5-2012

# Management of Switchgrass for the Production Of Biofuel

Leryn Elise Gorlitsky
*University of Massachusetts Amherst*

Recommended Citation
Gorlitsky, Leryn Elise, "Management of Switchgrass for the Production Of Biofuel" (2012). *Open Access Dissertations*. 548.
https://scholarworks.umass.edu/open_access_dissertations/548

# MANAGEMENT OF SWITCHGRASS FOR THE PRODUCTION OF BIOFUEL

A Dissertation Presented

by

Leryn E. Gorlitsky

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

MAY 2012

Department of Plant and Soil Science

# MANAGEMENT OF SWITCHGRASS FOR THE PRODUCTION OF BIOFUEL

A Dissertation Presented

by

LERYN E. GORLITSKY

Approved as to style and content by:

________________________________________
Stephen Herbert, Chair

________________________________________
Masoud Hashemi, Member

________________________________________
Stephen Simkins, Member

________________________________________
Erin Conlon, Member

________________________________________
Stephen Rich, Department Head
Plant and Soil Sciences

## DEDICATION

I dedicate this work to my loving family Glenn, Kendra, Brienne and Garett Gorlitsky who have always encouraged me in my academic pursuits and in loving memory of the Grandfather Solomon Gorlitsky who saved his entire life to provide a better future for his children.

# ACKNOWLEDGMENTS

A dissertation is a long journey requiring the support of many people and institutions. I would like to thank the University of Massachusetts, Amherst for this wonderful opportunity and all those individuals who made it possible.

Special thanks go to Dr. Stephen Herbert, not only my boss and advisor but also a father-like mentor. He gave me the freedom to explore my passions, the support to keep going, and the guidance to follow through. Thanks to Dr. Sarah Weis. I could not have finished this work without her help and guidance as well as her friendship. I thank Dr. Masoud Hashemi, who explained how to properly structure and write this paper. Thanks go to Edward Bodzinski and Neal Woodard, my field experts for helping harvest and collect data without complaint. Thanks to Tracy Allen and Jessica Morgan, in the West Experiment and the Cranberry Station respectively, for helping me with endless laboratory work. Special thanks go to the University of Massachusetts, Amherst professors Dr. Wesley Autio, Dr. Stephen Simkins, Dr. Erin Conlons, and Dr. Robert Wick. Dr. Lyle Craker made it possible for me to teach at the university, my proudest accomplishment to date.

There are several people outside of academia who made this journey possible. Thanks go to the Ostrovsky family for providing me a home every weekend I worked on the Cape. Benjamin Kelly, Robert Lindeman, and Brendan Gavin influenced my life during these five years, forever changing me. Most importantly I want to thank my family: Glenn, Kendra, Brienne, and Garett Gorlitsky whose support and encouragement has seen me through so many experiences.

I have learned a lot in the process of this dissertation, but most importantly... to be humble before science. The creator’s design is both far more simple and complicated than anything I might be able to imagine. With a little intuition, a lot of hard work,

and an open mind it is possible to understand a tiny piece of the puzzle. It has been an honor and a responsibility to learn this knowledge and share it with others.

# ABSTRACT

## MANAGEMENT OF SWITCHGRASS FOR THE PRODUCTION OF BIOFUEL

MAY 2012

LERYN E. GORLITSKY, B.A., PITZER COLLEGE

M.S., UNIVERSITY OF COLORADO

Ph.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Stephen Herbert

Switchgrass (*Panicum virgatum L.*) is a warm-season perennial being considered as a biofuel to meet energy challenges. In Massachusetts, a small state where the price of land is expensive, farmers want to determine if switchgrass can produce sufficient yields for consecutive years to warrant its production. The objective of this study was to determine what harvest management practices affect the vigor and health of switchgrass and which varieties produce the best yields for biofuel production.

Four experiments were conducted from 2009-2012. Twelve varieties were tested to determine their viability in the Massachusetts climate. Five were chosen for further chemical analysis. All varieties were harvested in August (senescence), November (killing frost), and April (early spring). A high yielding variety, Cave-in-Rock, known to grow well in northern latitudes, was chosen for more extensive research. In one experiment, a young stand, three years old, received three nitrogen treatments, was cut at two heights, and was harvested at three different times during the year. A mature stand, seven years old, of the same variety located on conservation land, was harvested three times at two cutting heights. These experiments were done to provide projections on the expected yields over the plant's 10 to 20 year life cycle. In our final experiment Switchgrass was harvested every two weeks from September to November.

A caliometer tracked how much energy was present in the dry matter throughout the growing season. Dry matter yield, chemical constituents, and carbohydrate reserves in the below ground tissues were measured as indicator variables to determine the health and quality of yield. Harvest time was the most significant variable observed.

## TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS ........ v

ABSTRACT ........ vii

LIST OF TABLES ........ xi

LIST OF FIGURES ........ xiii

CHAPTER

1. INTRODUCTION ........ 1

    Global problem ........ 1
    Switchgrass History ........ 5
    Varieties ........ 7
    Harvest Time and Non-structural Carbohydrates ........ 8
    Biofuel Sources ........ 9

        Ethanol Liquid Fuel ........ 9
        Combustion and Ash ........ 10

    Switchgrass in Massachusetts ........ 11
    Economics and Logistics ........ 13
    Description of Research ........ 15

2. EVALUATING SWITCHGRASS VARIETIES FOR BIOMASS YIELD AND QUALITY TO DEVELOP AN HERBACEOUS BIOFUEL IN MASSACHUSETTS ........ 18

    Abstract ........ 18
    Introduction ........ 19
    Material and Methods ........ 22
    Results ........ 26
    Discussion ........ 28
    Conclusion ........ 33

3. NITROGEN APPLICATION RATE AND HARVEST MANAGEMENT OF YOUNG AND MATURE STANDS OF SWITCHGRASS ........ 37

    Abstract ........ 37
    Introduction ........ 38
    Material and Methods ........ 41
    Results ........ 45

Discussion ........................................................................................ 49
Conclusion........................................................................................ 56

4. OPTIMAL FALL HARVEST TIME IN MASSACHUSETTS FOR CAVE-IN-ROCK SWITCHGRASS USED AS A BIOFUEL ................................................................. 63

Abstract.............................................................................................. 63
Introduction ....................................................................................... 64
Material and Methods ........................................................................ 67
Results................................................................................................ 70
Discussion ......................................................................................... 71
Conclusion.......................................................................................... 75

5. SUMMARY AND CONCLUSION ........................................................... 78

Upland Varieties ............................................................................... 79
Harvest Time ...................................................................................... 79
Cutting Height .................................................................................... 80
Weeds and Yield ................................................................................ 80
Nitrogen ............................................................................................. 81
Nutrients ............................................................................................ 81
Recommendation ............................................................................... 82

BIBLIOGRAPHY ...................................................................................... 83

# LIST OF TABLES

Table Page

2.1. Analysis of variance showing the *p*-values for yields and chemical analyses. 34

2.2. Switchgrass dry matter yield (Mg $ha^{-1}$) for high yielding varieties in 2009-2011. 34

2.3. Effect of harvest dry matter yield (Mg $ha^{-1}$) in 2009-2011. 34

2.4. Yield ($Mg.ha^{-1}$) of high yielding varieties by harvest for 2009-2011. 34

2.5. Ash content (%) in feedstock by harvest time 2009-2011. 35

2.6. Effect of harvest time on chemical constituents in dry matter yield, averaged across high yielding varieties, in 2009-2011. 35

2.7. Effect of harvest time on micronutrients present in dry matter yield, averaged across high yielding varieties, in 2009-2011 35

2.8. Low yielding varieties average yield 2010-2011 for all harvests. 36

3.1. Analysis of variance showing the *p*-values for yields and chemical analyses. 58

3.2. Yields (Mg $ha^{-1}$) for YS over three years for each of three harvest times. 58

3.3. Weed ratings† for YS in June for each of the harvest times 58

3.4. Weed species present in field in June 59

3.5. Percent Ash in YS dry matter tissue for each harvest treatment for each year. 59

3.6. Percent Ash in YS dry matter tissue for fertilizer treatment at different harvest. 59

3.7. Percent Nitrogen in YS feedstock at different times of harvest 59

3.8. Fertilizer treatment effect on macro nutrients for each harvest time 60

3.9. Nutrient content in YS feedstock in part per million for harvest time across all year. 60

3.10. Concentration of soluble nonstructural carbohydrates (mg/100mg dry matter) in below ground tissue at time of harvest of YS 60

3.11. Sucrose concentration (mg/ 100 mg dry matter) in below ground tissue of YS for different fertilizer treatments at harvest time 60

3.12. Sucrose Concentration (mg/ 100 mg dry matter) for in the roots in December before ground freeze for YS across all year. 60

3.13. Analysis of variance showing the *p*-values for yields and chemical analyses for mature stand (MS) ........ 61

3.14. Yields (Mg $ha^{-1}$) of MS for all harvest times for all years. ........ 61

3.15. Cutting Height vs. Harvest Time for MS (Mg $ha^{-1}$) ........ 61

3.16. Percent ash and nitrogen and ppm of macro-nutrients in feedstock of MS for different harvest times. ........ 61

3.17. Sucrose concentration (mg/100 mg dry matter yield) in the roots system at harvest time and in December for MS ........ 62

4.1. Analysis of variance showing the p-values for yields and chemical analyse ........ 76

4.2. Ash in percent dry matter and mineral content for each harvest time........ 76

4.3. Slag index† values present for each harvest time ........ 76

4.4. Energy present in the feedstock ........ 76

## LIST OF FIGURES

Figure Page

2.1. Chemical constituents in dry matter yield. 35

2.2. Soluble nonstructural carbohydrates at time of harvest for below ground roots and crown averaged for high yielding varieties for 2009-2010. 36

2.3. Soluble nonstructural carbohydrates at time of harvest for below ground roots and crown averaged for high yielding varieties for 2009-2010. 36

4.1. Dry matter yield (Mg $ha^{-1}$) vs. harvest time. 77

4.2. Mineral content in feedstock in percent of dry matter yield 77

4.3. Sucrose levels at time of harvest in mg Sucrose per 100 g dry matter yield 77

# CHAPTER 1

# INTRODUCTION

## Global problem

During the last decade, notable interest has been paid to biomass refined into biofuel mainly as ethanol and biodiesel (Colbran and Eide, 2008). It is widely claimed that the use of biofuel can contribute to the solution of a range of problems, both environmental and social in nature (Abbasi and Abbasi, 2012; Demirbas, 2008). In the face of the growing threat of global warming caused by greenhouse gas (“GHG”) emissions, it has been argued that biofuel used for transport can partly replace gasoline needs in the United States and lead to a significant reduction in our dependency of foreign imports (Demirbas, 2009). Biofuel may also provide a renewable energy source for heating that could promote the conservation of land rather than extraction and destruction associated with coal and oil production. Biofuel produced on farms my also increase agricultural income for rural poor in developing countries (Colbran and Eide, 2008).

If these goals could be achieved, there is a very strong ethical argument in favor of liquid and heating fuel produce from biomass. But, are these claims justified? Do they correspond with reality? Serious concerns have emerged over the past few years with regards to the long-term sustainability of biofuel production. These claims include requirements for oil-based fertilizers, thermodynamic inefficiencies, competition with food sources, and large scale transportation costs of bulky material.  As with coal or oil these consequences cannot be fully realized until production plants are in operation.  It is important, however, that the transitions that are made to incorporate new energy sources are well studied and their associated risks are mitigated.

Small scale implementation of new fuel production in a decentralized way might be an appropriate method to incorporate new fuel sources in the future.

Liquid biofuel is primarily produced as ethanol or biodiesel. The first generation feedstocks for ethanol were generally sugar cane and corn, and to a lesser extent wheat, sugar beet, and cassava. The feedstocks for biodiesel are oil-producing crops, such as rapeseed, palm oil, and jatropha (Worldwatch institute, 2006). The agricultural practice for these crops is monoculture. Monocultural production of feedstock for biofuel can cause a number of environmental harms. With the possible exception of sugarcane production for ethanol, there is increasing evidence that when the whole life-cycle of the production, distribution, and use of biofuel is taken into account, and when direct and indirect effects are counted, biofuel production actually increases GHG emissions and thereby intensifies rather than mitigates global warming (Colbran and Eide, 2008; Demirbas, 2008).

Compounding these negative environmental effects of biofuel production is the claim by critics that monoculture production is harmful to biodiversity, which in turn has considerable consequences for the necessary dietary diversity required for adequate food (Colbran and Eide, 2008; Demirbas, 2009). Furthermore, the production of biofuel causes both competition for water and the pollution of remaining water resources (Pimentel, 2003). Corn for instance, contains high sugar content in grain which is used to generate ethanol; however corn requires high fertilizer inputs and would force biofuel to compete with food crops. Palm oil for biodiesel is heavily dependent on water. The jatropha bush is less dependent on water and can grow in marginal and dry areas, but its yield is low compared to what can be obtained when grown in more fertile land or with more access to water. It is likely that even with jatropha, the competition for water can be severe. Also, the process of extracting oil from oil seed crops is complex and not sufficiently efficient to warrant its use, at this time (Schmer et al., 2008).

Second generation biofuel crops (prairie grasses, woods) are found to be more environmentally friendly than ones discussed above (Havik et al., 2011). Grass prairies generate a lot of cellulose in their cell walls relative to their dry matter yield. This cellulose can be broken down and converted into sugar for ethanol or burned in coal power plants and stoves as heating fuel.

A ten-year study beginning in 1980's at Oakland Ridge National Laboratory identified switchgrass (*Panicum virgatum* L.) as an ideal species for the production of cellulosic biofuel (Wright et al., 2007). Switchgrass is a native perennial prairie grass that grows from Mexico to Canada.  There are many characteristics that defined switchgrass as a "model" energy crop including its high productivity in diverse settings and its ability to grow on marginal or low value land (Sanderson et al., 1996, McLauglin et al., 2002). Switchgrass is easy to manage, requires low nitrogen fertilizer and pesticide use after establishment, and can be harvested using conventional hay-making equipment (Teel et al., 2003). Tolerant to heat, cold and draught, switchgrass can grow in hot months when cool-season grasses cease to be productive (Casler et al., 2007). Switchgrass can grow on a variety of different soils from sand to clay loam and can tolerate a large range of pH values from 4.9 – 7.6 (Lewandowski et al*.,* 2003).

In the last 30 years, there have been a wide variety of publications that discuss switchgrass-- its yield potentials, growth patterns, chemical composition, ability to survive in a range of climates (Parrish and Fike, 2005; Sanderson et al., 2006; Vogel et al., 2008; Keshwani and Cheng, 2009). Most of the research has been done in the mid-western and southern parts of the United States. Currently all research studies are speculative, to determine if appropriate harvest management can produce yields that would supply ethanol and coal power plants sufficient feedstock that would warrant farmers converting crop and pasture land to prairies for biofuel. There is no published research to date on yield potentials for switchgrass in Massachusetts.

Massachusetts has a farming culture that is different from those found in other areas in the United States, particularly in terms of the amount of land that is available for farming. According the United States Department of Agriculture 2007 Census, only 10.4% of Massachusetts is designated farm land, with average farm size around 27.1 ha. Hay farms are the number one agricultural producer in the state (USDA MA-Fact Sheet 2012). Scientists at the University of Massachusetts, Amherst conducted research to determine if the Massachusetts area could produce sufficiently high yields for farmers to consider converting portions of their fields to the production of biofuel. Four experiments were conducted in the area investigating different varieties, times of harvest, cutting heights, and fertilizer treatments to determine optimal yield potential and quality of the feedstock for the area. Shoots and roots were taken at the time of harvest for chemical analysis to determine consituents and explain why and when the crop was mobilizing nutrients throughout the season. All this research was done to provide farmers with strategies to determine if switchgrass would be appropriate for their fields.

In the following chapter a brief history and prior research conducted on switchgrass as it relates to biofuel are reviewed. When considering the use of switchgrass, a wide range of varieties, fertilizer treatments, and harvest times have been recommended. These recommendations are however, dependent on the crop's location. The current conversion technologies for cellulosic biofuel include simultaneous scarification fermentation for conversion to ethanol, combustion in coal-fired power plants and pelletizing and burning in wood stoves.  These technologies require the grass be “clean” i.e. that they have low nutrient content in the feedstock. We will describe these technologies and why a clean feedstock is as important as high yields. This is done to provide the reader with a better understanding of the goals of our research.

## **Switchgrass History**

Switchgrass (*Panicum virgatum L.*) is a $C_4$ warm-season perennial grass native to North America (Mazarei et al., 2011). It naturally grows from Mexico to Canada (Alexpoulou, 2008). Before the arrival of Europeans, switchgrass grew in two-thirds of the eastern United States tall grass prairies (Hitchcock, 1995; Parrish and Finke, 2005). Switchgrass begins its growth cycle in April or May of each year, depending on latitude, flowers in early summer, and goes to seed in late summer (Keyser, 1994). The plant spreads by seed, tillers, and through rhizomes. It has short rhizomes and produces seeds when moisture is adequate. The inflorescence is a diffuse panicle and spikelets. It is a cross-pollinated plant that is largely self-incompatible (Lewandowski et al., 2003). The seeds are a good source of food for birds and the plant has high forage value when young (Keyser, 1994). As the plant matures, it loses it nutritional values but serves as a refuge for wildlife.

Switchgrass was originally planted by conservation societies, around the United States, to create habitat for wildlife. It has a fibrous root structure, and is often used as a filter strip, grass hedge, and cover crop on the sides of rivers and levees for erosion control (Parrish and Fike, 2005). Originally, switchgrass was found throughout the United States, but when early settlers grazed cattle in open fields in the early spring, the new plants were too young to withstand the defoliation. Eventually this led to a weakening of the stands (Wolf and Fisk, 2009). The tall prairie grass was replaced by cool-season grasses that were more tolerant to early season grazing. Now, the majority of switchgrass growing wild in the United States is along roads and abandoned land sites.

The Food Security Act of 1985 created a land retirement program called Conservation Reserve Program (CRP). The intention of this program was to reduce soil erosion, reduce commodity surplus, and supplement farm income. Switchgrass was one of the native warm season grasses that were established on this land (Mulkey et al., 2006). Conservation societies have found that in established stands, there is little problem with disease and insects. Switchgrass develops a dense canopy and extensive fibrous root system that helps hold soil in place, preventing erosion and run off (Ichizen et al., 2001). It has thick stiff stems that provide barriers to wind and water flow at ground level. This generates a microclimate within the field, allowing it to hold water and nutrients in place until they can infiltrate the soil (Parrish and Fike, 2005). The fibrous root structure has the ability to sequester carbon in the soil and thus improve soil structure by increasing soil organic matter (Lal, 2009). Many studies have attempted to quantify the value that switchgrass adds to soil if planted on a large scale for biofuel production. Research indicates that soil sequestration of carbon requires extended periods of establishment, likely in excesses of 4 years (Lee et al., 2007; Sanders, 2008). The CRP is currently supporting research to determine if biomass production is a viable alternative for these established prairies instead of converting the land back to crop production once the contacts expire (Mulkey et al., 2006).

Switchgrass is slow to establish, taking one to two year, but it can grow in a wide variety of locations including, steep slopes and rocky soils (Wolf et al., 2008). Management of switchgrass on conservation land requires little maintenance. Federal transportation organizations in various states are studying the potential of growing switchgrass on the sides of roads for supplemental income. Growing switchgrass in no-till, sloped land, with little-to-no management may take longer to establish than on crop lands, but has the potential to create an alternative income for transportation systems and farmers. Research in this area is in its early stages.

## Varieties

There are more than 20 different varieties of switchgrass that grow native to United States. These varieties are generally separated into two groups, upland and lowland types (Sanderson et al., 2006). The various types have evolved in different latitudes and thrive in different growing conditions. This means there exist many ecotypes with diverse morphological and genetic characteristics. “Lowland” varieties are suited for humid and long growing seasons, while “upland” varieties, found in northern latitudes, perform well in semi-arid climates (Rineheart, 2006). Cultivars should not be grown more than 500 km north of their place of origin (Moser and Vogel 1995, Parrish and Fike, 2005). Strains originating in particular latitudes will be more productive and have a greater chance of survival if they stay at that latitude (Casler et al., 2004, Parrish and Fike, 2005). Lowland varieties generally are tall (0.6-3 m), with coarse stems and are adapted to poor drainage conditions, while upland varieties are short (0.9-1.5 m), fine stemmed, and drought and cold tolerant. The upland ecotypes are adapted to a shorter growing season and have a faster maturation rate and lower cell wall concentration (Cassida et al., 2006). Lowland switchgrass produces more biomass and can be harvest twice per season. Originally people wanted to grow lowland ecotypes in the northern climate in hopes of producing higher yields than the upland types, but the lowland types do not have enough time to go to seed in the short growing season and often cannot survive the harsh winters (Parrish and Fike, 2005). Upland and lowland ecotypes vary in their genetic characteristics. Current research is ongoing by breeds to select for traits that would produce larger yields, however attempts to cross up and low land varieties have, thus far, been unsuccessful. (Lemus et al., 2002; Casler et al., 2004; Cassidy et al., 2005).

There may not be significant differences among varieties in the chemical constituents of the raw material. This is important because it indicates that one variety is not superior to another when used for feedstock. Rather, it is the yield and the management of the crop that is important and not the variety that is grown (McLaughlin et al., 1996). Holo-cellulose and lignin are considered the most important components of the raw materials in terms of chemical quality when converting grass to ethanol. The Bioenergy Feedstock Development Program (BFDP) found holo-cellulose to vary by only 12% and lignin content by 4%, between Cave in Rock (upland cultivar) and Alamo (lowland cultivar) on a late harvest date. A study that compared digestibility among 28 varieties found differences of only 4-14% in chemical composition (Hoplins et al., 1995). It appears the major differences between varieties are the yields that they can produce in the climate to which they are adapted.

## **Harvest Time and Non-structural Carbohydrates**

Switchgrass' extensive root structure aids its survival during winter months and its re-growth in the period of spring to early summer (Ma et al., 2000). In order to maintain a healthy root structure for continual crop production while applying minimal amounts of fertilizer, it is important that carbohydrates and nutrients to retreat from the stalk into the root system (Thomason et al., 2004). Late summer and early fall harvests have a higher moisture content because the plants have not fully senesced (gone to seed), and there is a greater potential for dry matter to contain higher levels of nutrients such as potassium, nitrogen, phosphorus, and silicon (Davis and Ragauskas, 2010). These produce unwanted ash and air pollutants during combustion (Parrish and Fike, 2005). Spring and winter harvests are known to reduce ash content, also reduce the amount of dry matter harvested due to breakage of tillers and translocation of sugars (Samson and Mehdi, 1998; Adler et al., 2006). There is still much debate as to when the optimal time to harvest switchgrass is. It may depend on climate, location, and age of the stand.

## **Biofuel Sources**

Switchgrass has been identified by the DOE as one of the most promising species in the development of biomass for biofuel (Vogel, 1996). *Biomass* is organic matter including herbaceous and woody plants and their residues that can be used for energy production. *Biofuel* is the alcohols, ethers, esters and other chemicals that can be derived from this organic matter and used in the production of electricity and liquid fuel (Sanderson, 2002). Biofuel should contain a high concentration lignocelluloses and low content of ash and nitrogen. Dry matter yield parallels lignocelluloses yield which is the material needed to produce ethanol. Dry matter is therefore an adequate measure of the amount of cellulose in the shoots and therefore the amount of energy present in the feedstock. (Cassida, 2004). Crops with high lignin and low nutrient quantity are more suited for combustion or conversion (Cassida et al., 2005).

## Ethanol Liquid Fuel

Ethanol is the current liquid fuel alternative source of energy needed for transportation primarily provided now by gasoline. There is a debate among scientists as to whether the production of cellulosic ethanol is thermodynamically positive; i.e. does it take less energy to produce than what is obtained from the end product. This is important because unless the thermodynamics are positive one would always be operating at an energy loss.

Cellulosic ethanol is produced from an enzymatic breakdown of lignocelluloses found in the cell wall of plants. The greater amount of cell wall to dry matter content, the more ethanol one can produce (McLaughlin et al., 1996). Simple sugars are produced from the cellulose and structural polysaccharides. In crops such as switchgrass, 80% of the dry matter is comprised of the cell wall, 30-50% is cellulose, 10-40% is hemicelluslose, and 5-20% lignin (Sladden and

Bransby, 1989; McLaughlin et al., 1996). Lignin, under conventional technologies, cannot be used in the conversion to sugar. However, lignin is energy-rich and can be used to produce heat during the production process, with ethanol yields of 280 L $Mg^{-1}$ (McLaughlin et al., 1996). The conversion from switchgrass to ethanol has resulted in a negative return.  It requires more energy to produce a liter of ethanol than the energy gained from ethanol combustion (Pimetel and Patzek, 2004). The negative energy balance is due to the high cost of agricultural input and conversion technology, based on cellulosic ethanol bio-refineries that do not use the lignin portion of the plant material to power the process. When the lignin portion of the biomass is used to power the ethanol bio-refinery, an average of 13.1 MJ of ethanol will be produced for every MJ of petroleum used, which results in an excess of 3,500 L $ha^{-1}$ of ethanol produced (Schemer et al., 2008).

## Combustion and Ash

Switchgrass can be used in the combustion process either by being pelletized and burned in individual home stoves, or brought to a power plant and burned to produce electricity. It is estimated that a field that yields 10 Mg $ha^{-1}$ $yr^{-1}$ will return 11 kcal of energy per kcal of fossil fuel consumed (Pimentel and Patzek 2004). When switchgrass is pelletized and burned in an appropriate stove, the return can be as high as 1:14.6 kcal (Sanson et al., 2004). Most researchers currently agree that when switchgrass is used as a heating fuel, the overall energy balance is positive. (Pimentel and Patzek 2004; Sanson et al., 2004)

The primary components when considering biomass as a fuel for combustion include available energy, moisture, and ash. Moisture and ash both reduce available energy content, because high moisture requires an excess input heat to burn, and ash creates fouling in combustion equipment (McLaughlin et al., 1996). Ash is of particular concern when biomass is being used for combustion. The presence of alkali metals and silicates are the major contributors in the production of slag, thick black material. These constituents lower the melting point of ash and allow it to become a liquid with the tendency to coat surfaces of machinery (furnaces, boilers, fluidized beds, etc.). Slag causes fouling and prevents heat from being recovered (Cassida et al., 2005; McLaughlin et al., 1996), possibly becoming cost prohibitive. Part of the appeal of switchgrass is that is can be used with existing technologies to supplement current energy systems. It is imperative that the end product can be used without causing high external costs to existing systems. For every 10 g $kg^{-1}$ increase of ash there is a decrease in heat value of 0.2 MJ $kg^{-1}$ (Tillman, 2000).

One of the key components when dealing with ash involves the storage and handling of raw material. Contamination during storage and transport can causes the feedstock to appear to have much higher ash content than what is present when it is harvested in the field. Inappropriate handling of material resulted in 1.4 on the slag index (lb of water soluble alkali in ash per MM Btu of fuel energy), an excess of 0.80 $MMBt^{-1}$ is considered too high for combustion. But when the material was handled with care, the ash index went down to 0.37 lb $MBtu^{-1}$ (McLaughlin et al., 1996).

## Switchgrass in Massachusetts

Extensive research has been done on the efficacy of switchgrass as a biofuel source in the United States:

Midwest (Vogel et al., 2002; Casler and Boe, 2003)

Southern US (Sanderson et al., 1999; Muir et al., 2001; Cassida et al., 2005)

Northern Great Plains (Berdahl et al., 2005, Lee and Boe 2005)

Southern Canada (Madakadze et al., 1996)

Europe (Elbersen et al., 2001)

In spite of the plethora of data that have been collected throughout these regions, no research has yet been published for switchgrass in Massachusetts.

In Massachusetts, 10.4% of the area is designated as farmland (USDA, 2012). The average size of each farm on this land is currently 27.1 ha, compared to 52.6 ha in 1974. A significant portion of Massachusetts farmland has been abandoned in the last 20 years, largely due to financial infeasibility. When cultivated land is abandoned it is not long until the area reverts to forest, beginning with shrubs and bushes and eventually with woody trees. Switchgrass might serve as an excellent placeholder for cultivated land to be used again at a later date. Switchgrass has the ability to grow on marginal land with little or no low fertilizer, surviving for multiple years without replanting. It will also improve water quality, adapt to a variety of soil conditions, reduce soil erosion, and sequesters carbon when planted for an excess of four years (McLaughlin et al., 2002, Vogel et al., 2002, Adler et al., 2006).

Hay is the most common type of farm in Massachusetts (27%), with the second being fruit and tree nuts (13%). On average, hay farms tend to be larger than most other farms in Massachusetts at about 45 ha. In a ten-year span (1997-2007) there was a 50% increase in small farms, a 15-31% increase in mid range farms, and a 15-30% decrease in large scale farms (USDA 2007 Census). The fact that Massachusetts has abundant hay farms in good for switchgrass because they use the same equipment to harvest.  In order for Massachusetts to consider switchgrass-based biofuel as a potential market for farmers, switchgrass must produce significantly high yields at a price high enough to can compete with the market for hay. Another potential use for switchgrass on a small acreage farms is to pelletizing the yields for heating fuel and use it on site or in the local community.

Ethanol at the moment does not seem like a viable option for production in Massachusetts. According to Epplin 1996 National Renewable Energy Laboratory, a large process plant would need 9000 Mg Sg day$^{-1}$ year$^{-1}$, which would require 350,000 ha switchgrass at an average yield of 9 Mg ha$^{-1}$ yr$^{-1}$. The total amount of farm land in Massachusetts is 209,578 ha. Running a large scale ethanol plant requires more land than Massachusetts has available (2007 USDA Census) It is possible that if North Eastern states wanted to combine efforts and produce an ethanol plant, then Massachusetts could contribute to operations which would at least provide a location for farmers to bring their product to market.

## Economics and Logistics

United States Department of Agriculture and the Department of Energy goal for 2030 call for 5 percent of the nation's power to come from biomass feedstock (BRDI, 2006). The feedstock are supposed to come from biomass such as switchgrass, other perennial energy crops, crops residue, manures, grain and other waste material. Sanders and Adler (2008) estimated this would require 22.3 million ha of land (12 percent) of existing cropland to be converted to energy crops. Some are concerned that the conversion of this land would affect hay, forage and pasture land, such that ranchers would have to compete with land for energy crops and it would drive up the price of animal husbandry significantly. Crops such as switchgrass would directly and indirectly be competing with food crops. Despite this concern it is also important to evaluate the potential for farmers to earn income from energy crops.

The primary costs to farmers to produce switchgrass include cost of land, crop maintenance and market transport. Economic models place the cost of production for switchgrass at \$33-\$63 Mg$^{-1}$ (Graham et al., 2000; Cundiff and Shapouri, 1997) Massachusetts would likely be on the higher price spectrum due the high cost of land in the state. The production of wood chips from forest land in Massachusetts is estimated to be at \$33 $Mg^{-1}$ (Natural Capital Incentive 2010). The average price of hay in Massachusetts is \$153 $Mg^{-1}$ (USDA,NASS-Crop Value Summary ISSN: 1949-0372-74)

If switchgrass were to be palletized and burned in coal power plants the price of producing switchgrass would need to be half that of coal, as coal produces almost twice the energy on a per-weight basis. (Sanderson 2004) The current price of coal does not account for many of the negative environmental factors that are caused its production. An extensive economic analysis of the environmental impact of producing coal priced it at \$0.0924-0.2689/ kWh, which converts to \$26.17-\$74.69 per GJ (Epstein et al., 2011). Switchgrass can produce 60-146 $Gj^{-1}ha^{-1}yr^{-1}$ (Schmer et al., 2007; McLaughlin et al., 1996) which would be the equivalent to providing farmers and average close to \$5000 ha. The estimated cost of growing switchgrass is at \$500 per ha, farmers would have more than enough of a return to justify converting land. While it is unlikely that farmer would receive \$5000 $ha^{-1}$, the research done by Epstein et al., 2011 creates an argument to provide government incentives to farmers to help offset establishment and operations costs possible through carbon credits. (Parish and Fike, 2005).

Ethanol does not seem like a viable option for production in Massachusetts. According to Epplin 1996 NREL a large process plant would need 9000 Mg Sg $day^{-1}$ $year^{-1}$, which would require 350,000 ha switchgrass at an average yield of 9 Mg $ha^{-1}$ $yr^{-1}$. The total amount of farm land in Massachusetts is 209,578 ha (USDA Census, 2007), running a large scale ethanol plant requires more land than Massachusetts has to offer. It is possible that if North Eastern states wanted to combine efforts and produce an ethanol plant, then Massachusetts could contribute to operations providing a market location for the states' farmers. Switchgrass is a bulky material that is expensive to transport, therefore small ethanol that were localized in communities might be an alternative to large scale production.

The current energy cost for a single home in the United States is estimated at 129.64 Gj household$^{-1}$ yr$^{1}$ (EIA.doe, 1997). Net energy yields for switchgrass have been estimated at 60-136 Gj ha$^{-1}$ yr$^{-1}$ (Schmer et al., 2007; Sanderson et al., 2007), a farmer could provide enough energy for their home in one to two ha of land.

## Description of Research

Switchgrass trials were established during 2006 to 2009 growing seasons. Harvest management trials began to provide farmers and agronomists with information to determine whether high quantity and quality switchgrass production was feasible for combustion in the region.

The following experiments are described in more detail in the following chapters.

Chapter 2

### Evaluating switchgrass varieties for biomass yield and quality to develop an herbaceous biofuel in Massachusetts

Twelve varieties were tested to see how they would produce in Massachusetts climate. Of the twelve varieties, five were chosen for further chemical analysis. All varieties were harvested in August (senescence), November (killing frost), and April (early spring). Samples were taken from the five top yielding varieties and tested for nitrogen, alki metals, ash content, and non-structural carbohydrates. At different times of the year a perennial grass will move nutrients back and forth from the roots and shoots. Soluble non-structural carbohydrates were measured in the root system at harvest time, to provided information on the reserves the plant had to survive the winter. Chemical constituents such as (N, K, P, Ca, Mg, Al) were extracted from the shoots to identify the amount of nutrients present in the stalk at harvest time. Ideally the harvest time should maximize the efficiency of nutrient cycling giving the plant sufficient time to move unused nutrients into their roots system for growth the following year, but at the same time produce sufficiently high yields such that it is economical for farmers to cultivate. This experiment looks at these relative concentrations and determines if there are differences among varieties and what the effect harvest time has on yield and quality.

Chapter 3

### Nitrogen application rate and harvest management of young and mature stands of switchgrass

Harvest management could potentially be different for old and young stands. There are multiple old stands, in excess of seven years, on conservation land in Massachusetts and around the United States.  Harvest times and cutting heights 7.5 cm and 15 cm were evaluated to see which affected the vigor of a young and old stands of Cave-in-Rock (upland variety). In our young stands (three years old), nitrogen treatments were added to see how the crop preformed and how the addition of nitrogen would affect the feedstock. Prior research indicated that the plant yield capability changes as the plant ages. This experiment gave us an idea of the type yields one can expect from their crops at three years and how they produce after nine years. This is important to farmers so that they can make projections about the expected yields over the life cycle of the plant, anywhere from 10-20 years.  All plants at time of harvest were analyzed for mineral content and soluble sugar reserves, in a similar manner to that described in the previous chapter.

Chapter 4

### Optimal Fall Harvest Time in Massachusetts for ‘Cave-in-Rock’ Switchgrass used as a Biofuel

Fall season bi-monthly harvests were conducted in 2010 and 2011. From September to November plots were cut at a low cutting height and moisture content and yields were calculated. These plots were analyzed for chemical constituents in the roots and shoots throughout the fall season. In 2011 a caliometer was used to track how much energy in crop in Joules per gram of dry matter yield was present throughout the growing season. This was done to track the crop as it was changing throughout the fall growing season to determine if there is a better time, between senescence (mid-September) and killing frost (mid-November) such that an optimal amount yield is possible while allowing most of the unused nutrients to translocate into the root system.

The following chapters will describe the above experiments and discuss the benefits and flaws of the different treatments. The goal of this research is to provide farmers with strategies to determine if switchgrass would be an appropriate crop to add to their fields.

## Conclusion

Use of herbaceous crops to solve the energy challenges is a promising field of research. Switchgrass has many attributes that make it an excellent candidate for the development of cellulosic biofuel. The question of whether Massachusetts can play a role in the development of this crop is addressed in this study. More specifically, our objectives were (1) to determine if varieties in the region can produce sufficient yields for biofuel production, and (2) to find out what type of management strategies will maximize these yields over an extended period of time. Treatments conducted to answer these questions include harvest time, fertilizer, and cutting height and their effects on yield, nitrogen, alki metals, BTU, and non-structural carbohydrates. Massachusetts is a small state and the price of land is expensive. It is important for farmers to determine if growing switchgrass would result in a sufficient profit, as heating fuel or in the production of ethanol.

# CHAPTER 2

# EVALUATING SWITCHGRASS VARIETIES FOR BIOMASS YIELD AND QUALITY TO DEVELOP AN HERBACEOUS BIOFUEL IN MASSACHUSETTS

## Abstract

Currently there are no published data on switchgrass (*Panicum virgatum L.)* yield potential for the state of Massachusetts. Our objective was to determine how cultivars preform in this northeastern United States climate and how harvest management affected over all yield. Five high-yielding upland cultivars (Blackwell, Carthage, Cave-in-Rock-, Shawnee, and Shelter) were harvested at senescence, kill-frost, and spring (Fall, Winter, Spring) between 2009-2011. Nitrogen fertilizer was added to plots at a rate of 100 kg ha$^{-1}$ in June of each year. Measurements were taken of yield, ash, total nitrogen, and mineral content in the feedstock and non-structural carbohydrates in roots at each time of harvest. In the first year all varieties produced their highest yields at senescence. Carthage was the highest yielding variety, and harvesting in fall consistently produced higher yields than harvesting in winter or spring. Harvesting Cave-in-Rock, Shawnee, Blackwell, and Shelter as the plant went into senescence in the first year caused a dramatic reduction in yield the following year, such that winter harvests were equivalent to or better then fall harvests. Nutrients such as N, P, K, Mg and ash all decreased in the feedstock when the harvest was delayed from fall to winter or spring. Soluble nonstructural carbohydrate concentrations in the roots were three times higher in the winter than in the fall. These levels decreased again in the spring. Massachusetts yields ranged from 6.8 Mg ha$^{-1}$ to 12.6 Mg ha$^{-1}$ across upland varieties in all years. Seven lowland or low yielding

varieties were all harvested (fall, winter, spring). No nitrogen was added to these plots. In all plots winter harvest resulted in higher yields than fall or spring.

## Introduction

A growing global population coupled with long term economic growth is leading to unprecedented natural resource demand for use in heating, transportation and overall energy security in developing and industrial nations (David and Ragauskas, 2010; Yan et al., 2010). Yet, while traditional carbon fuel sources struggle to meet this newfound demand, they also release large amounts of otherwise locked-away carbon (fossil fuels) into the atmosphere as carbon dioxide, raising concerns that they may be leading to man-made global warming—an outcome with unknown and possibly catastrophic consequences. Alternative energy resources such as biofuels may be a solution to this energy challenge, because unlike traditional fuels, biofuels close the carbon cycle (Ragauskas et al., 2006; Yan et al., 2010). When biofuel crops are grown, they draw carbon dioxide from the atmosphere, rather than unlocking fossil carbon that would have otherwise been locked away as oil or coal. Biofuels, in other words, only release as carbon that which they already withdrew from the atmosphere.

A number of crops—so-called "first generation biofuels" (corn, sugar cane, oilseed rape)—have been identified as promising candidates for the production of biofuel, (Worldwatch institute, 2006). However, these potential fuel crops pose their own economic and environmental challenges (David and Ragauskas, 2010; Colbran and Eide, 2008; Demirbas, 2008). Grain corn, for example, was originally seen as a promising candidate for ethanol production due to its high sugar content; however, its high nitrogen requirements and its tendency to compete with corn-for-food has called into question grain corn's long-term suitability for use in biofuel production (Parrish and Fike, 2005; Sanderson et al., 2006). Oil seed crops were also originally thought to be promising for producing biodiesel, but converting oil seed to biodiesel has proven complicated and less efficient than producing fuel from cellulosic crops. (Schmer et al., 2008). These problems have led to widespread interest in “second” generation biofuel crops, such as prairie grasses, which are hardy, easily converted into cellulosic ethanol, and do not compete with food resources (Yan et al., 2010). In the early 1990’s, after a series of evaluation trials, the United States Department of Energy (DOE) identified switchgrass (*Panicum virgatum* L.) as a promising species for the development of herbaceous bio-fuel (Vogel, 1996).

Switchgrass is a warm season $C_4$ perennial grass with a deep fibrous root system native to North America (Ma et al., 2000; Parrish and Fike, 2005). Switchgrass has a number of useful attributes. Its high adaptability means it can be grown on marginal land, with little fertilization, in a variety of climates; It can survive for multiple years while preventing soil erosion, improving water quality, and serving as wildlife habitat between harvests; moreover, switchgrass can be harvested with conventional haying-equipment (Sanderson et al., 2006; Vogel et al., 2002; Adler et al., 2006; McLaughlin et al., 2002; Masse et al., 2010).

An important aim of contemporary switchgrass research is to determine which cultivars grow best under which growing conditions. Since producing healthy, high-yielding switchgrass plants with high feedstock quality is perhaps the utmost goal of a switchgrass grower, it is necessary to determine optimal cultivar selection and agronomic practices. Since both cultivar selection and harvest time are expected to exert significant influences on switchgrass biomass yield, re-growth, and quality for energy production, they are important areas for further research.

Switchgrass biomass production has been reported to have high variation among cultivars depending on the location (Fike et al., 2006). Hopkins et al., (1995) reported significant variation among switchgrass cultivars in date of heading and yield at heading. They also noted that early heading was associated with lower yields. Successive researchers (Casler et al., 2004; Fike et al., 2006) have shown the dramatic effects of the latitude of origin of a cultivar on its production in different geographic locations. There are generally thought to be two major groups of switchgrass cultivars, upland and lowland. They are divided according to the climate where the ecotype has developed (Casler et al., 2004; Adler et al., 2006).Upland varieties are more adapted to temperate weather of North East especially Massachusetts than the lowland types because the upland types are cold tolerant (Parrish and Fike, 2005).

Switchgrass' survival during winter months and re-growth in spring to early summer depends on the extent of its root structure. (Ma et al., 2000). In order to maintain a healthy root structure for continual crop production while applying minimal amounts of fertilizer, it is important to determine the appropriate time for allowing carbohydrates and nutrients to move from the stalk into the root system (Thomason et al., 2004). It is thought that the ideal time for harvest is after the primary nutrients have translocated into the plant's root structure (Adler et al., 2006; Casler and Boe, 2003), which would suggest that early fall harvests may be preferable to late fall or winter harvests because weather conditions are generally more favorable requiring less time and labor to cure the crop (Samson and Mehdi, 1998; Adler et al., 2006).

Harvest time not only influences switchgrass biomass production, it also affects the biofuel quality (Adler et al., 2006). As switchgrass matures during the growing season, its ash content decreases (Sanderson and Wolf, 1995; Adler et al., 2006), which leads to an increase in biofuel quality. In addition, less nitrogen is required by the plant because of the translocation of nutrients into the roots (Vogel et al., 2002). Delaying harvest until spring has been shown to reduce the biomass production of some biofuel crops such as reed canarygrass (*Phalaris arundinacea* L.), Miscanthus sp. and switchgrass. However because mineral concentrations continue to decrease as well (Burvall, 1997; Lewandowski et al., 2003; Adler et al., 2006), it is as-yet unclear whether the increase in fuel quality offsets the decrease in total production.

The objectives were (i) to select the high-yielding cultivars with the ability to survive winter in Massachusetts and (ii) to study how different harvest time influence switchgrass biomass yield, re-growth and the quality for energy production.

## Material and Methods

### Experimental site

Variety trials were established in 2006 at the University of Massachusetts Agricultural Experiment Station Farm in Deerfield in the Connecticut River valley (42°N, 73°W). The soil type was a Hadley fine sandy loam (nonacid, mesic Typic Udifluvent).

### Cultural practices and experimental design

Twelve varieties of switchgrass (Alamo, Blackwell, Carthage, Cave-in-Rock, Dacotah, Ecotype-WI, Forestburg, NE28, Pathfinder, Shawnee, Shelter, Sunburst) were obtained from two commercial companies in North America for an evaluation of their productive potential and adaptability to Western Massachusetts. These companies were Ernst Seed, Meadville, PA and Wind River Seed, Maderson, WY. Each variety was grown in pure cultures similar to forage grasses for permanent pastures. The plot size for each variety in a replication was 3 m x 6 m, allowing for a harvested sample and adequate borders. Plots were split so that one half of each plot received no fertilizer and the other half received 68 N kg $ha^{-1}$.

No irrigation was applied in this experiment, as that is not a common practice in Massachusetts due to adequate rainfall during the growing season. After establishment trials were completed, varieties were categorized into two groups; high-yielding varieties (HYV) and low-yielding varieties (LYV) this was based on plant vigor in June 2009 and yield results from 2007 and 2008.

### Experiment I

After establishment trials were completed, five HYV were selected for further analysis. A randomized complete block design with a split plot arrangement was conducted using the HYV (Blackwell, Carthage, Cave-In-Rock, Shawnee, and Shelter) as main plots and three harvest times (post-anthesis, killing frost, and early spring) as sub plots from 2009 to 2011. Spring harvest for each year took place the following April, such that in the 2009 trial, the spring harvest took place in April 2010. In order to keep descriptions simple the spring harvest will be referred to as in the year of 2009, since the harvested vegetation actually grew during 2009.

Each plot was divided into three sections for harvest time treatment and either side of the sectioned plot was discarded. A 2.8 $m^2$ area of the plot was mowed using a BCS sickle mower at 10-cm stubble height. Harvested switchgrass were hand gathered, and weighed in the field with a tarp and digital balance. In early June of 2009, each plot of the HYV was fertilized with calcium ammonium nitrate (27% N) at a rate of 136 N kg $ha^{-1}$.

### Experiment II.

The seven remaining low yielding varieties LYV (Alamo, Dacotah, Ecotype-WI, Forestburg, NE28,Pathfinder, and Sunburst) were arranged during establishment with a complete block design for the main effect of variety and were harvested three times (post-anthesis, killing frost, and early spring) as sub-plots from 2009 to 2011. The same cultural practices and harvest methods described for experiment I was used in this experiment except nitrogen fertilizer was not applied to these plots. Only dry matter yields were recorded for LYV’s.

### Measurements

At each time of harvest the fresh weight yields were measured and a representative subsample was collected from each plot. The subsamples were weighed and placed in a forced air oven at 50°C for 48 hours to determine moisture content at harvest. Harvested fresh weights were then adjusted by moisture content. After drying, samples were ground to pass a 1-mm screen of a Wiley mill (Thomas Scientific, Swedesboro, NJ). Tissue samples were collect to determine ash and mineral content. A cup cutter was used to remove a cylinder of roots 15 cm in diameter and 15 cm deep at time of harvest to determine non-structural carbohydrates.

### Nitrogen

Nitrogen content of plant tissue was determined using the Total Kjeldahl procedures. $CuSO_4$ (1.625 g) was added to a 0.2 g tissue sample which was then digested with 1.0 M sulfuric acid and boiled for one hour. Samples were allowed to cool and 46.5 ml of de-ionized water were added. These samples were then analyzed for ammonium content using a flow injection spectrophotometer (Lachat QC85100).

### Ash and Mineral Content

Plant tissue samples were ground using a 40-mesh Wiley Mill. Plant material was then weighed to 0.366 g and ashed in a Furnatoral Type 53600 Controller at 500°C for 5 hr, then cooled and reweighed. The contents were dissolved in 18 ml of 20% trace mineral grade HCl. The solution was filtered with Whatman 42 filter paper. This solution was then diluted 1:1 with de-ionized water and analyzed using an Inductively Coupled Plasma Spectro Cirsos CCD.

### Non-Structural Carbohydrate

The harvested roots along with the below-ground portion of the crown were washed carefully and dried at 50°C for 48 hr. The below ground tissue was dried, they were ground twice, once using a large grinder and then a second time using a 40-mesh Wiley mill. All machines were vacuumed and dusted clean between samples to reduce potential contamination.

Carbohydrate analysis for the nonstructural carbohydrates of the roots was performed using High Pressure Liquid Chromatography for sucrose, glucose, and fructose. The method was developed and described in Hagidimitriou and Roper (1994). Ground samples were weighted out at 0.1 g of tissue; 5 ml of 80% HPLC grade ethanol (with an internal standard of 0.06 g of sorbitol) were added to the tissue and incubated in a water bath at 55°C for one hour. The samples were then filtered through a 0.45-µm Millipore Swinnex membrane nitrocellulose filter provided by Fisher Scientific (Cat No. HAWPO1300). This process was repeated three times, and then samples were kept in the water bath for 18 hr or until liquid had evaporated. The filtrates were reconstituted using 5 ml of HPLC-grade water; they were then vortexed and incubated for 10 minutes in a water bath. The samples were then filtered through a Swinnex filter and a conditioned Sep-Pak cartridge obtained from Waters Corporation. The first 10 to 15 drips of filtrate were discarded and then the remainder was put into a 1-mL HPLC vial and capped. This material was placed into the HPLC machine for analysis. Samples were put into a 1-ml vial, after discarding the first 10-15 drops of filtrate. Soluble carbohydrates were separated with an ion-exchange column and refractive index was used to determine the relative concentration of sugar in the filtrate. Data were analyzed using Empower (Hagidimitriou and Roper, 1994).

## Statistical Analysis

Biomass yield, mineral content, and non-structural carbohydrate data were analyzed using the ANOVA procedure and proc GLM (SAS institute, 2003). Means were compared using least significant differences (LSD). Treatments including Harvest (Fall, Winter, Spring), Year (2009, 2010, 2011), High Yielding Varieties (Blackwell, CIR, Carthage, Shawnee, Shelter) and Low Yielding Varieties (Alamo, Dacotha, Ecotype, Forestburg, NE28, Pathfinder, and Sunburst) were all considered fixed effects with three replication. They were treated as random effects. Results were not averaged over years when interactions of year by main effects were found significant.

## Results

Experiment I.

Dry matter yield

A summary of the ANOVA results is presented in Table 2.1. Switchgrass dry matter yield was influenced by year. Yield performance of all HYV was not significantly different when averaged over three years (Table 2.1). However significant variety by year interaction (Table 2.1) indicates that weather had exerted an important influence on yield performance of the varieties. In 2009 biomass yields were on average 11.2 Mg $ha^{-1}$ but were reduced by 18 percent in the 2010 and then another 6.6 percent in the 2011 (Table 2.2). Among varieties, Carthage produced the highest biomass (12.6 Mg $ha^{-1}$ in 2009 and 9.5 Mg $ha^{-1}$ in 2011), whereas Blackwell was the superior variety in 2010 (10.5 Mg $ha^{-1}$). Shelter consistently produced lower yield compared with other varieties (Table 2.2).

Harvest time significantly affected the dry matter yield (Table 2.1). Dry matter yields were the highest in the harvest that occurred during the fall of the first year (14 Mg $ha^{-1}$) and they declined steadily in the second (9.6 Mg $ha^{-1}$) and third year(8.0 Mg $ha^{-1}$), reducing by as much as 43 percent (Table 2.3). Although harvest time had a significant impact on yield in 2009 and 2010, it had no effect on yield in 2011 and yields were on average at 8.5 Mg $ha^{-1}$ for all three harvest times. Overall the fall harvest produced the highest yields (Table 2.3).

There was a significant interaction between harvest and variety (Table 2.1). Carthage produced the highest dry matter yield in fall in all years; Blackwell, Cave-in-Rock, and Shawnee produced highest yields in the fall of 2009, winter 2010, and the spring 2011. Shelter produced higher yields in the winter in 2010 and 2011 (Table 2.4). The spring harvest yields were high for 2011 trails with average yields at 9.2 Mg $ha^{-1}$ , but in the 2010 trials were at 6.7 Mg $ha^{-1}$ which on average was 4.2 Mg $ha^{-1}$ lower than the yields of the preceding winter harvest (Table 2.3), these variation in spring yield are likely due to harshness of the proceeding winter.

### Ash Content

The effect of year and variety on ash content was not significant. However, total ash in harvested grasses depended on the time of harvest. Early harvest had almost twice the ash present in the feedstock compared with late harvests (Table 2.5). There are fluctuations in the ash content by year but this is likely due to the effect of variable weather.

### Mineral Content

The mineral content of biomass was significantly changed for all years (Table 2.1). The only mineral that was not affected by year was iron (Fe). Nitrogen showed a similar trend to ash, with the highest residues occurring in the fall harvest, whereas no significant differences were observed between the concentrations in the winter and following spring harvests (Table 2.6). Phosphorous, potassium, and magnesium (P, K, and Mg) all showed a steady decrease from the fall harvest to the spring harvest, with the most pronounced between harvest times (Figure 2.1) was observed in K concentrations. The concentrations of these minerals in the spring harvest were a little over half of what they were in the fall harvest with the exception of P. Calcium (Ca) concentration remained nearly constant across all harvest times, with the largest differences in Ca concentration occurring in the winter. Iron (Fe) and Aluminum (Al) concentrations were at their lowest in the winter harvest, and there was some accumulation in the spring harvest (Table 2.6).

Non-Structural Carbohydrates

Soluble non-structural carbohydrate levels in the roots and below ground tissue of the crown were affected significantly by year, variety and harvest time. Fluctuation of sugars in various years is expected to reflect changes in weather. The levels of glucose and fructose in all five HYV were similar (Figure 2.2). Sucrose which was the most abundant non-structural carbohydrate differed among varieties. Cave-in-Rock and Shelter had the lowest levels of sucrose, while Blackwell, Carthage, and Shawnee had similar levels of sucrose (Figure 2.2). The effect of time of harvest on the sugar levels was highly significant. Sucrose was highest when switchgrass was harvested in November and was lower in August and April harvest (Figure 2.3).

EXP II. Low –Yielding Varieties with No Nitrogen Fertilizer

There were significant differences among yields between the low-yielding varieties (Table 2.8). Pathfinder and Ecotype produced the yields at 6 Mg ha$^{-1}$, while Alamo produced the lowest at 1.1 Mg ha$^{-1}$. Average yields for all low-yielding varieties were 4.1, 6.1, and 4.7 Mg.ha$^{-1}$.

## **Discussion**

Our results yield five novel insights which to some extent confirm other research, while in other situations raising interesting challenges to the current academic view and open up new avenues for future study. We found that (1) switchgrass crops grown in Massachusetts achieve yields on par with the national average; (2) Carthage is a high performing variety for the Massachusetts climate;

(3) harvesting at senescence from most upland varieties initially showed an increase in yield but had detrimental effects on yield the following year; (4) harvest at senescence may increase weed-pressure reducing future yields; and (5) delaying harvest until after senescence

reduces nutrient quantity in feedstock but pH-dependent nutrients may increase in the spring harvest.

Our experiments indicated that all HYV preformed similarly. The response of the varieties depended on weather conditions. For Massachusetts environmental conditions it appears that Carthage and Cave-in-Rock on average are better adapted to the harsh winters and short summers found in this area. Blackwell preformed the best in 2010 but yields were the second lowest in 2011. Upland varieties; throughout the United States produce yields on average between 5-11 Mg $ha^{-1}$ (Sanders and Adler, 2008; Schmer et al., 2007). The trials at the University of Massachusetts across upland ecotypes ranged from 6.7-14 Mg $ha^{-1}$, which indicates that Massachusetts is able to produce similar yields to other areas in the United States. Dry matter yields were more susceptible to harvest time in the first and second year of the experiment but did not have an effect in the third year. Carthage and Cave-in-Rock produced yields at 17.0 Mg.$ha^{-1}$ and 16.2 Mg.$ha^{-1}$ in the fall of the first year and were then reduced by 28 and 51 percent, respectively, in the second year but remained more constant from the second to third year.

Switchgrass stand density declines over time, producing fewer tillers as the crop ages. This is more apparent in upland varieties than it is in low land varieties. The crop compensates for the thinning of the stand by increasing the size of the plant (Cassida et al., 2005). In the current experiment, there was a consistent decrease in dry matter yield from year to year that was more apparent when fields were harvested in fall than in the winter or spring. This might be attributed to the decrease in the amount of tillers that were put out as the plants aged. More years of data are needed to determine the overall expected yield for the crop over its life span and if the decrease in fall yield is significant enough that over a ten-year period it would recommend harvesting in the winter or spring when yields are more stable.

Many researchers claim that optimal harvest time is at senescence and that delaying the harvest until a killing frost will result in a significant decrease in dry matter yield and that harvesting prior to maturation in midsummer also negatively affects the yield (Sander and Adler, 2008; Taylor and Allinson, 1982; Vogel at al., 2002; Sanderson et al., 1996). Moore et al., (1991) stated that for Cave-in-Rock optimal harvest is in the third week of August for the Midwest when switchgrass plants have just completed the senescence stage of development. In our experiment this appeared to be true for Carthage, but not for Cave-in-Rock. Cave-in-Rock yields were similar among fall and winter harvest times; so that it appears that delaying the harvest had no effect on yield in 2010 and 2011. With Shawnee, Shelter, and Blackwell delaying the harvest resulted in higher yields. In 2011 the spring harvest produced on average the highest yields at 9.2 Mg $ha^{-1}$, but this was still significantly less when comparing overall yield for all three years.

In another experiment conducted at the same location, we investigated Cave-in-Rock response to nitrogen application rate and harvest time. The plots were larger and weed pressure was more apparent. In every plot where the field was harvested in the fall, 40-50% of the field was covered in weeds when evaluated in midsummer. More research is necessary but it appears that harvesting at senescence can damage the stand because leaving the fields bare for the entire fall season allows time for invasive weeds to establish. This issue may further be compounded by the stand thinning as the crop ages. In abandoned pasture and croplands where planting of switchgrass is being considered, a high diversity of weed species is likely to be present (Johnston et al., 1990).

Time of harvest influenced ash concentrations resulting from changes in mineral content, such that it decreased as the plants matured. This result confirmed prior findings reported by Sanderson and Wolf (1995). Ash content is an important factor when considering grass for combustion.

Mineral content significantly changed when harvest was delayed from senescence to later in the season. Across all years and all varieties, nitrogen and ash content showed similar trends, with the highest residues occurring in the fall harvest and no significant difference between concentrations in the winter and following spring harvest. Harvesting after kill forst caused a decrease in the percentage of nitrogen in plant tissue as opposed at the beginning of senescence. With respect to nutrients such as P, K, and Mg which had concentrations of 1000-10,000 ppm, a delay in the harvest until at least winter, can improve the feedstock quality for combustion. Calcium concentrations were not reduced as the plant matured over the season. One of the appeals of using switchgrass as a biofuel is that it efficiently recycles its nutrients. It was a consistent finding that harvesting in fall removed vital nutrients in the harvested biomass, such that N, P, and K removal over successive years would likely cause depletion in nutrients and require more fertilizer to be used.

An interesting trend to note involves micronutrients including Al and Fe. Their concentrations were 10-100’s ppm - small in comparison to N, P, K, Ca,- but delaying the harvest until spring in the 2011 (after a severe winter) actually caused the concentrations of Fe and Al to rise (Table 2.7 ). In situations where switchgrass is being considered for abandoned land, and where metal contamination might be present, delaying the harvest until spring might not improve feedstock quality, especially if the metal solubility is pH dependent, and could potentially be absorbed by the plant over winter.

### Non-Structural Carbohydrates

Parish and Wolf (1993) claimed that the reduction in yield from September to November was due to the remobilizing of carbohydrate reserves and nitrogen from the stem to the roots and that remaining loss in yield was due to leaf loss. In a study, Anderson et al. (1989) showed that peak concentration in total nonstructural carbohydrates (TNC) were present in the above ground tissue in September. Figures 2.2 and 2.3 appear to be consistent with these findings. There was three times more sucrose in the winter harvest than in the fall, which would be expected as the plant prepares for dormancy due to cold acclimation (Figure 2.3). By spring the carbohydrate levels were low again, due to the plants presumably having consumed some of their reserves to survive the winter. An analysis of the nonstructural sugars in the roots sampled at each harvest date showed sucrose to be the primary sugar, with much lower quantities of fructose and glucose which is consistent with finding by White (1973), that warm season grasses store reserves in the form of sucrose and starch.

### Low Yielding Varieties

Pathfinder and Ecotype were the top yielding varieties. Alamo produced so little in most plots that it was not harvested at most of the time, however, the few times that Alamo tillers did survive they grew taller and more vigorously than the rest of the plants in the area. In some areas around the United States yields have been reported to be as high as 22.5 Mg but these yields involve low land varieties like Alamo at southern latitudes, where growing seasons are significantly longer (Muir et al., 2001). Alamo cannot reliable survive the harsh winters and short growing season in Massachusetts and produce far lower yields then upland varieties.

For all the LYV varieties that received no fertilizer treatment, delaying the harvest until the winter increased yield. This is likely because of switchgrass' ability to mobilize nutrients to the root system before a killing frost (Casler and Boe 2003). It appears that when no fertilizer is added, delaying the harvest until a killing frost allows the plant to use its nutrients more efficiently for growing the subsequent year.

Mulkey et al. (2006) conducting research on 9-year old varieties, found that delaying the harvest until a killing frost actually produced higher yields. In our experiments an August harvest negatively impacts the yield on all no-nitrogen low yielding varieties.

## Conclusion

In high-yielding varieties such as Carthage, Cave-in-Rock, Blackwell, Shawnee, and Shelter where 136 kg $ha^{-1}$ of nitrogen was used, highest yields were seen in the late-August harvest of the first year of the experiment. In the following years all yields significantly decreased. In Carthage, the highest-yielding variety, harvesting in late-August consistently produced higher yields than harvesting in November and April. For Cave-in-Rock, Shawnee, Blackwell, and Shelter, yields in the fall fell dramatically enough that a winter harvest was equivalent to a fall harvest and sometimes better. In all low yielding varieties, where no nitrogen was added, winter harvest resulted in higher yields than fall or spring harvests. Ash content and nutrients such as N, P, K, and Mg all decreased in the feedstock when the harvest was delayed from fall to winter. A reduction in nutrients improves the quality of the feedstock for combustion. Soluble nonstructural carbohydrate concentrations in the roots were three time higher in the winter than in the fall. These levels decreased again in the spring. The increase in soluble nonstructural carbohydrate in the roots and the decrease in the mineral content in the feedstock are attributed to the remobilization of the nutrients from the crown to roots in perennial grasses. Harvesting in fall initially produces higher yields, but these yields steadily decline in subsequent years. Winter and spring harvests showed relatively stable yields. Massachusetts yields ranged from 6.7 to 13 Mg $ha^{-1}$ across upland varieties in all years. These yields are consistent with the results of other experiment throughout the United States at similar latitudes.

Table 2.1. Analysis of variance showing the *p*-values for yields and chemical analyses.

| Source of Variation | df | Yield | N | ASH | P | K | Ca | Mg | Fe | Al | NSC† |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year (Y) | 2 | ** | ** | ns | ** | *** | ** | * | ns | *** | ** |
| Variety (V) ‡ | 4 | ns | ns | ns | ns | ns | ** | ns | * | ** | ** |
| Harvest (H) | 2 | * | *** | *** | *** | *** | ns | *** | ** | *** | *** |
| Y x V | 8 | ** | ns | ns | ns | ns | ns | ns | ** | ** | ns |
| Y x H | 4 | *** | ns | *** | ns | ns | ns | ** | *** | *** | *** |
| H x V | 8 | ns | ns | ns | ns | ** | ns | ns | ns | *** | ns |
| Y x H x V | 16 | ns | *** | ns | ns | ns | ns | ns | ns | ns | ns |
| CV (%) | | 21.9 | 20 | 26 | 21 | 27 | 24 | 18.8 | 33 | 32.1 | 21.6 |

* Significant at the 0.1 level

**Significant at the 0.05 level

***Significant at the 0.01 level

† NSC-Nonstructural Carbohydrates (Soluble)

‡ Variety include Blackwell, Cave-in-Rock, Carthage, Shawnee, and Shelter

Table 2.2. Switchgrass dry matter yield (Mg $ha^{-1}$) for high yielding varieties in 2009-2011.

| Variety | 2009 | 2010 | 2011 | Mean |
|---|---|---|---|---|
| Blackwell | 9.9bc | 10.5a | 8.2ab | 9.5 |
| CIR | 12.3ab | 8.0a | 9.0ab | 9.7 |
| Carthage | 12.6a | 9.5a | 9.5a | 10.6 |
| Shawnee | 11.8abc | 8.4a | 8.7ab | 9.6 |
| Shelter | 9.6c | 9.0a | 7.1b | 8.6 |
| LSD Variety x Year † | 2.6 | 2.6 | 2.1 | |

†LSD calculated at 0.05 level

Table 2.3. Effect of harvest dry matter yield (Mg $ha^{-1}$) in 2009-2011.

| Harvest ‡ | 2009 | 2010 | 2011 | Overall |
|---|---|---|---|---|
| Fall | 14.0a | 9.6a | 8.0a | 10.6A |
| Winter | 10.1b | 10.9a | 8.2a | 9.8A |
| Spring | 9.5b | 6.7b | 9.2a | 8.5B |
| Overall | 11.2 | 9.1 | 8.5 | |
| LSD Yield x Harvest | 2.0 | 2.0 | 1.5 | |

†Averaged of High Yielding Varieties

‡ Harvest Fall (Senescence), Winter (Kill Frost), Spring (Snow melt)

Table 2.4. Yield ($Mg.ha^{-1}$) of high yielding varieties by harvest.

| | Blackwell | | | Carthage | | | Cave-in-Rock | | | Shawnee | | | Shelter | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Harvest† | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 |
| Fall | **11.0‡** | 11.2 | 7.0 | **17.0** | **12.1** | **12.1** | **16.2** | 8.0 | 8.9 | **13.8** | 7.0 | 7.4 | **12.0** | 9.6 | 5.8 |
| Winter | 9.0 | **12.6** | 8.7 | 11.8 | 11.2 | 7.5 | 10.6 | **9.8** | 8.3 | 10.7 | **10.0** | 8.7 | 8.6 | **11.0** | **7.9** |
| Spring | 9.8 | 7.7 | **8.8** | 8.9 | 5.2 | 9.9 | 10.0 | 6.2 | **9.7** | 11.0 | 8.1 | **10.0** | 8.1 | 6.6 | 7.7 |

†Harvest Fall (Senescence), Winter (Kill Frost), Spring (Snow melt)

‡Bold Numbers –Yields were highest for a variety in a particular year

Table 2.5. Ash content (%) in feedstock by harvest time 2009-2011.

| Harvest† | 2009 | 2010 | 2011 |
|---|---|---|---|
| Fall | 4.7a | 5.5a | 4.7a |
| Winter | 1.9b | 2.9b | 2.6b |
| Spring | 2.6b | 2.1c | |

† Harvest Fall (Senescence), Winter (Kill Frost), Spring (Snow melt

Table 2.6. Effect of harvest time on chemical constituents in dry matter yield, averaged across high yielding varieties, in 2009-2011.

| | | | | Nutreints† | | | |
|---|---|---|---|---|---|---|---|
| Harvest ‡ | N | P | K | Mg | Ca | Fe | Al |
| Fall | 0.58a | 1414a | 10305a | 1408a | 2028b | 42a | 66b |
| Winter | 0.30b | 743b | 5338b | 1085b | 2362a | 40a | 37a |
| Spring | 0.33b | 312c | 538c | 652c | 2215ab | 58ab | 59b |

‡ Harvest Fall (Senescence), Winter (Kill Frost), Spring (Snow melt)

‡ N % of Dry Matter Yield, P, K, Mg, Ca, Fe, Al reported in ppm

Table 2.7. Effect of harvest time on micronutrients present in dry matter yield, averaged across high yielding varieties, in 2009-2011

| Harvest† | | Fe‡ | | | Al | |
|---|---|---|---|---|---|---|
| | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 |
| Fall | 59.7a | 32.5b | 33.4a | 129.3a | 44.9 b | 23.8a |
| Winter | 42.5b | 41.9b | 35.3a | 62.2b | 29.8c | 20.5a |
| Spring | 42.7b | 73.2a | | 55.5b | 63.1a | |

† Harvest Fall (Senescence), Winter (Kill Frost), Spring (Snow melt)

‡ Fe, Al reported in ppm

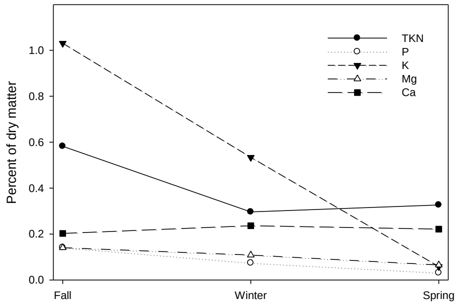

Figure 2.1. Chemical constituents in dry matter yield.

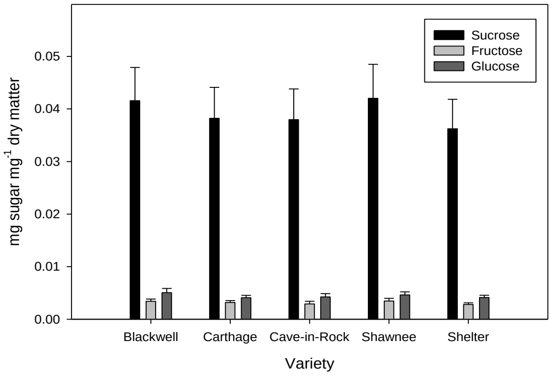

Figure 2.2. Soluble nonstructural carbohydrates at time of harvest for below ground roots and crown averaged for high yielding varieties for 2009-2010.

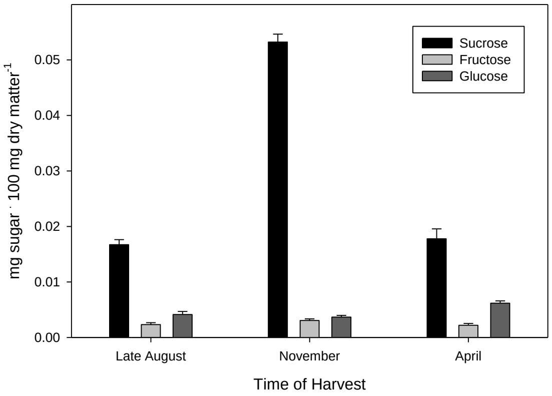

Figure 2.3. Soluble nonstructural carbohydrates at time of harvest for below ground roots and crown averaged for high yielding varieties for 2009-2010.

Table 2.8. Low yielding varieties average yield 2010-2011 for all harvests.

| Variety | Yield† |
|---|---|
| Pathfinder | 6.2 a |
| Ecotype | 6.2 a |
| NE28 | 5.1 b |
| Sunburst | 5.0 b |
| Forestburg | 4.6 b |
| Dacotha | 3.1 c |
| Alamo | 1.1 d |

†Yield Mg ha$^{-1}$, based on LSD 0.05

# CHAPTER 3

# NITROGEN APPLICATION RATE AND HARVEST MANAGEMENT OF YOUNG AND MATURE STANDS OF SWITCHGRASS

## Abstract

Switchgrass (*Panicum virgatum* L.) is a native perennial prairie grass that grows in a wide range of climatic conditions and is currently being researched as an energy crop for biofuel. Our objectives were to develop harvest management recommendations for an upland variety of switchgrass, Cave-in-Rock, and to determine how both young and mature stands response to agricultural manipulation. Two locations were studied in this experiment; the first supported a young stand (YS) that was three years old and grown on conventional crop land, the second was a mature stand (MS) that was seven years old and was being used for conservation purposes. Treatments included three harvest times (late summer, late fall, and spring) and two cutting heights (7.5, 15 cm). In the YS, an additional treatment of three nitrogen fertilizer rates (0, 67, 135 kg ha$^{-1}$) was used. Measurements were taken of yield, ash, total nitrogen, and mineral content in the feedstock and non-structural carbohydrates in the roots at the time of each harvest. Harvest time significantly affected the yield of the YS but did not affect the yield of the MS. Cutting to 7.5 cm increased yield for both the YS and MS by 1 Mega-gram per hectare (Mg ha$^{-1}$). Late-summer harvested plants were able to store as much sucrose reserves as late fall and spring plants. No correlation was observed between late summer harvest and the ability of the stand to store reserves for re-growth the following year. The largest decrease in yield occurred in our YS fall harvest and likely resulted from weed pressures in the field. The YS produced between on average 7.1 Mg ha$^{-1}$ in the first year and reduced to 6.8 Mg ha$^{-1}$ in the second and 5.8 Mg ha$^{-1}$ in third year. In the MS, the yields remained constant at 4.4 Mg ha$^{-1}$. Switchgrass

stands decrease in yield as they get older and then appear to level off. Yield projections should not be based on the initial years of production but should be averaged over the life span of the stand.

## Introduction

Switchgrass (*Panicum virgatum* L.) is a native perennial prairie grass that grows in a wide range of climatic conditions; from Mexico to Canada (Wright et al., 2007). Many characteristics define switchgrass as a "model" energy crop including its high productivity in diverse settings and its ability to grow on marginal land (Sanderson et al., 1996: McLauglin et al., 2002). Switchgrass is easy to manage, requires low nitrogen fertilizer and pesticide use after establishment, and can be harvested using conventional hay-making equipment (Teel et al., 2003). Tolerant of heat, cold and drought, switchgrass can grow in hot months when cool-season grasses cease to be productive (Casler et al., 2007). It grows in wide a range of soils from sand to clay loam and can tolerate a wide range of pH values from 4.9 – 7.6 (Lewandowski et al., 2003).

In the last 30 years there have been a wide variety of reports in the literature that discuss switchgrass; its yield potentials, growth patterns, chemical composition, and ability to survive across a range of climates (Parrish and Fike, 2005; Sanderson et al., 2006; Vogel et al., 2008; Keshwani and Cheng, 2009). Most of the research has been done in the mid-western and southern parts of the United States. Reported yields for upland varieties range from 4-13 Mg $ha^{-1}$ across various fertilizer application rates and harvest times throughout the USA (Adler et al., 2006; Sanderson et al., 2008; Vogel et al., 2002; Cassida et al., 2005; Wright, 2007).

Nitrogen is the primary nutrient of concern when determining nutrient requirements of switchgrass for a particular site. The optimal rates change depending on cultivar, management practices, climate, soil conditions and age of stands (Vogel et al., 2002, Thomason et al., 2004, Mulkey et al., 2006). Parrish and Fike, 1996 reported that the most unsettling and unsatisfying recommendation when managing switchgrass for biomass lies in the recommendations for fertilizer application rate. The capacity to create a sustainable energy crop that is economically viable and thermodynamically positive requires a crop that has a low nitrogen fertilizer requirement. This is due to the high energy costs of nitrogen fertilizer (40 MJ of natural gas per kilogram of $NH_3$). Using excess fertilizer not only reduces the effectiveness of producing fuel from biomass but also contributes to the risk of air pollutants such as nitrous oxide, which form during combustion, when high levels of nitrogen are present in raw materials.

Switchgrass can be used in the combustion process either by being pelletized and burned in individual home stoves, or by being burned in a power plant to produce electricity. It is estimated that a field that yields 10 Mg $ha^{-1}$ $yr^{-1}$ will return 11 kcal of energy per kcal of fossil fuel consumed (Pimentel and Patzek, 2004). The primary components when considering biomass as a fuel for combustion include available energy, moisture, and ash. Moisture and ash both reduce available energy content, because high moisture requires an excess input of heat to burn, and ash creates fouling in combustion equipment (McLaughlin et al., 1996).

Ash is of particular concern when biomass is being used for combustion. The presence of alkali metals and silicates in ash are major contributors in the production of slag, a thick black liquid material that forms when feedstock is burned at high temperatures. These constituents lower the melting point of ash and allow it to become a liquid with the tendency to coat surfaces of machinery (furnaces, boilers, fluidized beds, etc.). Slag causes fouling and prevents heat from being recovered (Cassida et al., 2005, McLaughlin et al., 1996), possibly becoming cost prohibitive. Part of the appeal of switchgrass is that is can be used with existing technologies to supplement current energy systems. It is imperative that the end product be used without causing high external costs to existing systems. Harvesting switchgrass at different times of the year may change the amount of unwanted nutrients present in the feedstock and contribute to a higher feedstock quality for burning.

Switchgrass traditionally is a mid-summer forage grass vigorously growing when cool-season grasses; such as tall fescue (*Festuca arundinacea* Schreb), cease to grow. Cutting height affects the crop's ability to re-grow when it is cut multiple times in the same season. Removal of the apical meristem weakens the plants and increases the non-rooted areal shoots, such that there is a significant reduction in yield between cuts that were 30 cm and 20 cm above ground (Trocsanyi et al., 2009). Growing the crop for biofuel is different from forage because under those circumstances, the grower is not interested in forage quality and digestibility but rather total biomass yield for combustion, therefore a poor nutrient stock is preferred. A single cut system produces higher dry matter yields for upland varieties than multiple cuttings (McLaughlin et al., 1999 and Sanderson et al., 1999).

Maintenance of perennial root systems, such as switchgrass' fibrous structure, is essential in developing a healthy stand of high-yielding plants which lasts for many years (McLaughlin et al., 1999). A single-cut system and a delayed harvest until after senescence allows nutrients to translocate from shoots to roots. This directly affects ash content of the stock (Sanderson and Wolf, 1995). Nonstructural carbohydrates are the primary source of energy reserve in perennial grasses. These reserves are essential for winter survival of the crop and re-growth in the spring. Cutting or grazing at elongation will weaken the plant as compared with cutting after flowering (Smith, 1975). Understanding how the roots store carbohydrates is vital for maintaining a healthy crop year after year.

One of the goals of University of Massachusetts, Amherst research facility is to develop best management practices for establishment and maintenance of switchgrass in and around the Northeast area. In this study we addressed four key points:

1. How does N fertilizer improve biomass yield?
2. What is the best cutting height for young and mature stands?
3. What is the best harvest time for young and mature stands?
4. Does N application rate, cutting height and time of harvest influence weed pressure?

## Material and Methods

Two experiments were conducted in western Massachusetts; the first was in South Deerfield with a three year old stand and the second experiment was conducted in Easthampton on a seven year old stand on conservation land. Treatments were the same, except no fertilizer was added to the Easthampton stand.

Cultural Practices

**Young stand (Deerfield, Massachusetts)**

For this experiment conducted in the Connecticut River valley (42°N, 73°W), at the University of Massachusetts Agricultural Experiment Station Farm in Deerfield, a 950 $m^2$ experimental field of two-year old stand of Cave-in-Rock switchgrass was used. The experiment was conducted from 2009-2012. The soil type was a Hadley fine sandy loam (nonacid, mesic Typic Udifluvent).

**Easthampton, Massachusetts**

An experiment using seven-year old Cave-in-Rock was conducted at Audubon Conservation Society in Easthampton, MA ( 47° N, 71° W) between 2009-2012. The soil type was Merrimac fine sandy loam (mesic Typic Udifluvent). These were 16 ha of land that was used for conservation purposes. The land was located in flood planes on an ox bow that was subject to yearly spring flooding. Prior to this experiment fields were mowed in early August each year. The Audubon society planted the grass to protect and preserve bird and other wildlife habitat.

Experimental Treatments

Young Stand (YS) South Deerfield, Massachusetts

In South Deerfield the experiment consisted of three nitrogen treatments, three harvest times and two cutting heights. The experiment was laid out as a factorial block design with three replications. Aisle 3 m wide were cut into the fields between replications, in early August to allow room for harvesting equipment. Each plot was 3 m x 5 m. Throughout this report the experiment in South Deerfield will be referred to as young stand (YS) as the stand was only 3 years

The three nitrogen treatments were applied once per year in early June by hand at a rate of (0, 67.5, and 135 N kg $ha^{-1}$ ) in the form of calcium ammonium nitrate (27% N). Each plot was harvested at different growth stages, including: post-anthesis, killing frost, and early spring (after ground thaw). At time of harvest a representative sample of approximately 2.8 $m^2$ was harvested from each plot using a BCS sickle mower; a guard of 1.5 m on either side of the sectioned plot was harvested as well and discarded. Fresh weight yields were measured in the field using a hanging scale. Sub-samples were taken from these samples, placed in paper bags, weighed, and put into a forced air oven at 50°C for 24 hrs. These samples were reweighed to determine moisture content and adjusted dry matter yield. Sub-samples were later used in tissue experiments. The cutting-height treatments consisted of cutting the grass at either 7.5 cm or 15 cm above ground at each harvest time. Spring harvest for each year took place the following April such that in a 2009 trial, the spring harvest took place in April 2010. In order to keep descriptions simple the spring harvest will be referred to as in the year of 2009, the harvested vegetation grew during 2009.

In mid-June of 2010 and 2011 each field was rated on a scale of 1 to 5; 1 if 10 percent or less of the plot was covered in weeds, 2 if 10 to 20 percent of the plot was covered in weeds, up to five where 5 was when 50 percent of the plot or greater was covered in weeds.

### Mature stand (MS) Easthampton, Massachusetts

A similar experimental design with three replications, as in South Deerfield was used at this location. A section of 1 ha of land was sectioned off and used in the experiment. Prior to this experiment the land was harvested at the end of June, for successive years. The crops were harvested in the same manner as described above; expect there was no fertilizer treatment used on the Easthampton land. The experiment on the conservation land will be referred to as mature stand (MS), as the stand was 7 years old at the beginning of experiment.

### Measurements

At each time of harvest fresh, weight yields were measured and a representative subsample was collected from each plot. The sub-samples were weighed and placed in a forced air oven at 50°C for 48 hr to determine moisture content at the harvest. Harvested fresh weights were then adjusted by moisture content. After drying, samples were ground to pass a 1-mm screen of a Wiley mill (Thomas Scientific, Swedesboro, NJ). Tissue samples were collected to determine ash and mineral content. A cup cutter was used to remove a cylinder of roots 15 cm in diameter and 15 cm deep at time of harvest to determine non-structural carbohydrates.

### Nitrogen

Nitrogen content of plant tissue was determined using the Kjeldahl procedure. $CuSO_4$ (1.625g ) was added to a 0.2 g tissue sample and then digested with 1.0 M $H_2SO_4$ and heated for one hour. Samples were allowed to cool down, and 46.5 ml of de-ionized water was added. These samples were then analyzed using a flow injection spectrophotometer (Lachat QC85100).

### Ash and Mineral Content

Dry Plant tissue samples were ground using a 40-mesh Wiley Mill. Plant material was then weighed to 0.366 g and ashed in a Furnatoral Type 53600 Controller at 500°C for 5 hrs, then cooled and reweighed. The contents were dissolved in 18 ml of 20% trace mineral grade HCL. The solution was filtered with Whatman 42 filter paper. This solution was then diluted 1:1 with de-ionized water and analyzed using an Inductively Coupled Plasma Spectro Cirsos CCD.

### Non-Structural Carbohydrate

At time of harvest a 15 cm diameter cup cutter was used to remove the below ground portion of crown and the roots to a depth of 15 cm. The harvested crown and roots were washed and dried at 50°C for 48 hr. Once the below ground tissue was dried they were ground twice, once using a large grinder and then a second time using a 40-mesh Wiley mill. All machines were vacuumed and dusted clean in between samples to reduce potential contamination.

Carbohydrate analysis for the nonstructural carbohydrates of the roots was performed using high pressure liquid chromatography for sucrose, glucose, and fructose. The method was developed and described in Hagidimitriou and Roper (1994). In this experiment only the soluble sugar portion of the roots was analyzed.

### Statistical Analysis

Biomass yield, mineral content, and non-structural carbohydrate data was analyzed (SAS institute, 2003) using a general linear model and analysis of variance (ANOVA). Least significant differences (LSD) were used when data indicated there was significance at a P=0.05. Treatments included Harvest (Late-Summer, Late-Fall, Spring), Year (2009, 2010, 2011), Nitrogen (0, 67.5, 135) kg ha$^{-1}$, and Cutting Height (7.5, 15) cm above ground. All were considered fixed effects with three replications that were treated as random effects.

## **Results**

Dry matter yield

The analysis of variance (ANOVA) for dry matter yield of switchgrass indicated that only cutting height influenced dry matter yield (Table 3.1). When harvested at a 7.5 cm cutting height, switchgrass produced over 18% more than a cut at 15 cm, with average yields at of 7.2 Mg ha$^{-1}$ and 5.9 Mg ha$^{-1}$ for a cutting height of 7.5 cm and 15 cm respectively. Although harvest time effect on total dry matter yield was not significant, the effect varied in different years (Table 3.1). The means of switchgrass dry matter yields harvested at different times in each year of the study are presented in Table 3.2. Results showed that the dry matter yield decreased when harvested in late summer, with advancing switchgrass maturity. However no decline was observed for late fall harvests (Table 3.2).

Weed rating

By 2010, it became apparent that YS fields were significantly impacted by weeds and that this factor would affect the overall yield. Measurements taken in June 2010 indicated that harvest time was the only treatment affecting the abundance of weeds in the fields (Table 3.1). Almost every field that was harvested in the late summer scored 4 or 5 (Table 3.3); the fields that scored 4 were in the inner section of the experiment. Plots that received 5 were closer to the edges. This indicated that the plots were protected by other standing grasses that were not harvested until November or April. Harvesting in August appeared to negatively impact the stand in terms of weed pressure because it left the fields bare throughout the fall growing season. Even leaving 15-cm of stubble behind did not protect the stand. An inventory of the different weeds presented in the fields is shown in (Table 3.4).

### Ash

Ash content decreased as stands of switchgrass matured. Therefore, the lowest ash content (3.5 %) was recorded from the 2011 harvest (Table 3.5). Nitrogen application rate and time of harvest both had a significant effect on ash content. The more nitrogen was applied and the earlier the switchgrass was harvested the more ash was present (Table 3.6). However no significant effect of cutting height on ash content was observed. No interaction between main effects on ash percentage was observed (Table 3.1).

### Mineral content

The Effect of year was significant for all of the mineral concentrations (Table 3.1). The highest nitrogen (N) content (0.71%) was detected when the switchgrass was harvested in late summer of 2010 (Table 3.7). Total N in biomass was also influenced by harvesting time and N application rate. Table 3.7 shows that late summer had twice as much N as late fall or spring. As expected, plant N content increased with increasing N application rate. The response of two other macro nutrients, phosphorous and potassium (P, K), to N application rate and harvest time was also highly significant. Plant phosphorus decreased and K content increased as more N fertilizer was applied to the stands (Table 3.8). Excluding Ca, all other mineral contents were most significantly influenced by time of harvest (Table 3.1). A decreasing trend as the season progressed was observed for Mg, P and K (Table 3.9). Calcium remained constant in the plant across harvest times.

## Carbohydrate Reserves

Of the non-structural carbohydrates analyzed, sucrose was the primary sugar form present in the roots and the below-ground portion of the crown. The amount of sucrose varied with harvest time and nitrogen application (Table 3.1). The sucrose concentration in the below ground tissue for the late summer harvest was significantly less than that of the late fall harvest (Table 3.10). Harvest in the spring showed sucrose levels similar to those in the late summer harvest. In late fall sucrose levels were higher when no nitrogen fertilizer was applied. When harvested in late fall, a decreasing trend was observed with increase in the rate of nitrogen from 0 to 135 kg $ha^{-1}$ (Table 3.11).

The interaction between year and harvest time was significant (Table 3.1). Below ground tissue samples were taken in December from all plots in the experiment; the winter sucrose (WS) levels were similar for each of the harvests, however, a decreasing trend in the levels of sucrose was observed as harvest was postponed (Table 3.12).

There was an interaction between harvest and cutting height for the sucrose levels at time of harvest. Sucrose levels were 0.0153 mg/ 100 mg dry matter at a cutting height of 15 cm and 0.0145 mg/ 100 mg dry matter for a cutting height of 7.5 cm for the late summer harvest but were insignificantly different for late fall or spring harvest.

There was an interaction between year and cutting height for winter sucrose levels, in 2009 and 2010 the concentration were insignificant but in 2011 concentration were 0.076 mg/ 100 mg dry matter for 7.5 cm cutting height and 0.067 mg/ 100 dry matter for 15 cm cutting height.

There was an interaction for winter sucrose levels between nitrogen rate and harvest time but there was no apparent trend within this interaction.

## Experiment II-Mature Stand

### Dry matter yield

Switchgrass dry matter yield was only influenced by cutting height (Table 3.13). Yields on average remained constant, at approximately 4.4 Mg $ha^{-1}$ for all years at all harvest times. The highest dry matter yield 5.0 Mg $ha^{-1}$ was obtained from a late fall and spring harvest in 2011 (Table 3.14). Biomass yield response to cutting height was similar to that seen in the YS, such that the 7.5 cm cutting height produced 1 Mg $ha^{-1}$ more biomass then a 15 cm cutting height (Table 3.15).

### Mineral Content

In the mature stand, the nitrogen and ash contents fell as harvest was delayed (Table 3.16). Harvest time also influenced the nutrient concentration in the feedstock. Fewer nutrients were present in the feedstock when plants were harvested either in late fall or spring compared to the late summer harvest (Table 3.16). Mg, Ca, P, K all show similar trends to those seen in the young stand.

### Nonstructural carbohydrates

Soluble nonstructural carbohydrate reserves showed the same trends in the below ground crown and root system for the mature stand as was seen in the young stand. A late summer harvest produced significantly lower levels of sucrose present at time of harvest then those seen in the November harvest in late fall. However when samples were taken again in December right before ground freeze, there was no significant difference between the sucrose levels in any of the plots (Table 3.17).

## Discussion

Our results, based on growing switchgrass in Massachusetts, yielded the following insights;

(1) Nitrogen fertilizer at rates of 67 kg ha-1, and 135 N kg ha$^{-1}$ failed to provide significant increases in yield. (2) Young stands showed more variation in response to treatments then mature stands. (3) A lower cutting height produced higher yields and did not diminish feedstock quality. (4) Weed pressure brought on by a late summer harvest significantly impacted yield the following year. (5) Nutrient content decreased as harvest time was delayed. (6) Harvesting in late summer did not affect the overall ability of the stand to store sucrose as a reserve in the below ground portion of the crown and roots. (7) Switchgrass stands decrease in yield as they get older for a late summer harvest.

### Harvest Treatments

### Nitrogen

In this study, we found there was no significant difference overall for harvest and nitrogen treatments. The year by harvest interaction was highly significant. In the first year of the study the YS produced late summer yields of 9.1 Mg ha$^{-1}$ which were reduced to 5.9 Mg ha$^{-1}$ by the third year. Yields remained constant at around 6.3 Mg ha$^{-1}$ for the late fall harvest and varied between 6.8-5.1 Mg ha$^{-1}$ for the spring harvest for all years. Nitrogen rates recommended by researchers throughout United States, Canada, and Europe range from 30-135 N kg ha$^{-1}$ (with an average of 92 kg ha$^{-1}$) for annual applications (Sanders et al., 2007). Our data showed an overall lack of response to nitrogen fertilizer treatments, such that the addition of nitrogen did not impact the overall yield. Numerically, but not statistically significantly, there was a trend suggesting that an increased yield occurred in the late summer from higher nitrogen input but this was less apparent in the later harvests. Nitrogen fertilizer is a “tricky topic” with regards to switchgrass, and recommendation for treatments span a vast arena. Our finds are similar to others in which the application of nitrogen fertilizer did not elicit a response after 3 years of harvest (Parrish and Fink 2005, Thomason et al., 2004; Parrish and Wolf, 1992, 1993; Mulkey et al., 2006).

Yields appeared to be greatly affected by harvest time when the stand was young. Our study found that there were significant differences over the different harvest times when the young stands was harvested in late summer and spring, but remain constant for a late fall harvest. Our results confirm the findings of Vogel et al. (2002) findings that harvesting Cave-in-Rock in November versus August decreases yields. This is attributed to leaf shattering, translocation of nutrients, and residue left on the field during harvest. In our first year the delay in harvest decreased the average yield by 3 Mg ha$^{-1}$, but by the second year this difference was only 0.8 Mg ha$^{-1}$, and by the third year the trends reversed, and late fall harvest was 0.7 Mg ha$^{-1}$ higher than late summer. These finding are consistent with those of Casler and Boe (2003) who found that August harvests were associated with decreases in stand density. They recommend that optimum harvest time for northern and mid-latitudes were after tops had completely died back (Parrish and Fink, 2005). In our MS experiment, the yields remained consistent for all harvest times indicating that older stands are less susceptible to yield variations based on harvest time.

Changing the cutting height from 7.5 cm to 15 cm resulted in reduction in yield by 1 Mg ha$^{-1}$ for both the YS and MS experiment. There did not appear to be any added benefit to the higher cutting height. Parrish and Fink suggested that leaving taller stubble could retain snow moisture, provide erosion control and reduce wear and tear on the tires of harvest equipment. None of these factors were an issue in our experiment and the increase in cutting height did not reduce nutrient content, show a consistent increasing trend in carbohydrate reserves, or reduce weed pressures. It is the recommendation of this paper to use a lower cutting height or a height that is the most convenient for the farming equipment.

### Weeds

Most research regarding switchgrass considers weed problems during the establishment phase (Cassida et al., 2000; Weimer et al., 1988; Bahler et al., 1984 ). Broadleaf weed herbicides at light rates are generally recommended during the first year of establishment. Atrazine as a pre-emergent in conventionally tilled plantings is used to suppress annual weeds but is effective in the treatment of fall panicum (*Panicum dichotomiflorum*), foxtail (*Setaria spp.*), and barnyardgrass (*Echinochloa crusgalli*) (Buhler et al., 1997). If switchgrass seeds are slow to establish, a field can be completely covered with weeds in its first year. Stands often recover in the second year without herbicides, if they are not harvested in the first year. Eventually they outgrow the weed competition (Lewandowski et al., 2003). In our fields there were certain plots that were removed from the design of the experiment due to heavy weed pressures. These plots were not harvested until the spring; in every one of those excluded plots switchgrass was growing vigorously by the second year of the experiment.

The plots that were harvested in late summer exhibited an effect opposite to that seen in plots excluded from the experiment. They grew less vigorously the following year. Late summer harvested plots scored 4 and 5 on weed scale (40 to 50 percent or greater impurities present among the stand) by the second year. In the establishment phase, the greatest threats to Switchgrass are cool-season weeds that germinate before switchgrass and shade out the newly emerging seedlings (Buhler et al., 1997). In our experiment winter annuals and perennials were the largest threats to an established stand (Table 3.5). Harvesting in the late summer provided the greatest yield early in the experiment but this also left the fields exposed during the entire fall season. During this time perennials and winter annuals were able to establish themselves and decrease yield and stand vigor the following year. This issue was further compounded by the fact that the stand thins as it ages (Casler and Boe, 2003). The higher cutting height of 15 cm did not sufficiently protect the field from emerging weeds.

If farmers intend to grow a monoculture of switchgrass, delaying the harvest until later in the season, past senescence, will produce a purer stand the following year. Of course, weed pressures will still vary from location to location. If a farmer wants to take advantage of the high yields in the early years of their stands, they can harvest in late August, and determine the following year if weeds become a significant problem. When weeds are a problem, harvest should be delayed in subsequent years to either the late fall or the following spring. This is only recommended if nutrient ash content is sufficiently low such that the product would be accepted by a power plant.

### Nutrient content

Mineral content is associated with the quality of the harvest. Lower mineral content implies higher quality of this product, when used for combustion. When the feedstock has high mineral content there is more potential for unwanted by products such as nitrous oxide and slag (alkyl-metals and silicates that coat machinery) to form when burned. The mineral content significantly changed when harvest was delayed from senescence to killing frost or early spring. For the YS, nitrogen levels were highest for the 135 N kg ha$^{-1}$ fertilizer treatment; there was no significant difference between the N or Ash levels between the 0 and 67.5 N kg ha$^{-1}$ fertilizer treatments. In the MS where no fertilizer was added, N levels were lowest in the late fall but went up in the spring. In the MS the N and ash content decreased year after year for each harvest (Table 3.16). This would be considered favorable in terms of biofuel quality, but it might indicate that the plant is not able to extract as much nutrient from the soil from one year to the next when no fertilizer is added, and in time no fertilizer might have a negative effect on the stand, depending on the soil. There were no significant differences in ash content between the two cutting heights of 7.5 cm and 15 cm. Ash content has been reported to vary at 20 cm where ash was 1.5% above 20 cm and 2.9% below 20 cm (Monti et al., 2009). Cutting at 20 cm would considerably reduce ash but would also reduce yield and may be inconvenient with harvesting equipment. When plots were harvested with the sickle mower at 15 cm in our experiments, the plant would sometimes get caught in the blades and be ripped out by its roots. Delaying the harvest from the late summer to late fall or spring reduced percent nitrogen in the feedstock by almost half from 4.5 % to 2.5% and ash content by 1% in late fall and 1.5% in the spring. Linear trends were noted for P and K, with a delay in harvest. Delaying the harvest until killing frost or later allows minerals to leach from the stand, thereby allowing beneficial nutrients to return to the soil and roots. This has the added bonus of improving the feedstock and reducing slag during the combustion process (Bakker and Jenkins, 2003; McLaughlin et al., 1996). On the slag index (lb of water soluble alkali in ash per MMBTU of energy), for a coal power plant, slag should be no greater than 0.80 (McLaughlin et al., 1996). Using a McLaughlin number for energy content of switchgrass at 17 MBtu Mg$^{-1}$, our switchgrass shows that the slag index for a late summer harvest across all nitrogen treatments was 0.58 for late fall it was 0.44 and for spring, 0.37. Originally switchgrass was considered to be unsuitable for combustion because its slag was 1.4 (Miles et al., 1993, 1995) but in 1996, reports stated that levels were lower than originally thought and it was the manner that the samples were transported to the site that contaminated the samples, resulting in the high slag number (McLaughlin et al., 1996). In our study, harvesting in the late fall put switchgrass at just below acceptable levels for slag at a power plant; this does not leave as much of a safety factor for potential contamination during storage and transport.

Delaying the harvest to later in the season places the potential for slag at less than half the acceptable limit, which leaves a much larger safety factor.

## Carbohydrate Reserves

Carbohydrate reserves including sucrose, fructose, glucose and starches are believed to be the essential substrates for growth and respiration. In this experiment we looked at the soluble nonstructural carbohydrate, in particular the non-reducing sugar, sucrose, in the crown and root from 0-15 cm below ground.  Grasses of subtropical or tropical origin such as switchgrass generally store reserves in the forms of sucrose and starch. (Smith, 1968; Ojima and Isawa, 1968)  Non-reducing sugars are less abundant but mimic starch levels throughout the fall growing season (Smith, 1973).  Perennial plants require the storage of these sugars for winter survival, early spring growth, and re-growth after cuttings. These reserves provide the plant with the energy it needs when there is insufficient herbage material for photosynthetic production (White, 1973).  Originally, we suspected the reason that the stand vigor was declining from a late summer harvest was because the plant was not given sufficient time to store its nutrients for the winter.  These speculations appeared justified when sucrose measurements were taken at time of harvest because August levels were significantly lower than November levels. However even though sucrose levels were low at the August harvest the plant was able to continue to store sucrose below ground throughout the fall growing season.  When measurements of all the plots were taken again right before ground freeze in December the YS and MS showed the same trends: that there were no differences in the sucrose levels for any of the harvest treatments.  Late summer harvested plants are able to store just as much sucrose as other harvests. More research needs to be done to determine what is happening with the starch levels, but based on the non-reducing sugars the plant appears to be able to recover its reserves during the months between September and December.  Insufficient sucrose does not appear to be the most significant cause of the decline in vigor resulting from a late summer harvest. Sucrose was used as the main indicator, as fructose and glucose levels were too low, and variation was too great. The low levels found in the spring harvest are due to the depletion of reserves (Brocklebank and Hendry, 1989). Non-structural carbohydrates of grasses are found in the lower region of the stems-stem bases, stolons, corms, and rhizomes (White 1973). Our findings showed that 15 cm cutting height did not provide more winter sucrose reserves to the plant compared to a 7.5 cm cut and in 2011 a cut of 15 cm provided significantly less.

Nitrogen fertilization can affect the carbohydrate reserves of grasses. Some research indicates that low to moderate rates of N applied to a field result in an increase in carbohydrate reserves, while high rates of N decrease the carbohydrate reserves. (Adegbola and McKell, 1966). This occurs most often when N is provided to the plant in excess, and other nutrients are not limiting the plant growth. The N in the plant will stimulate an excess of amino acids and amide compounds and the carbohydrate reserves are used in excess as a carbon-skeleton for protein synthesis (Prianisknikov, 1951). This is numerically, but not statistically, significant in our data (Table 3.14). When nitrogen was applied to the plots, concentrations of sucrose either remained constant or decreased with an increase of fertilizer across all harvest times. This was possibly due to the fertility of the soil in the plots and the low nitrogen requirement of switchgrass. This experiment was conducted in a river valley where the soil is known for its high fertility. The highest levels of sucrose were found in the 0 kg ha$^{-1}$ nitrogen treatment (Table 3.17) for the late fall harvest and these levels decreased with increasing in a fertilization rate, which could explain the lack of response to nitrogen fertilizer application. Switchgrass is associated with mycorrhizae and with rhizosphere microbes that are able to fix $N_2$. These traits, along with its ability to recycle N, during its growing season, make switchgrass a thrifty Nitrogen user (Parrish and Fink 2005; DuBois and Kapustka, 1983; Welbaum et al., 2004). It is possible and probable that when switchgrass is grown on fertile soils, very little nitrogen input is needed and may explain why reports of a response to N after 3 years of harvest appear in the literature (Parrish and Fink 2005; Thomason et al., 2004; Parrish and Wolf, 1992, 1993).

## Conclusion

The ideal switchgrass grown for combustion should produce the highest dry matter yield with the lowest nutrient content. There appears to be a tradeoff between these two qualities early in the life of a switchgrass stand. In the experiment where the stand was young, yields in the late August harvest were significantly high than those seen in early November in the first year, but as the stand aged the difference between these two harvest times became insignificant. In the mature stand, there was no difference between harvest times. To optimize switchgrass yield and reduce nutrient content over the life time of the stand, delaying harvest until later in season appear to be more beneficial to vitality of stand and to the quality of the product. Young stands showed more variation in response to treatments. The addition of fertilizer on the YS did not have significant effects on yield. Cutting at 7.5 cm increased the yield for both the YS and MS experiment by 1 Mg ha$^{-1}$. There was no advantage to cutting at 15 cm over 7.5 cm based on the response variables in this experiment. Ash, N, P, K were all significantly reduced when harvest was delayed from the end of August to November or the following April. Late summer harvested plants were able to store as much sucrose reserves as late fall and spring plants, we did not find a correlation between late summer harvest and ability of the stand to store non-reducing sugar reserves for re-growth the following year. The largest decrease in yield occurred in our YS fall harvest and reflected weed pressures in the field. The YS in fall produced on average 9.1 Mg ha$^{-1}$ in the first year and decreased to 7.2 Mg ha$^{-1}$ in the second and 5.9 Mg ha$^{-1}$ third years. In the MS the harvest time did not affect the yield, which remained constant at 4.4 Mg $ha^{-1}$ for all years. It appears that the stand will decrease in yield as it gets older and then level off; consequently, yield projections should not be based on the initial years of production but should be averaged over the life span of the stands.

Table 3.1. Analysis of variance showing the *p*-values for yields and chemical analyses.

| Source of Variation | df | Yield | Weed Ratings | ASH | N | Ca | Mg | P | K | Sucrose † | Winter Sucrose‡ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Harvest (H) | 2 | ns | *** | *** | *** | ns | *** | *** | *** | *** | ns |
| Year (Y) | 2 | ns | ns | * | *** | *** | ** | ** | * | ns | *** |
| Nitrogen (N) | 2 | ns | ns | ** | *** | ns | ns | *** | ** | ns | ns |
| Cutting Height ( C) | 1 | ** | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| Y x N | 4 | ns | ns | ns | *** | ns | ns | ** | ns | ns | ns |
| Y x H | 4 | *** | ns | ns | *** | * | ** | ** | ** | ** | * |
| Y x C | 2 | ns | ns | ns | ns | ns | ns | ns | ns | ** | *** |
| H x N | 4 | ns | ns | ns | ns | ns | ** | *** | ns | ns | *** |
| H x C | 2 | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| N x C | 2 | ns | ns | ns | ns | ns | ns | ** | ns | ns | ns |
| Y x H x N | 6 | ns | ns | ns | ns | ns | ns | ns | ** | ns | ns |
| Y x H x C | 4 | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |

* Significant at the 0.1 level

**Significant at the 0.05 level

***Significant at the 0.01 level

† Sucrose - Sucrose present in below ground tissue at time of harvest

‡ Winter Sucrose - Sucrose present in below ground tissue right before ground freeze in December

Table 3.2. Yields (Mg $ha^{-1}$) for YS over three years for each of three harvest times.

| Harvest† | 2009 | 2010 | 2011 | Overall |
|---|---|---|---|---|
| Late Summer | 9.1a | 7.2a | 5.9a | 7.4 |
| Late Fall | 6.0b | 6.5a | 6.6a | 6.3 |
| Spring | 6.1b | 6.8a | 5.1a | 6.0 |
| Overall | 7.1 | 6.8 | 6.2 | |
| LSD Year x Harvest‡ | 1.2 | 1.5 | 1.7 | |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

‡LSD calculated at 0.05 level

Table 3.3. Weed ratings† for YS in June for each of the harvest times.

| Harvest‡ | 2010 | 2011 |
|---|---|---|
| Late Summe | 4.1a | 4.6a |
| Late Fall | 1.4b | 1.2b |
| Spring | 1.3b | 1.1b |
| LSD Year x H | 0.3 | 0.4 |

†1-(10-20) percent field covered in weeds
2-(20-30)
3-(30-40)
4-(40-50)

‡Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

§ LSD calculated at 0.05 level

Table 3.4. Weed species present in field in June.

| Common Name | Scientific Name | Life Cycle |
|---|---|---|
| Clammy Ground Cherry | *Physalis heterophylla* | Perennial |
| Curley Dock | *Rumex crispus* | Perennial |
| Fleabane | *Erigeron philadelphicus* | Winter Annual |
| Goldenrod | *Solidago ragosa* | Perennial |
| Harry Vetch | *Vicia villosa R.* | Winter Annual |
| Milk Weed | *Asclepias syriaca* | Perennial |
| Prickly Lettuce | *Lactuca serriola* | Winter Annual |
| Quack Grass | *Elymus repens* | Perennial |
| Red Clover | *Trifolium pratense* | Perennial |
| Wild Carrot | *Daucus carota L.* | Perennial |

Table 3.5. Percent Ash in YS dry matter tissue for each harvest treatment for each year.

| Harvest† | 2009 | 2010 | 2011 | Overall |
|---|---|---|---|---|
| Late Summer | 4.98a | 4.85a | 3.92a | 4.59 |
| Late Fall | 3.47b | 3.92b | 3.08b | 3.49 |
| Spring | 3.37b | 2.37c | | 2.89 |
| Overall | 3.94 | 3.74 | 3.51 | |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

Table 3.6. Percent Ash in YS dry matter tissue for fertilizer treatment at different harvest.

| | Harvest† | | | |
|---|---|---|---|---|
| Nitrogen ‡ | Late Summer | Late Fall | Spring | Overall |
| Low | 4.78 | 3.68 | 3.03 | 3.9 A |
| Medium | 4.14 | 3.17 | 2.99 | 3.5 B |
| High | 4.83 | 3.62 | 2.64 | 3.8 AB |
| Overall | 4.6 A | 3.5 B | 2.9 C | |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

‡ Low (0 kg ha-1), Medium (67 kg ha-1), High (135 kg ha-1)

Table 3.7. Percent Nitrogen in YS feedstock at different times of harvest.

| Harvest† | 2009 | 2010 | 2011 | Overall |
|---|---|---|---|---|
| Late Summe | 0.57a | 0.71a | 0.31a | 0.59 A |
| Late Fall | 0.26b | 0.31b | 0.24b | 0.26 B |
| Spring | 0.25b | 0.24b | | 0.25 B |
| Overall | 0.36 | 0.42 | 0.28 | |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

Table 3.8. Fertilizer treatment effect on macro nutrients for each harvest time.

| | Nutreints† | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | | | P | | | K | | |
| Nitrogen‡ | Late Summer | Late Fall | Spring | Late Summer | Late Fall | Spring | Late Summer | Late Fall | Spring |
| Low | 0.57b | 0.20b | 0.19b | 1924a | 1149a | 280a | 8823a | 3874b | 1396a |
| Medium | 0.48b | 0.24b | 0.24b | 1575b | 845b | 274a | 8464a | 4135ab | 1066a |
| High | 0.71a | 0.34 a | 0.31a | 1520b | 754b | 320a | 9487a | 4977a | |

† N-Percent in dry matter yield, P,K-parts per million (ppm)

‡Low (0 kg ha$^{-1}$), Medium (67 kg ha$^{-1}$), High (135 kg ha$^{-1}$)

Table 3.9. Nutrient content in YS feedstock in part per million for harvest time across all year.

| | Nutreints † | | | |
|---|---|---|---|---|
| Harvest‡ | P‡ | K | Ca | Mg |
| Late Summe | 1675a | 8934a | 2233a | 1550a |
| Late Fall | 916b | 4329b | 2400a | 1190b |
| Spring | 292c | 507c | 2225a | 730c |

† Nutrients in ppm

‡Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

Table 3.10. Concentration of soluble nonstructural carbohydrates (mg/100mg dry matter) in below ground tissue at time of harvest of YS.

| Harvest† | Fructose | Glucose | **Sucrose** | NSC ‡ |
|---|---|---|---|---|
| Late Summe | 0.003 | 0.005 | **0.014c** | 0.022 |
| Late Fall | 0.004 | 0.005 | **0.055b** | 0.064 |
| Spring | 0.003 | 0.005 | **0.021a** | 0.029 |

† Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

‡ NSC soluble non-structural carbohydrates in the below ground roots and crown to 15 cm depth

Table 3.11. Sucrose concentration (mg/ 100 mg dry matter) in below ground tissue of YS for different fertilizer treatments at harvest time.

| | Harvest | | |
|---|---|---|---|
| Nitrogen† | Late Summer | Late Fall | Spring |
| Low | 0.014 | 0.060 | 0.020 |
| Medium | 0.014 | 0.053 | 0.022 |
| High | 0.013 | 0.051 | 0.019 |

†Low (0 kg ha$^{-1}$), Medium (67 kg ha$^{-1}$), High (135 kg ha$^{-1}$)

Table 3.12. Sucrose Concentration (mg/ 100 mg dry matter) for in the roots in December before ground freeze for YS across all year.

| Harvest† | 2009 | 2010 | 2011 |
|---|---|---|---|
| Late Summe | 0.027 | 0.066 | 0.077 |
| Late Fall | 0.030 | 0.061 | 0.068 |
| Spring | 0.028 | 0.051 | 0.069 |

†Late Summer (Senescence), Late Fall (Kill Frost), Spring (Snow melt)

## Audubon Society Conversation Land Mature Stand

Table 3.13. Analysis of variance showing the *p*-values for yields and chemical analyses for mature stand (MS).

| Source of Variation | Df | Yield | ASH | N | P | K | Ca | Mg | Sucrose† | Winter Sucrose‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Year (Y) | 2 | ns | ** | *** | *** | *** | * | ns | ns | *** |
| Harvest (H) | 1 | ns | *** | *** | *** | *** | * | *** | *** | ns |
| Cutting (C ) | 2 | ** | ns | ns | ns | ns | ns | * | ns | ns |
| Y x H | 2 | ns | ns | ** | ns | ns | ns | ns | ns | ns |
| Y x C | 4 | ns | ns | ns | ** | *** | ns | ** | ** | ns |
| H x C | 2 | ns | ns | ns | * | ns | ns | ns | * | ns |

* Significant at the 0.1 level

**Significant at the 0.05 level

***Significant at the 0.01 level

† Sucrose - Sucrose present in below ground tissue at time of harvest

‡ Winter Sucrose - Sucrose present in below ground tissue right before ground freeze in December

Table 3.14. Yields (Mg $ha^{-1}$) of MS for all harvest times for all years.

| Harvest† | 2009 | 2010 | 2011 | Overall |
|---|---|---|---|---|
| Late Summer | 4.4a | 3.6a | 4.6a | 4.2 |
| Late Fall | 4.1a | 4.7ab | 5.0a | 4.6 |
| Spring | 3.6a | 4.4b | 5.0a | 4.4 |
| Overall | 4.1 | 4.2 | 4.8 | |
| LSD‡ | 1.1 | 0.5 | 3.0 | |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)
‡LSD calculated at 0.05 level

Table 3.15. Cutting Height vs. Harvest Time for MS (Mg $ha^{-1}$).

| | Harvest† | | | |
|---|---|---|---|---|
| Cutting Heigh | Late Summer | Late Fall | Spring | Overall |
| 7.5 cm | 4.7 | 5.5 | 4.6 | 5.0a |
| 15 cm | 3.7 | 3.7 | 4.2 | 3.9b |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)
‡ Cutting Height- Stubble left on the field after cut

Table 3.16. Percent ash and nitrogen and ppm of macro-nutrients in feedstock of MS for different harvest times.

| | ASH | | | N | | | P | | | K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Harvest † | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 |
| Late Summer | 6.05a | 4.09a | 4.00a | 0.53a | 0.48a | 0.33a | 2423a | 2027a | 2341a | 7970a | 7305a | 7840a |
| Late Fall | 2.61b | 1.81b | 3.05a | 0.34b | 0.15c | 0.18b | 1617b | 1190b | 1453b | 3946b | 3211 b | 4415b |
| Spring | 3.07b | 1.17b | | 0.33b | 0.33b | | 434c | 187c | | 431c | 253c | |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

Table 3.17. Sucrose concentration (mg/100 mg dry matter yield) in the roots system at harvest time and in December.

| Harvest† | Concentration at Harvest | Concentration in December |
|---|---|---|
| Late Summer | 0.019b | 0.043a |
| Late Fall | 0.056a | 0.040a |
| Spring | 0.022b | 0.040a |

†Harvest Late-Summer (End August), Late-Fall (Beginning November), Spring (Mid April)

# CHAPTER 4

# OPTIMAL FALL HARVEST TIME IN MASSACHUSETTS FOR CAVE-IN-ROCK SWITCHGRASS USED AS A BIOFUEL

## Abstract

Switchgrass (*Panicum virgatum* L.) is a native perennial prairie grass that grows in a wide range of climatic conditions and is currently being researched as an energy crop for biofuel. The objective of this study was to develop harvest management recommendations for the production switchgrass biofuel in Massachusetts and other northeastern climates. Seasonal harvest time from senescence, after seed production, to killing frost affects yield and biofuel quality. A field study with five harvest times and four replications was conducted over a two-year period. The harvests were conducted twice a month from mid-September to mid-November. Measurements were taken of yield, ash, total nitrogen, mineral content, and energy content in the feedstock and non-structural carbohydrates in the roots at the time of each harvest. In Massachusetts, the 'Cave-in-Rock' upland variety showed maximum peak yields in early to mid-October ranging from 10-11 Mg ha$^{-1}$. These yields varied on average by 2.5 Mg ha$^{-1}$ over the fall growing season. Macro-nutrients including N, P, K, decreased linearly as harvest was delayed from mid-September to mid-November. Sucrose levels of the root system significantly increased in the harvest that follows peak yield. The unit energy content in the feedstock decreased linearly from mid-September to killing frost in mid-November. These values ranged from 7366-10,696 J g$^{-1}$. In 2011 energy per area was equivalent at mid-September to the values at peak yield in mid-October and then declined in the month of November. Although there was more energy per unit of dry matter in the mid-September harvest there were also more nutrients. When burned at high temperatures, these nutrients form unwanted bi-products

including ash, particular matter, and emissions. Raw material for the production of ethanol has different requirements. Nutrients and mobile non-structural carbohydrates are beneficial for the conversion to liquid fuel.

## Introduction

Refining biomass into biofuel in the form of ethanol or for combustion in coal power plants has been a growing interest since the 1980's (Colbran and Eide, 2008 and McLaughlin et al., 1996). Biofuel from agricultural land may alleviate some of environmental pressures from limited resources and increased demand for energy production (Abbasi and Abbasi, 2012; Demirbas, 2008). Fossil fuels release large amounts of locked-away carbon into the atmosphere. In contrast, biofuels such as switchgrass close the carbon cycle and thus do not increase atmosphere carbon dioxide (Ragauskas et al., 2006; Yan et al., 2010). Switchgrass may be a potential renewable energy source that promotes the conservation of land rather than its counterpart fossil fuels which require despoliation of land to obtain.

Switchgrass is a warm season $C_4$ perennial grass native to North America which has a deep fibrous root system (Ma et al., 2000; Parrish and Fike, 2005). Many characteristics define switchgrass as a model energy crop. These include productive yields in various locations, ability to grow on marginal land, low fertilizer requirements, survival for multiple years, capacity to improve soil and water quality, wildlife habitat, and can be harvested with conventional haying-equipment (Sanderson et al., 2006; Vogel et al., 2002; Adler et al., 2006; McLaughlin et al., 2002; Masse et al., 2010).

Stands that are not harvested during the first year of establishment will reach two-thirds of full yield capacity in their second year and generally obtain full capacity in the third year. A well managed stand can have a life span in excess of 10 years (Lewandowski et al., 2003). The time of harvest affects yield and nutrient content (Adler et al., 2006, Waramit et al., 2001, Madakadze et al., 1999, Sanders et al., 1999, Casler and Boe, 2003, and Vogel et al., 2002).

There are diverse recommendations for the ideal time to harvest switchgrass to produce consistent maximum yields. These recommendations vary depending on location and other environmental factors. In  southern USA, a mid-September harvest maximized yields (Sanderson et al., 1999), in the midwest a mid-September harvest maximized yields, and in north central USA, harvesting after killing frost produced highest yields (Mulkey et al., 2006). Casler and Boe (2003) reported that September harvest had a negative effect on yields the following year, while other reports noted that delaying the harvest from September until November in the south central USA reduced biomass yield (Sanderson et al., 1999).

There is general agreement in the literature that delaying the harvest of switchgrass until later in the growing season, past senescence, will reduce nitrogen (N), phosphorus (P), potassium (K), ash, and nutrients in the grass (Madakadze et al., 1999, Waramit, et. Al 2001, Yang et al., 2009). Lower ash content is associated with a translocation of mobile nutrients from the above ground-tissue into the root structure (Sanderson and Wolf 1995).  Nitrogen cycles down into the below ground shoots at the end of the growing season (Beaty et al., 1978). Low levels of N found in the leaf and stem during senescence is common in many prairie grasses.  It is a method perennials have adapted to efficiently utilize the nutrient during the following year (Hargrave and Seastedt 1994).

Low nutrient content in the feed stock is desirable when it is being used for combustion, but not necessarily advantageous when being considered for conversion to ethanol. It is the alcohols, ethers, esters and other chemicals that can be derived from the feedstocks' organic matter that are used in the production of energy (Sanderson 2002). Crops with high lignin and low nutrient quantity are more suited for combustion (Cassida et al., 2005). Ethanol produced from enzyme/yeast process or bacterial fermentation requires nutrients for microbial growth. Therefore reducing nutrient content offers no advantage (Adler et al., 2006).

Carbohydrate concentration changes in switchgrass stands throughout the growing season. Lignin and cell wall sugars increase from fall to winter. Non-cell wall carbohydrates can be directly fermented while cell wall polysaccharides require energy intense pretreatments. Delaying the harvest thickens the cell wall and elevates lignin concentrations, which making it harder for microbes in the fermentation process to breakdown tissue (Adler et al., 2006 and Dien et al., 2006). Therefore, harvesting earlier in the fall season may be better when utilizing switchgrass for ethanol production.

When switchgrass is used as fuel for combustion, the primary components to consider include dry matter yield, moisture, and ash. Moisture and ash both reduce available energy. High moisture requires an excess input of heat to burn. Ash creates fouling in combustion equipment (McLaughlin et al., 1996). Alkali metals and silicates ash are the major contributors to a product know as slag. This thick black material becomes a liquid at high temperatures and coats the surfaces of machinery (furnaces, boilers, fluidized beds, etc.). Slag prevents heat recovery (Cassida et al., 2005, McLaughlin et al., 1996). If the slag production is high enough, it may make a product cost prohibitive to use.

Part of the appeal of switchgrass is that is can be used with existing technologies to supplement current energy systems. The end product can be used without requiring extensive retrofitting costs to existing systems. This makes it economical. For every 10 g $kg^{-1}$ increase of ash there is a decrease in heat value of 0.2 MJ $kg^{-1}$ (Tillman, 2000).

University of Massachusetts, Amherst conducted many studies on switchgrass over the past seven years. Studies suggest that harvest time has the most significant effect on feedstock quantity and quality. Harvest in early September produced high yields in the early years of experiments but had a negative effect on yields in subsequent years.

The goals of this experiment include:

(1) To determine when yields are at their highest during the fall growing season.

(2) To track the concentrations of nutrients to determine when they are low enough to facilitate biofuel combustion.

(3) To track energy in the feedstock throughout the growing season

(4) Identify how the sucrose changes in the roots system as the plant proceeds into dormancy.

## **Material and Methods**

### Cultural Practices

#### Deerfield, Massachusetts

An experiment conducted in the Connecticut River valley (42°N, 73°W) at the University of Massachusetts Agricultural Experiment Station Farm in Deerfield used a three year old stand of Cave-in-Rock variety of switchgrass. The experiment was conducted from 2010-2011. The soil type was a Hadley fine sandy loam (*coarsely* mixed, nonacid, mesic Typic Udifluvent).

### Experimental Treatments

The experiment consisted of five harvest times that occurred two times per month from mid September to mid November for two years. The experiment was laid out as a factorial block design with 4 replications. Aisles 2 m wide were cut in the fields between replications, in early September to allow room for harvesting equipment. Each plot was 5 m x 5 m.

At each time of harvest, a representative sample of approximately 2.8 $m^2$ was harvested at ground level from each plot using a BCS sickle mower. A guard of 2.3 m on either side of the sectioned plot was harvested as well and discarded. Fresh weight yields were measured in the field using a hanging balance. Subsamples were taken from these samples, placed in paper bags, weighed and put into a forced air oven at 50°C for 24 hrs. These samples were reweighed to determine moisture content and were adjusted to dry matter yield. Tissue used in analysis for N, ash and mineral content were ground using a 60 mesh Wiley Mill. In the second year, four plants were taken from each sample at time of harvest, ground, fresh dried at 100°C, reground in a coffee grinder and analyzed with a calorimeter. At the time of harvest, a cup cutter was used to take one sample of crown and roots to a depth of 15 cm from each plot. These roots were stored on ice, cleaned and used in carbohydrate analysis.

### Nitrogen

Nitrogen content of plant tissue was determined using the Total Kjeldahl procedures. 1.625 g of $CuSO_4$ were added to a 0.2 g tissue sample and then digested with 1.0 Molar sulfuric acid and cooked for one hour. Samples were allowed to cool down and 46.5 ml of de-ionized water were added. These samples were then analyzed using a flow injection spectrophotometer (Lachat QC85100).

### Ash and Mineral Content

Plant tissue samples were ground using a 40-mesh Wiley Mill. Plant material was then weighed to 0.366 g and ashed in a Furnatoral Type 53600 Controller at 500°C for 5 hrs, then cooled and reweighed. The contents were dissolved in 18 ml of 20% trace mineral grade HCL. The solution was filtered with Whatman 42 filter paper. This solution was then diluted 1:1 with de-ionized water and analyzed using an Inductively Coupled Plasma Spectro Cirsos CCD. The Smart Analyzer Vision software package was used to interpret results.

### Non-Structural Carbohydrate

The harvested roots were washed to remove dirt and dried at 50°C for 48 hours. Once dried they were cut by hand to remove any remaining dirt and then ground twice, once using a large grinder and a second time using a 40 mesh Wiley mill. All machines were vacuumed and dusted clean in between samples to reduce potential contamination.

Carbohydrate analysis for the nonstructural carbohydrates of the roots was performed using High Pressure Liquid Chromatography for sucrose, glucose, and fructose. The method was developed and described in Hagidimitriou and Roper (1994). Of the total non-structural carbohydrates present in the roots system only soluble sugars were analyzed.

### Calorimeter

Four plants were ground fresh with a generic coffee grinder and dried at 100°C for 24 hrs. Samples were reground prior to analysis and then combusted in a DSC–TGA (TA instruments SDT Q600 system). Approximately 15–30 mg of initial biomass was loaded for each run and degassed at a rate of 30 °C $\text{min}^{-1}$ until it reached 110 °C for 30 min under a constant helium flow of 100 mL $\text{min}^{-1}$ (Airgas, UHP). This was done to remove any residual initial moisture. Samples were cooled to 100° C and then heated linearly at a rate of 15° C $\text{min}^{-1}$ from 100° C to 800° C under a constant compressed air flow of 100 mL $\text{min}^{-1}$. TGA was used to measure the heat changes of the residual mass.

### Statistical Analysis

Treatments included year and harvest time. Yield, mineral content, and non-structural carbohydrate data were analyzed using the ANOVA procedure and proc GLM (SAS institute, 2003). Means were compared using least significant differences (LSD). Treatments including harvest (Mid-September, early-October, mid-October, early-November, mid-November), year

(2010, 2011), were considered fixed effects with four replications. The replications were treated as random effects.

## Results

### Yield

The analysis of variance (ANOVA) for dry matter yield of switchgrass indicated that there were no significant differences among harvest times, but there was a significant year by harvest interaction (Table 4.1). In 2010 maximum yields occurred at the beginning of October. In 2011 biomass yield was significantly different among harvest times, with maximum average yields occurring in mid-October. Biomass yield ranged from 8 Mg ha$^{-1}$ to 11 Mgha$^{-1}$(Figure 4.1).

### Ash

The effect of year on ash content was not significant (Table 4.1). However, total ash in harvested grasses depended on the time of harvest and decreased linearly as harvest time was delayed (Table 1). The ash content of harvested grass in mid-October and mid-November were 21% and 40% lower than those harvested in mid-September, respectively (Table 4.2).

### Nutrients

The mineral content of biomass was significantly changed for both years. The only minerals that were not affected by year were K and Fe. Nitrogen, P, and K concentrations, all showed linear decreasing trends in the feedstock as harvest time was delayed (Table 4.1). The highest level of Fe and Al were in the mid-October harvest (Table 4.2). There was a 31.5% reduction in N between the first harvest in mid-September and the third harvest in mid-October. Another 31% reduction from mid- October to the last harvest in mid- November was noted. P and K showed similar treads (Figure 4.1). Magnesium did not begin to decrease in feedstock until the beginning of November (Table 4.2).

### Carbohydrates

Non-structural carbohydrate levels in the roots were significantly affected by year, harvest time and their interaction. Fluctuation of sugars in various years is expected due to weather changes. Sucrose was the most abundant non reducing sugar present in data, as starch was not analyzed. Non-reducing sugar are less abundant but mimic starch levels (Smith 1973). The sucrose was 30 percent higher in 2010 then 2011.

In 2010 sucrose concentration increased significantly by mid-October and remained high throughout the rest of the growing season. In 2011 increases in sucrose concentration did not occur until early-November (Figure 4.3).

### Energy Content

The Energy per unit dry matter varied significantly across harvest times and showed a linear decrease from mid-September to mid-November. The yield showed a quadratic relationship with the peak occurring in October, whereas energy content shows a linear, cubic relationship. There was no overall difference in the energy per unit area between mid-September harvest and mid-October harvest, although yields were higher in mid-October. This was because the unit energy content was higher in mid-September and therefore less dry matter was needed to produce an equivalent amount of energy in mid-October. There was a 41% decrease in energy per unit area between mid-October and mid- November.

## **Discussion**

### Yield

This study was conducted on a pre-established Cave-in-Rock switchgrass stand that had never been harvested until this experiment conducted three years after establishment. In other trials with Cave-in-Rock at the same location, plots were harvested in the second year of establishment and experienced subsequent heavy weed pressures that significantly affected harvest yields, particularly those that occurred in early September. In another experiment, yield started around 9 Mg ha$^{-1}$ and linearly decreased over three years to a low of 6 Mg ha$^{-1}$ from 2009-2011. In the experiment reported here, a mid-September harvest showed an increase in yield: 8 Mg ha$^{-1}$ to 9 Mg ha$^{-1}$ from 2010 to 2011.

Researchers have identified weed competition during the establishment phase for switchgrass as significant impedance (Cassida et al., 2000; Weimer et al., 1988; Bahler et al., 1984). Broadleaf weed herbicides at light rates are generally recommended during the first year of establishment. When seeds are slow to establish, a field can be completely infested during the first year and still recover in the second year without herbicides, when not harvested. Eventually stands outgrow the weed competition (Lewandowski et al., 2003). We speculate that the higher yield in the current study is speculated to be a result of the weed-free conditions of the stand. Because the stand was not harvested in the present study until its third year of establishment sufficient time permitted a strong mono-culture to grow and choke out the weeds.

Further research is required to investigate whether delaying harvest for a few years would eventually improve life span, vigor, and purity of the stand.

It is well documented that seasonal time of harvest significantly affects harvest yield (Adler et al., 2006; Madakadze et al., 1999; Sanderson et al., 1999; Vogel et al., 2002; Casler and Boe, 2003). The time of harvest to obtain maximum yield also depends on the geographical location and weather conditions. Sanderson et al. (1999) recommended mid -September, Vogel et al., (2002) mid-September, and Casler and Boe et al., (2003) recommend mid-October harvest. In this experiment yields did not reach their maximum until early to mid-October and then began to steadily decline in the month of November. The decrease in biomass yield as the season progressed is due to remobilization and translocation of carbon and nitrogen from the aerial portion of the plant to the below-ground tissue (Parrish and Wolf, 1993). The carbohydrate data in this experiment confirm these findings. The sucrose present in the roots significantly increase after the peak yield in 2010 and steadily increased throughout the fall growing season for 2011. Harvesting the stand in mid-October as it begins to prepare for dormancy appears to correlate with maximum yield.

### Nutrient content and Ash

Nitrogen, P, and K content linearly decreased with time throughout the fall. Ash also showed a linear decrease in concentrations for each bi-weekly harvest in both years. This trend is associated with the translocation of nutrients that occurs in warm season perennial grasses after senescence (Sanderson and Wolf 1995). The reduction in nutrients found in the feedstock is important when the grass is being used for combustion. When the feedstock is high in mineral content, particularly those responsible for the formation of ash, the feedstock produces a substance called slag, a thick black substance formed when alkali metals and silicates become liquefied at high temperatures. This substance coats surfaces of machinery causing fouling and preventing heat recovery (Cassida et al., 2005, and McLaughlin et al., 1996). The slag index (lb of water soluble alkali in ash per MMBTU of energy) should not be greater than 0.80. (McLaughlin et al., 1996). Using McLaughlin values for energy content of switchgrass at 17 M Btu $Mg^{-1}$, in the current study the switchgrass (Table 4.6) in mid-September scored a 0.62 on the slag index, and lowered to 0.49 and 0.32 in mid-October and mid-November, respectively. Originally switchgrass was considered to be unsuitable for combustion since its slag was reported to be around 1.4 (Miles et al., 1993, 1995). A 1996 report stated, however, that levels were lower than originally thought and it was actually the manner in which the samples were transported to site for analysis that contaminated the samples (McLaughlin et al., 1996).

Harvesting in mid-September not only reduced yield potential but also negatively impacted yield quality for combustion, according to our findings. The later the harvest, the lower the ash content in the feedstock and thus the lower the score on the slag index. Our maximum yield corresponded with a score between 0.47- 0.5 on the slag index when no nitrogen fertilizer was used (Table 4.3). Research is needed to determine if 0.5 score is sufficiently low enough to permit the product to reach the power plant in a form that is clean enough to be safely burned. If not, then a further delay in harvest would be necessary.

### Energy

Parrish and Wolf (1993) reported that part of the yield declines seen in a delayed fall harvests was due to the translocation of C and N to below ground plant tissue after senescence. In our study we saw that on an energy per unit dry matter basis (Joules/gram) the amount of energy present in the feedstock decreases linearly throughout the fall. As the fall progresses, the northeastern climate impose decreasing temperature light levels. Even though we saw an increase in yield in the beginning to mid –October, the plant is not producing as much carbohydrates. When switchgrass is burned for combustion, high lignocelluloses content and low levels of moisture and nutrients are desired. However, if switchgrass is being converted to ethanol, then the higher energy content per unit dry matter (particularly if soluble sugar levels are high) in feedstock and higher concentration of nutrients may be more desirable. More years of research are needed to determine how energy content in the tissue changes, and how that correlates to the amount of soluble sugar present in the tissue at different time of harvest. The overall energy content was 98.1 Gj ha$^{-1}$ in mid-September, 99.8 Gj ha$^{-1}$ mid-October, and reduced to 58.4 Gj ha$^{-1}$ by mid-November (Table 4.4).

## **Conclusion**

In Massachusetts the ‘Cave-in-Rock’ upland variety of switchgrass showed maximum yields in early to mid-October, with variability of 2.5 Mg $ha^{-1}$ over the fall growing season. Macro-nutrients including N, P, and K, decreased linearly as harvest was delayed from mid-September to mid-November. Ash present in the feedstock directly related to slag index and these values deceased linearly from 0.64 to 0.36 throughout the fall growing season. Sucrose levels significantly increased in the harvest following peak yield. The accumulation in sucrose and decrease in yield was likely due to cold acclimation as the plant prepares for dormancy. The energy content per unit of dry matter in the feedstock decreased linearly from mid-September to mid-November. The energy present per area at peak yield in mid-October was equivalent to that at mid-September. Although there is more energy in the crop in mid-September there were also more nutrients, and these nutrients cause fouling when the grass is used for combustion. Delaying the harvest until mid-October provides maximum yield and reduces nutrient contents, such that it is preferred over a mid-September harvest. However, if the slag found the feed stock is too high for a power plant to accept, then delaying the harvest until kill frost will further reduce nutrient content.

Table 4.1. Analysis of variance showing the p-values for yields and chemical analyses.

| Source of Variation | df | Yield | ASH | N | Mg | P | K | Fe | Al | Ca | Sucrose | Energy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year (Y) | 1 | ns | ns | *** | *** | ** | ns | ns | *** | *** | * | ns |
| Harvest (H) | 4 | ns | L *** | L *** | L *** | L*** | L*** | L *** | ns | Q *** | *** | LC *** |
| Y X H | 4 | Q ** | ns | ns | ns | ns | ns | ns | ns | * | L *** | na |
| CV % | | 14.5 | 19.3 | 24.5 | 12 | 16.8 | 11.1 | 30 | 43 | 16.2 | 21.2 | 4.8 |

L-Linear, Q-Quadratic, C-Cubic

Table 4.2. Ash in percent dry matter and mineral content for each harvest time.

| Harvest | Ash | N† | P | K | Mg | Ca | Fe | Al |
|---|---|---|---|---|---|---|---|---|
| Mid-Sept | 4.7 | 0.38 | 1920 | 5858 | 1534 | 1826 | 66 | 22 |
| Beg-Oct | 4 | 0.32 | 1691 | 4681 | 1459 | 2249 | 59 | 29 |
| Mid-Oct | 3.7 | 0.26 | 1444 | 3912 | 1593 | 2745 | 72 | 38 |
| Beg-Nov | 3.3 | 0.18 | 1275 | 4064 | 1142 | 2120 | 43 | 26 |
| Mid-Nov | 2.8 | 0.18 | 1070 | 2772 | 1085 | 1891 | 45 | 26 |

† N-Nitrogen reported in percent dry matter

Table 4.3. Slag index† values present for each harvest time.

| Harvest | 2010 | 2011 |
|---|---|---|
| Mid-Sept | 0.64 | 0.59 |
| Beg-Oct | 0.47 | 0.56 |
| Mid-Oct | 0.50 | 0.47 |
| Beg-Nov | 0.51 | 0.36 |
| Mid-Nov | 0.36 | 0.37 |

†lb of water soluble alkali in ash per MMBTU of energy

Table 4.4. Energy present in the feedstock.

| Harvest | Energy per Unit Dry Matter(J/g)† | Energy per Area (GJ/ha)‡ |
|---|---|---|
| Mid-Sept | 10696 | 98.1 |
| Beg-Oct | 8915 | 75.0 |
| Mid-Oct | 8775 | 99.8 |
| Beg-Nov | 8848 | 88.3 |
| Mid-Nov | 7366 | 58.4 |

†J-Joules

‡GJ-GigaJoules

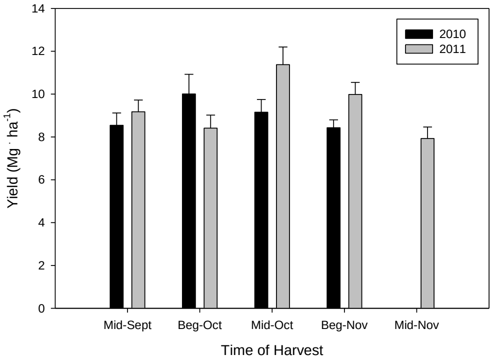

Figure 4.1. Dry matter yield (Mg ha$^{-1}$) vs. harvest time.

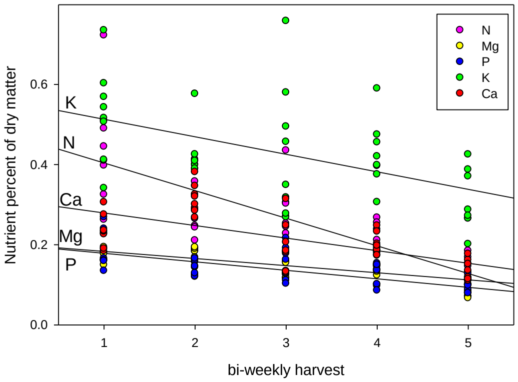

Figure 4.2. Mineral content in feedstock in percent of dry matter yield.

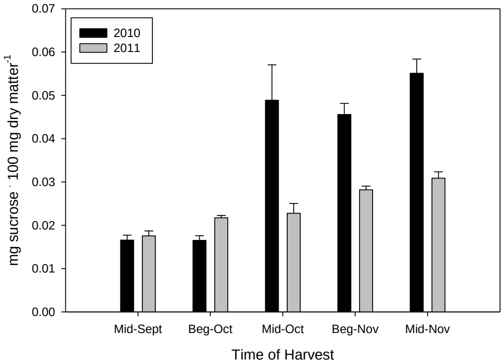

Figure 4.3. Sucrose levels at time of harvest in mg Sucrose per 100 g dry matter yield.

# CHAPTER 5

## SUMMARY AND CONCLUSION

Switchgrass has been researched throughout the United States as a potential feedstock for biofuel production since the 1980's. Much of the research done on switchgrass has been in the mid and southern parts of the United States. Researchers at the University of Massachusetts were the first to conduct switchgrass trails in the state. An appropriate cellulosic biomass crop for ethanol or combustion should be easy to manage, consistently high yielding, require low fertilizer input and be able to grow in a wide variety of locations. Switchgrass appears to meet most of these criteria for the state of Massachusetts. The goal of these experiments were to determine which agronomic harvest management practices would provide the healthiest stand for multiple years, and whether the result is good enough for efficient biofuel production. Three experiments were conducted to investigate the following topics:

1) Evaluating switchgrass varieties for biomass yield and quality to develop an herbaceous biofuel in Massachusetts

2) Nitrogen application rate and harvest management of young and mature stands of switchgrass

3) Optimal Fall Harvest Time in Massachusetts for 'Cave-in-Rock' Switchgrass used as a Biofuel

In all three experiments harvest time was the most significant treatment that affected dry matter yield and nutrient quality of the feedstock. Switchgrass is a perennial prairie grass that cycles nutrients above and below ground throughout each growing season. The cycling of nutrients allows the plant to efficiently use nitrogen, potassium, and phosphorous-- all essential elements in the growth and development of plants. Switchgrass is primarily being considered as a fuel crop for combustion in the state of Massachusetts. In the combustion process the ideal fuel should have high dry matter yield, low moisture and as few nutrients as possible. The reason one wants low nutrients in the feedstock is because the nutrients form air pollutants such as particulate matter, ash, and emissions. In each experiment we tested the harvested crop tissue for it chemical constituents to determine its quality. We investigated its carbohydrate reserves to determine if treatments were affecting the plant's ability to store carbohydrates over winter. We also conducted trials with twelve varieties that are grown around the United States to determine how they would perform in the Massachusetts climate.

## Upland Varieties

Carthage, an upland variety, produced the highest yields overall. This was an interesting finding because most literature on upland varieties focuses on Cave-in-Rock. Carthage's maximum yields occurred every year in late August after the plant went to seed and entered senescence. For all other high yielding upland varieties, harvesting in late August initially produced higher yields, but negatively impacted stands in subsequent years. In all low yielding varieties where no nitrogen was added, November harvest consistently produced the highest yields.

## Harvest Time

A bi-weekly harvest trial was added to the research in the second year because harvesting in late August appears to be too early for most stands. Harvesting in November seemed too late for optimal yields. The bi-weekly data placed peak yield at early to mid-October.

### Age of Stand

In the variety trials and in the young stand, yields dropped significantly from the first year to the second. They continued to drop, but by less, in the third year. For the mature stand, harvest time did not significantly affect yield. That result remained constant over the three years of the study. The variety and young stand were three years old at the beginning of the experiment, while the mature stand was seven years old. It therefore appears that switchgrass stands produce their highest yields when they are young and are more susceptible to agronomic practices. As the plant ages, variation in its responses to treatments decrease and the plant yield appears to stabilize and is less affected by harvest time. We speculate that this stabilized yield will depend on the purity of the stand and the fertility of the location.

## Cutting Height

The cutting height treatment in the young and mature stand demonstrated that cutting at 7.5 cm above ground increased yield in both the young and mature stand by 1 Mg ha$^{-1}$. There was no advantage to cutting at 15 cm over 7.5 cm with regards to weed suppression, feedstock quality, or carbohydrate content in the roots. Therefore the crop should be harvested at lowest height that is convenient for the machinery being used.

## Weeds and Yield

Fields harvested in late-August in the variety experiment and the young stand showed significant problems with weed infestation. This contributed to the lower yields in subsequent years. Plots that were harvested in either November or April did not have significant problems with weeds. An early fall harvest leaves the field exposed throughout the fall growing season. An inventory of weed species indicated that perennials and winter annuals were the greatest threat to purity of the stand. In both fields, harvest experiments began after the first year of establishment. In the bi-weekly experiment where plots were harvested in mid-September, we did not observe a decrease in yield the following year or find that the stand suffered from weed infestation. Research conducted on the bi-weekly harvested field did not begin until three years after establishment. This might have provided sufficient time for the grass to exclude other species and provide a healthier crop in subsequent years.

## **Nitrogen**

In the young stand, we did not see a significant response to nitrogen fertilizer at a rate of 0,67,or 135 kg ha-1. This was likely due to the high variability of yields caused by different cutting heights and weed pressure. When only a low cutting height of 7.5 cm was analyzed, there was a slight numeric trend that indicated that applying 67 kg $ha^{-1}$ increased yield.

## **Nutrients**

Nutrient content is directly related to feedstock quality. Lower nutrient content results in higher quality when the feedstock is being used for combustion. There were no variations in feedstock quality among varieties. Harvest time was the primary treatment that affected nutrient content. In all experiments nutrients such as nitrogen, phosphorous, potassium, and magnesium and ash all decreased in the feedstock when harvest was delayed from fall to spring. There appears to be a linear decrease in nutrient content as the plant senescence’s from post seed development to killing frost. Nutrient content is further reduced when the plant is harvested in the spring. Metals such as aluminum, iron and calcium do not share this trend. Calcium remained constant in the plant, while aluminum and iron are highest in the spring harvest and when the crop was at peak yield. Delaying a harvest until late in the growing season not only increases biofuel quality for combustion, but also allows the plant to store unused nutrients for the future.

Sucrose was the primary soluble nonstructural carbohydrate present in the roots at time of harvest and in December before ground freeze. The sucrose level was three times higher in the November harvest than in late August. These levels had decreased by the following spring.

Roots from late August harvested plots were able to maintain sucrose reserves similar to those of other harvests when plots were analyzed again in December. We did not find a correlation between late August harvest and the ability of the stand to store soluble sugar reserves for re-growth the following year. In the bi-monthly harvests the sucrose present in the roots began to increase significantly after peak harvest. The accumulation of sucrose in the plant roots and the decrease in dry matter harvest weight is likely due to the translocation of nutrients from the crown to roots as the plant prepares for dormancy.

## Recommendation

In Massachusetts, delaying harvest of switchgrass until mid-October is likely to produce the highest yields for biofuel production. If weeds or feed quality become a problem, farmers should delay harvest until killing frost or until the following spring. Switchgrass is a thrifty nitrogen user, so farmers may not need to use fertilizer, depending on the fertility of the soil. But if they choose to apply nitrogen, they should use low levels of fertilizer, around 67 kg $ha^{-1}$. Switchgrass should be cut at a height close to the ground that is convenient for the mechanical equipment. The stand will produce its highest yields when it is young and then begin to decrease in subsequent years. This decrease is likely to stabilize as the plant ages. Projections of yield capabilities should not be based solely on the first few years of switchgrass life span. This is because the stand is more susceptible to large variations in yields when it is young. Studies in excess of ten years are needed to understand full production capability of the grass over its life time. Further research is needed to determine if different types of treatments early in the stands life will help a mature stand continue to produce high stable yields, when this will occur, and if they are sufficiently to meet demands and ensure profit.

# BIBLIOGRAPHY

Adler, R., Sanderson, M., Boateng, A., Weimer, P., Jung, H. 2006 Biomass Yield and Biofuel Quality of Switchgrass Harvested in Fall or Spring. Agron. J.98:1518-1525.

Anex, R., Lynd, L., Laser, M., Heggenstaller, A., and Liebman, M. 2007 Potential for Enhanced Nutrient Cycling through Coupling of Agricultural and Bioenergy Systems. Crop Science 47: 1327-1335.

Alexopoulou, E., Sharma, N., Papotheohari, Y., Christou, M., Pisciomeri, I., Panoutsou, C., Pignatello, V. 2008 Biomass yields for upland and lowland switchgrass varieties grown in the Mediterraen region. Biomass and Eioenergy 32:926-933.

Beaty, E, Engel, J. and Powell, J. 1978. Tiller development and growth in switchgrass. J. Range Manage. 31:361-365

Bahler, C., Vogel, K., and Moser, L.1984. Atrazine tolerance in warm-season grass seedlings. Agron. J. 76:891-895.

Bakker, R., and Jenkins, B.2003. Feasibility of collecting naturally leached rice straw for thermal conversion. Biomass Bioenergy 25:597-614.

Biomass Research and Development Initiative. Vision for bioenergy and biobased products in the United States, 2006.; www.brdisolutions.com/publications/default.aspx.

Boe, A., Dwayne, B. 2008. Yield components of Biomass in Switchgrass. Crop Science 4: 1306-1311.

Brazier-Hicks, M., Edwards, L., Edwards, R. 2007. Selection of plants for roles in phytoremediation: the importance of glucosylation. Plant Biotechnology Journal 5, 627-635.

Brejda, J. 2000. Fertilization of native warm-season grasses. CSSA Spec. Publ.30. p. 177-200.

Brejda, J., Moser, L., Vogel, K. 1998. Evaluation of Switchgrass Rhizosphere Micro flora for Enhancing Seedling Yields and Nutrient Uptake. Agron J. 90: 753-758.

Brocklebank, J. and Hendry, G. 1989. Characteristics of Plant Species Which Store Different Types of Reserves Carbohydrates. New Phytologiest 112, No. 2, pp. 255-260.

Buhler,D., Netzer, D., Riemenschneider,D., and Hartzler, R. Weed Management in Short Rotation Poplar and Herbaceous Perennial Crops Grown for Biofuel Production. Biomass and Bioenergy, 14. No. 4: 385-394.

Clark, R., Baligar V., Zobel R. 2005. Response of Mycorrhizal Switchgrass to Phosphorus Fractions in Acidic Soil. Communications in Soil Science and Plant Analysis, 36: 1337-1359.

Casler, M.2005. Ecotyic variation among switchgrass populations from the northern USA. Crop Sci 45:388-398.

Casler, M. Bogel, K. Taliaferro, C. and Wynia, R. 2004. Latitudinal adaptation of switchgrass populations. Crop Sci.44:293-303.

Cassida, L, Ocumpaugh, W., and Grinchar,W. 2000. Using herbicides for improving establishment of switchgrass. Proc. Amer. Forage Grass Council. 196-200. Madison, WI, July 16-19.Georgetown, Tx.

Cassida, K. A., Muir, J. P., Hussey, M. A., Read, J. C., Venuto, B. C., Ocumpaugh, W. R.2005. Biofuel Component Concentration and Yield of Switchgrass in South Central USA Environments. Crop Sci. 45:682-692.

Colbran, N., Eide, A. 2008. Biofuel, the Environment, and Food Security: A Global Problem Explored Through a Case Study of Indonesia. *Sustainable Development Law and Policy*.*9 (4)*, 4- 11.

Demirbas A., 2008, Biofuels sources, biofuel policy, biofuel economy and global biofuel projections, Energy Conversion Management, 48, 2106-2116.

Demirbas A., 2009, Progress and recent trends in biofuels, En. Conv. Man., 50, 14-34.

Dien, B., Jung, H., Vogel, K., Casler, M., Lamb, J., Weimer, P, Iten,L., Mitchell, R., and Sarath. 2006. Chemical composoition and response to dilute-acid pretreatment and enzymatic saccharification of alfalfa, reed canarygrass, and switchgrass. Biomass Bioenergy (in press).

EIA, USA Energy Information Administration, Independent Statistics and Analysis. (Residential Consumption) http://www.eia.gov/emeu/recs/recs97_additions/recs_changes.html

Epplin, R. 1996. Cost to produce and deliver switchgrass biomass to an ethanol-conversion facility in the southern plains of the United States. Biomass Bioenergy 11:459-467.

Epplin, F., Clark, C., Roberts, R, Hwang, S. 2008. Challenges to the development of a dedicated energy crop. American Journal of Agriclutural Economics:89, 1296-1302.

Epstein, P., Buonocore, J., Eckerle, K., Hendryx, M.,Stout, B , Heinberg, R., Clapp, R. May, B., Reinhart, N., Ahern,M., Doshi,S., and Glustrom, L. 2011.Full cost accounting for the life cycle of coal in “Ecological Economics Reviews.” Robert Costanza, Karin Limburg & Ida Kubiszewski, Eds. Ann. N.Y. Acad. Sci. 1219: 73–98.

Gardner, F., Pearce, B., and Mitchell,R.1990. Physiology of Crop Plants. Iowa State University Press. Pg 187-209.

Hagidimitriou, M., Roper, T. 1994. Seasonal changes in nonstructural carbohydrates in cranberry. J. Amer. Soc. Hort. Sci. 119:1029-249.

Hangrave, B, and Seatedt, T. 1994. Nitrogen concentrations of senescent foliage in a relict tall-grass prairie. Prairie Naturalist 26:61-65.

Hitchcock, A. 1995. Manual of the Grasses of the United States. United States Department of Agriculture, Washington, DC.

Hopkins, A. Vogel, K., Moore, K., Johnson, Carlson, I. 1995. Genotype variability and genotype X environment interactions among switchgrass accessions from Midwest USA. CropSCi. 35:565-571.

Ichizen, N., Nishio, T., Liu, G., Li, D., and Huang, L. 2001. Relationship between management systems and soil erosion and screening of perennial gamineous plants for vegetation recovery in hilly land in loess plateau. J. Weed Sci. and Tech 46:97-103.

Ichizen, N., Takahashi, H., Nishio, T., Liu, G., Li, D., and Huang, J. 2005.Impact of switchgrass (Panicum virgatum L.) planting on soil erosion in the hills of the Loess Plateau in China. Weed Biology and Management 5, 31-34.

Johnston, J. 1990. Evaluation of the Potential for Using Old-Field Vegtation as an Energy Feedstock: Biomass Yield, Chemical Composition, Environmental Concerns and Economics. ORNL/TM-11615 Oak Ridge National Laboratory. http:/www.osti.gov/brigge/servlets/purl/6467844-Qfkbnw

Kasi D., Ragauskas, A. 2010. Switchgrass as an energy crop for biofuel production: A review of its ligno-cellulosic chemical properties. *Energy Environ. Sci.3*, 1182-1190.

Keyser, J. 1994. Switchgrass fact sheet. Natural Resource Conservation Education, Forest Service. www3.northern.edu/natsource/GRASSES/Switch1.htm

Lee, D., Owens, V., Doolittle, J. 2007. Switchgrass and Soil Carbon Sweuestration Response to Amonium Nitrate, Manure, and Harvest Frequency on Conservation Reserve Program Land. Agron. J. 99:462-468.

Lemus, R., Brummer, C., Burras, C., Moore, K., Moslstad, N., Burras, C. and Barker, M.2002. Biomass yieled andquality of 20 switchgrass populations in southern Iowa, USA. Biomass Bioenergy 23:433-442.

Lemus, R., Brummer, C., Burras, C., Moore, K., Barker, M., Molstad, N. 2008. Effects of nitrogen fertilization on biomass yield and quality in large fields of established Switchgrass in southern Iowa, USA. Biomass and Bioenergy 32 1187-1194.

Lewandowski, I and Kicherer, A. 1997. Combustion quality of biomass: Practical relevance and experiments to modify the biomass quality of Miscanthus x giganteus. Eur. J. Agron. 6:163-177.

Lewandowskia I., Scurlockb, J., Lindvallc, E., and Christoud, M.2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass and Bioenergy 25: 335-361.

Ma, Z., Wood, C.W., Brandsby, D.I. 2001. Impact of row spacing, nitrogen rate, and time on carbon partitioning of switchgrass. Biomass and Bioenergy 20: 413-419.

Massachusetts Center for Agriculture-Acers-Land in Farms, 2011. University of Massachusettes College of Natural Science. http://ag.umass.edu/index.php/research/agricultural-census/land-in-farms

McKenna, J., Wolf, D., Lenter, M. 1991. No-Till Warm-Season Grass Establishment as Affected by Atrazine and Carbofuran. Agron 83 : 311-316.

McLaughlin, S., Bouton, J., Bransby, D., Conger, B., Ocumpaugh, W., Parrish, D. , Taliaferro, C., Vogel, K. and Wullschleger, S. 1999. Developing Switchgrass as a Bioenergy Crop. ASHS Press, Alexandria, Va. 282-298.

McLaughlin, S. , De La Torre Ugarte , D., Garten, C., Lynd, L., Sanderson, M. Tobert, V., and Wolf, D. 2002. High-value renewable energy from prairie grasses. Environ. Sci. Technol. 36: 2122-2129.

McLaughlin, S., Samson, R., Bransby,D., Wiselogel, A. Evaulating Physical, Chemical and Energetic Properties of Perennial Grasses as Biofuels.1996.Bioenergy'96-The Seventh National Bioenergy Conference.Sept 15-20.

McLaughlin S, Walsh M. 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass and Bioenergy 14 (4) :317–24.

Monti, A., Fazio, S., Venturi, G. The discrepancy between plot and field yields: Harvest and storage losses of switchgrass. Biomass and Bioenergy 33: 841-847.

Muir, J., Sanderson, M, Ocumpaugh, W., Jones, R., Reed, R. 2001. Riomass production of 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. Agron.J. 93:896-901.

Mulkey, V., Owens, V., and Lee, D. 2006. Management of Switchgrass-Dominated Conservation Reserve Program Lands for Biomass Production in South Dakota. Crop Sci. 46: 712-720.

National Energy Technology Lab:NETL. 2012. IEP-Advance NOx Emissions Control Regulatory Drivers. http://www.netl.doe.gov/technologies/coalpower/ewr/nox/regs.html

Natural Capital Incentives at Manomet. June 2010. Biomass sustainability and Carbon Policy Study Chapter 3. Prepared for Department Energy Resources, Common Wealth of Massachusetts. http://www.mass.gov/eea/docs/doer/renewables/biomass/manomet-biomass-report-chapter3.pdf

Nyoka, B., Jeranyama, P., Owens, V., Boe, Arvid., and Moechnig, M. 2007. Management Guide for Biomass Feedstock Production from Switchgrass in the Northern Great Plains. South Dakota State University http://agbiopubs.sdstate.edu/articles/SGINC2-07.pdf .

Owens, V., Lee, D., Doolittle, J. 2007. Switchgrass and Soil Carbon Sequestration Response to Ammonium Nitrate, Manure, and Harvest Frequency on Conservation Reserve Program Land. Agron J 99:462-468.

Parrish, D., Fike, J.2005. The biology and agronomy of switchgrass for biofuels. Critical Review of Plant Sciences, 24 (5-6): 423-459.

Peters,E. and Linscott, D. 1998. Weeds and Weed Control In Alfalfa and Alfalfa Improvement, ed. A. A. Hanson, D. K. Barners and R. R. Hill. American Society of Agron., Madison, WI.: 705-735.

Pimental, D., Patzek, T. 2005. Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Prodution Using Soybean and Sunflower. Natual Resources Research, Vol. 14, No. 1:65-75.

Renz, M., Undersander, D.,and Casler, M. 2009. Establish and Managing Switchgrass. UW Extension in cooperation with Southwest Badger Resource Conservation & Development Council, Inc., USDA-Natural Resource Conservation Service, and Better Environmental Solutions.

Samson, R., Duxbury, P., and Mulkins, L.,2004. Research and development of fibre crops in cool season regions of Canada:Resource Efficient Agricultural Production-Canada. http://www.reap-canada.com/Reports/italy.html (June 26,2004).

Samson, R., Mehdi, B. 1998. Strategies to reduce ash content of perennial grasses. Expanding Bioenergy Partnership, Bioenergy 98, Great Lakes Regional Biomass Energy Program, Chicago, Illinois, pp. 1124-1131.

Sanderson, M. 2007. Upland Switchgrass Yield, Nutritive Value, and Soil Carbon Changes Under Grazing and Clipping. Agron J 100:510-516 .

Sanderson, M., Egg, R., and Wiselogel, A. 1997. Biomass Losses During Harvest and Storage of Switchgrass. Biomass and Bioenergy 12 No. 2: 107-114.

Sanderson, M., Jones, R., McFarland, M., Stroup, J., Reed, R., and Muir, J. 2001. Nutrient Movement and Removal in Switchgrass Biomass-Filter Strip System Treatment with Dairy Manure. J. Environmental Quality 30:210-216.

Sanderson, M., Martin, N., and Alder, Paul. 2007. Chapter 41. Biomass, Energy, and Industrial Uses of Forages. Agricultural Research Services, USDA. Pgs 635-647.

Sanderson, M., Read, C., Reed, R. 1999. Harvest management of Switchgrass for Biomass Feedstock and Forage Production. Agron. J. 91:5-10.

Sanderson. M., Reed, R., McLaughlin, S., Wullsuchleger, S.Conger, B., Parrish, D., Wolf, D., Taliaferro, C., Hopkins, A., Ocumpaugh,W., Hussey, M., Read, J., Tishchler, C. 1996. Switchgrass as a Sustainable Bioenergy Crop. Bioresource Technology 56: 83-93.

Sanderson, M., and Wolf, D. 1996. Morphological development of Switchgrass in diverse environments. Agron. J. 88:908-945.

Schmer, M.R., Vogel, K.P., Mitchell R.B., and Perrin, R,K. 2008. Net energy of cellulosic ethnol from switchgrass. Proceeding of the National jAcademy of Sciences of the United States of America. Vol. 105, No. 2:464-469.

Sladden, S., Bransby, D., and Aiken, G. Biomass yield, composition, and production costs for eight switchgrass varieiteis in Alabama. Biomass and Bioenergy 1:119-122.

Smith, Dale. 1975. Trends of Nonstructural Carbohydrates in the Stem Bases of Switchgrass. Journal of Rage Management. Vol. 28, No. 5:389-391.

Sui, Y., Thompson, M., Mize, C.1999. Redistribution of biosolids-derived total phosphorus applied to a mollisol. J. Enivronmental Quality : 28 (4), p. 1068-1074.

Teel, A., Barnhart, S., Miller, G. 2003 Management Guide for Production of Switchgrass for Biomass Fuel in South Iowa. Iowa State University Extension.

Thomason, W. E., Raun, W. R., Johnson, G. V., Taliaferro, C. M., Freeman, K. W., Wynn, K. J., and Mulle, R. W. 2004. Switchgrass Response to Harvest Frequency and Time and Rate of Applied Nitrogen. J. Plant Nutr. 27: 1119-1226.

Tillman, D.A. 2000. Biomass cofiring: the technology, the experience, the combustion consequences. Biomass Bioenergy 19:365-384.

Trocsanyi, Z., Fieldsend, A., and Wolf, D.2009. Yield and canopy characteristics of switchgrass (Panicum virgatum L.) as influenced by cutting management. Biomass and Bioenergy 33 442-448.

USDA Census of Agriuculture 2007. http://www.agcensus.usda.gov/Publications/2007/Full_Report/

USDA MA-Fact Sheet 2012. Economic Research Services United States Department of Agriculture. http://www.ers.usda.gov/StateFacts/ma.HTM#PIE

USDA NASS-Crop Value Summary Agricultural Pricing ISSN: 1949-0372, 1949-0373, 1949-0374

Van Esbroeck, G., Hussey, M., and Sanderson, M. Variation between Alamo and Cave-in-Rock Switchgrass in Response to Photoperiod Extension. Crop Sci. 43: 639-643.

Vogel, K. 1996. Energy production from forages (or American agriculture-back to the future). J. Soil Water Conserv. 51:137-139.

Weimer, M., Swisher, B., and Vogel, K. 1988. Metabolism as a basis for differential atrazine tolerance in warm-season forage grasses. Weed Sci. 36:436-440.

White, L. 1973. Carbohydrate Reserves of Grasses: A Review. J. of Range Management 26 (1): 13-18.

Wolf, D. and Fiske, D. 2009. Planting and Managing Switchgrass for Forage, Wildlife, and Conservation. Virginia Cooperative Extension. Publication 418-013.

Worldwatch Institute. 2006. Biofuels for transportation: global potential and implications for sustainable agriculture and energy in the 21st Century.

Wright, L. 2007. Historical Prespective on How and Why Switchgrass was selected as a “Model” High Potential Energy Crop. Oaklandridge National Laboratory. www.osti.gov/bridge