgrass stand's lifetime would have helped to ensure a maximum biomass recovery and subsequently a maximum amount of profit for a farmer in the Northern Corn Belt/Great Lakes Region.

Ensiling during an early fall harvest timing has many additional benefits that would support a farmer who is interested in growing feedstock biomass for cellulosic ethanol production. First, ensiling, unlike baling, is not dependent upon periods of rain free days prior to storage. This gives farmers greater harvest timing flexibility. Second, an early fall harvest timing does not typically interfere with corn and soybean harvesting which tend to take place during a mid fall harvest timing. Third, ensiling requires less time because it is a one pass harvest system. This helps minimize how long a farmer would have to spend in the field, which further adds to harvest timing flexibility. Fourth, since Michigan is a large dairy producing state and since ensiling is a forage process typically used in dairy production, many Michigan farmers may already have access to forage equipment and be more willing to adopt a bioenergy cropping system (Parrish et al., 1999). Finally, since ensiling is typically used to produce quality animal fodder that is more easily digested, ensiling can be seen as a value adding process because it integrates a biological pretreatment step (Digman et al., 2007; Ren et al., 2004; Ren et al., 2006; Ren et al., 2007; Richard et al., 2001). This may in turn help farmers earn better profits for the feedstock because it may have the flexibility to go into an animal feed market or a bioenergy production market. This in turn may also reduce subsequent pretreatment costs. Bridging the gap between these two markets could additionally help alleviate the environmental problems associated with animal production by producing feedstock that could also be used as an animal fodder (Dale et al., 2010).

Storage Loss Due to Baling

Storage loss due to baling was calculated as the percent change of mass between the zero month bale dry mass and six month bale dry mass (table 19). It was decided that statistical analysis should not be performed on the baling storage loss results due to the level of incompleteness and high levels of deviation within each measurement. The small size of the research plots was not conducive to bale spoilage measurements.

Much research on switchgrass storage loss due to baling has already been performed. Round bales that are stored at proper moisture content isolated from the elements usually have the least amount of storage loss both physically and chemically (< 5% dry matter loss) (Mooney et al., 2012; Sanderson et al., 1997; Monti et al., 2009; Shinners et al., 2010; Khanchi et al., 2010). Control of bale moisture and exposure to weather are the two main issues that determine dry matter storage loss. Round bales tend to lose less dry matter compared to square bales because round bales lose moisture faster and are held together better (Mooney et al., 2012; Shinners et al., 2010). Minimizing exposure to moisture would ensure minimal dry matter loss, regardless of the baling method (Mooney et al., 2012). However, biomass that is harvested and stored at too low of a moisture content (< 10%), an issue typically seen during a spring harvest, will more likely lose dry matter due to excessive shattering (Sanderson et al., 1997). Unfortunately, bales are typically stored outdoors and not indoors, like how this study was performed. This ultimately leads to dry matter loss even if the bales are stored covered (Mooney et al., 2012). These bales can have losses around 10% dry matter.

Storage Loss Due to Ensiling

Storage loss due to ensiling was calculated as the percent change of mass between the zero month silage dry mass and six month silage dry mass (table 20). Statistical difference between dry matter losses due to an interaction between year and harvest timing (P = 0.0047) was observed. See figure 5, below, for the storage loss results. The small size of the research plots was not conducive to bunker silo storage loss measurements. However, results allowed for assessing the suitability of the feedstock to ensiling.

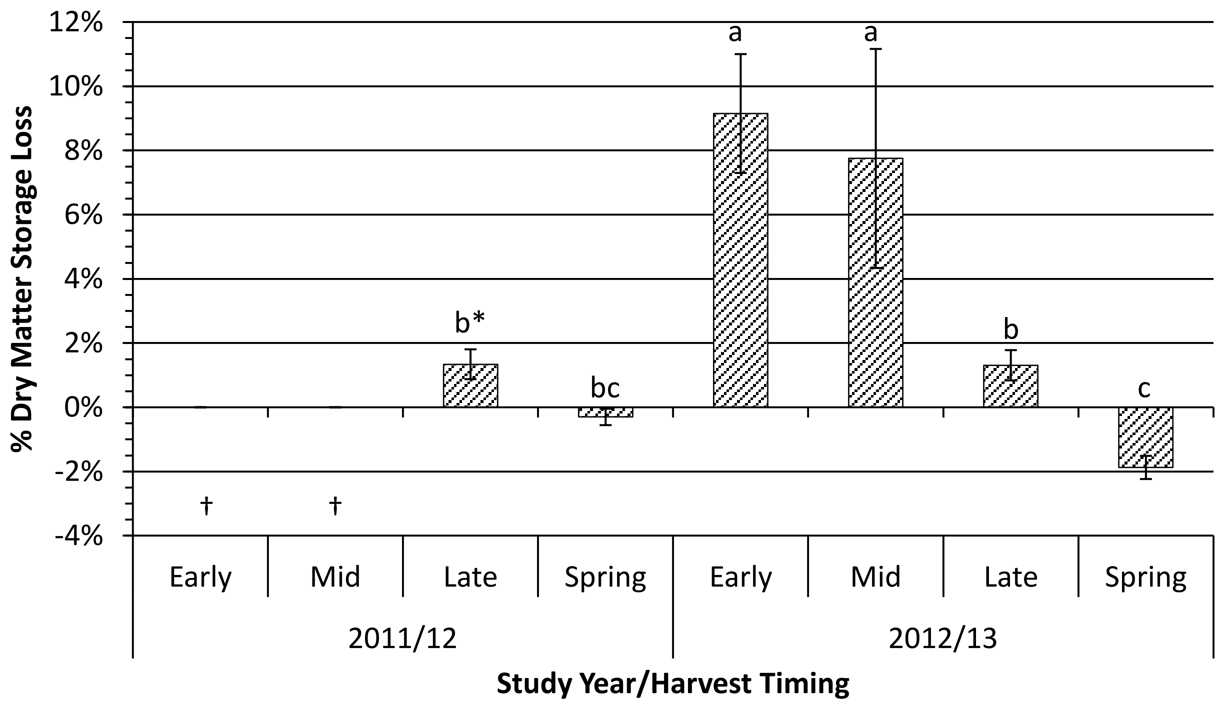

Figure 5. Percent dry matter storage loss due to ensiling. Error bars represent one standard deviation from the percent storage loss mean. *Average percent storage losses with the same letter are not statistically different (α = 0.05). †Measurements were not observed due to a protocol misunderstanding.

Measurements of dry matter loss due to an ensiling process were as expected. Dry matter loss was significantly highest (figure 5) for biomass that was harvested and ensiled during the early and mid fall harvest timings because the higher moisture and extractable nutrient content of the biomass encouraged aerobic and anaerobic metabolism of some of the biomass (Schroeder, 2013). No significance between the early and mid timings was observed (figure 5). The sweet smelling characteristic present in the silage of these two harvest timings indicated that the biomass was properly ensiled (Schroeder, 2013). Dry matter loss was significantly smaller for both the late and spring ensiled biomass compared to the early and mid timing dry matter losses (figure 5). Spring ensiling was measured to have a negative dry matter loss. This was most likely due to measurement error during silage weighing and moisture content analysis. These spring ensiling values were assumed to be essentially 0% dry matter loss. Compared to the early and mid timing silage, the late fall and spring timing biomass did not show the sweet smelling characteristic of properly ensiled forage. This observation, combined with minimal dry matter storage loss, suggested that the biomass did not undergo a proper ensiling process and that the biomass would have been better suited to a low moisture content storage method in order to avoid the potential for excessive heating and mold growth during storage. Overall, ensiling was a suitable storage choice for biomass harvested during an early or mid fall harvest timing and not suitable for biomass harvested during a late fall or spring harvest timing.

Stand Frequency

Switchgrass stand frequency was recorded in the spring of 2013 during the study (table 21). This observation provided insight for this study in terms of foreseeing potential winter hardiness and spring survival issues. Stand frequency was not significantly affected by harvest/storage method (P = 0.0596), nor was an interaction between harvest timing and harvest/storage method (P = 0.4742) observed. Statistical difference was observed due to harvest timing (P = 0.0025). See figure 6, below, for the detailed results.

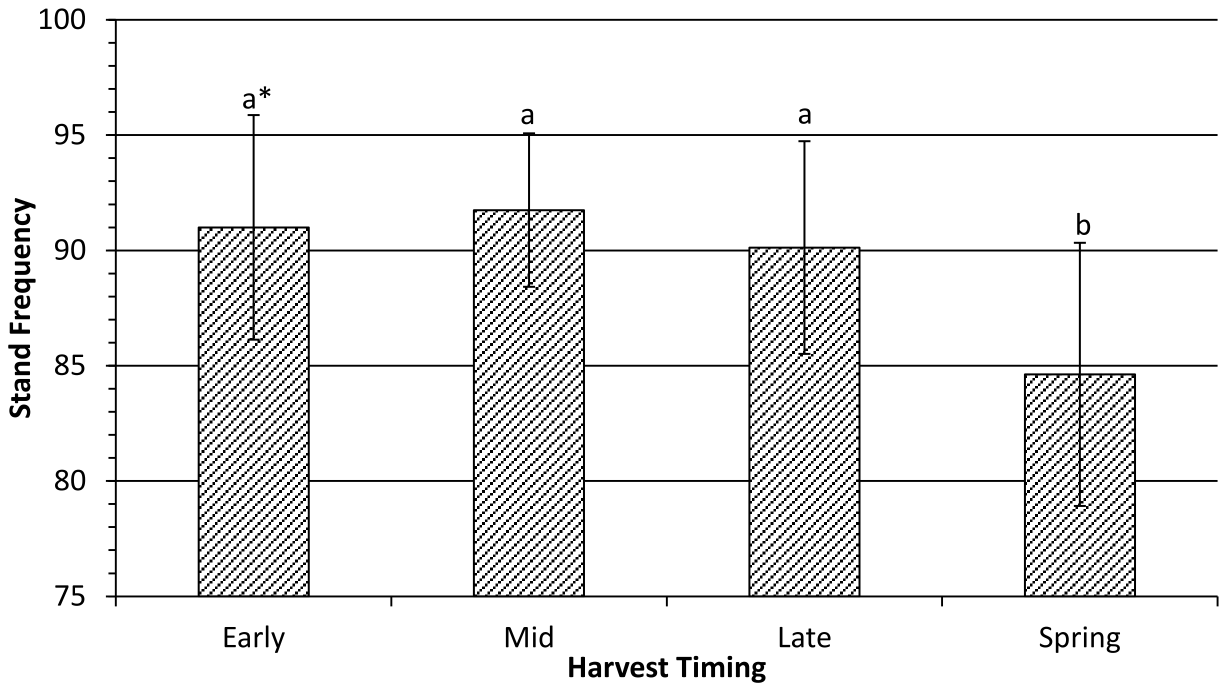

Figure 6. Spring 2013 stand frequency. Error bars represent one standard deviation from the stand frequency mean. *Average stand frequencies with the same letter are not statistically different ($\alpha = 0.05$).

The stand frequency of the spring harvest plots was the only statistically different observation. Upon further investigation, this observation was concluded to be due to a switchgrass lodging issue. The switchgrass had a tendency to develop lodging issues due to the particularly harsh climate conditions during the winter months in Michigan. Come harvest time, the lodged switchgrass could not be removed off the field because the cutter heads could not be set low enough. The result was that the lodged switchgrass stunted the switchgrass growth during the spring green-up. See figure 7, below, for additional details.

A.) B.)

Figure 7. Spring harvest lodging impact on stand frequency during spring green-up. A.) Severe switchgrass lodging issues during the spring harvest of 2013. B.) Lodging impact on stand frequency during spring green-up later that year.

Due to the stunted growth caused by lodging issues, combined with the observed spring harvest yield loss for both harvest/storage methods, it was not advisable to over-winter switchgrass in the Great Lakes region even though translocation of mineral nutrients back to the soil was potentially maximized. Since there were no statistical differences between the three fall harvest timing stand frequencies, this observation potentially suggested greater fall harvest timing flexibility without the risk of impaired winter hardiness and stunted growth during the spring green-up. This observation further suggested increased flexibility to allow maximum fall translocation of mineral nutrients back to the root crowns and soil given that weather conditions do not potentially compromise harvest yield. Future analysis should include more years of observation over the lifespan of a dedicated switchgrass biofuel cropping system.

Soil Nutrient Content

Soil nutrient content was recorded in the fall of 2013 after the study was completed. Statistical differences due to harvest timing were not observed for any of the key soil nutrients (table 5).

Harvest Timing	pH	Lime Index	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Organic Matter (%)
Early	6.68 ± 0.59	70.50 ± 0.71	20.25 ± 6.08	50.25 ± 10.21	648.00 ± 121.04	142.75 ± 20.82	2.55 ± 0.10%
Mid	6.63 ± 0.45	71.33 ± 0.58	16.25 ± 6.40	48.50 ± 8.89	705.75 ± 136.19	153.00 ± 16.41	2.60 ± 0.18%
Late	6.50 ± 0.29	70.67 ± 0.58	19.75 ± 4.99	51.25 ± 9.78	662.50 ± 82.73	150.75 ± 14.71	2.55 ± 0.19%
Spring	6.60 ± 0.49	70.00 ± 0.00	20.00 ± 6.83	63.75 ± 19.64	679.75 ± 78.36	153.50 ± 14.36	2.70 ± 0.14%

Table 5. Late summer 2013 soil analysis data by harvest timing. Soil samples were taken on 9/11/2013. Soils consisted predominantly of Capac loam (Web Soil Survey). Means and standard deviations are reported. No significant differences were reported for all soil data (α = 0.05).

Additional long-term soil testing throughout the switchgrass stand's lifetime would have been needed to fully understand the effects of how harvest timing could affect soil nutrient levels and how nutrient level differences could have affected the health and survivability of the stand. However, there were a few observations that suggested potential impacts on soil nutrient levels due to harvest timing. The calcium and magnesium levels for the early timing harvests were the lowest on average. This potentially suggested a future decreasing trend for these soil nutrients. Additionally, the potassium, magnesium and organic matter levels for the spring harvest timing were the highest on average. This supported previous studies that suggested over-wintering forages maximized soil nutrient retention. Overall, the soil data suggested that harvest timing has not had a significant impact on nutrient availability at this short-term stage of a dedicated bioenergy switchgrass stand.

CONCLUSION

Harvest yield data suggested that harvest yields are maximized during an early fall harvest timing using a direct chopping and ensiling harvest/storage method. Although dry matter storage loss due to ensiling was almost 10% when harvested during an early fall harvest timing, dry matter loss due to baling, even for bales that are covered, is also typically around 10% since bales are largely stored outside exposed to the elements. Dry matter loss during storage is inevitable, but initial harvest yield prior to storage is manageable. Short-term stand frequency data and soil nutrient analysis suggest that switchgrass winter hardiness and spring survivability will not be compromised at this stage in the switchgrass stand's lifetime. Stand frequencies during the spring were healthy in the plots repeatedly harvested during the early fall. Soil nutrient levels were not statistically different between early fall harvest timing and the later timings. Overall, the data support that harvest during the early fall with a direct chopping and ensiling harvest/storage method will not affect winter hardiness, will facilitate timely harvest, will maximize harvest yield, and would potentially be most profitable for farmers in the Northern Corn Belt/Great Lakes region.

CHAPTER 2

CRYSTALLINE CELLULOSE & MATRIX HEMICELLULOSE POLYSACCHARIDE COMPOSITION, LIGNIN CONTENT, ETHANOL YIELD, AND IN VITRO ENZYMATIC TRUE DIGESTIBILITY OF SWITCHGRASS BIOMASS AS A RESPONSE TO HARVEST TIMING AND TWO HARVEST/STORAGE METHODS OF A BIOENERGY CROPPING SYSTEM IN THE GREAT LAKES REGION

Abstract: Lignocellulosic ethanol production from switchgrass is optimized when there are high dry matter yields, high concentration of cellulose within the biomass, and low lignin content. This study investigated how crystalline cellulose (glucose), xylose, lignin, theoretical ethanol yield, and enzymatic digestibility of switchgrass at a whole-plant level were affected under four harvest timings and two harvest/storage methods in the Northern Corn Belt/Great Lakes region. Overall, biomass quality was not affected by harvest/storage method. Harvest timing had the greatest influence on biomass quality. Results suggested that successive early fall harvests may have significantly reduced both cellulose and lignin contents. However, theoretical ethanol yields indicated that early fall harvest ethanol yields were not significantly reduced compared to the other harvest timings. Harvest timing had no significant impact on xylose content. In vitro true digestibility data suggested that harvest/storage method affected glucose digestibility greatest during an early fall harvest timing. However, neither storage method consistently preserved the biomass digestibility better over the other. Results further suggested that an early fall harvest resulted in significantly higher glucose hydrolysis yields compared to the other harvest timings. This result suggests that an early fall harvest timing may have been most conducive to increasing enzymatic hydrolysis efficiency. Digestibility results suggested that delaying harvest timing potentially increased pentose hydrolysis yield.

INTRODUCTION

Cellulosic ethanol production is being pursued in the United States as mandated by the Energy Independence and Security Act of 2007 (EISA). EISA mandates the production of 36 billion gallons of renewable fuel by 2022, of which 16 billion gallons must be derived from lignocellulosic sources. Switchgrass (*Panicum virgatum* L.) was identified as a potential energy crop by the U.S. Department of Energy's Biomass Feedstock Development Program. Switchgrass is widely considered to be the model perennial grass for bioenergy production (U.S. Department of Energy, 2011). Positive characteristics of dedicated switchgrass bioenergy crop production for cellulosic ethanol production were discussed in the previous chapter, as was the importance of maximizing quantity aspects (recoverable harvest and storage yields) while maintaining stand longevity. This chapter will explore the importance of optimizing the quality aspects of lignocellulosic biomass feedstocks and how those aspects affect the downstream conversion efficiencies in cellulosic ethanol production.

Understanding the chemical composition of switchgrass is essential for optimizing downstream processes in a cellulosic ethanol production system (Hu et al., 2010). Biomass quality is the greatest determinant of downstream lignocellulosic ethanol processing efficiency. Knowing the quality of feedstock will help both feedstock growers and ethanol producers decide which pre-conversion harvest treatments will facilitate the supply of lignocellulosic biomass with the best qualities for efficient ethanol conversion.

Lignocellulosic biomass is a mixture of carbohydrate polymers (cellulose, hemicellulose and pectin in varying ratios) and the non-carbohydrate polymer lignin (Doran-Peterson et al., 2008). In regards to biomass quality, cellulosic ethanol research has predominantly been interested in cellulose, hemicellulose, and lignin contents. Cellulose is a polysaccharide that is made up of long microfibrils containing repeating units of beta-linked (β 1,4) dimers of glucose molecules known as cellobiose (Doran-Peterson et al., 2008). Hemicelluloses are branched heterogeneous polysaccharides, composed of both pentoses (xylose, arabinose) and hexoses (mannose, glucose, galactose), with backbones of neutral sugars hydrogen-bonded to cellulose which provide structural support (Saha, 2003; Doran-Peterson et al., 2008). Lignin is a non-carbohydrate polymer that surrounds cellulose and hemicelluloses, which imparts further strength and provides resistance against pests and diseases (Mosier et al., 2005). Due to their protective and resilient nature, the presence of lignin and hemicellulose contributes greatly to the recalcitrance of lignocellulosic biomass to enzymatic hydrolysis (Alizadeh et al., 2005; Mosier et al., 2005).

The two most prevalent monosaccharides present in cellulose and hemicellulose are glucose and xylose, respectively. After enzymatic hydrolysis of the lignocellulosic biomass, the resulting hydrolysate mostly contains these two monosaccharides. *Saccharomyces cerevisiae*, the species of yeast that is typically used during fermentation of the hydrolysate, prefers glucose over other monosaccharides. However, once glucose is mostly consumed, the yeast will utilize the other monosaccharides in the hydrolysate, the most abundant being xylose, although not as effectively (Saha, 2003). Improvements in hemicellulose (mainly xylose) conversion will improve the efficiency of the conversion process (Pauly and Keegstra, 2008). The level of cellulose within the lignocellulosic biomass will greatly influence the glucose levels in hydrolysate available for fermentation. Increasing cellulose content compared to the hemicellulose and lignin levels in biomass can be expected to increase both the conversion efficiency into glucose and the final yield of ethanol (Weimer et al., 2005; Dien et al., 2006, Sarath et al., 2008b). Until new switchgrass cultivars are developed with improved quality characteristics that facilitate more efficient conversion into ethanol, agricultural management practices are the primary method of optimizing these quality traits.

Research has predominantly focused on determining levels of cellulose, hemicellulose, and lignin of different potential lignocellulosic biomass feedstocks and their various cultivars, and how those compositions affect pretreatment and enzymatic hydrolysis of the biomass. However, less is known on how these lignocellulosic components and subsequent hydrolysis are affected by harvest timing and harvest/storage methods particularly in the Northern Corn Belt/Great Lakes region.

In terms of harvest timing, biomasses harvested before and after plant senescence and translocation have shown to have significantly different compositions (Adler et al., 2006; Bals et al., 2010b). Biomass collected after senescence had higher concentrations for all components, including lignin unfortunately. This was most likely due to translocation and environmental washing of soluble components (sugars, protein, lipids, and mineral nutrients) having a concentrating effect on the remaining lignocellulosic components (Adler et al., 2006).

In terms of harvest/storage methods, most research on lignocellulosic composition and enzymatic hydrolysis has been performed on pre-storage biomass or biomass that was stored at low moisture content (bale). Very few studies have fully compared the composition and enzymatic hydrolysis efficiency between pre-storage, baled, and ensiled biomass. It is suspected that ensiling lignocellulosic biomass may have a concentrating effect on lignin and hemicellulose (xylose) and subsequently produce biomass that does not facilitate efficient conversion into ethanol as well as baled material does. Ensiling encourages microbial growth that preferentially utilizes cellulose, which is more easily digestible compared to hemicellulose and lignin. However, ensiling also has a preservative effect since the pH of properly ensiled biomass decreases due to lactic acid formation via fermentation. This lactic acid formation potentially acts as a mild pre-treatment effect that could potentially reduce the cost of further downstream pretreatment and may not affect the fermentability of the hydrolysate (Digman et al., 2010).

Objective of Study

Lignocellulosic ethanol production from switchgrass is optimized when there are high dry matter yields, high concentration of cellulose within the biomass, and low lignin content. The objective of this study was to quantify crystalline cellulose (glucose), the predominant matrix hemicellulose monosaccharide (xylose), lignin content, theoretical ethanol yield, and the enzymatic digestibility of switchgrass biomass at a whole-plant level under four harvest timings and two general harvest/storage methods in the Northern Corn Belt/Great Lakes region. This research served to assess the quality of the switchgrass biomass due to these various pre-conversion harvest treatments and how these treatments potentially affect enzymatic hydrolysis of the biomass.

MATERIALS AND METHODS

Site Description and Experimental Design

Switchgrass Stand Establishment

Beginning in the fall of 2006, a field experiment site was established at the Michigan State University Agronomy Research Farm in East Lansing, Michigan (42°42’52” N 84°27’57”

W). Soils consisted predominantly of Capac loam (USDA Web Soil Survey). The site was conditioned using a conventional chisel plow tillage system in the fall of 2006 and was further conditioned twice over with a field cultivator in the spring of 2007 to ensure a flat, weed-free seed bed. The upland switchgrass cultivar 'Cave-In-Rock' was then seeded at a rate of 9 kg ha^{-1} using a double roller seeder (Brillion, Brillion Iron Works, WI) to about a 1.25 cm depth. The switchgrass was allowed to establish for three years. The switchgrass was cut and removed during the establishment years once senescence and a killing frost (-2.2 °C) had occurred to allow mineral nutrients to return to the root crowns and soil.

Weed Control

Weed control was most important during the establishment phase because broad leaf weeds and grasses could out-compete switchgrass seedlings if not controlled (Parrish et al., 1999). Weeds were controlled during the establishment phase with a tank mixture of S-metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl] acetamide) and atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) at rates of 1.3 and 1.8 kg ha^{-1}, respectively. Weeds were not chemically controlled after the establishment phase was completed.

Fertilization & Nutrient Management

Due to potential weed competitiveness during switchgrass establishment, the site was not fertilized during the establishment year. The site was fertilized with granular urea (46-0-0 NPK) at a rate of 78.5 kg N ha^{-1} during the spring green-up in the years after the first establishment year.

Description of Study Variables

Variable #1: Harvest Timing

Four harvest timings were chosen in order to observe how various harvest timings throughout the harvest period in the Northern Corn Belt/Great Lakes region affect switchgrass biomass cell wall composition, lignin content, and enzymatic digestibility. Table 6, below, outlines the four harvest timings and describes the specific details associated with each timing.

Timing	Time of Year	Description
Early Fall Harvest	Early September to Late September	Immediately following seeding and peak biomass production. Prior to major translocation of nutrients to root crowns. High moisture content (> 50%).
Mid Fall Harvest	Early October to Late October	Plant senescence has begun. Translocation of nutrients to root crowns begins. Mid-level moisture content (35-50%).
Late Fall Harvest	Early November to Late November	2 weeks after a killing frost (-2.2 °C). Frost-induced rupturing of cell walls. Mediated translocation of nutrients to root crowns and soil occurs. Low moisture content (20-35%).
Spring (Over-winter) Harvest	Mid March to Mid April	Environmental washing of a majority of the remaining mineral nutrients to the soil due to winter precipitation. Low moisture content (< 10%).

Table 6. Harvest timing variable descriptions. These harvest timing are specific to the Great Lakes region.

Variable #2: Harvest/Storage Method

Two general harvest/storage methods are suitable for collection of switchgrass biomass. Investigation of these two general harvest/storage methods served to provide new insights into optimizing the quality of feedstock at the production end of a cellulosic ethanol production system. In order to investigate the impact that these harvest/storage methods have on the feedstock quality, the biomass was stored for six months in order to model the effects of long term storage. Additionally, pre-storage biomass was retained to act as a control in quality analysis. Table 7, below, outlines the two harvest/storage methods and describes the specific details associated with each method.

Method	Description	Importance to the Study
Harvest (Fresh Processed) (0 month storage)	Biomass is collected at either high or low moisture content and is immediately processed into ethanol.	The biomass acted as a study control that provided a baseline which could be used to compare the effects that the two harvest/storage methods have on composition and enzymatic hydrolysis efficiency.
Cut/Bale (6 month storage)	Biomass is cut into windrows and allowed to dry to a proper moisture content suitable for bale storage (< 20%). Biomass is turned to allow even drying. Then it is round or square baled and stored covered or uncovered until further processing.	The biomass allowed assessment of the effects that low moisture content bale storage has on composition and enzymatic hydrolysis efficiency.
Chop/Ensile (6 month storage)	Biomass is directly chopped with a forage harvester at high moisture content (> 50%). It is blown directly into a silage cart and immediately compacted in piles or bunker silos and allowed to ensile. It is kept covered until further processing.	The biomass allowed assessment of the effects that high moisture content ensilage storage has on composition and enzymatic hydrolysis efficiency.

Table 7. Harvest/storage method variable descriptions.

Experimental Design

In the spring of 2010, the experimental design was marked off within the established switchgrass field. The experimental design was a randomized complete block design (RCBD) with four replications (blocks). The main plot variable was harvest timing. The sub-plot variable was harvest/storage method. The sub-plot variable could not be randomized within the main plots because the chop/ensile harvest system requires a minimum 3.66 m wide harvest clearance, whereas the sub-plots were only 3.05 m wide. See figure 8, below, for a complete visual description of the experimental design.

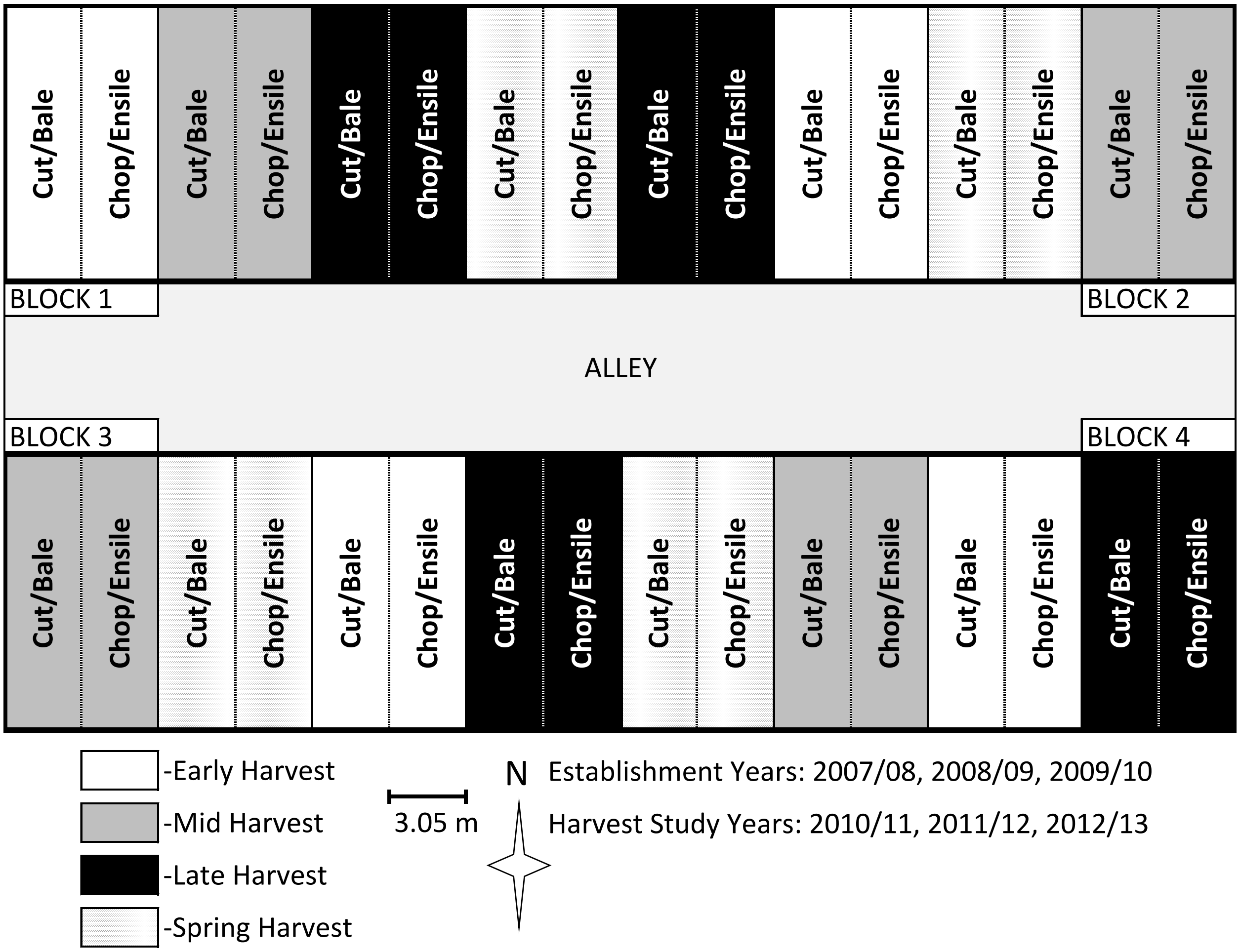

Figure 8. Switchgrass study site experimental design. Sub-plots were 3.05 m x 12.20 m. A 7.62 m wide alley ran down the center of the site. The total dimensions of the site were 32.0 m x 48.8 m (0.156 ha). Site located at 42°42'52" N 84°27'57" W.

Harvest, Storage, & Sampling

When weather permitted, the sub-plots were harvested within each main plot according to harvest/storage method during the harvest timings.

The cut/bale sub-plots were harvested using a custom built plot windrower (Swift Machine and Welding Ltd., Swift Current, SK, Canada) with a 1.52 m wide cutter head, set at an 18 cm cutting height, to cut the switchgrass into two windrows. Because of the small plot size, the biomass was hand raked into one windrow and was flipped as needed over the course of about two weeks to ensure even drying. Once the biomass reached the proper baling moisture content (< 20%) each sub-plot biomass was individually baled with a John Deere 7830 tractor (Deere & Company, Moline, Illinois) equipped with a John Deere 582 round baler. Due to baler mechanical issues during the early and mid fall harvest timings in 2012, each sub-plot had to be baled with a John Deere 7830 tractor equipped with a John Deere 338 small square baler. Moisture content was recorded for each bale by drying samples in forced-air oven at 66 °C until a constant mass was achieved. The bales were stored indoors for six months without any disturbance. The bales were then sampled. The samples were dried and their moisture content was recorded. The dry samples were ground through a 1.0 mm screen in a Christy-Norris mill (Christy and Norris Limited, Chelmsford, England). The ground samples were retained and stored in a -20 °C freezer until further quality analysis.

The chop/ensile sub-plots were harvested with a Hesston 7650 forage harvester (Hesston Co., Hesston, Kansas) equipped with a 3.66 m wide chopper head, set to an 18 cm cutting height, and a collection bin. The collection bin was emptied after each sub-plot harvest and the chopped biomass was immediately sampled. A fraction of the sample was used to determine biomass moisture content by drying the fraction in a forced-air oven at 66 °C until a constant mass was achieved. This dry biomass was retained and used as an at-harvest (fresh processed) control for biomass quality comparison after baled and ensiled biomass came out of storage. This biomass was ground through a 1.0 mm screen in a Christy-Norris mill (Christy and Norris Limited, Chelmsford, England). The ground biomass was retained and stored in a -20 °C freezer until further quality analysis. The remaining fraction was simulation ensiled at its harvest moisture content. A known mass of biomass was packed into a food vacuum bag and was evacuated of its air to simulate ensiling conditions. The vacuum bags were stored indoors for six months without any disturbance. After six months, the vacuum bags were unsealed and the silage moisture content was recorded. The dry silage was ground through a 1.0 mm screen in a Christy-Norris mill (Christy and Norris Limited, Chelmsford, England). The ground silage was retained and stored in a -20 °C freezer until further quality analysis.

<u>Compositional Analysis</u>

Crystalline cellulose content, matrix hemicellulose polysaccharide composition, and lignin content analysis were performed on switchgrass biomass from all four harvest timings, two harvest/storage methods (plus an additional at-harvest control), and three study years. Prior to compositional analysis, the dried biomass was ball milled to a fine powder (< 1mm). The powder was then used to prepare the alcohol insoluble residue (AIR) in a process that removes soluble components. The AIR then underwent amylase treatment to remove the residual starch. The final product was isolated cell wall material (York et al., 1986, Foster et al., 2010).

Crystalline Cellulose (Glucose) & Matrix Hemicellulose Polysaccharide (Xylose)

The protocol developed by Foster et al., 2010b was used for crystalline cellulose (glucose) and matrix hemicellulose polysaccharide (xylose) analysis. The isolated cell wall material underwent weak acid hydrolysis using [2M] trifluoroacetic acid. The resulting hydrolysate was separated from the insoluble material and the monosaccharides present in the hydrolysate were then further derivatized into their corresponding alditol acetates and quantified using a GC-MS (Albersheim, P. et al., 1967). The remaining insoluble material from the hydrolysis was further stripped of hemicelluloses and amorphous glucan by washing with the Updegraff reagent, an acetic acid and nitric acid mixture (Updegraff DM, 1969). The remaining material (crystalline cellulose) was hydrolyzed with 72% sulfuric acid (Selvendran, R. R. and O'Neill, M. A. 1987) and resulting monosaccharide (glucose) was quantified using a colorimetric assay (anthrone assay). Crystalline cellulose (glucose) and matrix hemicellulose polysaccharide (xylose) were reported as percent of total dry isolated cell wall material.

Lignin Content

The protocol developed by Foster et al., 2010a was used for lignin content analysis. The isolated cell wall material was treated with a 1:4 acetyl bromide/acetic acid (v/v) solution to render the lignin acetic acid soluble. After a volumetric dilution with glacial acetic acid, the solubilized lignin was quantified using a UV spectrophotometer set at 280 nm wavelength. The lignin content data were reported as percent acetyl bromide soluble lignin of total dry isolated cell wall material (Fukushima et al., 1991).

Theoretical Ethanol Yield

Theoretical ethanol yield was calculated using the equation below:

$$\left(\left([\text{Crystalline Cellulose}] \times \text{Glu Conv.}\right) + \left([\text{Xylose}] \times \text{Xyl Conv.}\right)\right) \times 51.1\% \times \text{metabolic yield} = \text{Theoretical Ethanol Yield}$$

Where [*Crystalline Cellulose*] and [*Xylose*] are the calculated crystalline cellulose (glucose) concentration and xylose concentration, respectively. *Glu Conv.* is the glucan conversion (%) following enzymatic hydrolysis of feedstock material and *Xyl Conv.* is the xylan conversion (%) following a separate enzymatic hydrolysis and fermentation (SHF) of feedstock material. Glucan and xylan conversion values were obtained from Jin et al., 2010. *Glu Conv.* and *Xyl Conv.* were 66.5% and 74.7%, respectively. The maximum theoretical mass conversion of fermentable sugars to ethanol is 51.1%, and the *metabolic yield* equals to the ratio of ethanol to the consumed sugars in the fermentation process divided by 51.1% (Lau and Dale, 2009). The *metabolic yield* was 89.7% (Jin et al., 2010). *Theoretical Ethanol Yield* was reported as grams per gram of dry biomass (table 22). Final results were reported as liters of ethanol per hectare by converting *Theoretical Ethanol Yield* to a per area basis using harvest yield data (table 22) and ethanol density (0.789 g/l).

In Vitro True Digestibility (Enzymatic Hydrolysis)

In vitro true digestibility screening was performed on switchgrass biomass from all four harvest timings, two harvest/storage methods (plus an additional at-harvest control), and the three study years. Digestibility was performed in order to assess how different harvest timings and harvest/storage methods affect enzymatic hydrolysis efficiency. Prior to digestibility screening, the dried biomass was ball milled to a fine powder (< 1mm). After milling was complete, approximately 2 mg of each sample was weighed out. The samples then underwent a dilute sulfuric acid (2% w/v) pretreatment at 120 °C (Santoro et al., 2010). The pretreated samples then underwent an enzymatic digestion. Digestion of one third or less of the total biomass glucan was targeted because keeping the percent of total glucose released below 50% provided higher resolution for identifying modified biomass with either increased or decreased enzymatic digestibility (Santoro et al., 2010). An Accellerase 1000 (Genencor, Rochester, NY) enzyme cocktail was added to the pretreated biomass and was incubated at 50 °C for 20 hours with end-over-end rotation (Santoro et al., 2010). The resulting hydrolysate was then tested for glucose concentration using an enzyme-based assay, D-GLUCOSE (Megazyme, Ireland). The hydrolysate was also tested for pentose concentration using a colorimetric assay (Deschatelets et al., 1986). The final glucose and pentose digestibility results were reported as grams of glucose/pentose released per gram of total dry biomass.

Statistical Analysis

All compositional analyses and digestibility screening were performed in triplicate. Data were analyzed using PROC MIXED in SAS 9.2 (2009, SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was conducted to measure the treatment effects on biomass monosaccharide composition, lignin content, in vitro true digestibility, and theoretical ethanol yield. Harvest year, harvest timing and harvest/storage method were treated as fixed effects while blocking was considered to be a random effect. Initially, harvest year was assumed to be a random effect, but upon evaluation, harvest year had obvious non-random effects and was chosen to be treated as a fixed effect. Regardless, this change had no effect on the ANOVA results. Normality of the residuals and homogeneity of variances were evaluated by examining normal probability plots and box plots. Fisher's protected least significant difference (LSD) multiple comparison procedure was used for mean separation when ANOVA was significant (Saxton, 1998). Results were reported as statistically significant at $\alpha = 0.05$.

RESULTS & DISCUSSION

Climatological Summary

Mean monthly air temperatures in East Lansing did not vary considerably between the study years, but they tended to be higher compared to the monthly mean over the last 30 years, especially during the switchgrass growth phase (table 8). Every monthly temperature mean, for all three study years during the switchgrass growth phase, was higher compared to the monthly 30 year average. The first killing frost (-2.2 °C) dates for the 2010/11, 2011/12, and 2012/13 study years were: November 1, October 28, and November 4, respectively.

Cropping Phase	Month	Total Precipitation			30-yr Avg	Mean Temperature			30-yr Avg
		'10/'11	'11/'12	'12/'13		'10/'11	'11/'12	'12/'13	
Growth Phase	May	10.4	14.6	6.2	8.5	15.9	15.0	16.8	13.9
	June	10.0	4.0	2.7	8.9	20.4	19.8	20.3	19.4
	July	4.4	13.0	3.7	7.2	23.2	24.1	24.4	21.6
	August	1.4	7.8	5.3	8.2	22.5	21.0	20.8	20.6
Fall Harvest Phase	September	8.9	6.7	5.5	8.9	16.3	15.9	16.3	16.3
	October	3.6	7.5	9.2	6.4	11.5	10.7	10.1	9.8
	November	4.2	6.2	0.8	7.1	4.6	6.0	3.3	3.8
Over-Wintering Phase	December	1.4	5.2	3.2	4.8	-4.1	0.3	0.9	-2.5
	January	0.7	3.2	6.9	4.2	-6.8	-1.9	-3.1	-5.1
	February	1.9	2.2	2.3	3.7	-4.6	-1.0	-4.2	-3.8
Spring Harvest Phase	March	6.4	5.9	1.7	5.2	0.4	9.4	-0.5	1.3
	April	11.6	4.4	16.5	7.7	7.4	8.3	6.5	8.2

Table 8. Monthly precipitation (cm) and mean temperatures (°C) during the study years compared to the 30-year means (1981-2010). The 30-year averages were obtained from NOAA. Weather data were obtained via the Michigan State University Enviro-Weather website (figure 28). The station was located 0.9 km away at the Hancock Turfgrass Research Center.

The 2010/11 and 2012/12 study years tended to be drier, while the 2011/12 study year tended to be average when compared to the 30-year mean (table 9). The 2010/11 study year was 19.9% drier and 2012/13 was 20.8% drier compared to the 30 year mean, while 2011/12 was essentially the same (0.1% drier). Additionally, the total precipitation during the switchgrass growth phase during the 2010/11 and 2012/13 study years were considerably lower (20.2% and 45.7%, respectively) while during the 2011/12 study year was considerably higher (20.0%) compared to the 30-year mean (table 9). The 2010/11 study year tended to be wet during May and June and drier during July and August compared to the 30-year means (table 8). However, these late drought stresses did not seem to have an effect on harvest yields. The 2011/12 study year tended to be significantly wetter during May and July, significantly drier in June, and average during August compared to the 30-year means (table 8). Finally, 2012/13 displayed very severe drought conditions throughout the growth phase (May-August). Each month was significantly drier compared to the 30-year means (table 8). Drought related stress responses were observed for this study year.

	Total Precipitation			30-yr
	2010/11	2011/12	2012/13	Average
Total Growth Phase Precipitation	26.2	39.4	17.9	32.9
Total Yearly Precipitation	64.7	80.7	64.0	80.8

Table 9. Total growth phase (May-August) and yearly (May-April) precipitation (cm) during the study years compared to the 30-year means (1981-2010). Weather data were obtained via the Michigan State University Enviro-Weather website (figure 28). The station was located 0.9 km away at the Hancock Turfgrass Research Center. The 30-year averages were obtained from NOAA.

Crystalline Cellulose (Glucose)

Significant difference between crystalline cellulose contents due to a three way interaction among study year, harvest timing, and harvest/storage method was not observed (P = 0.2789). Significant differences due to interactions between study year and harvest/storage method (P = 0.3101) and between harvest timing and method (P = 0.2010) were not observed. Significant difference due to an interaction between study year and harvest timing (P = < 0.0001) was observed (figure 9). Significant difference due to harvest/storage method (P = 0.4759) was not observed.

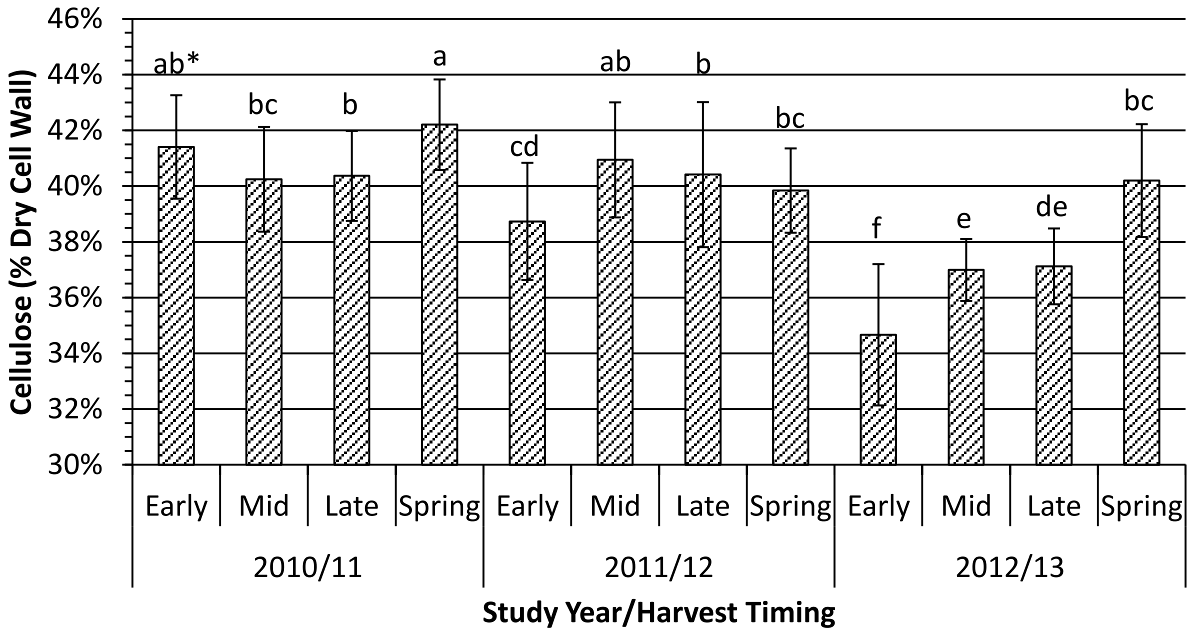

Figure 9. Crystalline cellulose (glucose) as a response to study year and harvest timing. Error bars represent one standard deviation from the crystalline cellulose mean. See table 22 for the raw data. *Crystalline cellulose means with the same letter(s) are not statistically different (α= 0.05).

For two out of the three study years (2011/12 and 2012/13), an early fall timing had a significantly less cellulose content compared to the other fall harvest timings (figure 9). The early fall cellulose content was also significantly less than the spring cellulose content during 2012/13. However, the early fall cellulose content was not significantly less compared to the other harvest timings in the first study year (2010/11) (figure 9). This may have suggested that successive years of removing biomass during an early fall harvest timing may have caused nutrient depletion in the switchgrass stand. Decreases in nutrient availability, particularly nitrogen, have been shown to decrease cellulose and lignin contents in switchgrass (Waramit et al., 2011). The pattern of significantly less early fall harvest cellulose contents in the last two years of the study was also seen in the early fall harvest lignin contents (figure 10).

Fall harvest cellulose contents from the 2012/13 study year were all significantly less than the corresponding cellulose contents from the other study years (figure 9). Drought conditions during the 2012/13 study year (table 9) could have limited nutrient availability to the switchgrass. Studies have shown that decreased nutrient availability, particularly nitrogen, causes reduced lignin and cellulose contents (Waramit et al., 2011). Reductions in lignin content during the 2012/13 study year (figure 10) further support this possibility.

There was no indication that harvest/storage method had any significant impact on the cellulose content of switchgrass when compared to the cellulose content of the at harvest controls.

Small reductions in cellulose content, although significant, may not ultimately be the greatest concern. For growers, harvest yield, long-term winter survivability, and soil nutrient availability would be their greatest concerns. As indicated in the first study, harvest yield, winter survivability, and soil nutrients all did not seem to be compromised by an early fall harvest, at least at this stage in a switchgrass stand’s lifetime. Further examination throughout a switchgrass stand’s lifetime would help understand if continuous early fall harvests would begin to significantly compromise harvest yield, winter survivability, and soil nutrient levels.

Matrix Hemicellulose Polysaccharide (Xylose)

Significant difference between xylose contents due to a three way interaction between study year, harvest timing, and harvest/storage method was observed (P = 0.0027) (table 10).

Timing	Method	2010/11			2011/12			2012/13		
		Mean	StdDev	*	Mean	StdDev	*	Mean	StdDev	*
Early	Harvest	26.05%	1.38%	h	30.50%	0.50%	cde	28.50%	1.10%	fg
	Cut/Bale	26.47%	1.03%	h	31.65%	0.64%	bc	29.94%	0.96%	def
	Chop/Ensile	26.29%	1.13%	h	30.33%	0.89%	cde	29.48%	1.25%	ef
Mid	Harvest	26.08%	1.56%	h	31.29%	0.49%	bcd	30.11%	0.36%	cde
	Cut/Bale	26.52%	1.77%	h	30.75%	0.37%	bcde	29.51%	0.74%	ef
	Chop/Ensile	26.17%	1.10%	h	31.31%	0.37%	bcd	32.23%	0.95%	b
Late	Harvest	26.67%	0.13%	h	30.05%	2.64%	cde	30.77%	1.26%	bcde
	Cut/Bale	26.91%	0.69%	h	31.20%	0.62%	bcd	31.00%	0.09%	bcde
	Chop/Ensile	26.17%	0.95%	h	31.16%	0.48%	bcd	30.89%	0.39%	bcde
Spring	Harvest	27.11%	0.63%	gh	31.53%	0.98%	bc	31.57%	0.84%	bc
	Cut/Bale	26.37%	0.83%	h	.	.	.	35.16%	1.05%	a
	Chop/Ensile	26.38%	0.49%	h	30.98%	0.97%	bcde	36.34%	2.07%	a

Table 10. Xylose content (% dry cell wall) as a response to study year, harvest timing, and harvest/storage method. See table 22 for the raw data. *Xylose content means with the same letter(s) are not statistically different (α = 0.05).

Upon examining the effects of a three way interaction between study year, harvest timing, and harvest/storage method, the only differences between xylose contents due to harvest/storage method were present in the 2012/13 study year during the mid fall and spring harvest timings (table 10). However, since there was not a consistent pattern across the study years, conclusions as to why those differences were observed could not be made. Very few differences in xylose content between both harvest timing and harvest/storage method, within the study years, were observed. The majority of significant differences were between the study years, which suggested that xylose content was more likely affected by climatological conditions than by harvest timing or by harvest/storage method.

Results concluded that xylose content was not significantly influenced by harvest timing or by harvest/storage method.

Lignin Content

Significant differences in lignin contents due to a three way interaction among study year, harvest timing, and harvest/storage method were not observed (P = 0.3602). Significant differences due to interactions between study year and harvest/storage method (P = 0.6933) and between harvest timing and method (P = 0.8898) were not observed. Significant difference due to an interaction between study year and harvest timing (P = 0.0528) was observed (figure 10). Significant difference due to harvest/storage method (P = 0.1698) was not observed.

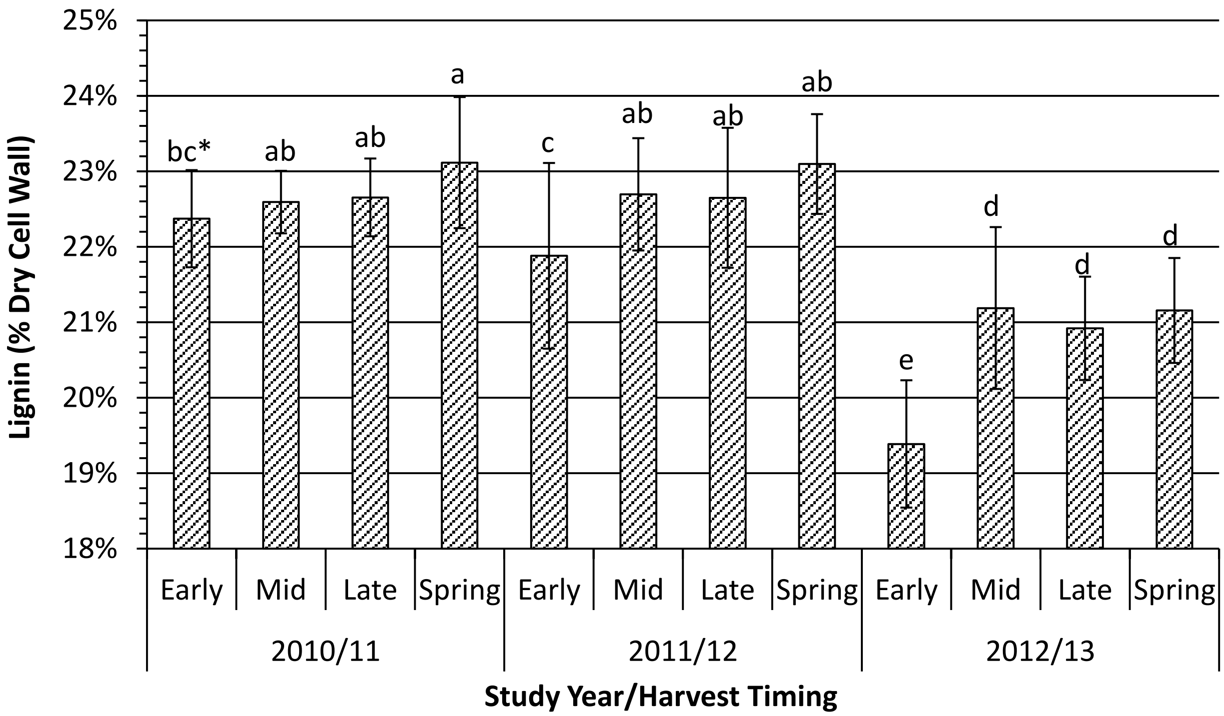

Figure 10. Lignin content as a response to study year and harvest timing. Error bars represent one standard deviation from the lignin content mean. See table 22 for the raw data. *Lignin content means with the same letter(s) are not statistically different (α = 0.0528).

In two out of three study years, early fall harvested switchgrass lignin contents were significantly less than the lignin contents of the other harvest timings (figure 10). This suggested that an early fall harvest of switchgrass, regardless of how the biomass is harvested and stored (figure 10), may help facilitate in the procurement of feedstock that has the lowest lignin content possible. This could potentially reduce recalcitrance towards enzymatic hydrolysis. However, the early fall lignin content is not significantly less compared to the other fall harvest timings in the first study year (figure 10). This may suggest that successive years of removing biomass during an early fall harvest timing may cause nutrient depletion in the switchgrass stand. Decreases in nutrient availability, particularly nitrogen, have been shown to decrease lignin and cellulose contents in switchgrass (Waramit et al., 2011). The pattern of significantly less early fall harvest lignin contents in the last two years of the study is also seen in the early fall harvest cellulose contents (figure 9). For the remaining harvest timings, mean lignin contents generally tended to increase in subsequent harvest timings (figure 10). However, this trend was not significant.

Lignin contents from the 2012/13 study year were all significantly less than the corresponding lignin contents from the other study years (figure 10). Drought conditions during the 2012/13 study year (table 9) may have increased the switchgrass leaf to stem ratio (Undersander, 2012). Switchgrass leaf lignin content tends to be significantly lower compared to stem lignin content (Mann et al., 2009). Therefore, biomass with a higher leaf to stem ratio would tend to have lower lignin contents. Furthermore, drought conditions could have limited nutrient availability to the switchgrass. Studies have shown that decreased nutrient availability, particularly nitrogen, causes reduced lignin and cellulose contents (Waramit et al., 2011). Reductions in cellulose content during the 2012/13 study year (figure 9) further support this possibility.

There was no indication that harvest/storage method had any significant impact on the lignin content of switchgrass when compared to the lignin content of the at harvest controls.

Theoretical Ethanol Yield

Significant difference between theoretical ethanol yields due to a three way interaction between study year, harvest timing, and harvest/storage method was not observed (P = 0.3566). Significant differences due to interactions between harvest timing and method (P = 0.0495), between study year and harvest/storage method (P = 0.0072) (figure 11), and between study year and harvest timing (P = < 0.0001) (figure 12) were observed.

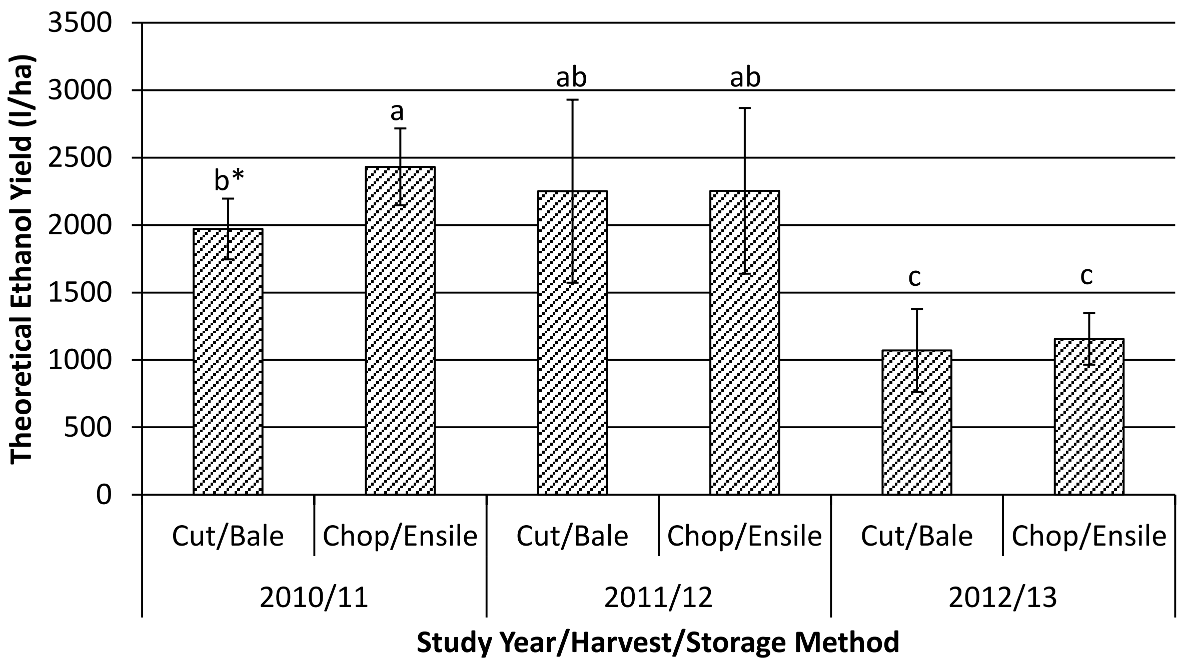

Figure 11. Theoretical ethanol yield as a response to study year and harvest/storage method. Error bars represent one standard deviation from the ethanol yield mean. See table 22 for the raw data. *Ethanol yield means with the same letter(s) are not statistically different (α = 0.05).

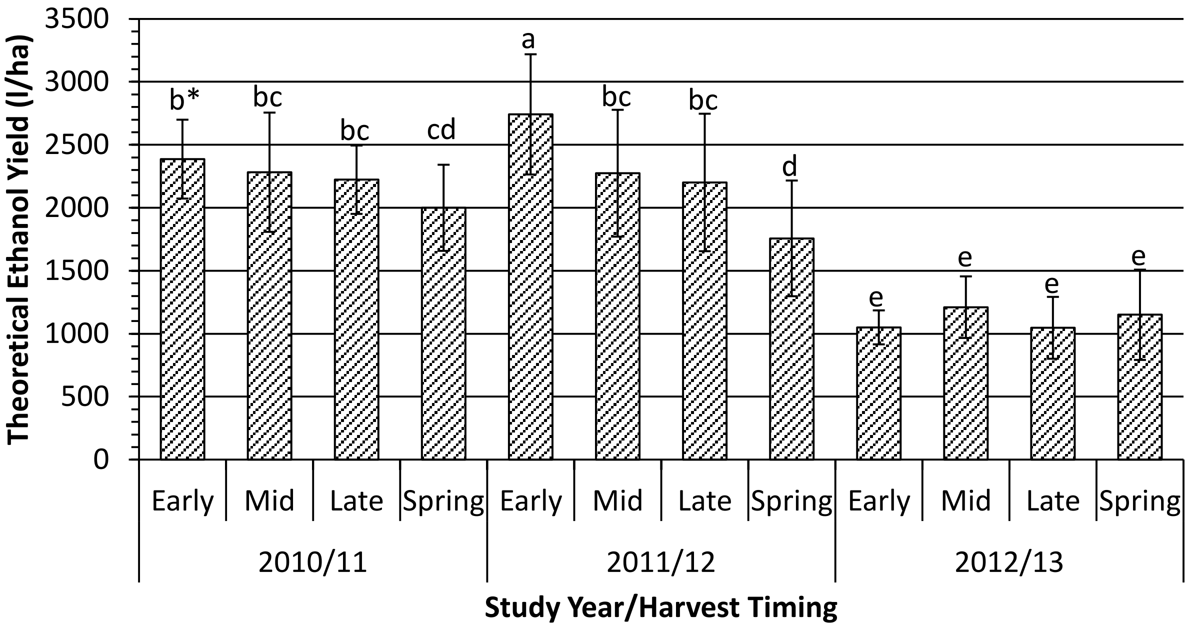

Figure 12. Theoretical ethanol yield as a response to study year and harvest timing. Error bars represent one standard deviation from the ethanol yield mean. See table 22 for the raw data. *Ethanol yield means with the same letter(s) are not statistically different (α = 0.05).

For study year and harvest/storage method, theoretical ethanol yields indicated that harvest/storage method potentially affect ethanol production. For 2010/11, chop/ensile biomass had a significantly higher ethanol estimate compared to cut/bale biomass (figure 11). However, this difference was not replicated in the other study years (figure 11). Overall, both storage methods helped preserve biomass quality and potential ethanol production.

There was concern that significant reductions in cellulose content during an early fall harvest timing may potentially reduce final ethanol yield (figure 9). However, theoretical ethanol yields indicated that early fall harvest ethanol yields were not significantly reduced compared to the other harvest timings (figure 12). The 2011/12 study even shows that early fall harvest ethanol predictions are significantly higher compared to the other three harvest timings. However, spring harvested biomass saw significant reductions in potential ethanol yield compared to the fall timings (figure 12). Overall, harvesting biomass in the fall will help ensure maximizing potential ethanol yield.

In Vitro True Digestibility

Glucose Hydrolysis Yield

Significant difference between glucose hydrolysis yields due to a three way interaction between study year, harvest timing, and harvest/storage method was observed (P = 0.0075) (table 11). Significant differences due to interactions between study year and harvest timing (P = 0.0066) (figure 13) and between harvest timing and method (P = 0.0069) were observed. Significant difference due to an interaction between study year and harvest/storage method (P = 0.1349) was not observed.

Timing	Method	2010/11			2011/12			2012/13		
		Mean	StdDev	*	Mean	StdDev	*	Mean	StdDev	*
Early	Harvest	0.1387	0.0064	a	0.1361	0.0079	ab	0.1278	0.0025	abc
	Cut/Bale	0.1238	0.0041	cd	0.1025	0.0099	ghij	0.1249	0.0086	bcd
	Chop/Ensile	0.1385	0.0030	a	0.1215	0.0136	cde	0.1143	0.0113	defg
Mid	Harvest	0.1173	0.0104	cde	0.0917	0.0086	jklm	0.1050	0.0083	fghi
	Cut/Bale	0.1103	0.0049	efgh	0.0867	0.0108	lm	0.0928	0.0048	jklm
	Chop/Ensile	0.1210	0.0057	cde	0.0909	0.0070	jklm	0.0931	0.0078	jklm
Late	Harvest	0.1181	0.0086	cde	0.0874	0.0091	lm	0.1013	0.0055	hij
	Cut/Bale	0.1154	0.0117	def	0.0896	0.0096	klm	0.0991	0.0079	hijkl
	Chop/Ensile	0.1165	0.0059	cde	0.0864	0.0152	m	0.0991	0.0064	hijk
Spring	Harvest	0.1230	0.0041	cd	0.0935	0.0063	jklm	0.1004	0.0059	hijk
	Cut/Bale	0.1253	0.0051	bcd	.	.	.	0.1142	0.0119	defg
	Chop/Ensile	0.1232	0.0054	cd	0.0946	0.0053	ijklm	0.1167	0.0084	cde

Table 11. Glucose hydrolysis yield (g/g dry biomass) as a response to study year, harvest timing, and harvest/storage method. See table 22 for the raw data. *Glucose yield means with the same letter are not statistically different (α = 0.05).

There were five instances where glucose hydrolysis yields were significantly different due to harvest/storage method (table 11). Two of the instances were observed in the 2012/13 study year during a mid fall and spring harvest timing. The mid fall timing showed that storage caused equal significant reduction in glucose digestibility compared to the at harvest control (table 11). The spring timing showed that storage caused equal significant increase in glucose digestibility compared to the at harvest control (table 11). However, since these observations were not seen in multiple years, it is difficult to suggest any reason as to why these phenomena occurred.

The other three instances all occurred during the early fall harvest timing of each study year. Although there was not a clear pattern, two of the study years (2010/11 and 2011/12) showed that an ensilage storage method tended to produce glucose hydrolysis yields that were more equal to the at harvest control yield compared to a bale method (table 11). The 2012/13 drought study year produced the opposite effect. These observations potentially suggested that an ensiling storage method was better suited to help preserve glucose enzymatic conversion efficiency. Ensiling may have also better preserved soluble biomass glucose that would have otherwise been available for aerobic respiration if the biomass was harvested and stored under baling conditions. Another significant observation about the early fall harvest timing glucose yields is that almost every glucose yield due to harvest/storage treatment is significantly higher compared to their alternative harvest timing counterparts within each study year (table 11). For each study year, averaged across harvest/storage method, glucose hydrolysis yield was significantly higher during an early fall harvest timing compared to the other harvest timings (figure 13). This observation was most likely due to higher levels of soluble biomass glucose during an early fall harvest timing. During the early fall, soluble glucose levels are higher because switchgrass just begins to translocate soluble nutrients to its root crown. Since digestibility screening was performed on raw biomass instead of extracted lignocellulosic material, residual soluble glucose became part of the final glucose hydrolysis yield. However, significantly less lignin was observed in the early fall harvest timing biomass in two out of the three study years (figure 10). This reduction of lignin may have resulted in reduced recalcitrance towards enzymatic hydrolysis of crystalline cellulose. This would lead to higher glucose yield.

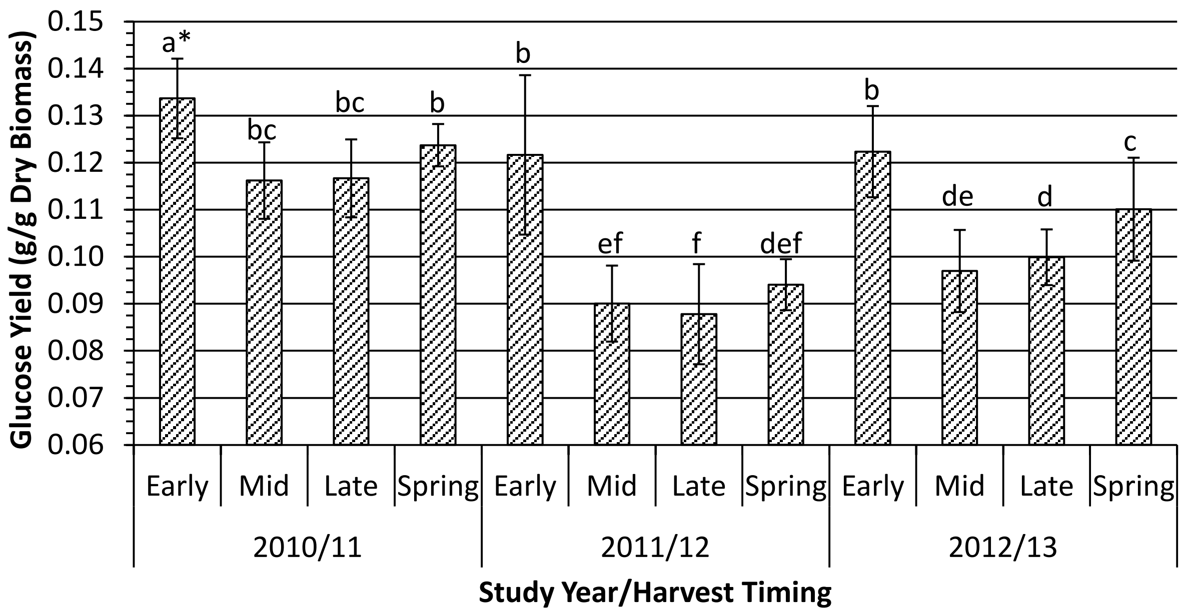

Figure 13. Glucose hydrolysis yield as a response to study year and harvest timing. Error bars represent one standard deviation from the glucose yield mean. See table 22 for the raw data. *Glucose yield means with the same letter are not statistically different (α = 0.05).

<u>Pentose Hydrolysis Yield</u>

Significant difference between pentose yields due to a three way interaction between study year, harvest timing, and harvest/storage method was not observed (P = 0.6536). Significant differences due to interactions between study year and harvest/storage method (P = 0.8805) and between harvest timing and method (P = 0.1030) were not observed. Significant difference due to an interaction between study year and harvest timing (P = 0.0025) was observed (figure 14). Significant difference due to harvest/storage method (P = 0.3240) was not observed.

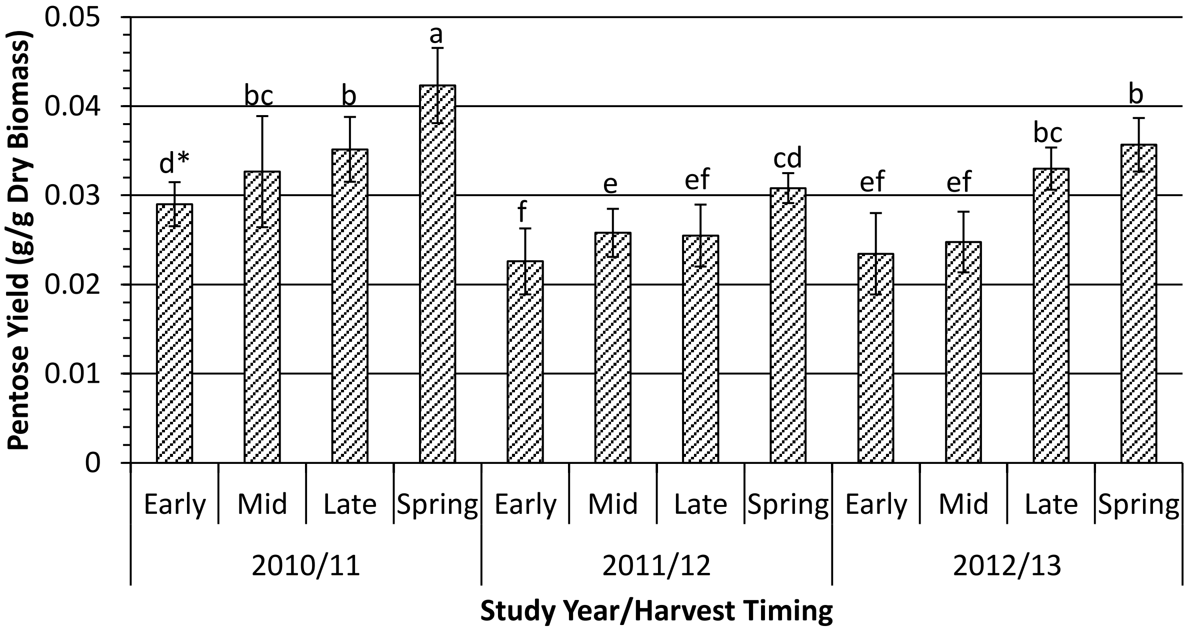

Figure 14. Pentose hydrolysis yield as a response to study year and harvest timing. Error bars represent one standard deviation from the pentose yield mean. See table 22 for the raw data. *Pentose yield means with the same letter are not statistically different (α = 0.05).

All three study years showed a consistent pentose hydrolysis yield pattern across harvest timing. Pentose yield generally tended to significantly increase as harvest timing was later (figure 14). Currently, there has been no additional research that could potentially explain this phenomenon. However, these differences in pentose yield may ultimately not matter when it comes to fermentation. The greatest difference between pentose yields was less than two percent (figure 14). Pentose (predominantly xylose) tends to not ferment as readily as glucose.

CONCLUSION

Overall, biomass quality was not affected by harvest/storage method. Harvest timing had the greatest influence on biomass quality. Results suggested that successive early fall harvests may significantly reduce both cellulose and lignin contents. Lignin reduction increases lignocellulose quality whereas cellulose reduction reduces lignocellulose quality. This may have been an early sign that repetitive early fall harvests were reducing nutrient availability. However, small reductions in cellulose content will not be growers' main concern; harvest yield, long-term winter survivability, and soil nutrient availability would be their greatest concerns. At this stage in the switchgrass stand's lifetime, there was no indication that harvest yield, winter survivability, and soil nutrient availability were compromised. Harvest timing had no significant impact on xylose content. Theoretical ethanol yields indicated that early fall harvest ethanol yield was not significantly reduced compared to the other harvest timings.

In vitro true digestibility data suggested that harvest/storage method affected glucose digestibility greatest during an early fall harvest timing. However, neither storage method consistently preserved the biomass digestibility better over the other. The results further suggested that an early fall harvest resulted in a significantly higher glucose hydrolysis yield compared to the other harvest timings. This result suggests that an early fall harvest timing may be most conducive to increasing enzymatic hydrolysis efficiency. However, higher levels of residual soluble glucose remaining in the early fall harvested biomass, prior to hydrolysis, may have skewed the final results. Digestibility results suggested that delaying harvest timing potentially increases pentose hydrolysis yield. However, these small increases may not affect ethanol production significantly.

CHAPTER 3

LIFE CYCLE ASSESSMENT OF A SWITCHGRASS BIOENERGY CROPPING SYSTEM UNDER VARIOUS HARVEST TIMING AND HARVEST/STORAGE METHOD SCENARIOS IN THE GREAT LAKES REGION

Abstract: Preliminary research has suggested that a chop/ensile harvest/storage method during an early fall harvest may result in higher biomass yield over a traditional cut/bale harvest/storage method and may be more sustainably advantageous in terms of environmental impact, energy use, and grower economics. To further investigate this potential, a life cycle assessment was performed using GaBi 6.0 in order to evaluate the environmental impact potentials of various harvest timing and harvest/storage method scenarios. Additionally, energy use and total production costs for each harvest scenario were calculated. Results were used to assess which harvest management system was the most environmentally and economically advantageous according to their calculated environmental impact potentials and total production costs. Results indicated that the chop/ensile harvest/storage method had consistently lower adverse environmental impact potentials across all harvest timings. Although energy consumption using a chop/ensile harvest/storage method was higher compared to a cut/bale harvest/storage method, environmental impacts were minimally affected. Overall, a chop/ensile harvest/storage method during an early fall harvest timing throughout the ten year lifetime of a dedicated switchgrass bioenergy stand may minimize environmental impacts while also possibly being the most economically sustainable option for a grower in the Northern Corn Belt/Great Lakes region.

INTRODUCTION

A crucial area to consider in maximizing cellulosic ethanol production is maximizing the amount of biomass harvested prior to being used in down-stream conversion processes. Two of the most important variables in crop harvest are harvest timing and the harvest/storage method. As outlined in the previous chapters, this study has included both a conventional bale method and a direct chop-and-ensile method during four specifically chosen harvest timings. Preliminary research has suggested that a chop/ensile harvest/storage method during an early fall harvest may result in higher biomass yield over a traditional cut/bale method and may be more sustainably advantageous in terms of environmental impact, energy use, and grower economics. To further investigate this potential, a life cycle assessment could be performed on the harvest scenarios of interest in order to assess differences in environmental impact.

Life cycle assessment (LCA) is a technique to assess environmental aspects and potential impacts associated with a product, process, or service (U.S. Environmental Protection Agency website). Life cycle assessments must be performed in accordance with the ISO 14040 and 14044 standards (International Organization for Standardization, 2006). An LCA involves four main phases in order to be complete. These four phases include: 1. Goal and scope definition phase; 2. Life cycle inventory (LCI) phase; 3. Life cycle impact assessment (LCIA) phase; and 4. Interpretation phase.

Goal & Scope Definition Phase

The goal and scope definition of an LCA provides a description of the product system in terms of the system boundaries and a functional unit. Defining the system boundaries serves to explain the exact context of the product system. The functional unit is the important basis that enables alternative goods, or services, to be compared and analyzed (Rebitzer et al., 2004). It defines what precisely is being studied and quantifies the service delivered by the product system, providing a reference to which inputs and outputs can be related. The goal and scope are critical parts to an LCA and thus need to be clearly defined and consistent with intended application (ISO 14040, 2006).

Life Cycle Inventory (LCI) Phase

The LCI phase of an LCA is an inventory of input/output data with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study (ISO 14040, 2006). Inventory data must be related to the functional unit.

Life Cycle Impact Assessment (LCIA) Phase

The purpose of the LCIA phase is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance (ISO 14040, 2006). Results are quantified by various LCIA methodologies into environmental impact measurements. There are many impact measurements, e.g., global warming potential. These impact measurements are expressed in common equivalence units that are then summed to provide an overall impact total that can be used to compare the potential environmental impacts between different system scenarios.

Interpretation Phase

The interpretation phase is the final phase of an LCA in which the results of both the LCI and LCIA are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition (ISO 14040, 2006).

Life cycle assessment of this study serves to assess which harvest timing and harvest/storage method scenario is most sustainably advantageous in terms of environmental impact potentials and grower economics.

Objective of Study

The objectives of this LCA study were to: 1. Calculate the environmental impact potentials of switchgrass harvest/storage methods over four harvest timing scenarios using GaBi 6.0 in accordance with the ISO 14040 and 14044 LCA standards; 2. Calculate energy and total production costs for each harvest scenario modeled in the LCA; and 3. Assess which harvest management system is the most environmentally and economically advantageous according to their calculated environmental impact potentials and total production costs.

MATERIALS AND METHODS

Goal & Scope

Goal

The goal of the LCA of this study was to identify which harvest/storage method during which harvest timing had the best economic and environmental performance during the ten year lifetime of a dedicated switchgrass bioenergy stand in the Northern Corn Belt/Great Lakes region. Since production, harvest, and storage are the first steps in a cellulosic ethanol production system, harvest efficiency is a crucial area to consider before developing a system that will produce and deliver lignocellulosic biomass to a lignocellulose pretreatment facility. Maximizing the feedstock stream to a pretreatment facility will increase both final ethanol output and the energy production capacity of a given area of land. Assessment of the environmental impacts and economic costs of various harvest/storage management scenarios at different harvest timings will enable growers and industry to make environmentally and economically sustainable decisions when choosing harvest management systems and infrastructure.

Scope

The scope of this study ranged from the initial establishment of the switchgrass plots and the yearly chemical inputs, followed by the two harvest/storage methods at the four harvest timings, then by the transportation scenarios to the pretreatment facility, and then finally ending with the end of life disposal of the polyethylene netting for the cut/baling harvest/storage method and the polyethylene tarp for the chop/ensiling harvest/storage method. The function of this system model was to produce and store switchgrass feedstock and deliver it to a regional pretreatment facility during the ten year average lifetime of a switchgrass stand in the Northern Corn Belt/Great Lakes region. The scope included consideration of global warming potential, acidification, and eutrophication as environmental impact categories. The reference flow was 1000 kg of dry switchgrass feedstock. The functional unit was 1000 kg of dry switchgrass feedstock stored for six months and delivered 80.5 km to a regional pretreatment facility. Environmental impact assessment was calculated in GaBi 6.0 using TRACI 2.1 methodology (U.S. Environmental Protection Agency) for all the impact categories. Allocation procedures were not necessary in this study since all the environmental burden was on the switchgrass feedstock alone. Switchgrass harvest yield data were collected during three study years (2010-2013) and were intended to be representative of the Northern Corn Belt/Great Lakes region. Yield data were collected from a switchgrass field study at the Agronomy Research Farm on Michigan State University’s campus. Equipment and input data that were not available during the study were collected from scientific journal publications and the 2013 Custom Machine and Work Rate Estimates datasheet (Stein, 2012) created by the Michigan State University Extension. Selected data needed to be as current as possible and as representative of the Northern Corn Belt/Great Lakes region as possible. A summary of the collected data, along with any flow and cost calculations, are presented in the appendix. Finally, a data quality pedigree matrix was created in order to assess the accuracy of the LCA model.

Site Description and Experimental Design

Switchgrass Stand Establishment

Beginning in the fall of 2006, a field experiment site was established at the Michigan State University Agronomy Research Farm in East Lansing, Michigan (42°42’52” N 84°27’57” W). Soils consisted predominantly of Capac loam (USDA Web Soil Survey). The site was conditioned using a conventional chisel plow tillage system in the fall of 2006 and was further conditioned twice over with a field cultivator in the spring of 2007 to ensure a flat, weed-free seed bed. The upland switchgrass cultivar ‘Cave-In-Rock’ was then seeded at a rate of 9 kg ha^{-1} using a double roller seeder (Brillion, Brillion Iron Works, WI) to about a 1.25 cm depth. The switchgrass was allowed to establish for three years. The switchgrass was cut and removed during the establishment years once senescence and a killing frost (-2.2 °C) had occurred to allow mineral nutrients to return to the root crowns and soil. Stand frequency was not taken at the onset of the study after three establishment years, but visual evidence showed a full complete stand with at least a 40% stand frequency (Vogel et al., 2001).

Weed Control

Weed control was most important during the establishment phase because broad leaf weeds and grasses could out-compete switchgrass seedlings if not controlled (Parrish et al., 1999). Weeds were controlled during the establishment phase with a tank mixture of S-metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl] acetamide) and atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) at rates of 1.3 and 1.8 kg ha^{-1}, respectively. Weeds were not chemically controlled after the establishment phase was completed.

Fertilization & Nutrient Management

Due to potential weed competitiveness during switchgrass establishment, the site was not fertilized during the establishment year. The site was fertilized with granular urea (46-0-0 NPK) at a rate of 78.5 kg N ha^{-1} during the spring green-up in the years after the first establishment year.

Description of Study Variables

Variable #1: Harvest Timing

Four harvest timings were identified in order to observe how various harvest timings throughout the harvest period in the Northern Corn Belt/Great Lakes region affect switchgrass harvest yield, storage loss, stand frequency, and soil nutrient content. Table 12, below, outlines the four harvest timings and their specific details.

Timing	Time of Year	Description & Pros/Cons
Early Fall Harvest	Early September to Late September	Immediately following seeding and peak biomass production. Prior to major translocation of nutrients to root crowns. High moisture content (> 50%). Ideal biomass for ensiling. Potential weather impact on harvest yield is low.
Mid Fall Harvest	Early October to Late October	Plant senescence has begun. Translocation of nutrients to root crowns begins. Mid-level moisture content (35-50%). Marginally ideal biomass for ensiling. Potential weather impact on harvest yield is slight.
Late Fall Harvest	Early November to Late November	2 weeks after a killing frost (-2.2 °C). Frost-induced rupturing of cell walls. Mediated translocation of nutrients to root crowns and soil occurs. Low moisture content (20-35%). Not ideal for ensiling. Unpredictable weather not ideal for drying time required for baling. Potential weather impact on harvest yield is moderate. Increased frequency of extreme weather could compromise harvest yield.
Spring (Over-winter) Harvest	Mid March to Mid April	Environmental washing of a majority of the remaining mineral nutrients to the soil due to winter precipitation. Low moisture content (< 10%). Ideal for baling. Too dry for ensiling. Potential weather impact on harvest yield is high.

Table 12. Harvest timing descriptions, benefits and potential issues. These harvest timings are specific to the Northern Corn Belt/Great Lakes region.

Variable #2: Harvest/storage Method

Two general harvest/storage methods are suitable for collection of switchgrass biomass. Investigation of these harvest/storage methods served to provide new insights into optimizing the feedstock production end of a cellulosic ethanol production system in the Northern Corn Belt/Great Lakes region. Table 13, below, outlines the two harvest/storage methods and describes the specific details, benefits and issues associated with each method.

Method	Description	Pros/Cons
Cut/Bale	Biomass is cut into windrows and allowed to dry to a proper moisture content suitable for bale storage (< 20%). Biomass is turned to allow even drying. Then it is round or square baled and stored covered or uncovered until further processing.	This harvest and storage method is ideal for biomass with low moisture content. It is a multiple-pass harvest system, requiring more harvest management input. Impact on harvest yield is potentially high due to physical and mechanical loss when drying and handling the biomass.
Chop/Ensile	Biomass is directly chopped with a forage harvester at high moisture content (> 50%). It is blown directly into a silage cart and immediately compacted in piles or bunker silos and allowed to ensile. It is kept covered until further processing.	This harvest and storage method is ideal for biomass with high moisture content. It is a one pass harvest system that requires relatively less harvest management input. Impact on harvest yield due to physical and mechanical loss is low.

Table 13. Harvest/storage method variable descriptions, benefits, and potential issues.

Experimental Design

In the spring of 2010, the experimental design was marked off within the established switchgrass field. The experimental design was a randomized complete block design (RCBD) with four replications (blocks). The main plot variable was harvest timing. The sub-plot variable was harvest/storage method. The sub-plot variable could not be randomized within the main plots because the chop/ensile harvest system requires a minimum 3.66 m wide harvest clearance, whereas the sub-plots were only 3.05 m wide. See figure 15, below, for a complete visual description of the experimental design.

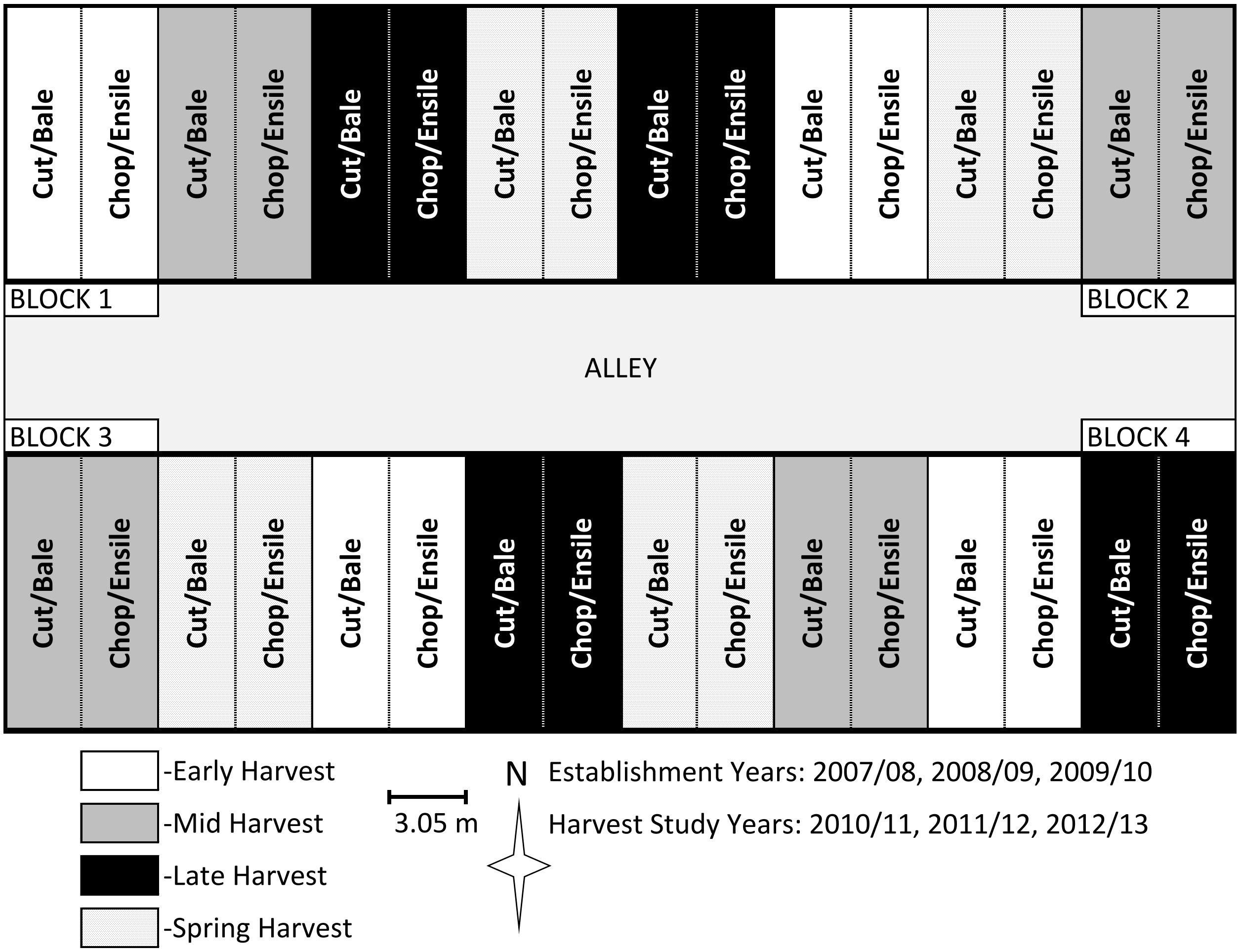

Figure 15. Switchgrass harvest management study site experimental design. Sub-plots were 3.05 m x 12.20 m. A 7.62 m wide alley ran down the center of the site. The total dimensions of the site were 32.0 m x 48.8 m (0.156 ha). The site was located at 42°42'52" N 84°27'57" W.

Harvest Yield

When weather permitted, the sub-plots were harvested within each main plot according to their harvest/storage method during the harvest timings.

The cut/bale sub-plots were harvested using a custom built plot windrower (Swift Machine and Welding Ltd., Swift Current, SK, Canada) with a 1.52 m wide cutter head, set at an 18 cm cutting height, to cut the switchgrass into two windrows. Because of the small plot size, the biomass was hand raked into one windrow and was inverted as needed over the course of about two weeks to ensure even drying. Once the biomass reached the proper baling moisture content (< 20%) each sub-plot biomass was individually baled with a John Deere 7830 tractor equipped with a John Deere 582 round baler (Deere & Company, Moline, Illinois). Due to baler mechanical issues during the early and mid fall harvest timings in 2012, each sub-plot had to be baled with a John Deere 7830 tractor equipped with a John Deere 338 small square baler. The mass of each bale was recorded. Bale moisture content was recorded by drying samples in a forced-air oven at 66 °C until a constant mass was achieved. Harvest yield was reported as dry kg ha^{-1}.

The chop/ensile sub-plots were harvested with a Hesston 7650 forage harvester (Hesston Co., Hesston, Kansas) equipped with a 3.66 m wide chopper head set at an 18 cm cutting height that was modified for plot research with the addition of a weigh bin for sub-plot harvest yield determination. The sub-plot mass was recorded. A sample of chopped biomass was used to determine biomass moisture content by drying the sample in a forced-air oven at 66 °C until a constant mass was achieved. Yearly harvest yields were reported as dry kg ha^{-1}.

The study's three year dry harvest yields were compiled together and scaled up to ten year harvest yields under the assumption that the three study years represented average ten year climatological variability for the Northern Corn Belt/Great Lakes region (table 23).

Post-Harvest Scenario Descriptions

All post-harvest scenario descriptions, below, were hypothetical and were not actually performed during the study. Inputs and associated costs were calculated from existing literature. See the appendix for a complete list of general model assumptions and harvest scenario-specific assumptions.

Cut/Bale Storage and Delivery Scenario

Upon harvest time, switchgrass was harvested using a windrower that cut the switchgrass into windrows within the field. The biomass was then turned and raked with a raker until it dried to a low enough moisture content that facilitated proper baling. A tractor with a round baler baled the switchgrass into round bales and applied polyethylene netting around the bale to ensure that it held together. The bales were stored uncovered in an enclosure for six months prior to being transported. The bales were then loaded onto a flatbed truck and trucked 80.5 km to a regional pretreatment facility.

Chop/Ensile Storage and Delivery Scenario

Upon harvest time, switchgrass was harvested using a forage chopper. The biomass was poured into a bunker silo, packed to a proper ensiling density, and then covered with a polyethylene tarp. The biomass was stored for six months. The silage was then collected, put into a high walled truck trailer until full, and was trucked 80.5 km to a regional pretreatment facility.

End of Life Polyethylene Waste Disposal Scenario

An end of life scenario was incorporated into each post-harvest scenario in order to model disposal of the polyethylene (PE) waste. Since the PE netting had pieces of biomass mixed within it and the PE tarp was degraded from being exposed to the elements, it was assumed that the PE was not recycled. As a result, 90% of the PE was assumed to be land filled and the remaining 10% was incinerated.

Model Assumptions

A list of assumptions was too lengthy to include in this section. However, a full list of the model assumptions can be found in the appendix.

RESULTS & DISCUSSION

Life Cycle Inventory (LCI)

Cumulative switchgrass dry harvest yield data, collected during the three study years (table 18), were adjusted to represent ten year cumulative harvest yields (table 23). These values were used to standardize model input and output values to the reference flow of 1000 kg of dry switchgrass. Model input and output data that were not available during the study were collected from the 2013 Custom Machine and Work Rate Estimates datasheet (Stein, 2012), created by the Michigan State University Extension, and from scientific journal publications. Input and output calculations are presented in the appendix. Final model input and output values are presented in tables 25 through 27. Final input costs are presented in tables 28 through 30. A data quality pedigree matrix is provided in order to assess the accuracy of the LCA model (table 31).

Final GaBi 6.0 Models

The final study models created in GaBi 6.0 are displayed below. The switchgrass cultivation phase plan was modeled separately (figure 16). This plan was added into each harvest/storage and delivery method phase plan (see in figures 18 and 19). Finally, the end of life scenario PE waste plan (figure 19) was added into each harvest/storage and delivery method phase plan (see in figures 18 and 19).

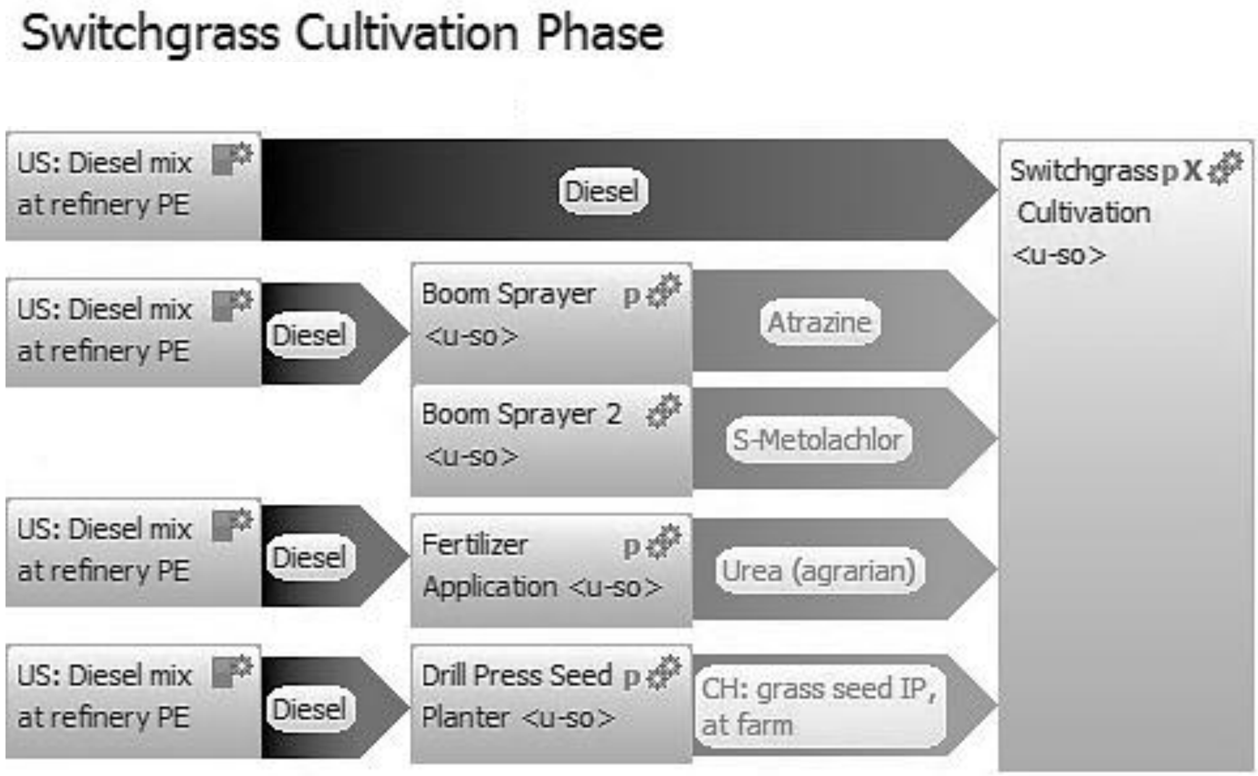

Figure 16. Final switchgrass cultivation phase model in GaBi 6.0. Boxes represent individual unit processes. Arrows represent tracked flows. Elementary (environmental) flows are not displayed. See appendix for a full list of unit process inputs and outputs and calculations.

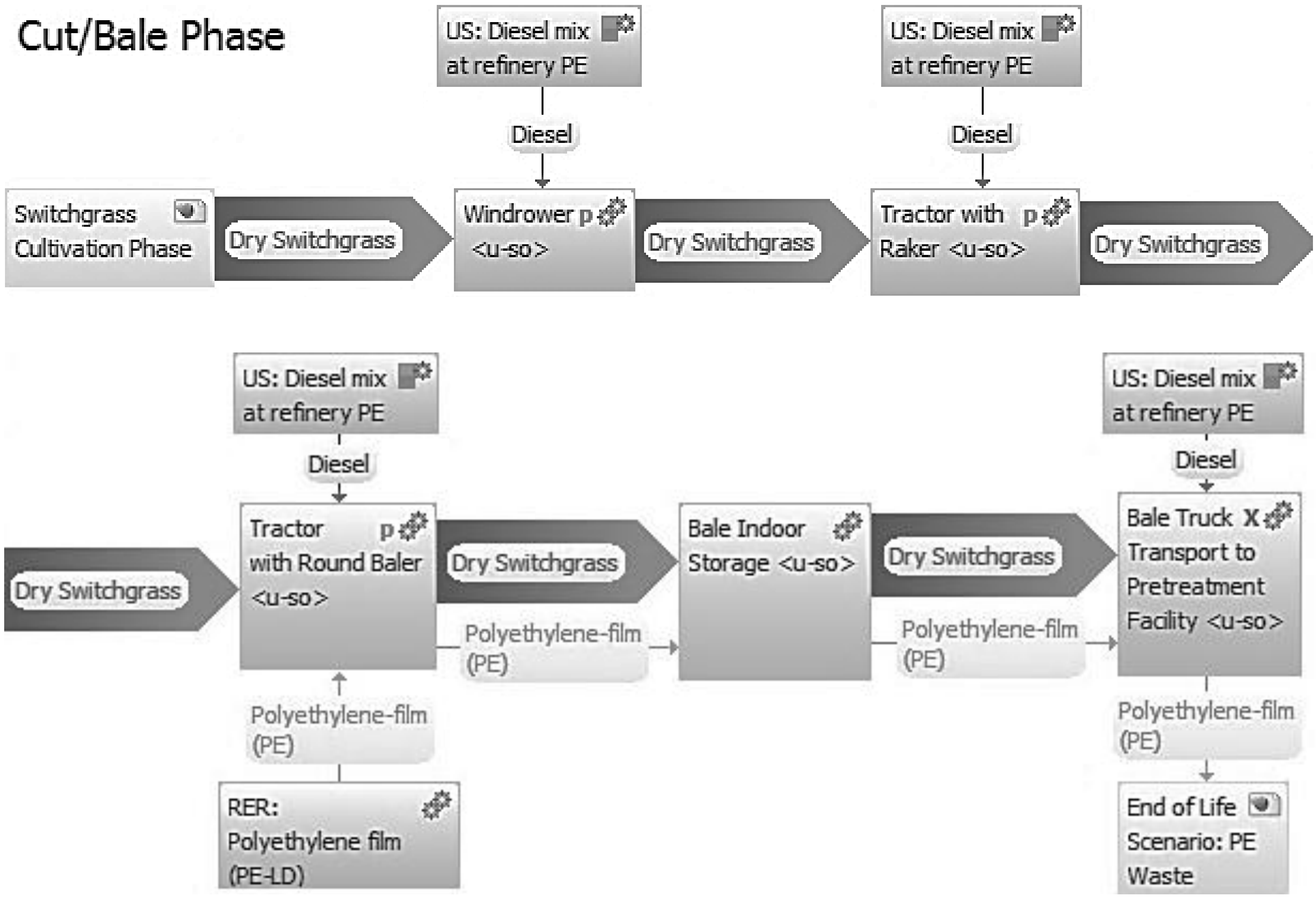

Figure 17. Final cut/bale phase model in GaBi 6.0. Boxes represent individual unit processes. Arrows represent tracked flows. Elementary (environmental) flows are not displayed. See appendix for a full list of unit process inputs and outputs and calculations.

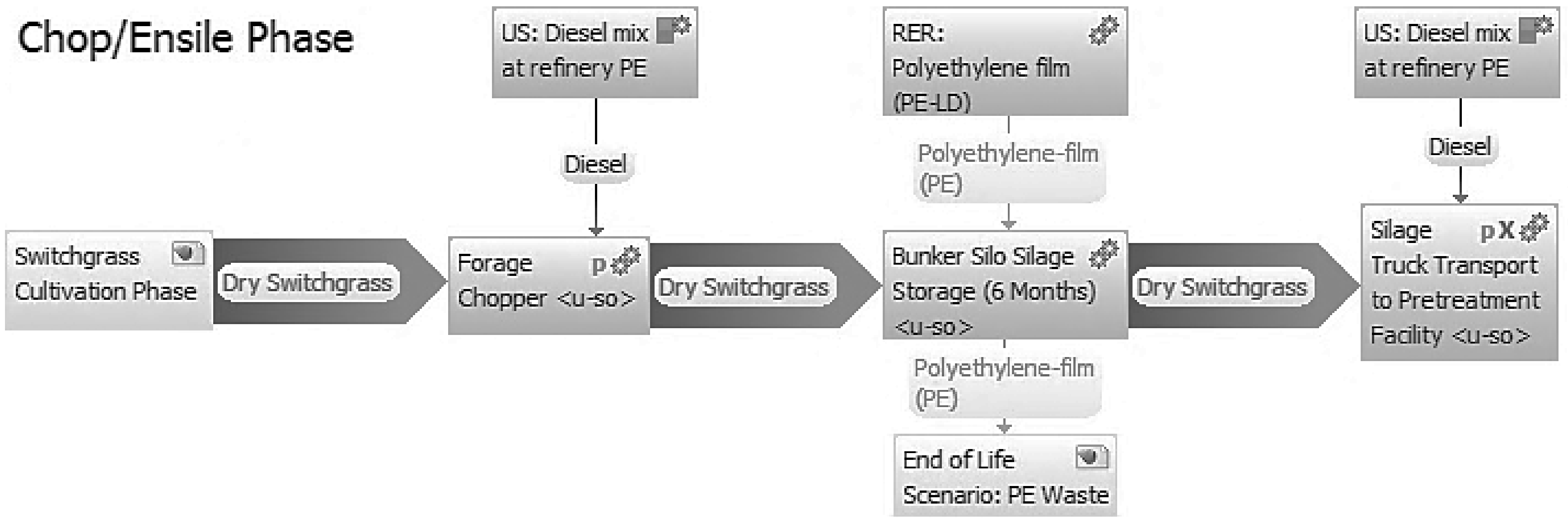

Figure 18. Final chop/ensile phase model in GaBi 6.0. Boxes represent individual unit processes. Arrows represent tracked flows. Elementary (environmental) flows are not displayed. See appendix for a full list of unit process inputs and outputs and calculations.

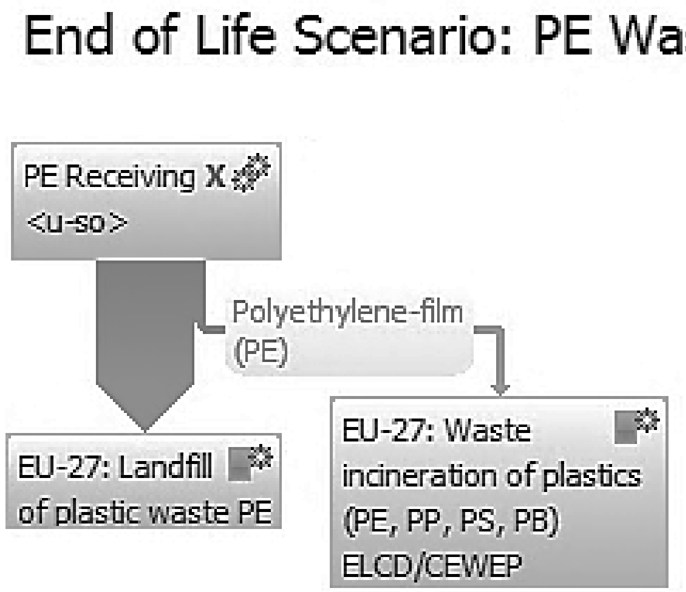

Figure 19. Final GaBi 6.0 end of life scenario model for polyethylene (PE) waste material. Boxes represent individual unit processes. Arrows represent tracked flows. Elementary (environmental) flows are not displayed.

Life Cycle Impact Assessment (LCIA)

Environmental impact potentials were calculated in the GaBi 6.0 parameter explorer using the TRACI 2.1 LCIA methodology, developed by U.S. Environmental Protection Agency. Global warming potential (figure 20), acidification potential (figure 21), and eutrophication potential (figure 22) were calculated. Global warming potential (GWP) is a relative measurement of total greenhouse gas contribution to global warming. Greenhouse gases produced from a system are expressed in carbon dioxide mass equivalents and then compiled together resulting in a total GWP of a system. Acidification potential (AP) is a relative measurement of total acid gas contribution to acid rain formation. Acid rain can lead to leaf damage on plants as well as acidic soils and surface waters. AP is expressed as a mass of H^+ moles. Eutrophication potential (EP) is a relative measurement of total eutrophying substance contribution to the eutrophication of water bodies. It is expressed as a mass of N equivalents.

Environmental Impact Potentials

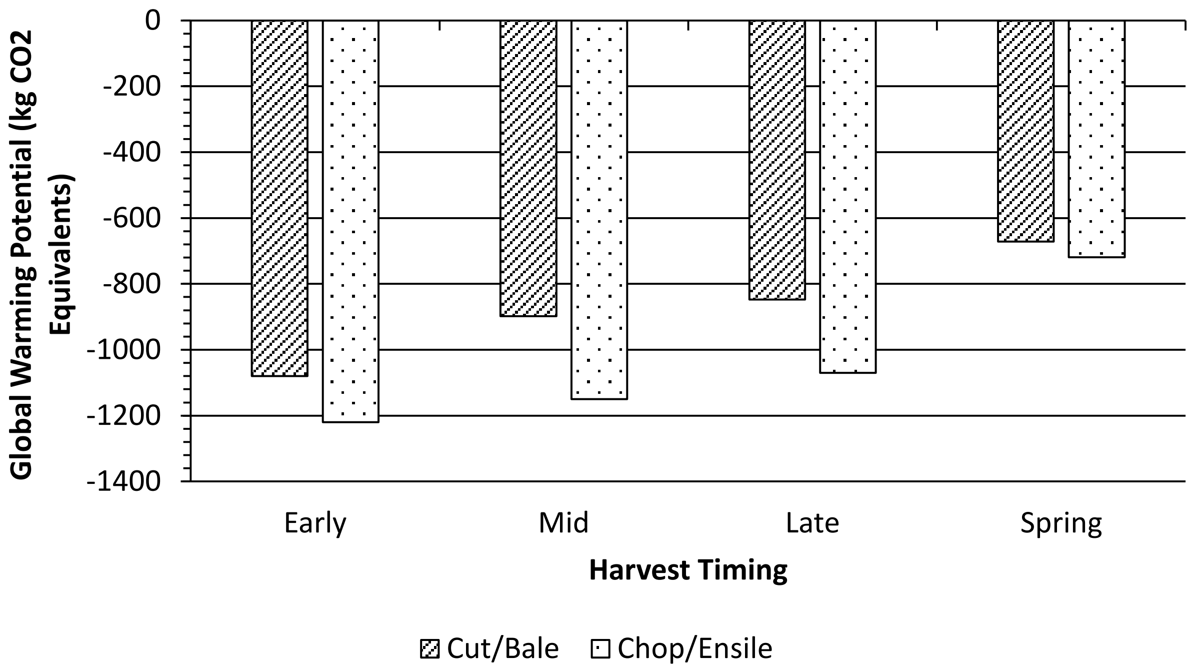

Figure 20. Net 100 year global warming potential as a response to harvest timing and harvest/storage method. Results reflect TRACI 2.1 (U.S. EPA) environmental impact calculations.

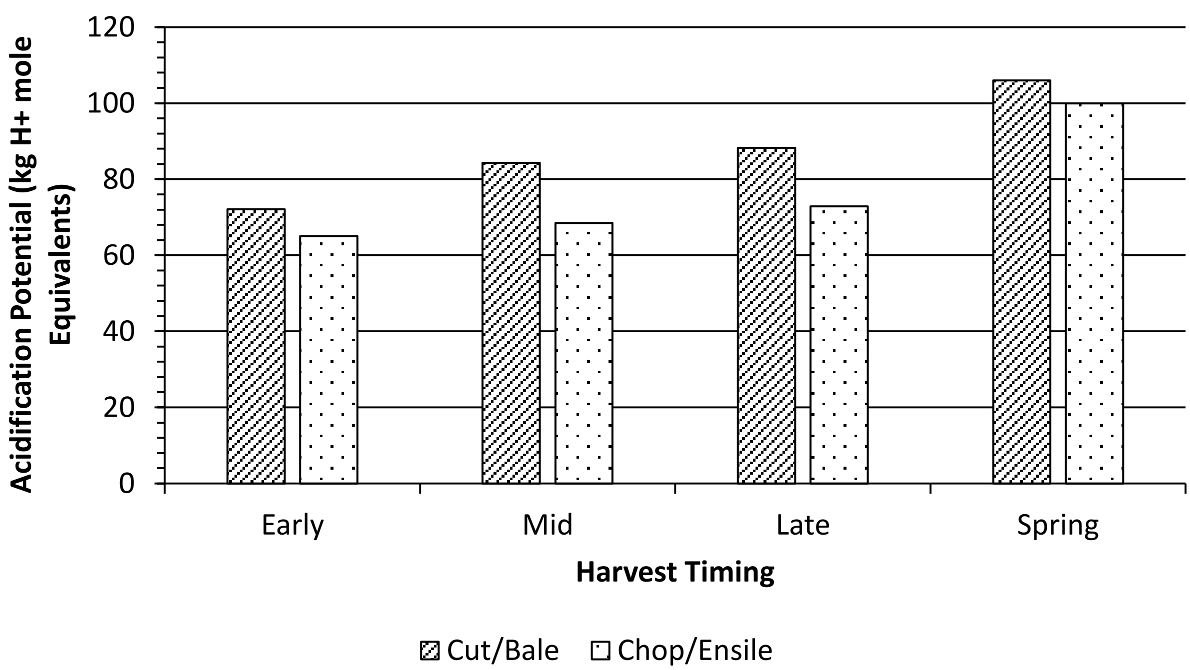

Figure 21. Net acidification potential as a response to harvest timing and harvest/storage method. Results reflect TRACI 2.1 (U.S. EPA) environmental impact calculations.

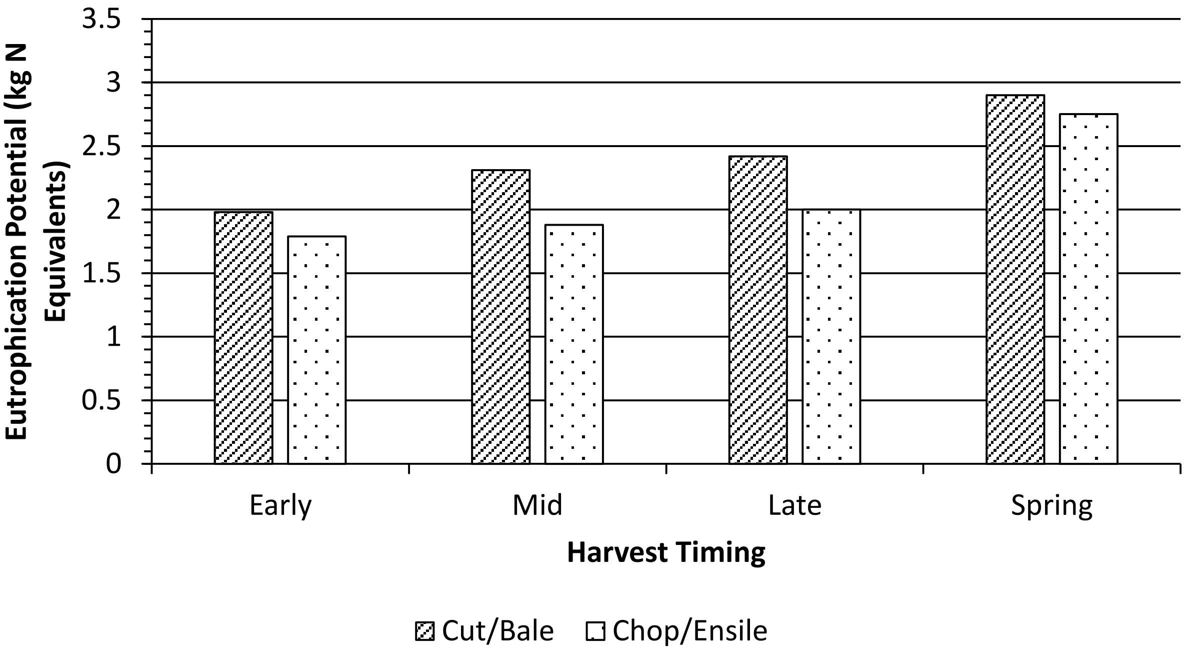

Figure 22. Net eutrophication potential as a response to harvest timing and harvest/storage method. Results reflect TRACI 2.1 (U.S. EPA) environmental impact calculations.

Interpretation

Results indicated that both harvest/storage methods for all four harvest timing scenarios had negative global warming potentials (GWP) (figure 20). This indicated that both systems had a negative net greenhouse gas flux. Since this study focused on a cradle to pretreatment facility gate, negative net fluxes mainly reflected the carbon dioxide autotrophically partitioned to the switchgrass biomass. It did not take into account any greenhouse gas emissions from downstream ethanol production processes or the final combustion of the produced ethanol. Combustion of the produced ethanol would ultimately re-release the harvested above-ground carbon. Unless non-ethanol byproducts are permanently stored, the combined above ground activity of any lignocellulosic ethanol production system can only, at best, be carbon-neutral. Furthermore, below-ground carbon sequestration, due to root growth, was also not taken into account. Below-ground carbon sequestration is a critical aspect in whether or not a complete ethanol production system will have a negative net greenhouse gas flux. This is why grower practices that help protect soil carbon levels are so important. However, the main purpose of this study was to observe the differences between the various harvest scenarios. The chop/ensile system resulted in the lowest GWP for all four harvest timings (figure 20). Although there were slight differences in greenhouse gas emissions between the harvest scenarios, they were miniscule in comparison to the differences in the switchgrass carbon sequestration. This indicated that the greatest factor that determines differences between the GWPs of the harvest scenarios is harvest yield. Although it is most likely that this harvested above-ground carbon would have been re-released further downstream in an actual system, the differences between the other emitted greenhouse gases (methane and nitrous oxide) still exist. Maximizing harvest yield will serve to minimize these non-carbon dioxide greenhouse gas emissions. Overall, the global warming potential results supported that a chop/ensile harvest system, during an early fall timing, over the ten year lifetime of a dedicated switchgrass stand, may have the best environmental sustainability potential from a greenhouse gas emissions standpoint.

Results indicated that the chop/ensile system had the lowest acidification potential for all four harvest timings (figure 21). Like global warming potential, the difference between the harvest/storage method acidification potentials was mainly due to differences in harvest yield. Higher yields meant that the same amount of environmental burden could be attributed to a larger amount of biomass. This further emphasizes the importance of maximizing harvest yields. Overall, the results supported that a chop/ensile harvest system, during an early fall timing, over the ten year lifetime of a dedicated switchgrass stand, may have the best environmental sustainability potential from an acidification standpoint.

Results indicated that the chop/ensile system had the lowest eutrophication potential for all four harvest timings (figure 22). Like global warming and acidification potential, the difference between the harvest/storage method eutrophication potentials was mainly due to differences in harvest yield. Overall, the results supported that a chop/ensile harvest system during an early fall timing over the ten year lifetime of a dedicated switchgrass stand may have the best environmental sustainability potential from a eutrophication standpoint.

Net Energy Consumption

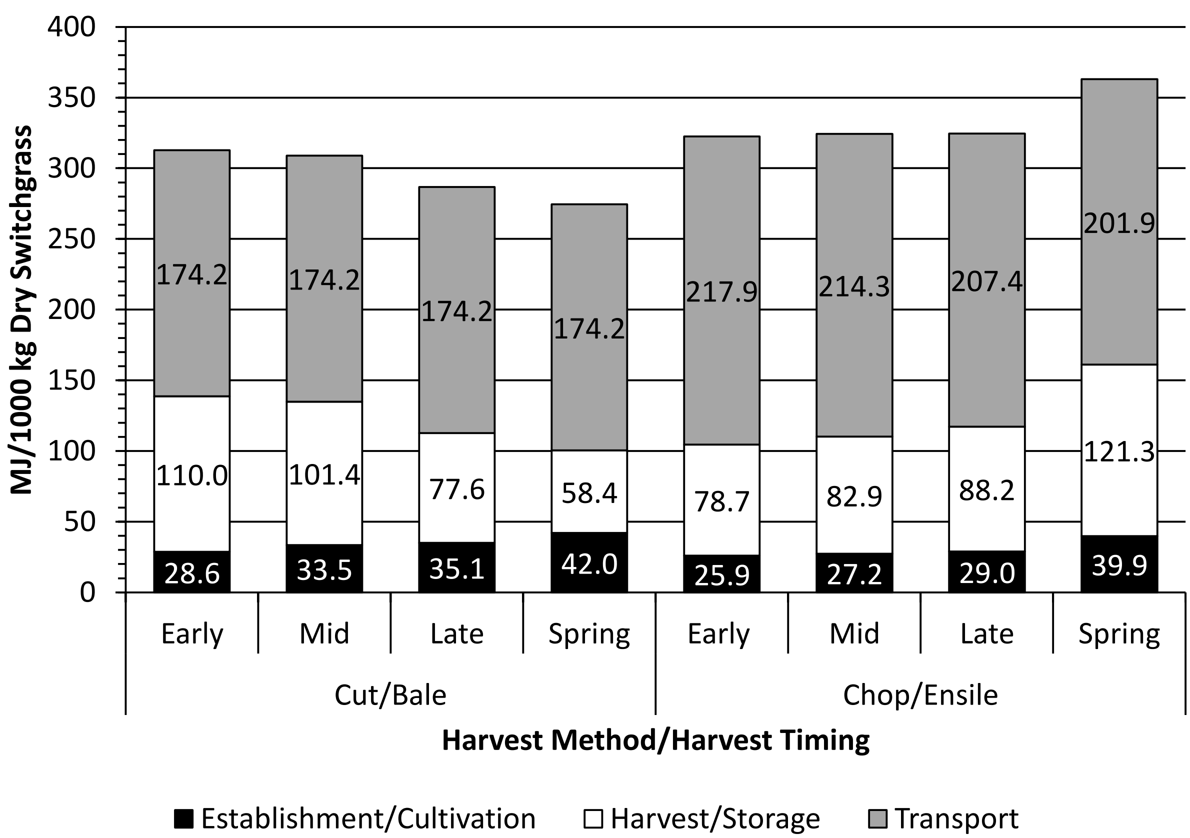

Figure 23. Net diesel energy consumption per 1000 kg of dry switchgrass. Diesel energy density = 35.86 MJ/L. See tables 25-27 for all the diesel calculations.

Net diesel fuel use was highest during a chop/ensile scenario for all harvest timings compared to the fuel use in the cut/bale scenarios (figure 23). This highlights the potential drawback to a chop/ensile system. A chop/ensile system requires transportation of silage with high moisture content. This in turn increases the transport fuel use (figure 23). Unlike the chop/ensile scenarios, the cut/bale scenarios' total fuel use decreases as harvest timing is postponed (figure 23). This was because biomass drying management prior to baling was less needed since biomass moisture content naturally declines later into the harvest season. While these fuel use estimates are less supportive of a chop/ensile scenario, total production costs will provide a better overall assessment of the grower economics between the harvest systems and timings.

Total Production Cost

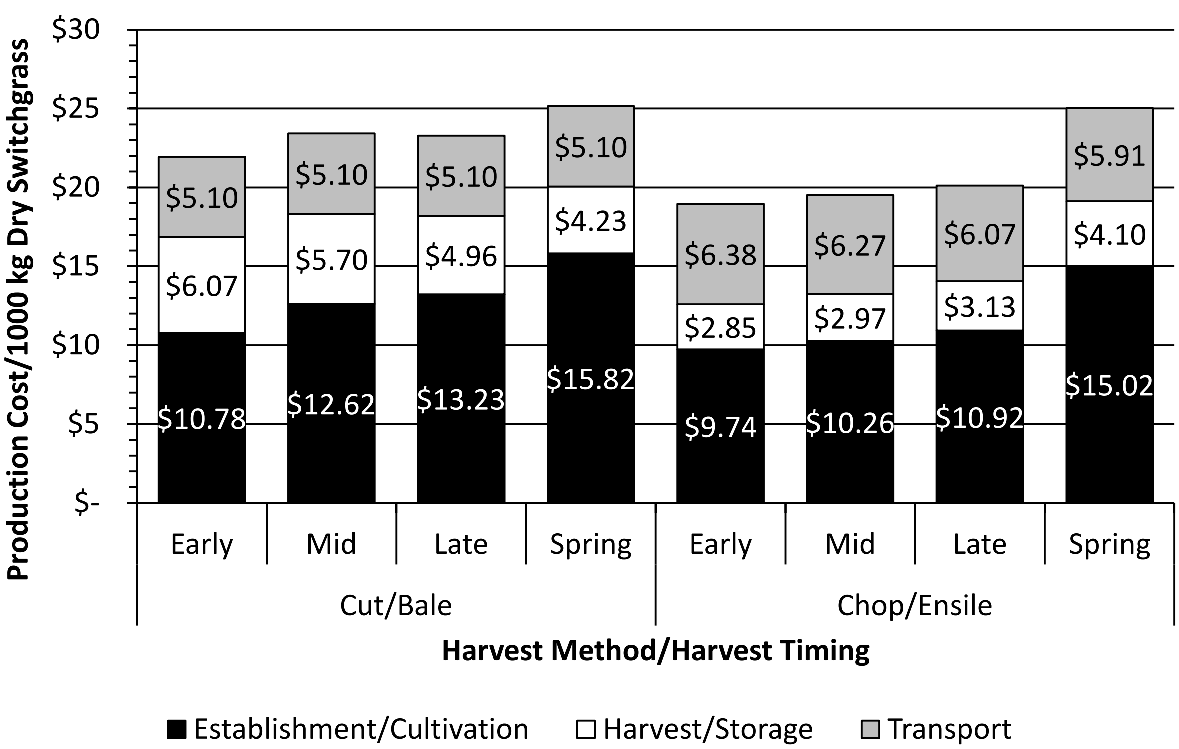

Figure 24. Total production cost of 1000 kg dry switchgrass as a response to various harvest timing and harvest/storage method scenarios. See tables 28-30 for cost calculations.

Results show that a chop/ensile system, for all harvest timings, has a lower total production cost compared to a cut/bale system (figure 24). However, the total production cost of a chop/ensile scenario during a spring harvest was only minimally less compared to a spring cut/bale scenario. The establishment/cultivation costs for the cut/bale system, for all timings, were higher compared to the chop/ensile system because its harvest yields were smaller relative to the chop/ensile yields. An equal amount of establishment/cultivation cost was ultimately distributed over a smaller harvest yield. Although transport costs were greater in the chop/ensile scenarios, it was not enough to push production costs above cut/bale levels (figure 24). Overall, the data suggested that a chop/ensile harvest system during an early fall timing may be the most economically sustainable option for a grower. If however, in a given year a fall harvest is not possible, a spring cut/bale harvest is a good option to take advantage of the over-winter drying of the biomass.

CONCLUSION

Results indicated that the chop/ensile harvest/storage method had consistently lower adverse environmental impact potentials across all harvest timings. Adverse environmental impact potentials increased during later harvest timings. Although energy consumption using a chop/ensile harvest/storage method was higher compared to a cut/bale harvest/storage method, environmental impacts were minimally affected. Overall, a chop/ensile harvest/storage method during an early fall harvest timing throughout the ten year lifetime of a dedicated switchgrass bioenergy stand may minimize environmental impacts while also possibly being the most economically sustainable option for a grower in the Northern Corn Belt/Great Lakes region.

CHAPTER 4

SWITCHGRASS ASH CONTENT RESPONSE TO HARVEST TIMING AND TWO HARVEST/STORAGE METHODS OF A BIOENERGY CROPPING SYSTEM IN THE GREAT LAKES REGION

Abstract: Energy production from the cofiring of plant residue is optimized when ash content of the biomass is minimized. Combustion of bioenergy crop material to produce energy may provide a transition market as cellulosic production systems are being developed. A study was conducted to quantify the ash content of switchgrass biomass at a whole-plant scale under four harvest timings and two general harvest/storage methods in the Northern Corn Belt/Great Lakes Region. Results showed that switchgrass ash content was significantly reduced when the biomass was left to overwinter in the field. Although overwintering maximized mineral nutrient retention in the field and produced the best quality biomass for cofiring, it was at the expense of harvest yield. Ash content was largely not significantly influenced by harvest timing during the fall. This suggested increased harvest timing flexibility that was not at the expense of soil nutrient retention. This would allow farmers a wider harvest window to maximize harvest yields. Results showed that harvest/storage method did not have a significant effect on ash content. This further suggested flexibility and adaptability to farmers and the bioethanol industry. This would give the flexibility to choose an appropriate storage method in the context of region-specific conditions without compromising on ash content and the potential for cofiring the biomass or lignocellulosic ethanol production byproducts.

INTRODUCTION

As energy demands continue to grow, the pursuit of developing and utilizing alternative sources of reliable and renewable energy continues to grow as a response to the future decline of available fossil fuels. Ethanol is one of the most popular liquid fuel candidates to replace liquid fossil fuels. Currently, most research has focused on developing energy efficient and sustainable systems that will process various forms of lignocellulosic biomass into ethanol. Biomass contains cellulose and hemicellulose, two long chain polymers of monosaccharides, which make up a majority of plant cell walls. Already, much research has emphasized on exposing and deconstructing these cellulosic components into their readily fermentable monosaccharide components, predominantly glucose and xylose. Switchgrass is widely considered to be the model perennial grass feedstock for lignocellulosic ethanol production (U.S. Department of Energy, 2011). Positive environmental and economical characteristics of dedicated switchgrass bioenergy crop production for cellulosic ethanol production were discussed in the first chapter.

Currently, there is still much research needed in order to make cellulosic ethanol production an economically and environmentally sustainable system. Meanwhile, various biomass feedstocks and co-products derived from cellulosic ethanol production can already be cofired with traditional fuel sources, such as coal, in electricity production (Tillman, 2000). The remaining ligneous residue after hydrolysis and fermentation can be used as a combustion fuel source to power a cellulosic ethanol biorefinery with the possibility of selling surpluses to the electrical grid (Farrell et al., 2006; Lynd et al., 2009). This could not only help in the transition to a bio-based economy (Samson et al., 1998), it can also make cellulosic ethanol production more efficient as a whole.

However, using lignocellulosic feedstock and ligneous residues for electricity generation has its challenges. The main problem with combustion of lignocellulosic material is that it can produce high amounts of ash as a waste product. The major obstacle in using herbaceous biomass material for heat and electricity generation is their unsuitability as efficient combustion material compared to wood. Ash from grasses are typically made up of silica (1-4%), alkali metals (sodium and potassium) (0.2-2.0%), Chlorine (0.01-0.5%), and sulfur (0.07-0.15%) (Cherney et al., 2006). High silica, potassium, sodium, chorine, and sulfur contents of herbaceous feedstocks can combine to cause fouling and slagging of combustion systems when temperatures exceed the melting point of ash (Samson et al., 1998). Fouling is deposition from ash materials that have vaporized and then condense in cooler regions of the furnace (Cherney et al., 2006). Slagging is deposition of molten or highly viscous ash found in the flame section of a furnace. Both of these problems lead to destructive effects and severely decrease the lifespan of the furnaces at an electricity plant. The alkali metals in the ash, potassium and sodium, combined with the catalyst effect of chlorine, can react with the surface of the furnace and cause corrosion (Cherney et al., 2006). If herbaceous feedstock or cellulosic ethanol production co-products are going to be used as a feedstock substitute in electricity production, there are a number of different strategies that can be taken to minimize ash content in order for them to be more suitable for combustion.

Harvest timing management is well established as an effective way in controlling ash content. Allowing switchgrass to senesce and translocate nutrients (particularly potassium and chlorine) back to their root crown will effectively reduce the ash content of the above ground biomass (Bakker et al., 2005; Cherney et al., 2006). This effect is further promoted when the biomass is cut and allowed to undergo in-field leaching facilitated by environmental washing. Ash reduction is maximized if the biomass is overwintered in the field. However, this is usually at the expense of harvest yield loss caused by excessive leaf shattering (Samson et al., 1998).

Impacts of harvest/storage method and long-term storage on herbaceous biomass ash content have generally been assumed to be small, as long as the biomass is stored at sufficiently low moisture content (< 20%) (Bakker et al., 2005). Microbial degradation of the stored biomass causes loss of organic matter and subsequently increases ash content on a volumetric basis. However, specific effects of long term ensiling on total ash content have, so far, not been analyzed (Bakker et al., 2005). If performed correctly, ensiling can preserve much of the biomass from microbial degradation due a lowering of pH caused by the build-up of lactic acid during the fermentation stage of ensiling. Thus, an ensiling storage technique may prove to be a viable alternative storage method for farmers and energy producers who wish to minimize total ash content.

Objective of Study

Energy production from the cofiring of plant residue is optimized when ash content of the biomass is minimized. The objective of this study was to quantify the ash content of switchgrass biomass at a whole-plant scale under four harvest timings and two general harvest/storage methods in the Northern Corn Belt/Great Lakes Region. Results of this research could aid bioenergy conversion facilities in choosing raw biomass or lignocellulosic ethanol production byproducts that have the lowest ash contents if ash damage is suspected to be an issue. Additionally, results of this study serve to expand knowledge on how harvest/storage methods impact ash content.

MATERIALS AND METHODS

Site Description and Experimental Design

Switchgrass Stand Establishment

Beginning in the fall of 2006, a field experiment site was established at the Michigan State University Agronomy Research Farm in East Lansing, Michigan (42°42’52” N 84°27’57” W). Soils consisted predominantly of Capac loam (USDA Web Soil Survey). The site was tilled using a conventional chisel plow tillage system in the fall of 2006 and was further conditioned twice over with a field cultivator in the spring of 2007 to ensure a flat, weed-free seed bed. The upland switchgrass cultivar ‘Cave-In-Rock’ was then seeded at a rate of 9 kg ha^{-1} using a double roller seeder (Brillion, Brillion Iron Works, WI) to about a 1.25 cm depth. The switchgrass was allowed to establish for three years. The switchgrass was cut and removed during the establishment years once senescence and a killing frost (-2.2 °C) had occurred to allow mineral nutrients to return to the root crowns and soil.

Weed Control

Weed control was most important during the establishment phase because broad leaf weeds and grasses could out-compete switchgrass seedlings if not controlled (Parrish et al., 1999). Weeds were controlled during the establishment phase with a tank mixture of S-metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl] acetamide) and atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) at rates of 1.3

and 1.8 kg ha^{-1}, respectively. Weeds were not chemically controlled after the establishment phase was completed.

Fertilization & Nutrient Management

Due to potential weed competitiveness during switchgrass establishment, the site was not fertilized during the establishment year. The site was fertilized with granular urea (46-0-0 NPK) at a rate of 78.5 kg N ha^{-1} during the spring green-up in the years after the first establishment year.

Description of Study Variables

Variable #1: Harvest Timing

Four harvest timings were chosen in order to observe how various harvest timings throughout the harvest period in the Northern Corn Belt/Great Lakes region affect switchgrass biomass ash content. Table 14, below, outlines the four harvest timings and describes the specific details associated with each timing.

Timing	Time of Year	Description
Early Fall Harvest	Early September to Late September	Immediately following seeding and peak biomass production. Prior to major translocation of nutrients and minerals to root crowns. High moisture content (> 50%). Ash content is potentially highest.
Mid Fall Harvest	Early October to Late October	Plant senescence has begun. Translocation of nutrients and minerals to root crowns begins. Mid-level moisture content (35-50%). Ash content is potentially lower due to translocation of minerals.
Late Fall Harvest	Early November to Late November	2 weeks after a killing frost (-2.2 °C). Frost-induced rupturing of cell walls. Mediated translocation of nutrients to root crowns and soil occurs. Low moisture content (20-35%). Ash content is further potentially lower.
Spring (Over-winter) Harvest	Mid March to Mid April	Environmental washing of a majority of the remaining mineral nutrients to the soil due to winter precipitation. Low moisture content (< 10%). Ash content is potentially the lowest because mineral nutrient translocation is maximized.

Table 14. Harvest timing variable descriptions. These harvest timing are specific to the Great Lakes region.

Variable #2: Harvest/Storage Method

Two general harvest/storage methods are suitable for collection of switchgrass biomass. Investigation of these two general harvest/storage methods served to provide new insights into minimizing the ash content of feedstock at the production end of a cellulosic ethanol production system. In order to investigate the impact that these harvest/storage methods have on the ash content, the biomass was stored for six months in order to model the effects of long term storage. Additionally, pre-storage biomass was retained to act as a control in ash content analysis. Table 15, below, outlines the two harvest/storage methods and describes the specific details associated with each method.

Method	Description	Pros/Cons
Cut/Bale	Biomass is cut into windrows and allowed to dry to a proper moisture content suitable for bale storage (< 20%). Biomass is turned to allow even drying. Then it is round or square baled and stored covered or uncovered until further processing.	This harvest and storage method is ideal for biomass with low moisture content. It is a multiple-pass harvest system, requiring more harvest management input. Ash content is potentially reduced due to environmental washing of mineral nutrients from the cut biomass during the biomass drying period. However, raking operations can increase ash content due to soil contamination. Since the bales in the study are stored indoors, the ash content most likely was not affected during the storage period.
Chop/Ensile	Biomass is directly chopped with a forage harvester at high moisture content (> 50%). It is blown directly into a silage cart and immediately compacted in piles or bunker silos and allowed to ensile. It is kept covered until further processing.	This harvest and storage method is ideal for biomass with high moisture content. It is a one pass harvest system that requires relatively less harvest management input. Ash content is potentially increased due to respiration during ensiling which would concentrate the ash during storage.

Table 15. Harvest/storage method variable descriptions.

Experimental Design

In the spring of 2010, the experimental design was marked off within the established switchgrass field. The experimental design was a randomized complete block design (RCBD) with four replications (blocks). The main plot variable was harvest timing. The sub-plot variable was harvest/storage method. The sub-plot variable could not be randomized within the main plots because the chop/ensile harvest system requires a minimum 3.66 m wide harvest clearance, whereas the sub-plots were only 3.05 m wide. See figure 25, below, for a complete visual description of the experimental design.

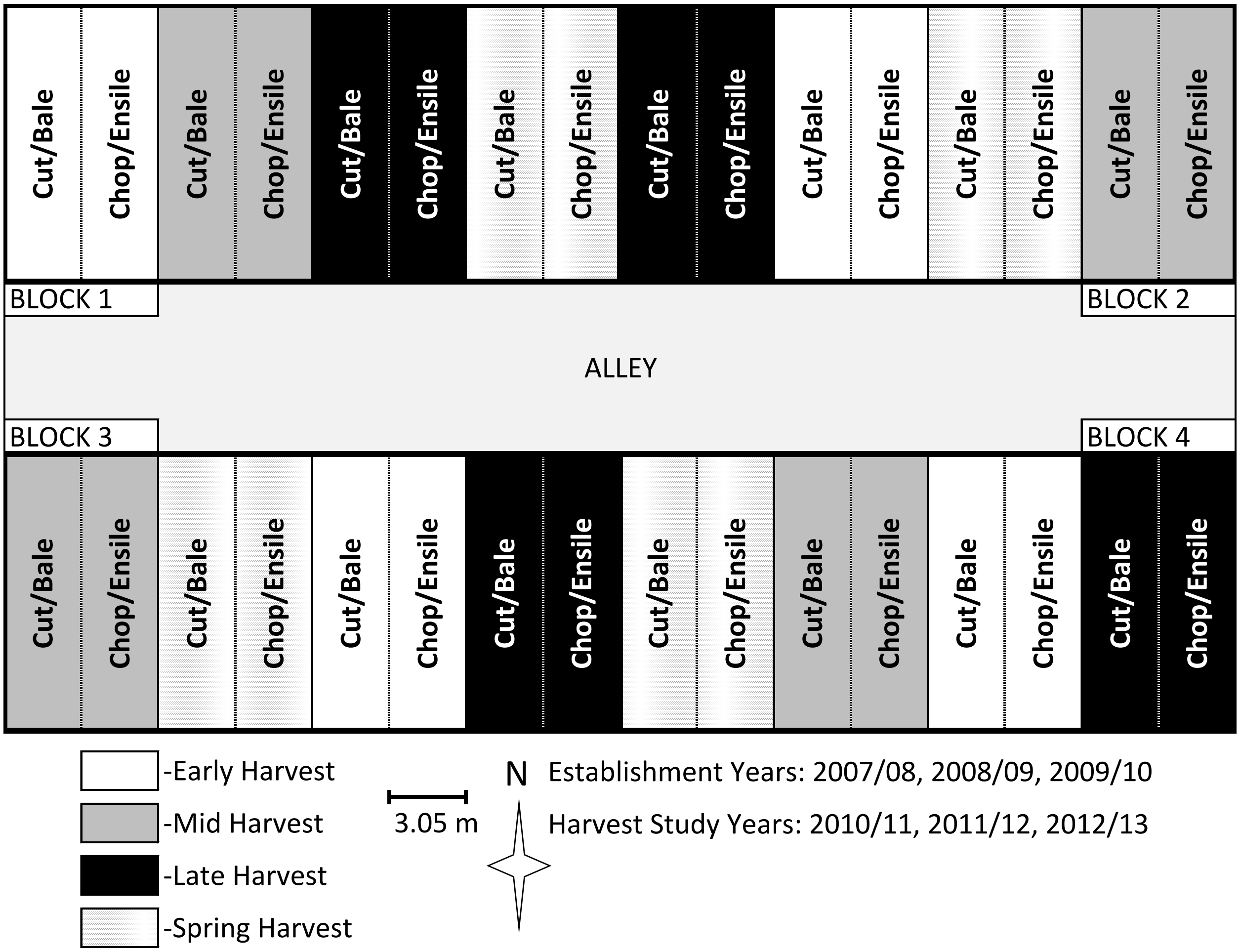

Figure 25. Switchgrass study site experimental design. Sub-plots were 3.05 m x 12.20 m. A 7.62 m wide alley ran down the center of the site. The total dimensions of the site were 32.0 m x 48.8 m (0.156 ha). Site located at 42°42’52” N 84°27’57” W.

Harvest, Storage, & Sampling

When weather permitted, the sub-plots were harvested within each main plot according to their harvest/storage method during the harvest timings.

The cut/bale sub-plots were harvested using a custom built plot windrower (Swift Machine and Welding Ltd., Swift Current, SK, Canada) with a 1.52 m wide cutter head, set at an 18 cm cutting height, to cut the switchgrass into two windrows. Because of the small plot size, the biomass was hand raked into one windrow and was flipped as needed over the course of about two weeks to ensure even drying. Once the biomass reached the proper baling moisture content (< 20%) each sub-plot biomass was individually baled with a John Deere 7830 tractor (Deere & Company, Moline, Illinois) equipped with a John Deere 582 round baler. Due to baler mechanical issues during the early and mid fall harvest timings in 2012, each sub-plot had to be baled with a John Deere 7830 tractor equipped with a John Deere 338 small square baler. Moisture content was recorded for each bale by drying samples in forced-air oven at 66 °C until a constant mass was achieved. The bales were stored indoors for six months without any disturbance. The bales were then sampled. The samples were dried and their moisture content was recorded. The dry samples were ground through a 1.0 mm screen in a Christy-Norris mill (Christy and Norris Limited, Chelmsford, England). The samples were retained and stored in a -20 °C freezer until further ash content analysis.

The chop/ensile sub-plots were harvested with a Hesston 7650 forage harvester (Hesston Co., Hesston, Kansas) equipped with a 3.66 m wide chopper head, set to an 18 cm cutting height, and a collection bin. The collection bin was emptied after each sub-plot harvest and the chopped biomass was immediately sampled. A fraction of the sample was dried in a forced-air oven at 66 °C. This dry biomass was retained and used as an at-harvest (fresh processed) control for ash content comparison after baled and ensiled biomass came out of storage. This biomass was ground through a 1.0 mm screen in a Christy-Norris mill (Christy and Norris Limited, Chelmsford, England). The ground biomass was retained and stored in a -20 °C freezer until further ash content analysis. The remaining fraction was simulation ensiled at its harvest moisture content. The biomass was packed into a food vacuum bag and was evacuated of its air to simulate ensiling conditions. The vacuum bags were stored indoors for six months without any disturbance. After six months, the vacuum bags were unsealed and the biomass was dried. The dry silage was ground through a 1.0 mm screen in a Christy-Norris mill (Christy and Norris Limited, Chelmsford, England). The ground silage was retained and stored in a -20 °C freezer until further ash content analysis.

Ash Content

Ash content was measured using a standard method developed by the National Renewable Energy Laboratory (NREL) (Sluiter et al., 2005). Pre-ashed porcelain crucibles were filled with 0.5 to 1.0 grams of the ground switchgrass biomass. Moisture contents were obtained for each switchgrass sample. The crucibles were then placed in a 575 °C muffle oven for at least 3 hours. The samples were weighed and then ashed in one hour intervals until the weight of the crucibles remained constant. The crucibles were stored in a desiccator when they were not being weighed. The ash content was then calculated and reported as percentage of dry biomass.

Statistical Analysis

Ash content testing was performed in triplicate. Data were analyzed using PROC MIXED in SAS 9.2 (2009, SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was conducted to measure the treatment effects on ash content. Harvest year, harvest timing and harvest/storage method were treated as fixed effects while blocking was considered to be a random effect. Initially, harvest year was assumed to be a random effect, but upon evaluation, harvest year had obvious non-random effects and was chosen to be treated as a fixed effect. Regardless, this change had no effect on the ANOVA results. Normality of the residuals and homogeneity of variances were evaluated by examining normal probability plots and box plots. Fisher's protected least significant difference (LSD) multiple comparison procedure was used for mean separation when ANOVA was significant (Saxton, 1998). Results were reported as statistically significant at $\alpha = 0.05$.

RESULTS & DISCUSSION

Climatological Summary

Mean monthly air temperatures in East Lansing did not vary considerably between the study years, but they tended to be higher compared to the monthly mean over the last 30 years, especially during the switchgrass growth phase (table 16). Every monthly temperature mean, for all three study years during the switchgrass growth phase, was higher compared to the monthly 30 year average. The first killing frost (-2.2°C) dates for the 2010/11, 2011/12, and 2012/13 study years were: November 1, October 28, and November 4, respectively.

Cropping Phase	Month	Total Precipitation			30-yr Avg	Mean Temperature			30-yr Avg
		'10/'11	'11/'12	'12/'13		'10/'11	'11/'12	'12/'13	
Growth Phase	May	10.4	14.6	6.2	8.5	15.9	15.0	16.8	13.9
	June	10.0	4.0	2.7	8.9	20.4	19.8	20.3	19.4
	July	4.4	13.0	3.7	7.2	23.2	24.1	24.4	21.6
	August	1.4	7.8	5.3	8.2	22.5	21.0	20.8	20.6
Fall Harvest Phase	September	8.9	6.7	5.5	8.9	16.3	15.9	16.3	16.3
	October	3.6	7.5	9.2	6.4	11.5	10.7	10.1	9.8
	November	4.2	6.2	0.8	7.1	4.6	6.0	3.3	3.8
Over-Wintering Phase	December	1.4	5.2	3.2	4.8	-4.1	0.3	0.9	-2.5
	January	0.7	3.2	6.9	4.2	-6.8	-1.9	-3.1	-5.1
	February	1.9	2.2	2.3	3.7	-4.6	-1.0	-4.2	-3.8
Spring Harvest Phase	March	6.4	5.9	1.7	5.2	0.4	9.4	-0.5	1.3
	April	11.6	4.4	16.5	7.7	7.4	8.3	6.5	8.2

Table 16. Monthly precipitation (cm) and mean temperatures (°C) during the study years compared to the 30-year means (1981-2010). The 30-year averages were obtained from NOAA. Weather data were obtained via the Michigan State University Enviro-Weather website (figure 28). The station was located 0.9 km away at the Hancock Turfgrass Research Center.

The 2010/11 and 2012/12 study years tended to be drier, while the 2011/12 study year tended to be average when compared to the 30-year mean (table 17). The 2010/11 study year was 19.9% drier and 2012/13 was 20.8% drier compared to the 30 year mean, while 2011/12 was essentially the same (0.1% drier). Additionally, the total precipitation during the switchgrass growth phase during the 2010/11 and 2012/13 study years were considerably lower (20.2% and 45.7%, respectively) while during the 2011/12 study year was considerably higher (20.0%) compared to the 30-year mean (table 17). The study year 2010/11 tended to be wet during May and June and drier during July and August compared to the 30-year means (table 16). However, these late drought stresses did not seem to have an effect on harvest yields. The study year 2011/12 tended to be significantly wetter during May and July, significantly drier in June, and average during August compared to the 30-year means (table 16). Finally, 2012/13 displayed very severe drought conditions throughout the growth phase (May-August). Each month was significantly drier compared to the 30-year means (table 16). Drought related stress responses were observed for this study year.

	Total Precipitation			30-yr
	2010/11	2011/12	2012/13	Average
Total Growth Phase Precipitation	26.2	39.4	17.9	32.9
Total Yearly Precipitation	64.7	80.7	64.0	80.8

Table 17. Total growth phase (May-August) and yearly (May-April) precipitation (cm) during the study years compared to the 30-year means (1981-2010). Weather data were obtained via the Michigan State University Enviro-Weather website (table 32). The station was located 0.9 km away at the Hancock Turfgrass Research Center. The 30-year averages were obtained from NOAA.

Ash Content

Ash contents were reported as percent of dry switchgrass mass. See table 32 for the raw data. Statistical difference between ash contents due to a three way interaction between year, harvest timing, and harvest/storage method (P = 0.0692) was not observed. Statistical difference due to interactions between harvest timing and harvest/storage method (P = 0.1782) and harvest year and harvest/storage method (P = 0.7056) were not observed. Statistical difference due to an interaction between harvest year and harvest timing (P = 0.0004) was observed (figure 26). Statistical difference due to harvest/storage method was observed (P = 0.0333). However, due to a number of missing ash content calculations, mean estimates were off from the actual mean value of the successfully collected data, which subsequently led to results indicating significance. Harvest/storage method turned out to be not significant (figure 27).

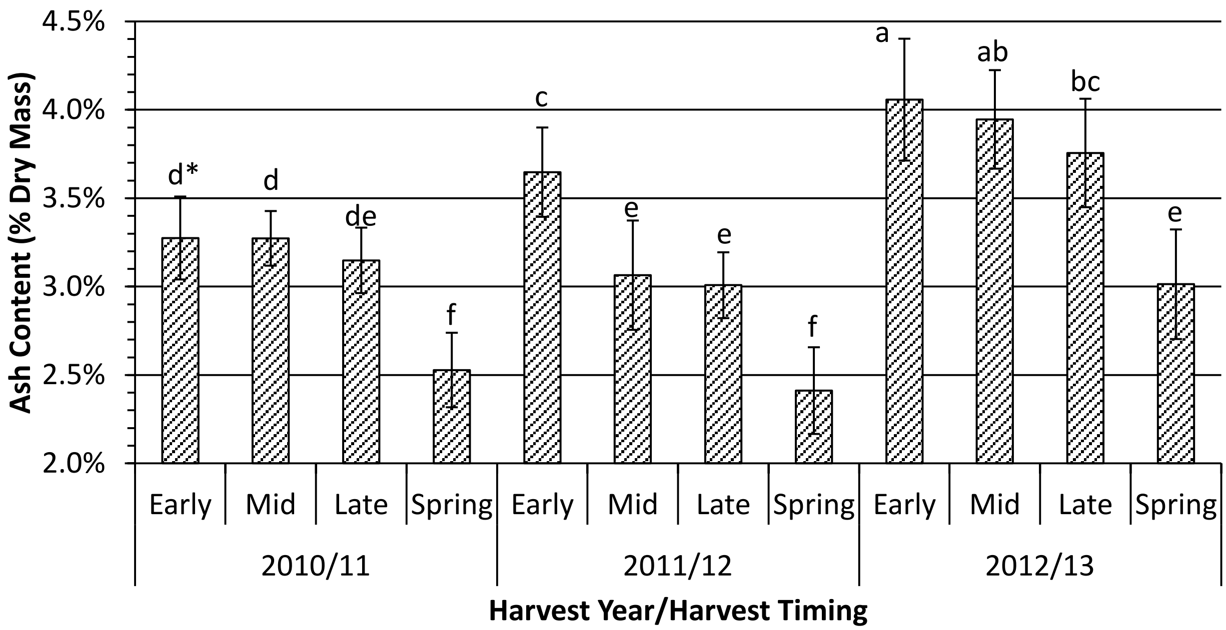

Figure 26. Ash content response to harvest year and timing. *Average ash contents with the same letter are not statistically different (α = 0.05).

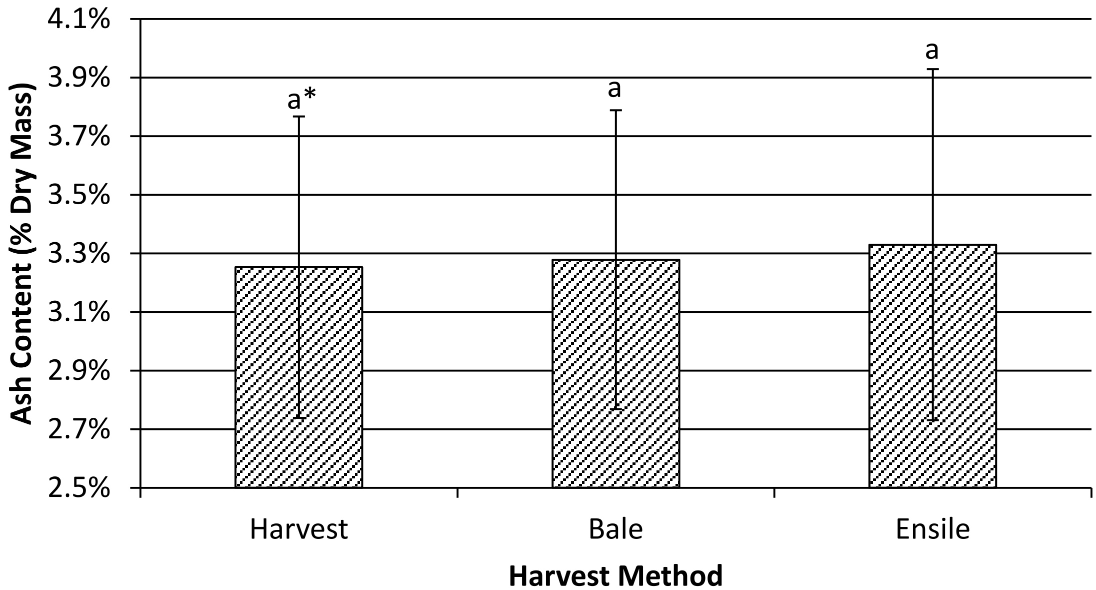

Figure 27. Ash content as a response to harvest/storage method. *Average ash contents with the same letter are not statistically different (α = 0.05).

For all harvest years, ash content tended to decrease successively during the fall harvest timings (figure 26). All decreases were not significant except during the 2011 fall harvest year. In 2011, ash content for the early fall harvested biomass was significantly higher compared to the mid and late fall harvested biomass ash contents. This might have been due to the fact that the biomass was harvested at an earlier date within the early fall harvest window (figure 2). Although there were slight decreases in mean ash contents, the data suggested that ash content decreased no more than one half of a percentage point between the first and last fall harvest for a given year. Mineral nutrient translocation was not significantly greater later into the harvest season. Soil nutrient analysis data concurred with this conclusion (table 5).

For all harvest years, ash content of spring harvested biomass was significantly lower compared to the fall harvested biomass ash content (figure 26). This suggested that overwintering switchgrass does maximize mineral nutrient translocation and washing. This biomass would have been the most ideal for combustion since the reduction of the alkali metals would have reduced the potential for slagging and fouling. However, this ash reduction was at the expense of harvest yields (figure 3).

One significant observation was that all the ash contents during the 2012/13 harvest year were significantly higher than the corresponding ash contents in the other two harvest years. This may have been due to a combination of reasons. First, both significantly lower plant moisture contents (figure 4) and lower cumulative precipitation during the harvest period (table 16) might have resulted in less nutrient translocation and environmental washing, respectively. Second, drought conditions during the 2012/13 study year (table 17) may have increased the switchgrass leaf to stem ratio (Undersander, 2012). Silica is predominantly found in the leaves of switchgrass (Samson et al., 1998; Cherney et al., 2006) and it makes up the majority of ash and largely remains in the biomass (Cherney et al., 2006). Therefore, biomass with a higher leaf to stem ratio, caused by severe drought conditions, would, have higher ash content. Overall, severe drought conditions have a negative impact on switchgrass feedstock both quantitatively and qualitatively.

Harvest/storage method and storage technique did not have a significant effect on ash content (figure 27). These results suggested that both baling (low moisture) and ensiling (high moisture) storage equally and effectively limited any potential increase in ash content from their pre-storage levels.

CONCLUSION

Results showed that switchgrass ash content was significantly reduced when the biomass was left to overwinter in the field. Although overwintering maximized nutrient retention in the field and produced the best quality biomass for cofiring, it was at the expense of harvest yield. Ash content was largely not significantly influenced by harvest timing during the fall. This result suggests increased harvest timing flexibility that is not at the expense of soil nutrient retention. This allows farmers a wider harvest window to maximize harvest yields. Results showed that harvest/storage method and storage technique did not have a significant effect on ash content. This further suggests flexibility and adaptability to farmers and the bioethanol industry. This gives the flexibility to choose an appropriate storage method in the context of region-specific conditions without compromising on ash content and the potential for cofiring the biomass or lignocellulosic ethanol production byproducts.

CONCLUSIONS

A study was conducted to help develop agronomic suggestions on how to create an economically viable and sustainable switchgrass crop production phase of a lignocellulosic ethanol production system, in the Northern Corn Belt/Great Lakes region, that facilitates the procurement, storage, and delivery of a high quantity of high quality lignocellulosic feedstock. The study focused on how harvest timing and harvest/storage method influenced these crop production aspects.

Harvest yield data suggested that harvest yield was maximized during an early fall harvest timing using a direct chopping and ensiling harvest/storage method. Short-term stand frequency data and soil nutrient analysis suggested that switchgrass winter hardiness and spring survivability were not compromised at this stage in the switchgrass stand’s lifetime. A harvest during the early fall with a direct chopping and ensiling harvest/storage method may not affect winter hardiness, may facilitate a more timely harvest, may maximize harvest yield, and could potentially be most profitable for growers.

Biomass quality was not affected by harvest/storage method, whereas harvest timing did have an influence. Successive early fall harvests may significantly reduce both cellulose and lignin contents. Harvest timing did not impact xylose content. Theoretical ethanol yields indicated that harvest timing did not significantly impact potential ethanol yield. Digestibility was not affected significantly by harvest/storage method. Delayed harvest timing potentially increased pentose hydrolysis. An early fall harvest resulted in significantly higher glucose hydrolysis yields, which potentially suggested that an early fall harvest timing may be most conducive to increasing enzymatic hydrolysis efficiency.

A life cycle assessment of the different harvest scenarios indicated that a chop/ensile harvest/storage method had consistently lower adverse environmental impact potentials across all harvest timings. Although energy consumption using a chop/ensile harvest/storage method was higher compared to a cut/bale harvest/storage method, environmental impacts were minimally affected. Overall, a chop/ensile harvest/storage method during an early fall harvest timing throughout the ten year lifetime of a dedicated switchgrass bioenergy stand may minimize environmental impacts while also possibly being the most economically sustainable option for a grower in this region.

Ash content analysis indicated that switchgrass ash content was significantly reduced when the biomass was left to overwinter in the field. Ash content was mostly not significantly influenced by harvest timing during the fall. This suggested increased harvest timing flexibility that was not at the expense of soil nutrient retention. Harvest/storage method did not have a significant effect on ash content. This would give the flexibility to choose an appropriate storage method in the context of region-specific conditions without compromising on ash content and the potential for cofiring.

Overall, an early fall chop/ensile harvest system may be the best switchgrass management option to help facilitate the procurement, storage, and delivery of a high quantity of high quality lignocellulosic feedstock as economically and environmentally sustainable as possible in the Northern Corn Belt/Great Lakes region.

APPENDIX

APPENDIX

Year	Block	Timing	Method	Moisture Content (%)	Harvest Yield (Dry kg/ha)	Notes
2010	1	Early	Bale	22.17%	7486.00	
2010	2	Early	Bale	21.76%	7544.18	
2010	3	Early	Bale	22.80%	7670.61	
2010	4	Early	Bale	23.06%	8329.91	
2010	1	Early	Ensile	47.31%	9132.58	
2010	2	Early	Ensile	47.95%	9656.72	
2010	3	Early	Ensile	45.19%	9164.68	
2010	4	Early	Ensile	47.50%	10573.30	
2010	1	Mid	Bale	24.95%	7209.27	
2010	2	Mid	Bale	20.41%	6936.51	
2010	3	Mid	Bale	20.92%	5579.33	
2010	4	Mid	Bale	17.93%	8825.70	
2010	1	Mid	Ensile	46.01%	9390.07	
2010	2	Mid	Ensile	46.16%	9397.28	
2010	3	Mid	Ensile	41.51%	9031.33	
2010	4	Mid	Ensile	48.48%	10879.34	
2010	1	Late	Bale	23.12%	7778.88	
2010	2	Late	Bale	26.96%	6775.55	
2010	3	Late	Bale	23.59%	7200.35	
2010	4	Late	Bale	23.31%	8068.75	
2010	1	Late	Ensile	29.47%	8737.92	
2010	2	Late	Ensile	29.99%	8630.91	
2010	3	Late	Ensile	30.46%	8572.47	
2010	4	Late	Ensile	28.90%	9807.09	
2010	1	Spring	Bale	7.73%	6779.99	
2010	2	Spring	Bale	7.74%	6419.13	
2010	3	Spring	Bale	8.35%	.	*
2010	4	Spring	Bale	8.04%	6051.05	
2010	1	Spring	Ensile	5.71%	7020.51	
2010	2	Spring	Ensile	6.02%	7341.79	
2010	3	Spring	Ensile	6.18%	7443.24	
2010	4	Spring	Ensile	6.00%	7917.16	
2011	1	Early	Bale	22.23%	8267.60	
2011	2	Early	Bale	23.12%	10463.84	

Table 18. Raw harvest yield data. *Baler mechanical issue. Could not bale plot. †Difficulty baling plot. Not used in final analysis. ‡Difficulty chopping plot. Not used in final analysis. Δ Round baler was out of order. Plot was baled with a small square baler.

Table 18 (cont'd)

2011	3	Early	Bale	16.92%	.	*
2011	4	Early	Bale	17.55%	11322.36	
2011	1	Early	Ensile	48.06%	10428.28	
2011	2	Early	Ensile	50.10%	10719.99	
2011	3	Early	Ensile	47.56%	7713.37	
2011	4	Early	Ensile	49.55%	10500.12	
2011	1	Mid	Bale	22.84%	6781.50	
2011	2	Mid	Bale	23.35%	7326.05	
2011	3	Mid	Bale	25.02%	5436.39	
2011	4	Mid	Bale	25.51%	8828.48	
2011	1	Mid	Ensile	43.67%	8595.22	
2011	2	Mid	Ensile	44.52%	8904.38	
2011	3	Mid	Ensile	42.28%	6763.27	
2011	4	Mid	Ensile	45.02%	8321.74	
2011	1	Late	Bale	32.59%	7668.62	
2011	2	Late	Bale	33.85%	8058.00	
2011	3	Late	Bale	31.98%	3258.61	†
2011	4	Late	Bale	26.87%	9586.90	
2011	1	Late	Ensile	35.48%	8386.71	
2011	2	Late	Ensile	30.91%	8095.62	
2011	3	Late	Ensile	30.06%	7597.73	
2011	4	Late	Ensile	31.57%	7851.95	
2011	1	Spring	Bale	6.59%	.	*
2011	2	Spring	Bale	6.60%	4508.92	
2011	3	Spring	Bale	6.46%	2648.71	
2011	4	Spring	Bale	6.86%	4505.26	
2011	1	Spring	Ensile	6.59%	5643.82	
2011	2	Spring	Ensile	6.60%	6156.06	
2011	3	Spring	Ensile	6.46%	4566.93	
2011	4	Spring	Ensile	6.86%	3581.09	‡
2012	1	Early	Bale	12.58%	3335.77	Δ
2012	2	Early	Bale	12.85%	3358.47	Δ
2012	3	Early	Bale	12.30%	4583.26	Δ
2012	4	Early	Bale	13.46%	3576.87	Δ
2012	1	Early	Ensile	44.69%	4306.99	
2012	2	Early	Ensile	44.39%	4357.61	
2012	3	Early	Ensile	43.99%	4178.08	

Table 18 (cont'd)

2012	4	Early	Ensile	45.04%	4403.95	
2012	1	Mid	Bale	24.21%	4288.62	Δ
2012	2	Mid	Bale	24.59%	4767.48	Δ
2012	3	Mid	Bale	22.53%	2965.92	Δ
2012	4	Mid	Bale	22.78%	4510.86	Δ
2012	1	Mid	Ensile	35.44%	5542.10	
2012	2	Mid	Ensile	35.06%	5050.31	
2012	3	Mid	Ensile	34.52%	3704.07	
2012	4	Mid	Ensile	36.97%	4732.08	
2012	1	Late	Bale	13.83%	.	*
2012	2	Late	Bale	15.86%	3358.36	
2012	3	Late	Bale	13.47%	2566.43	
2012	4	Late	Bale	14.68%	2827.36	
2012	1	Late	Ensile	19.50%	4716.27	
2012	2	Late	Ensile	19.30%	4088.11	
2012	3	Late	Ensile	19.81%	4111.00	
2012	4	Late	Ensile	20.14%	4240.10	
2012	1	Spring	Bale	5.47%	5111.73	
2012	2	Spring	Bale	5.14%	5337.55	
2012	3	Spring	Bale	5.52%	2583.29	
2012	4	Spring	Bale	5.33%	.	*
2012	1	Spring	Ensile	5.82%	2873.94	
2012	2	Spring	Ensile	6.21%	3319.81	
2012	3	Spring	Ensile	5.92%	2813.35	
2012	4	Spring	Ensile	6.26%	3032.21	

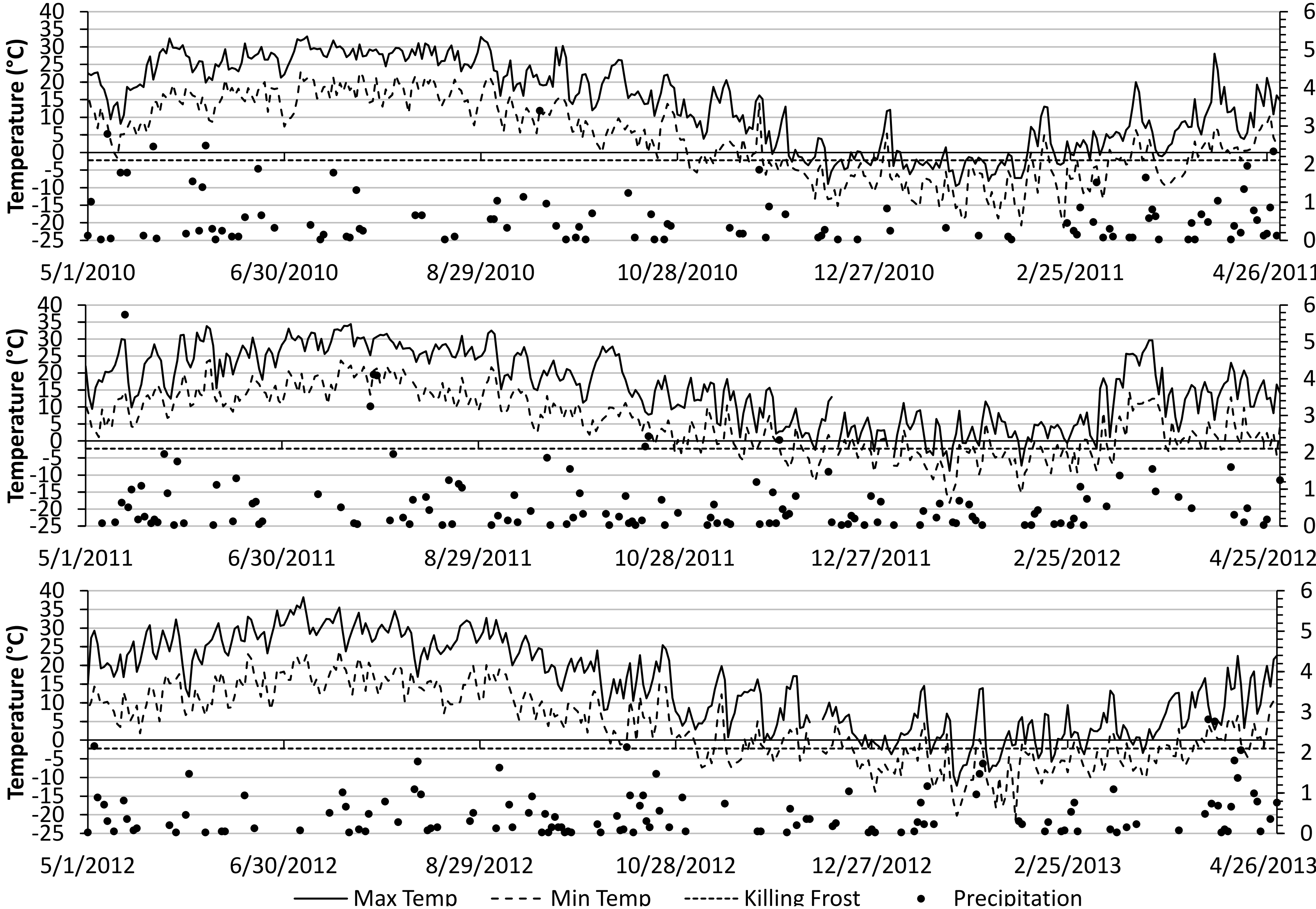

Figure 28. Climatological data during the study years. Data were obtained via the Michigan State University Enviro-Weather website. The station was located at the nearby Hancock Turfgrass Research Center.

Year	Block	Timing	0m Bale Moisture (%)	6m Bale Moisture (%)	0m Dry Bale Mass (kg)	6m Dry Bale Mass (kg)	% Dry Bale Loss	Notes
2010	1	Early	22.17%	.	27.82	.	.	‡
2010	2	Early	21.76%	.	28.04	.	.	‡
2010	3	Early	22.80%	.	28.50	.	.	‡
2010	4	Early	23.06%	.	30.96	.	.	‡
2010	1	Mid	24.95%	.	26.79	.	.	‡
2010	2	Mid	20.41%	.	25.78	.	.	‡
2010	3	Mid	20.92%	.	20.73	.	.	‡
2010	4	Mid	17.93%	.	32.80	.	.	‡
2010	1	Late	23.12%	.	28.91	.	.	‡
2010	2	Late	26.96%	.	25.18	.	.	‡
2010	3	Late	23.59%	.	26.76	.	.	‡
2010	4	Late	23.31%	.	29.99	.	.	‡
2010	1	Spring	7.73%	11.87%	25.20	24.85	1.39%	
2010	2	Spring	7.74%	11.82%	23.85	23.48	1.57%	
2010	3	Spring	8.35%	.	.	.	.	*
2010	4	Spring	8.04%	11.82%	22.49	21.90	2.61%	
2011	1	Early	22.23%	8.56%	30.72	28.37	7.66%	
2011	2	Early	23.12%	9.18%	38.88	37.98	2.32%	
2011	3	Early	16.92%	.	.	.	.	*
2011	4	Early	17.55%	6.83%	42.08	38.37	8.80%	
2011	1	Mid	22.84%	10.66%	25.20	26.14	-3.72%	
2011	2	Mid	23.35%	12.23%	27.22	27.41	-0.68%	
2011	3	Mid	25.02%	11.03%	20.20	20.46	-1.28%	
2011	4	Mid	25.51%	.	32.81	.	.	+
2011	1	Late	32.59%	13.39%	28.50	27.83	2.33%	
2011	2	Late	33.85%	11.84%	29.94	28.27	5.59%	
2011	3	Late	31.98%	8.58%	12.11	12.30	-1.53%	
2011	4	Late	26.87%	7.97%	35.63	34.29	3.75%	
2011	1	Spring	6.59%	.	.	.	.	*
2011	2	Spring	6.60%	.	16.76	.	.	†
2011	3	Spring	6.46%	.	9.84	.	.	†

Table 19. Raw bale storage loss data. *Baler mechanical issue. Could not bale plot. †Bale accidentally discarded by a third party. Could not obtain six month measurements. ‡Protocol misunderstanding. Measurements were not obtained. +Baler mechanical issue. Plot accidentally baled around another bale stuck in the baler. Obtained zero month bale mass, but needed to discard bale. Δ Round baler was out of order. Plot was baled with a small square baler.

Table 19 (cont'd)

2011	4	Spring	6.86%	.	16.74	.	.	†
2012	1	Early	12.58%	11.14%	12.40	13.26	-6.97%	Δ
2012	2	Early	12.85%	11.77%	12.48	13.23	-5.98%	Δ
2012	3	Early	12.30%	11.58%	17.03	13.68	19.70%	Δ
2012	4	Early	13.46%	10.69%	13.29	10.94	17.71%	Δ
2012	1	Mid	24.21%	14.25%	15.94	15.91	0.18%	Δ
2012	2	Mid	24.59%	15.31%	17.72	15.23	14.03%	Δ
2012	3	Mid	22.53%	13.10%	11.02	10.84	1.65%	Δ
2012	4	Mid	22.78%	14.36%	16.76	15.64	6.72%	Δ
2012	1	Late	13.83%	.	.	.	.	*
2012	2	Late	15.86%	10.07%	12.48	12.36	0.96%	
2012	3	Late	13.47%	10.06%	9.54	9.32	2.25%	
2012	4	Late	14.68%	10.19%	10.51	10.43	0.75%	
2012	1	Spring	5.47%	8.20%	18.99	19.25	-1.33%	
2012	2	Spring	5.14%	8.23%	19.84	20.02	-0.90%	
2012	3	Spring	5.52%	7.78%	9.60	9.67	-0.68%	
2012	4	Spring	5.33%	.	.	.	.	*

Year	Block	Timing	0m Silage Moisture (%)	6m Silage Moisture (%)	0m Dry Silage Mass (g)	6m Dry Silage Mass (g)	% Dry Silage Loss	Notes
2010	1	Early	47.31%	46.49%	.	161.50	.	†
2010	2	Early	47.95%	47.34%	.	151.30	.	†
2010	3	Early	45.19%	43.27%	.	151.80	.	†
2010	4	Early	47.50%	46.82%	.	159.70	.	†
2010	1	Mid	46.01%	.	.	.	.	†
2010	2	Mid	46.16%	.	.	.	.	†
2010	3	Mid	41.51%	.	.	.	.	†
2010	4	Mid	48.48%	.	.	.	.	†
2010	1	Late	29.47%	.	.	.	.	†
2010	2	Late	29.99%	.	.	.	.	†
2010	3	Late	30.46%	.	.	.	.	†
2010	4	Late	28.90%	.	.	.	.	†
2010	1	Spring	5.71%	7.06%	.	116.05	.	†
2010	2	Spring	6.02%	7.60%	.	142.42	.	†
2010	3	Spring	6.18%	7.51%	.	143.95	.	†
2010	4	Spring	6.00%	7.20%	.	142.29	.	†

Table 20. Raw ensilage storage loss data. *Measurement issue. Not used in final analysis. †Protocol misunderstanding. Measurements were not obtained.

Table 20 (cont'd)

2011	1	Early	48.06%	45.82%	.	239.16	.	†
2011	2	Early	50.10%	49.31%	.	292.18	.	†
2011	3	Early	47.56%	45.48%	.	282.67	.	†
2011	4	Early	49.55%	50.39%	.	273.56	.	†
2011	1	Mid	43.67%	43.76%	.	182.25	.	†
2011	2	Mid	44.52%	44.40%	.	190.63	.	†
2011	3	Mid	42.28%	43.38%	.	166.60	.	†
2011	4	Mid	45.02%	44.97%	.	157.20	.	†
2011	1	Late	35.48%	32.19%	196.37	198.60	-1.13%	*
2011	2	Late	30.91%	29.33%	207.85	204.36	1.68%	
2011	3	Late	30.06%	26.22%	120.59	119.61	0.81%	
2011	4	Late	31.57%	25.83%	71.01	69.92	1.53%	
2011	1	Spring	6.59%	6.47%	153.16	153.77	-0.40%	
2011	2	Spring	6.60%	6.65%	182.71	183.02	-0.17%	
2011	3	Spring	6.46%	6.60%	139.98	140.02	-0.03%	
2011	4	Spring	6.86%	6.38%	144.40	145.28	-0.61%	
2012	1	Early	44.69%	45.88%	180.50	160.07	11.32%	
2012	2	Early	44.39%	44.75%	188.53	175.07	7.14%	
2012	3	Early	43.99%	45.78%	211.80	190.74	9.94%	
2012	4	Early	45.04%	46.81%	208.13	191.06	8.20%	
2012	1	Mid	35.44%	33.08%	109.55	99.03	9.60%	
2012	2	Mid	35.06%	33.13%	134.54	124.71	7.31%	
2012	3	Mid	34.52%	34.91%	136.47	121.54	10.94%	
2012	4	Mid	36.97%	33.23%	129.13	125.06	3.15%	
2012	1	Late	19.50%	13.55%	124.07	123.02	0.85%	
2012	2	Late	19.30%	12.63%	140.97	142.12	-0.82%	*
2012	3	Late	19.81%	13.94%	124.76	123.15	1.29%	
2012	4	Late	20.14%	14.90%	137.70	135.24	1.79%	
2012	1	Spring	5.82%	5.66%	147.54	150.01	-1.67%	
2012	2	Spring	6.21%	4.79%	218.65	223.84	-2.37%	
2012	3	Spring	5.92%	6.06%	133.30	135.37	-1.55%	
2012	4	Spring	6.26%	5.44%	186.24	189.77	-1.90%	

Block	Timing	Method	Stand Frequency
1	Early	Bale	85
2	Early	Bale	88
3	Early	Bale	96
4	Early	Bale	85
1	Early	Ensile	97
2	Early	Ensile	89
3	Early	Ensile	95
4	Early	Ensile	93
1	Late	Bale	86
2	Late	Bale	84
3	Late	Bale	96
4	Late	Bale	87
1	Late	Ensile	91
2	Late	Ensile	89
3	Late	Ensile	97
4	Late	Ensile	91
1	Mid	Bale	86
2	Mid	Bale	93
3	Mid	Bale	91
4	Mid	Bale	94
1	Mid	Ensile	92
2	Mid	Ensile	94
3	Mid	Ensile	96
4	Mid	Ensile	88
1	Spring	Bale	87
2	Spring	Bale	76
3	Spring	Bale	94
4	Spring	Bale	82
1	Spring	Ensile	80
2	Spring	Ensile	83
3	Spring	Ensile	90
4	Spring	Ensile	85

Table 21. Raw spring 2013 stand frequency data.

Year	Block	Timing	Method	GluDigest	PenDigest	Cellulose	Xylose	Lignin	EtOH	EtOH (l/ha)	Notes
2010	1	Early	Harvest	0.1314	0.0302	42.99%	26.28%	22.57%	0.2210	.	
2010	2	Early	Harvest	0.1388	0.0287	39.44%	24.31%	22.02%	0.2035	.	
2010	3	Early	Harvest	0.1470	0.0279	39.97%	25.93%	20.91%	0.2106	.	
2010	4	Early	Harvest	0.1374	0.0279	42.78%	27.66%	22.61%	0.2251	.	
2010	1	Early	Bale	0.1206	0.0286	42.32%	25.63%	22.19%	0.2167	2056	
2010	2	Early	Bale	0.1291	0.0299	42.57%	27.05%	23.44%	0.2224	2126	
2010	3	Early	Bale	0.1204	0.0244	43.53%	27.62%	22.37%	0.2273	2210	
2010	4	Early	Bale	0.1249	0.0267	38.37%	25.56%	21.79%	0.2045	2159	
2010	1	Early	Ensile	0.1342	0.0321	42.75%	26.60%	22.87%	0.2214	2562	
2010	2	Early	Ensile	0.1404	0.0339	42.50%	26.99%	22.32%	0.2219	2716	
2010	3	Early	Ensile	0.1406	0.0279	38.47%	24.61%	23.04%	0.2015	2341	
2010	4	Early	Ensile	0.1388	0.0300	41.17%	26.98%	22.34%	0.2179	2920	
2010	1	Mid	Harvest	0.1292	0.0439	40.08%	26.56%	22.44%	0.2131	.	
2010	2	Mid	Harvest	0.1084	0.0278	39.08%	23.78%	22.01%	0.2006	.	
2010	3	Mid	Harvest	0.1088	0.0230	40.34%	27.21%	22.91%	0.2161	.	
2010	4	Mid	Harvest	0.1227	0.0398	42.00%	26.77%	22.40%	0.2197	.	
2010	1	Mid	Bale	0.1093	0.0337	37.49%	24.63%	22.11%	0.1986	1815	
2010	2	Mid	Bale	0.1160	0.0320	42.43%	28.17%	22.23%	0.2258	1985	
2010	3	Mid	Bale	0.1114	0.0268	38.98%	27.88%	22.95%	0.2143	1515	
2010	4	Mid	Bale	0.1043	0.0296	40.98%	25.42%	22.22%	0.2120	2371	
2010	1	Mid	Ensile	0.1201	0.0353	43.81%	27.55%	23.17%	0.2279	2712	
2010	2	Mid	Ensile	0.1144	0.0304	40.23%	25.82%	22.60%	0.2111	2514	
2010	3	Mid	Ensile	0.1282	0.0291	39.92%	26.38%	23.11%	0.2120	2427	

Table 22. Raw in vitro true digestibility, structural polysaccharide, lignin content, and theoretical ethanol yield data. Digestibility results are expressed as grams per gram dry biomass. Composition data are expressed as percent of dry biomass. Ethanol yield is expressed as grams per gram dry biomass and as liters per hectare. *Baler mechanical issue. Could not bale plot. †Bale accidentally discarded by a third party. Could not obtain six month measurements.

Table 22 (cont'd)

2010	4	Mid	Ensile	0.1213	0.0406	37.58%	24.92%	22.98%	0.1999	2756	
2010	1	Late	Harvest	0.1203	0.0370	41.71%	26.63%	23.22%	0.2183	.	
2010	2	Late	Harvest	0.1226	0.0444	41.61%	26.81%	22.32%	0.2187	.	
2010	3	Late	Harvest	0.1053	0.0316	39.06%	26.73%	21.59%	0.2106	.	
2010	4	Late	Harvest	0.1240	0.0358	40.32%	26.52%	21.86%	0.2137	.	
2010	1	Late	Bale	0.1307	0.0371	40.64%	27.00%	23.01%	0.2163	2133	
2010	2	Late	Bale	0.1157	0.0357	42.64%	27.42%	22.96%	0.2239	1922	
2010	3	Late	Bale	0.1126	0.0334	39.58%	27.32%	23.27%	0.2142	1955	
2010	4	Late	Bale	0.1024	0.0296	37.29%	25.91%	22.80%	0.2024	2070	
2010	1	Late	Ensile	0.1227	0.0355	38.27%	24.80%	22.76%	0.2016	2232	
2010	2	Late	Ensile	0.1138	0.0339	40.19%	26.52%	22.85%	0.2133	2333	
2010	3	Late	Ensile	0.1096	0.0332	42.28%	26.41%	22.79%	0.2193	2383	
2010	4	Late	Ensile	0.1200	0.0348	40.80%	26.97%	22.43%	0.2167	2693	
2010	1	Spring	Harvest	0.1264	0.0448	44.28%	26.29%	22.48%	0.2250	.	
2010	2	Spring	Harvest	0.1259	0.0400	42.81%	27.71%	22.04%	0.2254	.	
2010	3	Spring	Harvest	0.1223	0.0430	41.82%	27.50%	22.90%	0.2216	.	
2010	4	Spring	Harvest	0.1175	0.0383	42.28%	26.94%	23.44%	0.2211	.	
2010	1	Spring	Bale	0.1284	0.0498	38.23%	25.49%	23.40%	0.2038	1751	
2010	2	Spring	Bale	0.1282	0.0420	42.00%	26.46%	23.08%	0.2186	1779	
2010	3	Spring	Bale	.	.	.	.	.	.	.	*
2010	4	Spring	Bale	0.1194	0.0466	42.42%	27.15%	22.79%	0.2222	1704	
2010	1	Spring	Ensile	0.1309	0.0462	41.21%	25.97%	22.62%	0.2145	1909	
2010	2	Spring	Ensile	0.1184	0.0369	44.33%	26.69%	25.30%	0.2265	2108	
2010	3	Spring	Ensile	0.1222	0.0369	42.28%	25.97%	22.56%	0.2178	2054	
2010	4	Spring	Ensile	0.1211	0.0411	42.59%	26.91%	23.68%	0.2220	2227	
2011	1	Early	Harvest	0.1293	0.0228	37.78%	30.72%	22.38%	0.2203	.	

Table 22 (cont'd)

2011	2	Early	Harvest	0.1294	0.0238	37.46%	30.03%	22.67%	0.2170	.	
2011	3	Early	Harvest	0.1442	0.0311	36.44%	30.16%	19.09%	0.2143	.	
2011	4	Early	Harvest	0.1416	0.0247	37.11%	31.10%	23.12%	0.2196	.	
2011	1	Early	Bale	0.0984	0.0184	38.36%	32.09%	22.44%	0.2268	2376	
2011	2	Early	Bale	0.1138	0.0215	40.84%	31.95%	20.76%	0.2339	3102	
2011	3	Early	Bale	.	.	.	.	.	.	.	*
2011	4	Early	Bale	0.0954	0.0174	37.37%	30.92%	22.86%	0.2198	3154	
2011	1	Early	Ensile	0.1355	0.0211	40.13%	31.63%	23.11%	0.2306	3048	
2011	2	Early	Ensile	0.1251	0.0252	43.21%	29.66%	21.34%	0.2333	3169	
2011	3	Early	Ensile	0.1224	0.0218	37.07%	30.20%	21.18%	0.2164	2115	
2011	4	Early	Ensile	0.1029	0.0208	40.31%	29.85%	21.59%	0.2251	2995	
2011	1	Mid	Harvest	0.1039	0.0264	40.04%	31.89%	23.39%	0.2312	.	
2011	2	Mid	Harvest	0.0910	0.0264	40.12%	31.14%	23.21%	0.2289	.	
2011	3	Mid	Harvest	0.0841	0.0239	39.35%	30.72%	22.71%	0.2251	.	
2011	4	Mid	Harvest	0.0877	0.0272	44.29%	31.42%	22.99%	0.2426	.	
2011	1	Mid	Bale	0.0762	0.0212	42.67%	30.45%	21.91%	0.2343	2014	
2011	2	Mid	Bale	0.0978	0.0289	41.01%	30.65%	23.51%	0.2299	2135	
2011	3	Mid	Bale	0.0860	0.0217	37.61%	31.16%	21.20%	0.2213	1525	
2011	4	Mid	Bale	.	.	.	.	.	.	.	*
2011	1	Mid	Ensile	0.0971	0.0281	42.03%	31.21%	21.93%	0.2350	2560	
2011	2	Mid	Ensile	0.0898	0.0286	43.44%	31.37%	23.21%	0.2398	2707	
2011	3	Mid	Ensile	0.0952	0.0240	41.27%	30.89%	22.81%	0.2316	1985	
2011	4	Mid	Ensile	0.0814	0.0274	38.53%	31.77%	23.28%	0.2263	2386	
2011	1	Late	Harvest	0.0932	0.0279	38.89%	26.24%	23.11%	0.2084	.	
2011	2	Late	Harvest	0.0819	0.0244	42.19%	30.77%	23.19%	0.2340	.	
2011	3	Late	Harvest	0.0968	0.0266	36.91%	32.33%	21.77%	0.2232	.	

Table 22 (cont'd)

2011	4	Late	Harvest	0.0775	0.0240	44.58%	30.88%	22.39%	0.2416	.	
2011	1	Late	Bale	0.0931	0.0262	41.26%	31.21%	22.07%	0.2327	2261	
2011	2	Late	Bale	0.0878	0.0276	37.12%	30.47%	23.71%	0.2175	2221	
2011	3	Late	Bale	0.0773	0.0218	38.81%	31.98%	22.37%	0.2278	941	
2011	4	Late	Bale	0.1001	0.0270	39.88%	31.13%	23.28%	0.2282	2772	
2011	1	Late	Ensile	0.0957	0.0300	43.74%	31.36%	20.75%	0.2407	2558	
2011	2	Late	Ensile	0.0636	0.0180	37.95%	30.82%	23.97%	0.2212	2270	
2011	3	Late	Ensile	0.0923	0.0228	40.38%	30.73%	23.24%	0.2283	2198	
2011	4	Late	Ensile	0.0939	0.0297	43.21%	31.75%	21.94%	0.2404	2392	
2011	1	Spring	Harvest	0.0843	0.0281	41.29%	32.12%	22.87%	0.2358	.	
2011	2	Spring	Harvest	0.0953	0.0321	39.24%	30.29%	22.45%	0.2233	.	
2011	3	Spring	Harvest	0.0957	0.0308	41.41%	31.22%	22.36%	0.2331	.	
2011	4	Spring	Harvest	0.0988	0.0296	41.77%	32.49%	23.57%	0.2386	.	
2011	1	Spring	Bale	.	.	.	.	.	.	.	†
2011	2	Spring	Bale	.	.	.	.	.	.	.	†
2011	3	Spring	Bale	.	.	.	.	.	.	.	†
2011	4	Spring	Bale	.	.	.	.	.	.	.	†
2011	1	Spring	Ensile	0.0943	0.0321	37.59%	30.36%	24.19%	0.2185	1563	
2011	2	Spring	Ensile	0.0944	0.0299	39.60%	30.38%	22.56%	0.2247	1753	
2011	3	Spring	Ensile	0.0883	0.0306	38.41%	32.40%	23.68%	0.2280	1320	
2011	4	Spring	Ensile	0.1012	0.0334	39.41%	30.80%	23.09%	0.2256	1024	
2012	1	Early	Harvest	0.1263	0.0253	36.23%	29.88%	19.89%	0.2128	.	
2012	2	Early	Harvest	0.1301	0.0209	30.02%	27.23%	18.84%	0.1847	.	
2012	3	Early	Harvest	0.1298	0.0234	34.18%	28.64%	18.25%	0.2022	.	
2012	4	Early	Harvest	0.1251	0.0267	32.30%	28.27%	18.41%	0.1952	.	
2012	1	Early	Bale	0.1265	0.0232	36.37%	29.28%	18.40%	0.2111	893	

Table 22 (cont'd)

2012	2	Early	Bale	0.1173	0.0224	37.52%	29.21%	19.56%	0.2144	913	
2012	3	Early	Bale	0.1195	0.0203	38.73%	31.27%	19.67%	0.2251	1308	
2012	4	Early	Bale	0.1363	0.0269	36.04%	29.98%	20.07%	0.2125	963	
2012	1	Early	Ensile	0.1305	0.0348	33.83%	27.72%	18.97%	0.1980	1081	
2012	2	Early	Ensile	0.1128	0.0180	31.57%	29.97%	19.27%	0.1988	1098	
2012	3	Early	Ensile	0.1091	0.0192	35.30%	30.65%	20.52%	0.2126	1126	
2012	4	Early	Ensile	0.1046	0.0204	33.88%	29.59%	20.81%	0.2046	1142	
2012	1	Mid	Harvest	0.1158	0.0274	37.31%	29.92%	21.21%	0.2162	.	
2012	2	Mid	Harvest	0.0995	0.0240	36.62%	29.75%	19.48%	0.2135	.	
2012	3	Mid	Harvest	0.1069	0.0255	36.39%	30.20%	20.35%	0.2143	.	
2012	4	Mid	Harvest	0.0976	0.0221	37.66%	30.57%	20.86%	0.2195	.	
2012	1	Mid	Bale	0.0963	0.0232	36.94%	30.09%	20.21%	0.2156	1172	
2012	2	Mid	Bale	0.0899	0.0209	34.37%	28.42%	21.12%	0.2021	1221	
2012	3	Mid	Bale	0.0876	0.0216	35.96%	29.78%	22.28%	0.2116	795	
2012	4	Mid	Bale	0.0973	0.0233	37.88%	29.74%	22.60%	0.2173	1242	
2012	1	Mid	Ensile	0.1041	0.0325	37.03%	33.48%	20.79%	0.2275	1598	
2012	2	Mid	Ensile	0.0911	0.0249	38.80%	32.23%	22.69%	0.2286	1463	
2012	3	Mid	Ensile	0.0915	0.0291	37.64%	32.01%	22.42%	0.2244	1053	
2012	4	Mid	Ensile	0.0858	0.0228	37.31%	31.18%	20.27%	0.2205	1322	
2012	1	Late	Harvest	0.1068	0.0317	38.71%	32.19%	21.60%	0.2282	.	
2012	2	Late	Harvest	0.0937	0.0333	35.07%	31.38%	21.76%	0.2143	.	
2012	3	Late	Harvest	0.1028	0.0319	38.40%	30.17%	21.28%	0.2203	.	
2012	4	Late	Harvest	0.1017	0.0332	36.31%	29.35%	20.35%	0.2112	.	
2012	1	Late	Bale	.	.	.	.	.	.	.	*
2012	2	Late	Bale	0.1047	0.0329	35.52%	31.06%	21.03%	0.2146	913	
2012	3	Late	Bale	0.1025	0.0341	36.95%	31.04%	20.39%	0.2189	712	

Table 22 (cont'd)

2012	4	Late	Bale	0.0900	0.0304	36.47%	30.89%	20.39%	0.2169	777	
2012	1	Late	Ensile	0.1047	0.0341	36.34%	30.69%	20.82%	0.2159	1290	
2012	2	Late	Ensile	0.0981	0.0315	39.43%	31.17%	20.01%	0.2269	1176	
2012	3	Late	Ensile	0.0905	0.0309	37.36%	30.44%	20.65%	0.2181	1136	
2012	4	Late	Ensile	0.1031	0.0391	37.77%	31.24%	22.18%	0.2221	1194	
2012	1	Spring	Harvest	0.0984	0.0348	39.90%	32.47%	20.59%	0.2328	.	
2012	2	Spring	Harvest	0.0930	0.0318	37.36%	30.96%	21.36%	0.2199	.	
2012	3	Spring	Harvest	0.1058	0.0361	40.55%	32.09%	20.55%	0.2335	.	
2012	4	Spring	Harvest	0.1045	0.0356	37.77%	30.77%	22.38%	0.2205	.	
2012	1	Spring	Bale	0.1275	0.0422	42.85%	35.88%	20.89%	0.2535	1642	
2012	2	Spring	Bale	0.1045	0.0312	41.25%	33.96%	22.17%	0.2420	1637	
2012	3	Spring	Bale	0.1105	0.0361	38.79%	35.64%	21.52%	0.2403	787	
2012	4	Spring	Bale	.	.	.	.	.	.	.	*
2012	1	Spring	Ensile	0.1222	0.0385	40.89%	37.49%	20.31%	0.2530	922	
2012	2	Spring	Ensile	0.1252	0.0368	41.70%	33.51%	20.45%	0.2419	1018	
2012	3	Spring	Ensile	0.1075	0.0343	37.94%	36.17%	21.36%	0.2395	854	
2012	4	Spring	Ensile	0.1119	0.0351	43.18%	38.20%	20.79%	0.2624	1008	

GaBi 6.0 Model Assumptions

General Model Assumptions

- The 2013 MSU Custom Work Rates fuel consumption estimates represented the fuel consumption for all the farm equipment used and modeled in this study. Fuel price per liter reflects ten year fuel cost.

- Lubrication and any other additional maintenance requirements, beyond diesel, were not taken into account for any of the equipment or transportation in this study. Lubrication was taken into account in the cost analysis. Costs were obtained from 2013 MSU Custom Work Rates.

- All lost biomass during establishment, harvest, transportation, and storage was accounted for in the net CO_2 flux elementary input flow in the switchgrass stand cultivation unit process. All harvest, transport, and storage unit processes were assumed to preserve 100% of the biomass.

- Environmental burdens due to the production and disposal of any farm equipment or transportation equipment were not taken into account.

- All diesel requirements came from average diesel production in the United States.

- Empirical harvest yield data were representative of a typical switchgrass bioenergy production system, with a ten year lifetime, in the Northern Corn Belt/Great Lakes region.

- Cumulative three year harvest yield data, scaled up to ten years, are representative of actual cumulative harvest yields of a ten year dedicated switchgrass bioenergy system.

Specific Unit Process Assumptions

Boom Sprayer

- S-metolachlor and atrazine was sprayed evenly across the field.

- Atrazine was $16.08 per kg and s-metolachlor was $72.04 per kg (Pestrong.com).

Fertilizer Application

- Granular urea was applied evenly across the field.

- Granular urea (46-0-0) was $310.00 per 1000 kg (Alibaba.com)

Drill Press Seed Planter

- The Cave-In-Rock switchgrass seed was planted evenly across the field.
- The "CH: grass seed IP, at farm" flow was representative of Cave-In-Rock switchgrass seed.
- Seeding rate was 9 kg/ha.
- Cave-In-Rock switchgrass was $33.07 per kg (Welter Seed & Honey Co.)

Switchgrass Cultivation

- Soil properties and soil quality was uniform across the study field.
- Switchgrass growth was uniform across the study field.
- CO_2 was not released during chisel plowing and field cultivating.
- Any CO_2 sequestration due to increases of soil organic matter or below-ground biomass growth was not taken into accounted.
- Literature values for environmental elementary flow outputs for switchgrass fields were representative of this study.
- Total harvestable dry biomass was assumed to be 10,000 kg/ha for ease of comparison.
- Hemeroby occupied arable land flow, available in GaBi 6.0, represented the agricultural land use input needed for the switchgrass cultivation unit process.

Forage Chopper

- Exactly 3.05 m x 12.2 m of switchgrass was harvested from each plot.
- Truck fuel use during biomass loading in the field was not taken into account.

Silage Truck Transport to Pretreatment Facility

- Transported at 70 km/hr, on average, for 80.5 km.

- Truck weight and fuel efficiency were uniform across the entire truck fleet.
- Truck trailer volumes were uniform across the entire truck fleet.
- Dry matter density was independent of moisture content for switchgrass. (The Dairy Advisory Group)

Bunker Silo Silage Storage

- Bunker silo material and construction environmental burdens were not included in assessment.
- Bunker silo size was 9.1 m x 4.88 m x 36.6 m (w x h x l).
- The biomass angle at the front end of the bunker silo was 30 degrees.
- Fuel use due to shoveling and compaction of the biomass into the bunker silo was not taken into account.
- 8 mil, white plastic polyethylene (PE) tarp was used to cover the biomass.
- Tarp cost $7.70 per kg. (Secure Covers, Thomas & Fontaine Ltd)
- PE tarp was reused for 5 years before disposal.
- Dry matter density was independent of moisture content for switchgrass. (The Dairy Advisory Group)
- Data for corn stover silage was representative of switchgrass silage.

PE Film Production (Both Harvest/Storage Method Scenarios)

- European PE film production unit process was representative of both PE netting and PE tarp production.

Windrower

- Exactly 3.05 m x 12.2 m of switchgrass was windrowed in each plot.

Tractor with Raker

- Early fall harvests require three turns, mid fall harvests require two turns, late fall harvests require one turn, spring harvests require zero turns.

Tractor with Round Baler

- Bales were uniform in size (1.22 m wide x 1.52 m diameter) and weight.
- Bales were wrapped three times around with PE netting. John Deere CoverEdge wrap netting was used.
- Wrap netting was $7.64 per kg.

Bale Truck Transport to Pretreatment Facility

- Fuel use for loading bales was not taken into account.
- Transported at 70km/hr, on average, for 80.5 km.
- Truck weight and fuel efficiency were uniform across the entire truck fleet.
- Truck trailer bale capacity was uniform across the entire truck fleet.
- Bales were transported at the same moisture content of 10%.

Bale Indoor Storage

- Fuel use for unloading and storing bales was not taken into account.
- Bales were stored indoors and uncovered.
- Barn material and construction environmental burdens were not included in assessment.
- Additional operations (electricity and heating) were not needed for the storage barn.

End of Life Scenario: PE Waste

- 90% landfill rate. 10% incineration rate. 0% recycling rate due to PE degradation and biomass contamination.
- The tarp was made of 100% PE.

Cumulative Ten Year Average Switchgrass Harvest Yields and Moisture Contents at Transport

Avg Cumulative 10 Year Dry Harvest Yield (kg/ha)	Harvest Timing			
Harvest/Storage Method	Early	Mid	Late	Spring
Cut/Bale	71631	61213	58388	48828
Chop/Ensile	79280	75259	70697	51425

Table 23. Average cumulative ten year switchgrass dry yields (kg/ha).

Avg 10 Year Moisture Content at Transport	Harvest Timing			
Harvest/Storage Method	Early	Mid	Late	Spring
Cut/Bale	10.00%	10.00%	10.00%	10.00%
Chop/Ensile	46.78%	41.64%	27.13%	6.22%

Table 24. Average cumulative ten year switchgrass moisture contents at transport.

Final Model Unit Process Input/Output Values

Unit Process	Inputs	Scenario		Unit	Outputs	Scenario	Unit
Boom Sprayer	Diesel	EarlyChop	0.0118	L/1000 kg dry SG	Atrazine		
		MidChop	0.0124		S-Metolachlor		
		LateChop	0.0132				
		SpringChop	0.0182				
		EarlyBale	0.0131				
		MidBale	0.0153				
		LateBale	0.0160				
		SpringBale	0.0192				
Fertilizer Application	Diesel	EarlyChop	0.4770	L/1000 kg dry SG	Granular Urea		
		MidChop	0.5025				
		LateChop	0.5349				
		SpringChop	0.7354				
		EarlyBale	0.5279				
		MidBale	0.6178				
		LateBale	0.6477				
		SpringBale	0.7745				
Drill Press Seed Planter	Diesel	EarlyChop	0.0720	L/1000 kg dry SG	SG Seeds		
		MidChop	0.0758				
		LateChop	0.0807				
		SpringChop	0.1110				
		EarlyBale	0.0797				
		MidBale	0.0932				
		LateBale	0.0977				
		SpringBale	0.1169				

Table 25. Switchgrass cultivation phase unit process input/output data. All data are standardized to the reference flow of 1000 kg of switchgrass.

Table 25 (cont'd)

Switchgrass Cultivation	Land	EarlyChop	0.1261	ha/1000 kg dry SG	Switchgrass		1000	kg dry SG
		MidChop	0.1329		N2O	EarlyChop	0.2296	kg/1000 kg dry SG
		LateChop	0.1414			MidChop	0.2418	
		SpringChop	0.1945			LateChop	0.2574	
		EarlyBale	0.1396			SpringChop	0.3539	
		MidBale	0.1634			EarlyBale	0.2541	
		LateBale	0.1713			MidBale	0.2973	
		SpringBale	0.2048			LateBale	0.3117	
	CO2	EarlyChop	-1292.97	kg/1000 kg dry SG		SpringBale	0.3727	
		MidChop	-1227.40		CH4	EarlyChop	0.0547	kg/1000 kg dry SG
		LateChop	-1152.99			MidChop	0.0576	
		SpringChop	-838.69			LateChop	0.0613	
		EarlyBale	-1168.22			SpringChop	0.0843	
		MidBale	-998.33			EarlyBale	0.0605	
		LateBale	-952.24			MidBale	0.0708	
		SpringBale	-796.34			LateBale	0.0742	
	Atrazine	EarlyChop	0.0227	kg/1000 kg dry SG		SpringBale	0.0887	
		MidChop	0.0239		NH3	EarlyChop	0.6565	kg/1000 kg dry SG
		LateChop	0.0255			MidChop	0.6915	
		SpringChop	0.0350			LateChop	0.7362	
		EarlyBale	0.0251			SpringChop	1.0120	
		MidBale	0.0294			EarlyBale	0.7266	
		LateBale	0.0308			MidBale	0.8502	
		SpringBale	0.0369			LateBale	0.8914	
	S-Metolachlor	EarlyChop	0.0164	kg/1000 kg dry SG		SpringBale	1.0659	
		MidChop	0.0173		NO3-	EarlyChop	7.2033	kg/1000 kg dry SG
		LateChop	0.0184			MidChop	7.5881	
		SpringChop	0.0253			LateChop	8.0779	

Table 25 (cont'd)

		EarlyBale	0.0181			SpringChop	11.1051
		MidBale	0.0212			EarlyBale	7.9725
		LateBale	0.0223			MidBale	9.3293
		SpringBale	0.0266			LateBale	9.7808
	Granular Urea	EarlyChop	11.8820	kg/1000 kg dry SG		SpringBale	11.6956
		MidChop	12.5167				
		LateChop	13.3246				
		SpringChop	18.3180				
		EarlyBale	13.1508				
		MidBale	15.3888				
		LateBale	16.1335				
		SpringBale	19.2920				
	SG Seed	EarlyChop	0.1135	kg/1000 kg dry SG			
		MidChop	0.1196				
		LateChop	0.1273				
		SpringChop	0.1750				
		EarlyBale	0.1256				
		MidBale	0.1470				
		LateBale	0.1541				
		SpringBale	0.1843				
	Diesel	EarlyChop	0.1605	L/1000 kg dry SG			
		MidChop	0.1690				
		LateChop	0.1799				
		SpringChop	0.2474				
		EarlyBale	0.1776				
		MidBale	0.2078				
		LateBale	0.2179				
		SpringBale	0.2605				

Unit Process	Inputs	Scenario		Unit	Outputs		Unit
Tractor with Round Baler	Diesel	EarlyBale	0.4570	L/1000 kg dry SG	Switchgrass	1000	kg dry SG
		MidBale	0.5348		PE Netting	0.4621	kg/1000 kg dry SG
		LateBale	0.5607				
		SpringBale	0.6705				
	PE Netting		0.4621	kg/1000 kg dry SG			
	Switchgrass		1000	kg dry SG			
Tractor with Raker	Diesel	Early (3 turns)	1.9588	L/1000 kg dry SG	Switchgrass	1000	kg dry SG
		Mid (2 turns)	1.5281				
		Late (1 turn)	0.8010				
		Spring (0 turns)	0				
	Switchgrass		1000	kg dry SG			
Windrower	Diesel	EarlyBale	0.6529	L/1000 kg dry SG	Switchgrass	1000	kg dry SG
		MidBale	0.7640				
		LateBale	0.8010				
		SpringBale	0.9578				
	Switchgrass		1000	kg dry SG			
Bale Truck Transport	Diesel		4.8600	L/1000 kg dry SG	Switchgrass	1000	kg dry SG
	Switchgrass		1000	kg dry SG	PE Netting	0.4621	kg/1000 kg dry SG
	PE Netting		0.4621	kg/1000 kg dry SG			
PE Netting Production					PE Netting	0.4621	kg/1000 kg dry SG
Bale Indoor Storage	Switchgrass		1000	kg dry SG	Switchgrass	1000	kg dry SG
	Land		1.4516	m^2/1000 kg dry SG	PE Netting	0.4621	kg/1000 kg dry SG
	PE Netting		0.4621	kg/1000 kg dry SG			
EOL: PE Netting Disposal	PE Netting		0.4621	kg/1000 kg dry SG			

Table 26. Cut/bale phase unit process input/output data. All data are standardized to the reference flow of 1000 kg of switchgrass.

Unit Process	Inputs	Scenario		Unit	Outputs		Unit
Forage Chopper	Diesel	EarlyChop	2.1945	L/1000 kg dry SG	Switchgrass	1000	kg dry SG
		MidChop	2.3117				
		LateChop	2.4609				
		SpringChop	3.3832				
	Switchgrass		1000	kg dry SG			
Silage Truck Transport	Diesel	EarlyChop	6.0772	L/1000 kg dry SG	Switchgrass	1000	kg dry SG
		MidChop	5.9754				
		LateChop	5.7835				
		SpringChop	5.6289				
	Switchgrass		1000	kg dry SG			
Bunker Silo Silage Storage	Switchgrass		1000	kg dry SG	Switchgrass	1000	kg dry SG
	PE Tarp		0.0706	kg/1000 kg dry SG	PE Tarp	0.0706	kg/1000 kg dry SG
	Land		0.8878	m2/1000 kg dry SG			
PE Tarp Production					PE Tarp	0.0706	kg/1000 kg dry SG
EOL: Plastic Tarp Disposal	PE Tarp		0.0706	kg/1000 kg dry SG			

Table 27. Chop/ensile phase unit process input/output data. All data are standardized to the reference flow of 1000 kg of switchgrass.

Unit Process Input/Output Flows & Data Calculations

Boom Sprayer

Inputs: Diesel

Outputs: Atrazine, S-Metolachlor

Diesel

Fuel Use Rate: 0.9354 L/ha (Stein, 2012)

Calculation: (Fuel Use Rate/Switchgrass Dry Yield)*1000 = L of diesel/1000 kg dry switchgrass

Final Data:

EarlyChop	0.011798729
MidChop	0.012429024
LateChop	0.013231194
SpringChop	0.018189624
EarlyBale	0.013058651
MidBale	0.015280958
LateBale	0.016020507
SpringBale	0.019156853

Fertilizer Application

Inputs: Diesel

Outputs: Granular Urea (46-0-0 NPK)

Diesel

John Deere 5225 (45hp PTO) with 4.57 m applicator

Fuel Use Rate: 37.8156 L/ha for 12 years (Stein, 2012)

Calculation: (Fuel Use Rate/Switchgrass Dry Yield)*1000 = L of diesel/1000 kg dry switchgrass

Final Data:

EarlyChop	0.476989524
MidChop	0.502470604

LateChop	0.534900068
SpringChop	0.735355495
EarlyBale	0.527924645
MidBale	0.617766295
LateBale	0.647664188
SpringBale	0.774457888

<u>Drill Press Seed Planter</u>

Inputs: Diesel

Outputs: Switchgrass Seed

Diesel

Fuel Use Rate: 5.7059 L/ha (Stein, 2012)

Calculation: (Fuel Use Rate/Switchgrass Dry Yield)*1000 = L of diesel/1000 kg dry switchgrass

Final Data:

EarlyChop	0.07197174
MidChop	0.075816515
LateChop	0.080709715
SpringChop	0.110955926
EarlyBale	0.079657211
MidBale	0.09321319
LateBale	0.097724407
SpringBale	0.116855987

<u>Switchgrass Cultivation</u>

Inputs: Diesel, Occupied Arable Land, Carbon Dioxide (CO_2), Atrazine, S-Metolachlor, Granular Urea, Switchgrass Seed

Outputs: Switchgrass, Nitrous Oxide (N_2O), Methane (CH_4), Ammonia (NH_3), Nitrate (NO_3^-)

Diesel

Fuel Use for Chisel Plow: 5.6124L/ha (Stein, 2012)

Fuel Use for Field Cultivator (2x passes): 7.1090L/ha (Stein, 2012)

Total Fuel Use Rate: 12.7214 L/ha

Calculation: (Total Fuel Use Rate/Switchgrass Dry Yield)*1000 = L of diesel/1000 kg dry switchgrass

Final Data:

EarlyChop	0.160462204
MidChop	0.169034196
LateChop	0.179943667
SpringChop	0.247378103
EarlyBale	0.177597091
MidBale	0.207820374
LateBale	0.217878209
SpringBale	0.260532388

Occupied Arable Land

Assume: 100000 kg possible harvestable switchgrass per ha in ten years

Calculation: 10000/Switchgrass Dry Yield = ha/1000 kg dry switchgrass

Final Data:

EarlyChop	0.126135649
MidChop	0.132873894
LateChop	0.141449578
SpringChop	0.194458238
EarlyBale	0.13960499
MidBale	0.163362817
LateBale	0.17126905
SpringBale	0.204798519

Carbon Dioxide

Cave-In-Rock Switchgrass = 444.8 kg C/1000 kg dry switchgrass = -1630.9 kg sequestered CO_2/1000 kg dry switchgrass (Alexander et al., 2008)

Calculation: ((Switchgrass Dry Yield/(100000 kg harvestable switchgrass/ha))* (-1630.9 kg sequestered CO_2/1000 kg dry switchgrass)) = kg sequestered CO_2/1000 kg dry switchgrass

Final Data:

EarlyChop	-1292.97
MidChop	-1227.4
LateChop	-1152.99
SpringChop	-838.689
EarlyBale	-1168.22
MidBale	-998.33
LateBale	-952.244
SpringBale	-796.344

Atrazine

Application Rate: 1.8 kg/ha

Calculation: (Application Rate/Switchgrass Dry Yield)*1000 = kg atrazine/1000 kg dry switchgrass

Final Data:

EarlyChop	0.022704
MidChop	0.023917
LateChop	0.025461
SpringChop	0.035002
EarlyBale	0.025129
MidBale	0.029405
LateBale	0.030828
SpringBale	0.036864

S-Metolachlor

Application Rate: 1.3 kg/ha

Calculation: (Application Rate/Switchgrass Dry Yield)*1000 = kg s-metolachlor/1000 kg dry switchgrass

Final Data:

EarlyChop	0.016398
MidChop	0.017274
LateChop	0.018388
SpringChop	0.02528
EarlyBale	0.018149
MidBale	0.021237
LateBale	0.022265
SpringBale	0.026624

Granular Urea

Yearly Application Rate: 78.5 kg/ha

Application Rate: 942 kg/ha over 12 years (2 of the 3 establishment years + 10 cultivation years)

Calculation: (Application Rate/Switchgrass Dry Yield)*1000 = kg granular urea/1000 kg dry switchgrass

Final Data:

EarlyChop	11.88198
MidChop	12.51672
LateChop	13.32455
SpringChop	18.31797
EarlyBale	13.15079
MidBale	15.38878
LateBale	16.13354
SpringBale	19.29202

Switchgrass Seed

Seeding Rate: 9.0 kg/ha

Calculation: (Seeding Rate/Switchgrass Dry Yield)*1000 = kg switchgrass seed/1000 kg dry switchgrass

Final Data:

EarlyChop	0.113522
MidChop	0.119587
LateChop	0.127305
SpringChop	0.175012
EarlyBale	0.125644
MidBale	0.147027
LateBale	0.154142
SpringBale	0.184319

Nitrous Oxide (air emission)

Emission Rate: 0.042 kg N_2O/kg N applied in the form of granular urea (Cherubini and Jungmeier, 2009)

Calculation: ((kg granular urea/1000kg dry switchgrass)*46% N)*Emission Rate = kg N_2O/1000 kg dry switchgrass

Final Data:

EarlyChop	0.229559817
MidChop	0.241823047
LateChop	0.257430312
SpringChop	0.353903104
EarlyBale	0.254073263
MidBale	0.297311179
LateBale	0.311700079
SpringBale	0.372721836

Methane (air emission)

Emission Rate: 0.01 kg CH_4/kg N applied in the form of granular urea (Cherubini and Jungmeier, 2009)

Calculation: ((kg granular urea/1000 kg dry switchgrass)*46% N)*Emission Rate = kg CH_4/1000 kg dry switchgrass

Final Data:

EarlyChop	0.054657
MidChop	0.057577
LateChop	0.061293
SpringChop	0.084263
EarlyBale	0.060494
MidBale	0.070788
LateBale	0.074214
SpringBale	0.088743

Ammonia (air emission)

At study's granular urea application rate, Emission Rate: 52.044 kg NH_3/ha for 12 years (Cherubini and Jungmeier, 2009)

Calculation: (Emission Rate/Switchgrass Dry Yield)*1000 = kg NH_3/1000 kg dry switchgrass

Final Data:

EarlyChop	0.65646037
MidChop	0.691528896

LateChop	0.736160186
SpringChop	1.012038455
EarlyBale	0.726560208
MidBale	0.850205446
LateBale	0.891352642
SpringBale	1.065853413

Nitrate (fresh water emission)

At studies granular urea application rate, Emission Rate: 571.0776 kg NO_3^-/ha for 12 years (Cherubini and Jungmeier, 2009)

Calculation: (Emission Rate/Switchgrass Dry Yield)*1000 = kg NO_3^-/1000 kg dry switchgrass

Final Data:

EarlyChop	7.203324357
MidChop	7.588130476
LateChop	8.077868578
SpringChop	11.10507439
EarlyBale	7.972528242
MidBale	9.329284563
LateBale	9.780791786
SpringBale	11.69558468

<u>Tractor with Round Baler (John Deere 582 Baler)</u>

Inputs: Switchgrass, PE Netting, Diesel

Outputs: Switchgrass, PE Netting

Diesel

Fuel Use Rate: 32.7388 L/ha (Stein, 2012)

Calculation: (Fuel Use Rate/Switchgrass Dry Yield (Baled scenarios))*1000 = L of diesel/1000 kg dry switchgrass

Final Data:

EarlyBale	0.457049983
MidBale	0.53483026
LateBale	0.560714316
SpringBale	0.670485776

Polyethylene Netting (John Deere Cover Edge Netting Wrap)

PE net wrap: 0.01119 kg PE/m of wrap (Ambraco, Inc.)

At 3 wraps, it requires 16.52 m of wrap per bale according to John Deere Cover Edge Calculator (John Deere)

One bale assumed to be 400 kg dry switchgrass (Mani et al., 2009). 0.18486 kg PE/bale.

Final Data: 0.46214 kg PE/1000 kg dry switchgrass

<u>Tractor with Raker</u>

Inputs: Switchgrass, Diesel

Outputs: Switchgrass

Diesel

Fuel Use Rate: 46.7698 L/ha for ten years (Stein, 2012)

Calculation: (Fuel Use Rate/Switchgrass Dry Yield (Baled scenarios))*1000*# of turns = L of diesel/1000 kg dry switchgrass

Final Data:

EarlyBale (3 turns)	1.958789233
MidBale (2 turns)	1.528089258
LateBale (1 turn)	0.80102192
SpringBale (0 turns)	0

<u>Windrower</u>

Inputs: Switchgrass, Diesel

Outputs: Switchgrass

Diesel

Fuel Use Rate: 46.7698 L/ha for ten years (Stein, 2012)

Calculation: (Fuel Use Rate/Switchgrass Dry Yield (Baled scenarios))*1000 = L of diesel/1000 kg dry switchgrass

Final Data:

EarlyBale	0.652929744
MidBale	0.764044629
LateBale	0.80102192
SpringBale	0.957838578

Bale Truck Transport of Bales to Pretreatment Facility

Inputs: Switchgrass, PE Netting, Diesel

Outputs: Switchgrass PE Netting

Diesel

Truck empty weight was 14515 kg (Cook and Shinners, 2011). 27 bales per truck (Cook and Shinners, 2011). Bales were 444.44 kg wet switchgrass (Mani et al., 2009). All bales were baled at an assumed 10% moisture content (table 24).

Truck gross weight = empty truck weight + total wet weight of switchgrass

Fuel use equation: km/L = -0.00005052(truck gross weight (kg)) + 4.133 (Cook and Shinners, 2011).

Fuel use (full load of bales): 2.794 km/L = 2.668 L/1000 kg dry switchgrass at 80.5 km traveling distance to pretreatment facility (Broeren, 2012).

Fuel use (empty load): 3.4 km/L = 2.193 L/1000 kg dry switchgrass during empty return trip.

Total Fuel Use: 4.86 L/1000 kg dry switchgrass

Bale Indoor Storage

Inputs: Occupied Arable Land, Switchgrass, PE Netting

Outputs: Switchgrass, PE Netting (waste)

Occupied Arable Land

Assume bales stacked four high on their ends.

Bale base area = 2.323 m^2. Bale weight = 400 kg dry switchgrass (Mani et al., 2009)

Calculation: 2.323 m^2 land/1600 kg dry switchgrass = 1.4516 m^2/1000 kg dry switchgrass

Final data: 1.4516 m^2/1000 kg dry switchgrass

Forage Chopper (Hesston Field Queen 7650)

Inputs: Switchgrass, Diesel

Outputs: Switchgrass

Diesel

Fuel Use Rate: 173.98 L/ha for ten years (Stein, 2012).

Calculation: (Fuel Use Rate/Switchgrass Dry Yield (Chopped scenarios))*1000= L of diesel/1000 kg dry switchgrass

Final Data:

EarlyChop	2.194508
MidChop	2.31174
LateChop	2.46094
SpringChop	3.383184

Silage Truck Transport to Pretreatment Facility

Inputs: Switchgrass, Diesel

Outputs: Switchgrass

Diesel

Assumed: Truck empty weight was 14515 kg (Cook and Shinners, 2011). Truck bed volume is 114 m^3 (Cook and Shinners, 2011). Dry matter density is independent of moisture content for grasses (The Dairy Advisory Group). Silage biomass density = 80 dry kg silage/m^3 (Mani et al., 2009). Truck travels at 70 km/hr (Cook and Shinners, 2011).

Total wet weight of switchgrass per truck = (80 kg dry switchgrass/m^3)*((100%-Harvest Moisture Content at Transport % (table 24))$^{-1}$)*114 m^3

Truck gross weight = empty truck weight + total wet weight of switchgrass per truck

Fuel use equation: km/L = -0.00005052(truck gross weight (kg)) + 4.133 (Cook and Shinners, 2011).

Fuel use (full load):

EarlyChop	2.533994
MidChop	2.610263
LateChop	2.767396
SpringChop	2.908401

Fuel use (empty load): 3.4 km/L (Cook and Shinners, 2011).

Total Fuel Use at 80.5 km (Broeren, 2012) trip to storage facility plus an empty return trip:

EarlyChop	55.42384
MidChop	54.49596
LateChop	52.74552
SpringChop	51.33577

Final calculation: Total Fuel Use/(Silage biomass density*truck bed volume)*1000 = L diesel/1000 kg dry switchgrass

Final Data:

EarlyChop	6.077176
MidChop	5.975434
LateChop	5.7835
SpringChop	5.628922

Bunker Silo Silage Storage (6 Months)

Inputs: Occupied Arable Land, Switchgrass, PE tarp

Outputs: Switchgrass, PE tarp (waste)

Occupied Arable Land

Switchgrass silage bulk density = 261.1 kg dry switchgrass/m^3 (The Dairy Advisory Group)

Bunker switchgrass volume filled to the top with a 30 degree biomass angle at the front of the bunker silo: 1442.8 m^3 (Huhnke)

Total kg dry switchgrass/bunker = (Switchgrass silage bulk density)*(Bunker switchgrass volume) = 376715.08 kg dry switchgrass/bunker

Bunker land surface area = length x width = 36.576 m x 9.144m = 334.45 m^2 (Huhnke)

Total Land Use = ((Total kg dry switchgrass/bunker)/(Bunker land surface area))$^{-1}$*1000

Final Data: 0.8878 m^2 Land/1000 kg dry switchgrass

PE Tarp Cover

Total dry kg switchgrass/bunker: 376715.08 kg dry switchgrass/bunker

Switchgrass surface area: 346.44 m^2

Tarp weight: 0.19183 kg PE/m^2

Total Tarp Use = ((Total kg dry switchgrass/bunker)/(Switchgrass surface area))$^{-1}$*1000 = 0.9196 m^2 tarp/1000 kg dry switchgrass.

Final PE Requirement = Total Tarp Use*(Tarp weight* 2 tarps (five years of reuse per tarp)) = kg PE/1000 kg dry switchgrass

Final Data: 0.07057 kg PE/1000 kg dry switchgrass

Unit Process	Inputs	Scenario		Unit	Cost
Boom Sprayer	Diesel	EarlyChop	0.0118	L/1000 kg dry SG	$0.01
		MidChop	0.0124	$1.05	$0.01
		LateChop	0.0132	Per L of Diesel and Lube	$0.01
		SpringChop	0.0182		$0.02
		EarlyBale	0.0131		$0.01
		MidBale	0.0153		$0.02
		LateBale	0.0160		$0.02
		SpringBale	0.0192		$0.02
Fertilizer Application	Diesel	EarlyChop	0.4770	L/1000 kg dry SG	$0.50
		MidChop	0.5025	$1.05	$0.53
		LateChop	0.5349	Per L of Diesel and Lube	$0.56
		SpringChop	0.7354		$0.77
		EarlyBale	0.5279		$0.55
		MidBale	0.6178		$0.65
		LateBale	0.6477		$0.68
		SpringBale	0.7745		$0.81
Drill Press Seed Planter	Diesel	EarlyChop	0.0720	L/1000 kg dry SG	$0.08
		MidChop	0.0758	$1.05	$0.08
		LateChop	0.0807	Per L of Diesel and Lube	$0.08
		SpringChop	0.1110		$0.12
		EarlyBale	0.0797		$0.08
		MidBale	0.0932		$0.10
		LateBale	0.0977		$0.10
		SpringBale	0.1169		$0.12
Switchgrass Cultivation	Atrazine	EarlyChop	0.0227	kg/1000 kg dry SG	$0.37
		MidChop	0.0239	$16.08	$0.38
		LateChop	0.0255	Per kg of Atrazine	$0.41
		SpringChop	0.0350		$0.56
		EarlyBale	0.0251		$0.40
		MidBale	0.0294		$0.47
		LateBale	0.0308		$0.50
		SpringBale	0.0369		$0.59
	S-Metolachlor	EarlyChop	0.0164	kg/1000 kg dry SG	$1.18
		MidChop	0.0173	$72.04	$1.24
		LateChop	0.0184	Per kg of S-Metolachlor	$1.32
		SpringChop	0.0253		$1.82
		EarlyBale	0.0181		$1.31
		MidBale	0.0212		$1.53
		LateBale	0.0223		$1.60

Table 28. Input costs during the switchgrass cultivation phase. All costs are standardized to the reference flow of 1000 kg of switchgrass.

Table 28 (cont'd)

		SpringBale	0.0266		$1.92
	Granular Urea	EarlyChop	11.8820	kg/1000 kg dry SG	$3.68
		MidChop	12.5167	$0.31	$3.88
		LateChop	13.3246	Per kg of Urea (46-0-0)	$4.13
		SpringChop	18.3180		$5.68
		EarlyBale	13.1508		$4.08
		MidBale	15.3888		$4.77
		LateBale	16.1335		$5.00
		SpringBale	19.2920		$5.98
	SG Seed	EarlyChop	0.1135	kg/1000 kg dry SG	$3.75
		MidChop	0.1196	$33.07	$3.95
		LateChop	0.1273	Per kg Cave in Rock Seed	$4.21
		SpringChop	0.1750		$5.79
		EarlyBale	0.1256		$4.16
		MidBale	0.1470		$4.86
		LateBale	0.1541		$5.10
		SpringBale	0.1843		$6.10
	Diesel	EarlyChop	0.1605	L/1000 kg dry SG	$0.17
		MidChop	0.1690	$1.05	$0.18
		LateChop	0.1799	Per L of Diesel and Lube	$0.19
		SpringChop	0.2474		$0.26
		EarlyBale	0.1776		$0.19
		MidBale	0.2078		$0.22
		LateBale	0.2179		$0.23
		SpringBale	0.2605		$0.27

Unit Process	Inputs	Scenario		Unit	Cost
Tractor with Round Baler	Diesel	EarlyBale	0.4570	L/1000 kg dry SG	$0.48
		MidBale	0.5348	$1.05	$0.56
		LateBale	0.5607	Per L of Diesel and Lube	$0.59
		SpringBale	0.6705		$0.70
	PE Netting		0.4621	kg/1000 kg dry SG $7.64 Per kg PE Netting	$3.53
Tractor with Raker	Diesel	EarlyBale	1.9588	L/1000 kg dry SG	$2.06
		MidBale	1.5281	$1.05	$1.60
		LateBale	0.8010	Per L of Diesel and Lube	$0.84
		SpringBale	0		$0.00
Windrower	Diesel	EarlyBale	0.6529	L/1000 kg dry SG	$0.69
		MidBale	0.7640	$1.05	$0.80
		LateBale	0.8010	Per L of Diesel and Lube	$0.84
		SpringBale	0.9578		$1.01
Bale Truck Transport	Diesel		4.8600	L/1000 kg dry SG $1.05 Per L of Diesel and Lube	$5.10

Table 29. Input costs during the cut/bale phase. All costs are standardized to the reference flow of 1000 kg of switchgrass.

Unit Process	Inputs	Scenario		Unit	Cost
Forage Chopper	Diesel	EarlyChop	2.1945	L/1000 kg dry SG	$2.30
		MidChop	2.3117	$1.05	$2.43
		LateChop	2.4609	Per L of Diesel and Lube	$2.58
		SpringChop	3.3832		$3.55
Silage Truck Transport	Diesel	EarlyChop	6.0772	L/1000 kg dry SG	$6.38
		MidChop	5.9754	$1.05	$6.27
		LateChop	5.7835	Per L of Diesel and Lube	$6.07
		SpringChop	5.6289		$5.91
Bunker Silo Silage Storage	PE Tarp		0.0706	kg/1000 kg dry SG $7.70 Per kg of PE Tarp	$0.54

Table 30. Input costs during the chop/ensile phase. All costs are standardized to the reference flow of 1000 kg of switchgrass.

Data	Data Quality Index	Data	Data Quality Index
Boom Sprayer		**Windrower**	
Diesel	(1,3,1,1,1)	Diesel	(1,3,1,1,1)
Fertilizer Application		Switchgrass	(1,1,1,1,1)
Diesel	(1,3,1,1,1)	**Bale Truck Transport**	
Drill Press Seed Planter		Diesel	(1,4,1,2,2)
Diesel	(1,3,1,1,1)	Switchgrass	(1,1,1,1,1)
Switchgrass Cultivation		PE Netting	(2,3,1,1,1)
Diesel	(1,3,1,1,1)	**PE Netting Production**	
Land Use	(1,1,1,1,1)	PE Netting	(2,3,1,1,1)
CO_2 Sequestration	(1,1,1,3,1)	**Bale Indoor Storage**	
Atrazine Application	(1,1,1,1,1)	Land Use	(2,1,1,1,1)
S-Metolachlor Application	(1,1,1,1,1)	Switchgrass	(1,1,1,1,1)
Granular Urea Application	(1,1,1,1,1)	PE Netting	(2,3,1,1,1)
Switchgrass Seed	(1,1,1,1,1)	**Forage Chopper**	
N_2O Emission	(1,1,1,4,2)	Diesel	(1,3,1,1,1)
CH_4 Emission	(1,1,1,4,2)	Switchgrass	(1,1,1,1,1)
NH_3 Emission	(1,1,1,4,2)	**Silage Truck Transport**	
NO_3^- Emission	(1,1,1,4,2)	Diesel	(1,4,1,2,2)
Switchgrass	(1,1,1,1,1)	Switchgrass	(1,1,1,1,1)
Tractor with Round Baler		**Bunker Silo Silage Storage**	
Diesel	(1,3,1,1,1)	Land Use	(3,5,1,3,2)
PE Netting	(2,3,1,1,1)	PE tarp	(2,3,1,1,1)
Switchgrass	(1,1,1,1,1)	Switchgrass	(1,1,1,1,1)
Tractor with Raker		**EOL: Polyethylene**	
Diesel	(1,3,1,1,1)	Polyethylene	(2,3,1,1,1)
Switchgrass	(1,1,1,1,1)		

Table 31. Data quality pedigree matrix. Each unit process (bold) with their corresponding input and output data flows. See Ciroth, 2009 for a description of the data quality index numbers.

Year	Block	Timing	Method	Ash	Notes
2010	1	Early	Harvest	3.33%	
2010	2	Early	Harvest	3.12%	
2010	3	Early	Harvest	3.24%	
2010	4	Early	Harvest	3.47%	
2010	1	Early	Bale	3.08%	
2010	2	Early	Bale	2.88%	
2010	3	Early	Bale	3.02%	
2010	4	Early	Bale	3.27%	
2010	1	Early	Ensile	3.18%	
2010	2	Early	Ensile	3.49%	
2010	3	Early	Ensile	3.62%	
2010	4	Early	Ensile	3.60%	
2010	1	Mid	Harvest	3.14%	
2010	2	Mid	Harvest	3.49%	
2010	3	Mid	Harvest	3.07%	
2010	4	Mid	Harvest	3.27%	
2010	1	Mid	Bale	3.04%	
2010	2	Mid	Bale	3.30%	
2010	3	Mid	Bale	3.50%	
2010	4	Mid	Bale	3.26%	
2010	1	Mid	Ensile	3.10%	
2010	2	Mid	Ensile	3.35%	
2010	3	Mid	Ensile	3.39%	
2010	4	Mid	Ensile	3.35%	
2010	1	Late	Harvest	3.12%	
2010	2	Late	Harvest	3.08%	
2010	3	Late	Harvest	3.25%	
2010	4	Late	Harvest	3.38%	
2010	1	Late	Bale	2.91%	
2010	2	Late	Bale	2.98%	
2010	3	Late	Bale	3.16%	
2010	4	Late	Bale	2.92%	
2010	1	Late	Ensile	3.37%	
2010	2	Late	Ensile	2.93%	
2010	3	Late	Ensile	3.37%	
2010	4	Late	Ensile	3.30%	
2010	1	Spring	Harvest	2.51%	
2010	2	Spring	Harvest	2.75%	
2010	3	Spring	Harvest	2.85%	

Table 32. Raw ash content data. *Baler mechanical issue. Could not bale plot. †Bale accidentally discarded by a third party. Could not obtain six month measurements.

Table 32 (cont'd)

2010	4	Spring	Harvest	2.51%	
2010	1	Spring	Bale	2.09%	
2010	2	Spring	Bale	2.50%	
2010	3	Spring	Bale	.	*
2010	4	Spring	Bale	2.63%	
2010	1	Spring	Ensile	2.59%	
2010	2	Spring	Ensile	2.34%	
2010	3	Spring	Ensile	2.65%	
2010	4	Spring	Ensile	2.37%	
2011	1	Early	Harvest	3.56%	
2011	2	Early	Harvest	3.59%	
2011	3	Early	Harvest	3.82%	
2011	4	Early	Harvest	3.60%	
2011	1	Early	Bale	4.01%	
2011	2	Early	Bale	3.38%	
2011	3	Early	Bale	.	*
2011	4	Early	Bale	3.55%	
2011	1	Early	Ensile	3.12%	
2011	2	Early	Ensile	3.82%	
2011	3	Early	Ensile	3.74%	
2011	4	Early	Ensile	3.91%	
2011	1	Mid	Harvest	2.88%	
2011	2	Mid	Harvest	2.98%	
2011	3	Mid	Harvest	3.37%	
2011	4	Mid	Harvest	3.15%	
2011	1	Mid	Bale	2.84%	
2011	2	Mid	Bale	2.48%	
2011	3	Mid	Bale	2.92%	
2011	4	Mid	Bale	.	*
2011	1	Mid	Ensile	3.10%	
2011	2	Mid	Ensile	2.99%	
2011	3	Mid	Ensile	3.57%	
2011	4	Mid	Ensile	3.43%	
2011	1	Late	Harvest	2.99%	
2011	2	Late	Harvest	2.63%	
2011	3	Late	Harvest	3.04%	
2011	4	Late	Harvest	3.01%	
2011	1	Late	Bale	3.15%	
2011	2	Late	Bale	3.22%	
2011	3	Late	Bale	3.15%	

Table 32 (cont'd)

2011	4	Late	Bale	3.02%	
2011	1	Late	Ensile	3.15%	
2011	2	Late	Ensile	2.65%	
2011	3	Late	Ensile	3.06%	
2011	4	Late	Ensile	3.01%	
2011	1	Spring	Harvest	2.16%	
2011	2	Spring	Harvest	2.75%	
2011	3	Spring	Harvest	2.17%	
2011	4	Spring	Harvest	2.35%	
2011	1	Spring	Bale	.	*
2011	2	Spring	Bale	.	†
2011	3	Spring	Bale	.	†
2011	4	Spring	Bale	.	†
2011	1	Spring	Ensile	2.24%	
2011	2	Spring	Ensile	2.80%	
2011	3	Spring	Ensile	2.43%	
2011	4	Spring	Ensile	2.39%	
2012	1	Early	Harvest	3.81%	
2012	2	Early	Harvest	3.83%	
2012	3	Early	Harvest	4.07%	
2012	4	Early	Harvest	4.19%	
2012	1	Early	Bale	3.91%	
2012	2	Early	Bale	3.76%	
2012	3	Early	Bale	3.40%	
2012	4	Early	Bale	4.10%	
2012	1	Early	Ensile	4.22%	
2012	2	Early	Ensile	4.62%	
2012	3	Early	Ensile	4.22%	
2012	4	Early	Ensile	4.57%	
2012	1	Mid	Harvest	4.02%	
2012	2	Mid	Harvest	3.86%	
2012	3	Mid	Harvest	3.96%	
2012	4	Mid	Harvest	3.66%	
2012	1	Mid	Bale	3.78%	
2012	2	Mid	Bale	3.83%	
2012	3	Mid	Bale	4.62%	
2012	4	Mid	Bale	3.52%	
2012	1	Mid	Ensile	4.08%	
2012	2	Mid	Ensile	4.10%	
2012	3	Mid	Ensile	3.79%	

Table 32 (cont'd)

2012	4	Mid	Ensile	4.12%	
2012	1	Late	Harvest	3.57%	
2012	2	Late	Harvest	4.10%	
2012	3	Late	Harvest	4.04%	
2012	4	Late	Harvest	3.54%	
2012	1	Late	Bale	.	*
2012	2	Late	Bale	3.76%	
2012	3	Late	Bale	4.01%	
2012	4	Late	Bale	3.81%	
2012	1	Late	Ensile	3.30%	
2012	2	Late	Ensile	3.97%	
2012	3	Late	Ensile	3.98%	
2012	4	Late	Ensile	3.22%	
2012	1	Spring	Harvest	3.13%	
2012	2	Spring	Harvest	2.68%	
2012	3	Spring	Harvest	3.07%	
2012	4	Spring	Harvest	2.95%	
2012	1	Spring	Bale	2.82%	
2012	2	Spring	Bale	3.09%	
2012	3	Spring	Bale	3.18%	
2012	4	Spring	Bale	.	*
2012	1	Spring	Ensile	2.71%	
2012	2	Spring	Ensile	2.70%	
2012	3	Spring	Ensile	3.04%	
2012	4	Spring	Ensile	3.77%	

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