ABSTRACT

CAFFREY, KEVIN ROBERT. A Comparison of Alternative Bioenergy Logistical Operations in North Carolina. (Under the direction of Mari S. Chinn).

Biomass logistical operations are an important aspect of a biomass based industry, which accounts for a major portion of the total costs related to biomass chemical production systems. Biomass feedstocks are low value, high in bulk density, perishable during storage, and required in high quantities on a continual basis. Optimization of biomass logistics operations include: harvest, storage, handling, and transportation of feedstocks to the conversion facility. These operations are interconnected requiring optimization of the system as a whole, considering piecemeal optimization of components may inhibit other portions of the biomass supply chain.

Giant reed (*Arundo donax* L.) displays traits of invasiveness related to its high growth rate, clonal propagation, and tendency towards aquatic ecosystems. During large scale production operations there is the potential for spread of chopped material during harvest, handling, and transportation. Forage chopped giant reed was evaluated for its growth potential in aquatic and terrestrial media. Giant reed was found to have negligible growth after forage harvesting, making it an attractive potential harvest method.

Ensiled storage of biomass feedstocks (Giant Reed, Switchgrass (*Panicum virgatum* L.), Miscanthus (*Miscanthus x giganteous*), Sweet Sorghum (*Sorghum bicolor* (L.) Moench)) is a probable storage method for forage chopped high moisture biomass material. Losses were found to be greatest in wet biomass feedstocks low in soluble carbohydrates, not allowing rapid production of organic acids to lower pH and reduce growth of spoilage microbes. Reduction in moisture content of biomass was also found to be an adequate

method for inhibition of dry matter loss, which was pronounced in March harvested feedstocks.

Storage of biomass feedstocks in baled form has been proposed to mimic traditional hay operations, as related to the maturity of the technology, availability of equipment, and experience of local farmers with the practice. Bale format (big square, round indoor) of indoor stored biomass did not have a major impact on dry matter loss for selected biomass feedstocks (Giant Reed, Switchgrass, Miscanthus). Proportional composition changes of weathered and core samples of outdoor stored bales (outdoor round, fully wrapped outdoor round) were significantly different between the majority of the sampling periods, suggesting a difference between the composition of the weathered and core portions of these bales. This study found that traditional core sampling methods for outdoor stored bales did not properly represent moisture content, and therefore may not properly represent composition of the biomass material. Development of alternative, possibly more intense, methods may be necessary to accurately assess changes in composition for bales stored outdoors.

Since large scale biomass feedstock production does not exist in North Carolina a profit based probabilistic model was developed to determine cropland conversion to biomass feedstocks. For perennial grasses, switchgrass was found to exhibit higher profitability at a greater proportion than giant reed or miscanthus, for the regions analyzed. Sorghum exhibited greater profitability in Duplin (Coastal Plain Region) and Henderson (Mountains Region) counties within some of the scenarios, and was closely related to increases in income from winter rotation crops.

A proposed logistical system was developed for multiple feedstocks (Sorghum, Switchgrass) and multiple harvest methods (big square baler, forage chopper) implementing increased just-in-time operations during a late season harvest period. This approach reduces storage time, safety stock requirements, increases utilization of high capital harvest equipment, and simplifies supply chain operations. Using the cropland conversion prediction equation developed, when simulated the proposed system reduced radial production area and distance from conversion facility to bale storage sites.

The results generated during this research can be used to assist in biorefinery siting, feedstock production, and development of optimized biomass logistics operations for the emerging biomass based industry. Past research has primarily focused on piecemeal portions of the biomass based chemical production system, which does not account for the complex interactions within that system. Integrated research methods similar to those studied in this work and implementing multi-disciplinary approaches, at a minimum of pilot scale, are required to advance the knowledge base in the area of biomass feedstocks.

A Comparison of Alternative Bioenergy Logistical Operations in North Carolina

by
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DEDICATION

This dissertation is dedicated to all past and present mentors who have influenced my research focus, advancing my personal and professional development.

BIOGRAPHY

Kevin Caffrey was originally from western Pennsylvania where he attended Gannon University in Erie, PA, receiving a bachelor of science in Environmental Science, and subsequently a master of science in Environmental Health and Engineering. He spent a year as a traveling consultant for his fraternity (Delta Chi), a year working on engineering undergraduate coursework at Virginia Tech, and most recently a year on an advanced short term research opportunity (ASTRO) at Oak Ridge National Laboratory prior to beginning his PhD program at North Carolina State University, in the Department of Biological & Agricultural Engineering.

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1.1 U.S. Bioenergy Production

Bioenergy production has increased as a contributor to U.S. energy production, from 4.40% of total U.S. energy production in 1950 to 5.42% in 2013, while total energy production increased by 130% in that same time period (U.S. EIA 2014). With incorporation of the Renewable Fuel Standard (RFS) under the Energy Policy Act (EPAct) of 2005 (U.S. Cong 2005) and subsequent update under the Energy Independence and Security Act (EISA) of 2007 (U.S. Cong 2007) biofuel production in the U.S. has increased from 564 trillion Btu in 2005, to 978 trillion Btu in 2007, and further increasing to 2,000 trillion Btu in 2013 (U.S. EIA 2014).

The primary feedstocks for ethanol and biodiesel production in the U.S. come from agricultural commodities such as corn for ethanol (additionally sugarcane, wheat, grain sorghum, etc.) and soybean for biodiesel (additionally waste cooking oils, other vegetable oils, animal fats, etc.). In 2013 ethanol production reached 13.29 billion gallons (87% of total biofuel energy production), which was much higher than the 1.36 billion gallons of biodiesel in the same year (U.S. EIA 2014).

The updated RFS values set by EISA has mandated an increase in biofuel production by 2022 to reach 46 billion gallons for use in the U.S., broken down into four primary categories: cellulosic biofuels (16 billion gallons), advanced biofuels (14 billion gallons), biomass-based biodiesel (1 billion gallons), and conventional biofuels (15 billion gallons) (U.S. DOE 2011). Though definitions of biofuel categories are relatively vague one designation method is by feedstock utilized for production. First generation biofuels are those currently produced from traditional commodity crops, such as corn and soybeans. Biofuels produced from wood, waste products, and dedicated biomass crops (e.g perennial grasses, fast-growing trees) make up second generation biofuel production. Use of algal strains and fast growing aquatic plants makes up third generation biofuel feedstocks, which can be engineered to produce high value products in conjunction with biofuels, while utilizing land, water, nutrients, and carbon sources that are of low value or unsuitable for other uses. A fourth generation of biofuels could be included, which are tied to advanced genetically modified feedstocks and produced in such a manner such that carbon dioxide is captured and stored throughout the production process, making the fuels carbon negative instead of just carbon neutral. The designation of fourth generation biofuels is still relatively ambiguous, with some commonly referred to first generation biofuels appearing to fit all criteria of this so called “advanced” technological category (e.g. heat activated alpha amylase corn grain processed at an ethanol facility with carbon dioxide sequestration).

The Biomass Research & Development Technical Advisory Committee set goals in 2002 for biopower (2% annual gain until 2030), biobased transportation fuels (4% of transportation fuels in 2010, 10% in 2020), and biobased products (12% of target US chemical commodities in 2010, 20% in 2030) (BTAC 2002). In 2006 an updated report by the committee found that biofuels were on track or exceeding expectations, biopower was not on track, and biobased products were difficult to measure due to confidentiality issues (BTAC 2006). The expectation was that by 2030 meeting the biopower (5% U.S. power), biofuel (20% of transportation fuels), and biobased product (25% of chemicals) goals would require approximately one billion dry tons of feedstock annually (U.S. DOE 2003). To evaluate the potential feedstock production capabilities of the U.S. necessary to meet these goals the Billon Ton Study was conducted in 2005 (U.S. DOE 2005), with a subsequent update in 2011 (U.S. DOE 2011). The original Billon Ton Study found that 1366 million dry tons could be available annually by 2030 (368 forest resources, 428 crop residues, 377 perennial crops, 87 grain, 106 animal manure) (U.S. DOE 2005), while the updated report found 1094 million dry tons using a $60/dry ton baseline assumption (forestry 328, agricultural 768) and between 1374 to 1633 million dry tons with a high yield scenario at the same price (forestry 328, agricultural 1047 to 1306) could potentially be available (U.S. DOE 2011).

In 2014 the first production scale cellulosic ethanol facilities came on board in the U.S., with a number of additional facilities proposed and under construction (Table 1). This does not include bolt on cellulosic ethanol facilities that are combined with traditional corn ethanol facilities, converting residual cellulosic material after conversion of starch to first generation ethanol.

Table 1: Production Scale US Cellulosic Biofuel Production Facilities (>15 MMgal/year)

Facility	Nameplate	Daily Use	Location	Feedstock	Status
Abengoa Bioenergy Biomass of Kansas	25 MMgal	1,100 dry ton	Hugoton, KS	Corn Stover, Straw, Switchgrass	Open (2014)
POET-DSM's Project Liberty	20 MMgal	770 dry ton	Emmetsburg, IA	Corn Cobs, Corn Stover	Open (2014)
DuPont Biofuel Solutions	30 MMgal	1,070 dry ton	Nevada, IA	Corn Stover	Under Construction (Mar 2015 opening)
BlueFire Renewables Fulton LLC	19 MMgal		Fulton, MS	Wood Waste	Under Construction
Canergy LLC-Rockwood Plant	28 MMgal		Brawley, CA	Energy Cane	Proposed
Chemtex International Inc.-Project Alpha	20 MMgal		Clinton, NC	Energy Grasses	Proposed
Woodland Biofuels Inc.- Newton Falls	20 MMgal		Newton Falls, NY	Wood Waste	Proposed
ZeaChem Boardman Biorefinery, LLC	25 MMgal		Boardman, OR	Poplar/Wheat Straw	Proposed

1.2 Bioenergy Production Issues

Two major issues that have been raised concerning biofuel production are: indirect landuse change (Searchinger et al. 2008) and the food versus fuel debate (HLPE 2013). These two issues are interconnected and are the result of increased biofuel production reducing land available for food and feed production in developed counties, reducing exports, and raising total agricultural commodity prices globally. ActionAid (2010) estimate that biofuels were at least 30% responsible for the 2008 global food price spike, which has been implied to increase poverty and hunger in developing counties, resulting in widespread food riots. There have also been issues with large multi-national corporations acquiring land in under-developed countries (termed "land-grabbing"), specifically in Africa and Southeast Asia. It is believed that this activity removes fertile land from small scale farmers, increases exports of agricultural products, creates low value bids on land area, exploits local workers, and unsustainably manages agricultural production (EuropAfrica 2011).

Using data on actual landuse change, Babcock & Iqbal (2014) found that developed countries commonly will intensify agricultural production in response to greater world agricultural prices, rather than convert additional non-agricultural land. Though biofuels can be linked to some increases in food scarcity, the greater issue is waste throughout the production and end use of food stuffs, estimated at 30-50% of total global production (IME 2013). Additionally in developed countries a relatively small portion of the money spent on food actually is related to agricultural products, which in the U.S. in 2008 was calculated to be only 11.6% by industry sector (Canning 2011). So an increase in primary agricultural products should not have a major effect on food prices. Baffes & Dennis (2013) found that long term drivers of food prices are most strongly related to crude oil prices, as well as a number of other factors unrelated to increased biofuel production. After accounting for inflation Urbanchuk (2013a) found that U.S. consumers were not spending a greater proportion of money on food than before the RFS was implemented. Urbanchuk (2013b) additionally found that the increase in biofuels production in Iowa had beneficial impacts on the swine and cattle industry, which may be related to lower production costs for these industries. After seven years of the updated RFS (U.S. Cong 2007), the Renewable Fuels Association, RFA (2014) reported that biofuels had beneficial impacts on economics and fuel prices, while having limited agricultural impacts, environmental issues, and impacts on food prices in the U.S. Increases in ethanol production has been shown to reduce wholesale gasoline prices by $0.25/gallon across the U.S., with a range of $0.16/gallon (East Coast) and $0.39/gallon (Midwest) (Du & Hayes 2011). McPhail & Babcock (2012) found that biofuel policies have decreased price elasticity of demand of both gasoline and corn, increasing price volatility. Bioenergy production is a complex, interrelated operation, which can have wide reaching effects to multiple sectors of our economy and environment.

1.3 Lignocellulosic Biomass Feedstocks

There are multiple designations for lignocellulosic biomass feedstocks (Figure 1), each with specific quality constraints, available quantity by location, and operational issues related. One method for characterizing this biomass material is by primary categories: dedicated feedstocks and residues & wastes. Dedicated feedstocks are purpose grown crops specifically for use as biomass in bioenergy production, and include woody or herbaceous crops. Residues & wastes consist of any organic waste material that may be converted to bioenergy: waste/trash, agricultural, and forestry.

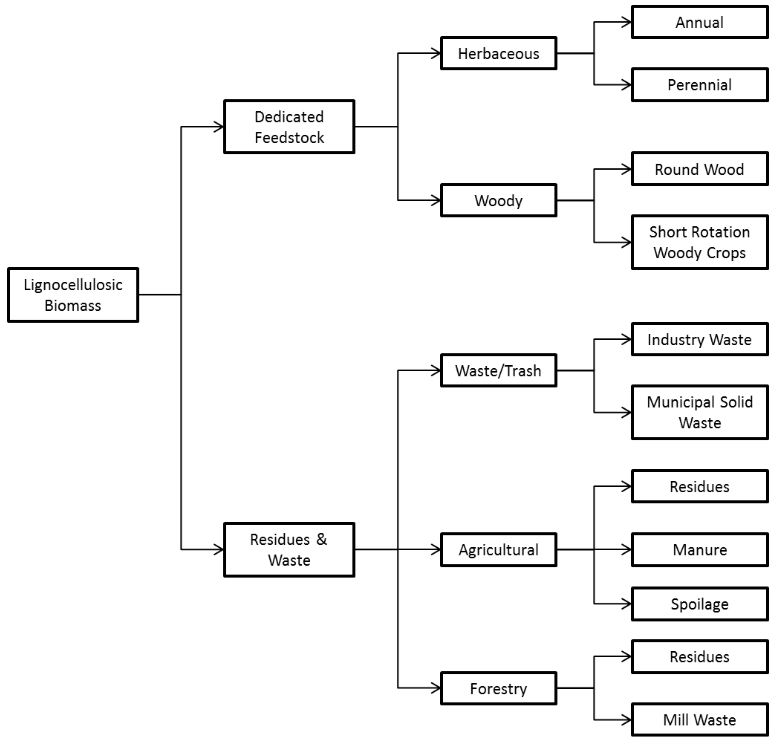

Figure 1: Lignocellulosic Biomass Feedstock Categories

Use of organic residues and waste material is thought of as economically favorable, since in some cases prices are either relatively low, zero, or negative by charging a tipping fee. Depending on the source of this material the quality may be poor and inconsistent, which may require additional processing to remove unfavorable component material. For example Fiberight LLC has shown in their demonstration plant in Virginia (with a production scale facility planned in Iowa) that the organic fraction of municipal solid waste, after separation of metals and plastics, can be converted to sugars for ethanol production (Fiberight 2015). Agricultural residues (e.g. corn stover, straw) are the primary feedstocks in current cellulosic ethanol facilities (Table 1), though extensive experimentation was required to determine optimal harvestable yields to manage nutrient removal and erosion control with economical feedstock production. Proposed biorefineries utilizing forestry residues are facing similar issues to determine optimal harvestable quantities.

Purposely grown dedicated biomass feedstocks are commonly split between woody and herbaceous crops, which require very different production techniques. Woody crops are usually harvested on a multi-year schedule from either common round wood, primarily pulp wood, or short rotation woody crops, which are grown on an accelerated harvest schedule compared to traditional forestry operations. Herbaceous crops are harvested annually and can be divided between annuals, planted each year, and perennials, planted once and harvested for multiple years (the time scale is dependent on management strategy).

1.4 Biomass Logistics

Biomass production, storage, transportation, and processing are a major cost of cellulosic ethanol production, with Aden et al. (2002) determining feedstock costs accounting for $0.34 of the $1.07 per gallon (31.4%) and in an updated report by Humbird et al. (2011) reporting feedstock production and handling as a cost of $0.74 of the minimum ethanol selling price of $2.15 per gallon (34.4%). Woody feedstocks, primarily wood chips and pellets, have existing commodity scale logistical operations, both of which are traded internationally (IEA 2011; IEA 2012). Hay has become an increasingly important international commodity, reaching $1.2 billion in 2012 for western U.S. states (Putnam et al. 2013). U.S. DOE (2009) has designed a commodity scale system for herbaceous lignocellulosic biomass, which theoretically would reduce handling issues and compositional variation, but may increase total feedstock logistic costs.

Conventional biomass logistics systems (biomass format categories: square bales, round bales, round wood, loose biomass, and forage) require different transportation, storage, handling, and processing equipment prior to entry into the biorefinery throat (U.S. DOE 2009). This means that inclusion of a multi-feedstock system for a single biorefinery would require specialized logistical equipment for each of the biomass format categories, which are commonly high in moisture content, have a low bulk density, and require preprocessing to support cellulosic sugar production. U.S. DOE (2009) proposes progressing towards a more uniform system (Pioneer Uniform), with preprocessing depots after the field gate allowing multiple feedstocks to be processed at small specialized facilities prior to delivery to the biorefinery. Inclusion of this preprocessing step outside of the biorefinery can allow for reduced transportation needs of bulky unprocessed feedstocks. The final proposal from U.S. DOE (2009) is the Advanced Uniform system, where biomass is processed at preprocessing depots, and then the uniform biomass is stored in elevators similar to traditional grain crops for bulk transportation to multiple biorefineries. This system mimics traditional agricultural commodity management systems, which allows for feedstocks to be treated as a tradable commodity crop.

1.5 Bioenergy Production Pathways

There are various methods for converting biomass material into bioenergy. While other classification systems can be used, bioenergy can be split into four common conversion pathways: Thermal, Thermochemical, Biochemical, and Chemical (Figure 2). Thermal conversion is related to simple combustion of organic material, which can produce heat, power, and electricity, with ash as a potential by-product from these systems. Although simple combustion fits under the thermochemical pathway, it can be considered different because it does not result in the production of multiple chemical products common to the thermochemical pathway. The biochemical pathway uses biological catalysts and processes to produce bioenergy, and can include anaerobic digestion. Although anaerobic digestion does incorporate some fermentation processes it is much less controlled than most fermentation operations and generally less focused on high value-product production. Finally the chemical pathway uses chemical reactions to produce bioenergy, specifically the transesterification of fatty acids to produce biodiesel.

Thermal

- Combustion
  - Heat
  - Power
  - Electricity
  - Ash

Thermochemical

- Gasification
  - Syngas
  - Ash
- Pyrolysis
  - Tars
  - Char
- Torrefaction
  - Bio-Coal

Biochemical

- Anaerobic Digestion
  - Biogas
  - Nutrients
- Fermentation
  - Alcohol
  - Protein & Solubles
  - Carbon Dioxide

Chemical

- Transesterification
  - Biodiesel
  - Glycerin

Figure 2: Primary Bioenergy Conversion Pathways

1.6 Integrated Biorefinery System

The bioenergy industry has continued to expand its product portfolio to increase total economic gains, while reducing the potential risk for price volatility of a single product. Traditional corn ethanol facilities can be split between wet and dry mill operations. Wet mill facilities fractionate corn into multiple value added products prior to fermentation: starch, gluten feed, gluten meal, and corn oil (U.S. DOE 2015). Dry mills are commonly less capital intensive producing primarily ethanol and a dried distiller's grain with solubles, used as an animal feed (U.S. DOE 2015). Advances in dry fractionation and processing of fermentation products have allowed dry mills to produce additional products. This has been seen in Green Plains Renewable Energy Inc. (Green Plains 2015), which has installed industrial corn oil extraction equipment to its facilities. A bolt-on cellulosic ethanol component has been included to Quad County Corn Processors facility (Quad County 2015) to convert the cellulosic component of the corn grain to produce cellulosic ethanol. A number of POET facilities (POET 2015) have included processing capability to purify and liquefy carbon dioxide produced during fermentation processes, which meet food grade specifications. Depending on facility design a single corn based, dry mill ethanol facility can now produce 1st generation ethanol, 2nd generation ethanol, industrial corn oil, food grade carbon dioxide, and/or dried distiller's grains with solubles (minus the cellulose and oil). This same trend of product diversification is being applied to next generation bioenergy production facilities, known as an integrated biorefinery.

The Energy Technologies Office of the United States Department of Energy's Energy Efficiency & Renewable Energy has taken the initiative to determine methods to replace all products from a barrel of crude oil by biomass feedstocks. Crude oil produces a number of important products (Table 2); since much of the material is imported it caused a major trade deficit in 2012 of $291 billion in the US (U.S. DOE 2013). Increasing production of products shown in Table 2 can increase energy security, promote rural development, and have beneficial economic impacts on the U.S. economy. Focused primarily on energy security issues and national security the U.S. Navy has implemented steps to reduce dependence on foreign oil, termed the Great Green Fleet (Chambers & Yetiv 2011). Using authority under the Defense Production Act of 1950 (U.S. Cong 1950) the U.S. Defense Department has awarded three contracts totaling $210 million to develop "drop-in" biofuel facilities: Fulcrum Bioenergy (Fulcrum Bioenergy 2015), Redrock Biofuels (Red Rock Biofuels 2015), and Emerald Biofuels (Emerald Biofuels 2015).

Table 2: U.S. Crude Oil Products (U.S. EIA 2015)

	2008	2009	2010	2011	2012	2013
Finished Products (10^9 barrels)	6.40	6.09	6.17	6.07	5.91	6.01
Finished Motor Gasoline	51.4%	53.9%	53.2%	52.7%	53.7%	53.7%
Conventional	*65.6%*	*65.7%*	*65.8%*	*65.8%*	*66.7%*	*67.5%*
Reformulated	*34.4%*	*34.3%*	*34.2%*	*34.2%*	*33.3%*	*32.5%*
Distillate Fuel Oil	22.6%	21.8%	22.5%	23.5%	23.2%	23.3%
<15 ppm Sulfur	*81.3%*	*78.3%*	*84.5%*	*89.5%*	*91.9%*	*92.4%*
>500 ppm Sulfur	*12.8%*	*12.5%*	*12.7%*	*10.1%*	*8.3%*	*6.9%*
15< & <500 ppm Sulfur	*5.9%*	*9.2%*	*2.8%*	*0.5%*	*0.4%*	*0.7%*
Kerosene- Type Jet Fuel	8.8%	8.4%	8.5%	8.6%	8.7%	8.7%
Still Gas	3.8%	4.0%	4.0%	4.1%	4.2%	4.3%
Petrochemical Feedstocks	3.2%	2.7%	2.8%	2.6%	2.3%	2.3%
Naphtha	*45.0%*	*55.2%*	*54.6%*	*58.2%*	*63.7%*	*72.0%*
Other Oils	*55.0%*	*44.8%*	*45.4%*	*41.8%*	*36.3%*	*28.0%*
Asphalt & Road Oil	2.4%	2.2%	2.1%	2.1%	2.1%	2.0%
Residual Fuel Oil	3.6%	3.1%	3.2%	2.8%	2.3%	1.9%
Lubricants	0.7%	0.7%	0.8%	0.7%	0.7%	0.7%
Miscellaneous Products	0.4%	0.4%	0.4%	0.5%	0.5%	0.5%
Special Naphthas	0.3%	0.1%	0.1%	0.1%	0.0%	0.3%
Finished Aviation Gasoline	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Waxes	0.1%	<0.1%	0.1%	<0.1%	<0.1%	<0.1%
Kerosene	0.1%	0.1%	0.1%	0.1%	<0.1%	<0.1%

Using a set of integrated production methods multiple products can be produced from biomass material, increasing total profits and reducing risk, which has been outlined in the goals set by the U.S. Department of Energy (U.S. DOE 2014). Currently the major co-products produced in cellulosic ethanol facilities (Table 1) are electricity, process heat, and limited animal feed products. There has also been some advancement in market diversification, such as increased use of distiller's grains outside of animal feed markets (Bonnardeaux 2007) and the collaboration of DuPont with Proctor & Gamble to use cellulosic ethanol in Tide Coldwater laundry detergent (DuPont 2015). With many consumers preferring "green" alternatives, biobased products are seen as a substitute for petroleum based plastics, chemicals, fuels, and other products (Singh et al. 2003). An integrated biorefinery should be able to use multiple feedstocks to produce multiple different products, which like the petroleum industry can change as demand and economics switch between products. This approach could allow use of the most sustainable low cost feedstock available, while reducing security issues related to single feedstock systems that may halt energy production (such as in the case of crude oil embargos).

Algal feedstock production systems are being designed to produce high value products through specialized bioengineered algae, with the excess biomass available for processing for oil, sugars, and protein production, while utilizing waste nutrient and carbon streams (Veal et al. 2013). Other crops such as industrial purple sweetpotatoes may have high value anthocyanins extracted prior to use of excess biomass material for sugar production (Bridgers et al. 2010). A variety of feedstocks systems are being investigated to produce multiple different products, while producing bioenergy products as a low value co-product. This trend of production of high value products, with secondary or waste products going toward lower value commodities (such as biofuels), represents the guiding principle of the an integrated biorefinery.

1.7 Conclusion

The bioenergy industry is part of a dynamic evolving biobased market, that is increasingly diversifying feedstocks and end products. Improvements to feedstock production systems, logistical operations, and conversion pathways are reducing total production costs, allowing production of an increasing number of biobased products. With the complexity and interconnected nature of bioenergy production systems, a total systems approach is required to further the industry to accomplish social, environmental, economic, and political goals associated with biobased production systems, this is especially true as related to 2nd generation bioenergy pathways.

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CHAPTER 2: GIANT REED (*ARUNDO DONAX* L.) CLONAL PROPAGATION AFTER HARVEST OPERATIONS

2.1 Introduction

Interest in bioproducts and bioenergy production has increased globally as a result of challenges surrounding natural resource acquisition, fossil fuel energy and related agricultural market variability, and associated environmental consequences. Giant reed (*Arundo donax* L.), a rhizomal reed-like perennial grass, has been considered as a potential biomass feedstock to support an emerging biobased economy. This emergent C_3 grass (Spencer et al., 2006) was thought to have originated in Asia but has become widespread in southern Europe, North Africa, the Middle East, Australia, and North and South America (Boose & Holt, 1999). A number of agronomic benefits are associated with giant reed: low nutrient requirements, high productivity, and resistance to biotic and abiotic stress (Mariani et al., 2010); making it a promising alternative to other high yielding perennial grasses such as switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus x giganteus*). Comparisons to miscanthus in Italy have shown higher dry matter yields and net energy returns for giant reed (Angelini et al., 2009; Angelini & Bonari, 2005). Seed heads of giant reed have been observed to be sterile in many regions, including North America (Decruyenaere & Holt, 2005), requiring clonal propagation of plugs, rhizomal fragments, or partial canes. Characteristics related to propagation, high yield, rapid growth rate, and preference for aquatic ecosystems (e.g. stream banks, poorly drained soils) support claims that giant reed exhibits invasive traits (Boose & Holt, 1999).

Several U.S. states have described giant reed as a problematic plant, including: Texas (noxious weed), California (exotic plant pest), Hawaii (invasive weed), Nevada (category A weed), South Carolina (significant threat), Georgia (invasive), Virginia (invasive), Alabama (invasive) and Tennessee (invasive, exotic plant) (McWilliams, 2004; Ervin & Madsen, 2014). Using the Australian Weed Risk Assessment (WRA) survey, giant reed scored above the set threshold designating it as invasive (Gordon et al., 2011). Spread of giant reed has commonly been associated with unmanaged aquatic environments, where canes and rhizomes disassociate leading to rooting and growth in distant locations, with successful propagation requiring proper shoot/rhizome length, orientation, and environmental conditions (Boose & Holt, 1999). Virtue et al. (2010) found that cultivation of giant reed outside of aquatic ecosystems and floodplains has negligible invasiveness potential, using the South Australian Weed Risk Management System (SAWRMS). McCormick & Howard (2013) made five recommendations to reduce potential invasiveness of bioenergy feedstocks: cautious species selection, stakeholder cooperation, properly maintained regulations, production and utilization of an environmental management plan, and expanded management practices beyond cultivated areas.

A set of voluntary best management practices are under development for energy crops in North Carolina (Iverson et al., 2011), highlighting the substantial risk of spread during logistical operations. The U.S. EPA set a standard of “no significant likelihood of spread beyond the planting area” requiring registration, reporting, and record keeping for giant reed (78 Fed. Reg. 41703, 2013). Though production of cultivation protocols is underway there remains a significant risk of spread during logistical operations, including: harvest, storage, handling, and transportation.

Mann et al. (2013) observed that intact giant reed nodes propagate year round in both terrestrial and aquatic media, between two and fourteen days. Boose & Holt (1999) determined that orientation, size ($\geq$2 cm), storage time, and temperature effected propagation, though soil type and depth (10 to 25 cm) did not. While these studies provide valuable insight into growth habits of giant reed, the parameters were not related to realistic harvest operations.

The objective of this short communication was to determine potential pathways for spread of giant reed (*Arundo donax* L.) under realistic logistical operations for: round baling, big square baling, and forage chopping; including a determination of nodal emergence from chopped stalks. This rapid investigation was required to ensure environmentally sensitive harvest operations of larger field trials, with the potential for further evaluation of potential invasiveness at increased scale.

2.2 Materials & Methods

2.2.1 Logistical Operations

The most common perennial grass harvest method in the Southeast is round baling, though the potential for big square baling or forage chopping exists (Figure 3). There are a number of benefits and challenges related to each of these harvest operations (Table 3). Each harvest operation, with subsequent storage and transportation methods, were qualitatively evaluated for operational issues and potential pathways for spread of giant reed. Operational observations were conducted during field operations in October of 2012 and March of 2013, on a two year old 12 hectare plot of giant reed, approximately 4 hectares were harvested during each of these observations.

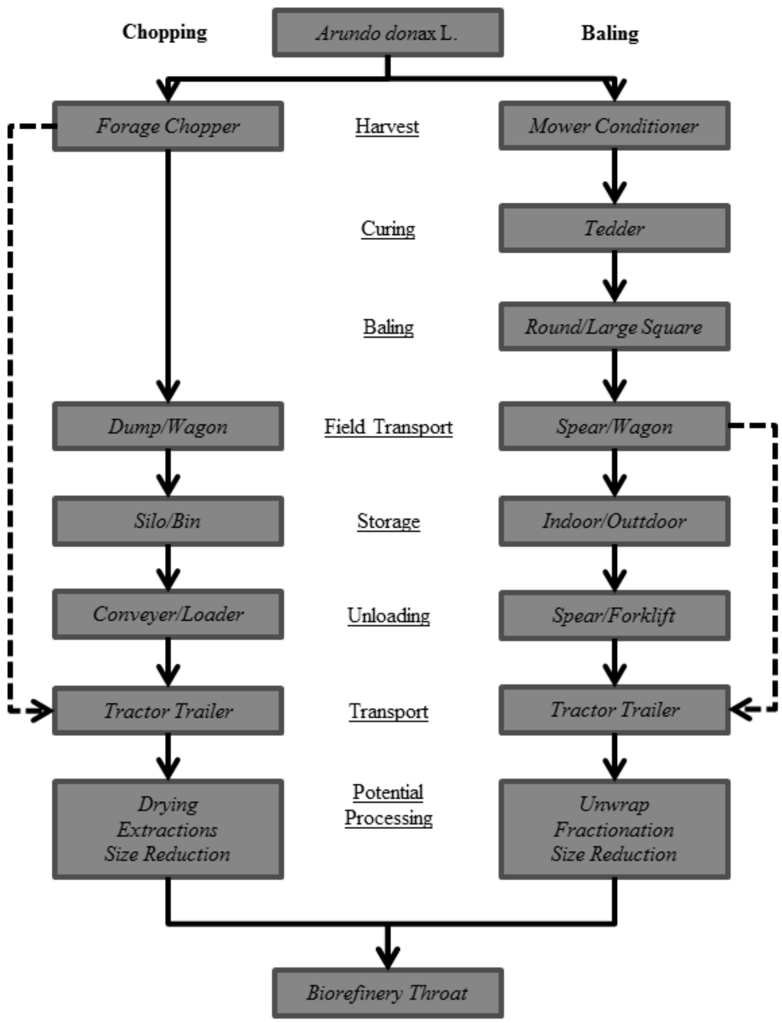


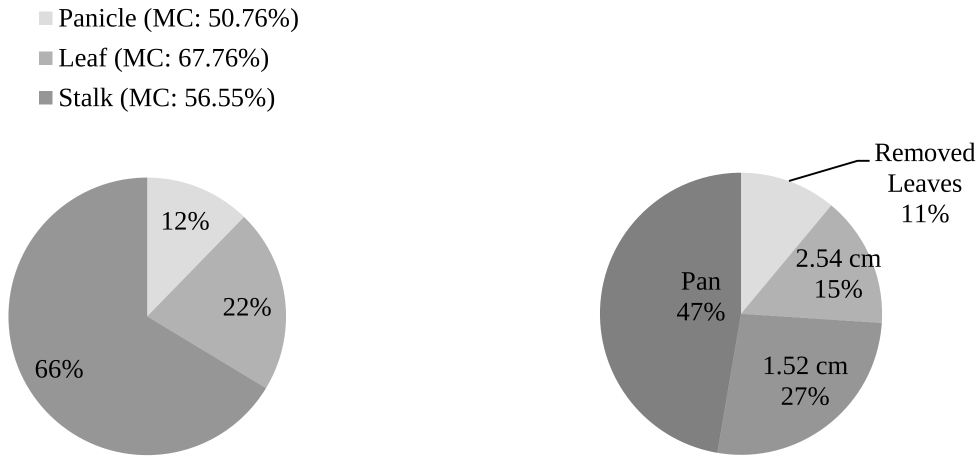
Figure 3: Traditional Hay & Forage Logistical Operations (dashed line represents just in time operations)

Table 3: Benefits & Challenges of Traditional Hay & Forage Harvest Operations

Harvest	Benefit	Challenge
Round Bale	Single Operator Possible	Drying Requirements
	Field Storage (short/long term)	Low Transportation Capacity
	Relatively Low Capital	Weathered/Core Portions
	Equipment Availability	Unwinding Required
	Maneuverable	Soil Incorporated Ash
	Low Compaction (light weight)	
Big Square Bale	High Transportation Capacity	High Capital Requirements
	Highly Productive	Larger Turning Radius
	Simpler Processing	Drying Requirement
	Covered Outdoor Storage Possible	Soil Incorporated Ash
		Increased Compaction (heavier)
Forage Chop	Partial Size Reduction	Possible High Moisture
	Expanded Harvest Range	Elevated Storage Costs
	High Field Efficiency	Coordinated Harvest Operation
	Lower Field Losses	Higher Storage Losses

2.2.2 Forage Harvested Stalk Material Propagation

Node emergence of giant reed stalks from second year rhizomal crowns comminuted with a PTO driven wood chipper and pull-behind single row maize chopper were determined using 125 gram samples placed in paint trays (40 cm x 30 cm), watered and monitored for thirty days. Samples were placed in different locations (ambient & greenhouse) and media (aquatic & terrestrial) with four stalks placed in water baths as controls. Four post-anthesis stalks were measured for height (3.9 m ± 1.14 m), diameter (17.6 mm ± 7.48 mm) and height-to-diameter ratio (222.8 ± 54.98), then stalks were differentiated by leaf, seedhead, and stalk for weight and moisture content measurements (Figure 4).



A. Differentiated Wet Mass

B. Wood Chipper Size Distribution

Figure 4: Physical Properties of Giant Reed used for Experimental Design [A. Differentiated Mass, B. Chipped Size Distribution]

2.2.2.1 Wood Chipper

Stalks were hand harvested in early August pre-anthesis, and subsequently fed into a wood chipper (Farmi Forest Corporation, Farm Chipper, CH 260). Large leaf portions were removed and comminuted material was divided into three size classes (>2.54 cm, >1.5 cm, Pan) (Figure 4). Three replicates of each size class, location, and media were used to evaluate propagation.

2.2.2.1 Forage Chopper

In early October post-anthesis stalks were hand harvested, and subsequently fed into a forage chopper (MH 90S, PZ Greenland: 4.5 mm chop size). Using the statistical analysis in section 2.2.2.2.1 a risk of 0.05 and p-value of 0.1 were selected corresponding to thirty replicates of location and media to evaluate propagation. Four whole control stalks and four additional differentiated stalks (panicle, top, middle, bottom) were used to determine location of nodal emergence.

2.2.2.2.1 Statistical Determination of Sample Replicates

A Poisson sampling formula was used, where emerged nodes were considered a function of nodes and represented the probability that a node would sprout. Probability of sprouted nodes from a random sample of n nodes $Pr(x=0 \mid n, p) = 0.01$ or 0.05, with p as the probability that a node would sprout. Sprouting values were used from a differentiated stalk submerged in a water bath (Table 4) and node counts used ten random 125 gram forage chopped samples, with no entire nodes observed but the partial node count recorded (12.9 ± 2.69 node sections) from hand harvested stalks in early September at the anthesis stage.

Table 4: Differentiated Stalk Data Used for Statistical Analysis

	Panicle	**Top**	**Middle**	**Bottom**	**Total**
Height (m)	0.75	1.28	1.25	1.25	4.53
Stalk (g)	22.02	186.53	181.61	253.40	643.56
Leaf & Panicle (g)	152.36	104.44	62.58	36.99	356.37
Total (g)	174.38	290.97	244.19	290.39	999.93
Emergence	0/0 (0%)	6/8 (75%)	5/8 (62.5%)	6/7 (85.7%)	17/23 (73.9%)

2.3 Results

During our giant reed production trials, there were a number of operational issues and potential pathways for spread utilizing traditional hay and forage operations (Table 5). Some of the challenges were tied to the suitability of equipment to handle a crop like giant reed with the common points of wear and collection issues on traditional equipment. Maintenance of equipment post-harvest seemed to be the most critical in addressing the potential to spread giant reed outside production areas.

Table 5: Observed Logistical Operation Obstacles & Pathways for Invasiveness of Giant Reed (observations on 2 harvested hectares each on October 2012 & March 2013)

Operation	Operational Obstacle	Invasiveness Pathway
Mower-Conditioner	Roller Wear	Projectile Stalks
Field Curing	Long Duration	Propagation may Initiate
Tedder	Rake Clogging	Improperly Cleaned Equipment
Round Baler	Bale Chamber Abrasion	Improperly Cleaned Equipment
	Twine Snagging	
	Pickup Clogging	
Big Square Baler	Pre-compression Chamber Clogs	Improperly Cleaned Equipment
	Pickup Clogging	
Forage Chopper	Pickup Clogging	Improperly Cleaned Equipment
		Blown Field Losses
Storage	Poor Bale Thatching	Node Propagation Observed on Bale
	Bale Cover Rupture	Storage/Handling Losses
Transportation		Transportation Losses

2.3.1 Wood Chipper

No emergence was observed for any of the replications in the thirty day trial for stalks harvested in early August, though control samples (whole stalks) showed approximately 80% node emergence within two weeks. During disposal of samples one sprout was observed (greenhouse, terrestrial media, >2.54 cm), but it did not break soil surface due to orientation.

2.3.2 Forage Chopper

There were no sprouts observed within the thirty day trial from any of the replications harvested in early October, with whole stalk controls having approximately 81% emergence (± 7.91%) and differentiated stalks 64% emergence (± 10.10%) (Table 6).

Table 6: Emergence Values for Forage Chopped Control Stalks (Differentiated & Whole)

	Stalk 1	Stalk 2	Stalk 3	Stalk 4	Total
		Differentiated Stalks			
Diameter	7.64 mm	16.14 mm	22.93 mm	23.77 mm	
Bottom	2/2 (100%)	7/7 (100%)	6/6 (100%)	7/8 (87.5%)	22/23 (95.7%)
Middle	8/8 (100%)	5/13 (38.5%)	7/7 (100%)	6/9 (66.7%)	26/37 (70.3%)
Top	0/7 (0%)	6/14 (42.9%)	3/7 (42.9%)	0/3 (0%)	9/31 (29%)
Panicle	NA	0/0 (0%)	0/0 (0%)	0/0 (0%)	0/0 (0%)
Total	10/17 (58.8%)	18/34 (52.9%)	16/20 (80%)	13/20 (65%)	57/91 (62.6%)
		Whole Stalks			
Emergence	23/34 (67.6%)	29/35 (82.9%)	30/34 (88.2%)	17/20 (85%)	99/123 (80.5%)

2.4 Discussion & Conclusions

Many of the logistical challenges that may be influential to invasiveness risk for giant reed can be mitigated using an annual multi-harvest system, harvesting smaller pliable stalks. Since most harvest costs are static, independent of yield, use of a multi-cut harvest system can increase logistical costs significantly. If just-in-time harvest operations are employed multi-cut harvests can assist with temporal biorefinery feedstock requirements, increasing annual harvest equipment utilization.

Equipment obstacles that were observed (Table 5) can be overcome by altering harvest methods or specific equipment modifications, with other bioenergy crops having similar requirements (Womac et al. 2012; Coates & Lorenzen 1990). Observation of actual logistical operations allows for these issues to be observed, in addition to their related consequences.

Best management practices, proposed in Iverson et al. (2011), can decrease the spread of giant reed. As preliminarily observed in this study, forage chopping is an alternative to whole stalk harvest methods that can further reduce invasiveness, utilizing less equipment across the logistical chain and reducing potential for propagation.

There is a major difference in comminution performance between a wood chipper and forage chopper, with respect to the material end product. A wood chipper produces long thin chips, which may disrupt intact nodes, while a forage chopper may increase the potential for production of small intact nodes (when similar blade clearances are utilized). Since both methods displayed no nodal emergence, the results of this analysis may justify the use of a wood chipper for weed management operations and a forage chopper as a harvest method for reducing potential spread of giant reed.

The annual environmental damages and losses related to alien species in the U.S. has been estimated at $120 billion (Pimentel et al. 2005), though the accounting method utilized may have overinflated this value. Using seventy-nine harmful species OTA (1993) estimated a total economic loss of $97 billion in the U.S. over 85 years, with $100 million annually for aquatic weed control (the majority of which were non-indigenous species). Though use of forage chopping as a harvest method may reduce propagation compared with whole stalk harvest operations, the high potential cost of spreading necessitates investigation of other factors, including chop size, seasonality, chemical application, and mechanical conditioning. A larger chop size may increase field efficiency and reduce engine power requirements of harvest machinery, resulting in lower equipment costs, though an increased chop size may also elevate propagation potential. Seasonality of propagation has been investigated in Italy (Ceotto et al. 2010) and California, U.S.A. (Wijte et al. 2005), but it has not been explored for the Southeast U.S., which may impact regional management decisions. Broadcast herbicide effect on giant reed is well documented (Santin-Montanya et al., 2013; Spencer et al., 2008; Odero & Gilbert., 2012) but application of small quantities during harvest operations has not been explored. Elevated mechanical conditioning may disrupt nodes, resulting in reduced propagation, lower field curing duration, and minimize hay operational challenges (Table 3).

Results of this study support use of forage chopping as a harvest method to reduce potential spread of giant reed during biomass logistical operations, in conjunction with other best management practices. Additional research is required to optimize giant reed feedstock production, integrating cost and environmental sustainability related to multiple management strategies (single cut, multi-cut, just-in-time, etc.). It will be crucial to evaluate the entire biomass supply chain and take into account the multiple metrics of interest when evaluating biomass feedstock production alternatives to meet the U.S. EPA's standard of "no significant likelihood of spread beyond the planting area."

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CHAPTER 3: ENSILED STORAGE OF BIOMASS FEEDSTOCKS

3.1. Introduction

Bioenergy production is an important component of the global energy portfolio, related to energy security, rural development, economic growth potential, and global climate change, with its various implications. Use of renewable herbaceous biomass crops for bioenergy production on an industrial scale requires year round feedstock availability for economical operations. Since herbaceous feedstocks, including lignocellulosic biomass, can only be harvested within specified harvest windows some storage period is required. The two primary storage methods for forages are hay and ensilage, with increased losses occurring during harvest with hay and during storage with silage (Muck & Kung 2003). Reduction in losses along the supply chain can increase profitability, since it represents a loss in investment. Both systems have benefits, with hay having the ability to be transported while silage operations can be mechanized (Collins & Owens 2003). Further examination of ensilage for bioenergy feedstocks is required to determine optimal economic conditions, minimize storage losses, and assess it as a means to pre-process biomass for production of biobased chemicals. Evaluation of the entire supply chain, including storage operations, can facilitate optimization of bioenergy production systems.

The two mechanisms for preservation of dry matter during the ensilage process are production of an anaerobic environment and the rapid reduction in pH (Muck & Kung 2003). Traditionally, ensilage is meant to preserve the maximum amount of forage nutrients during storage, yet the process is uncontrolled and can possibly lead to undesired outcomes (Kung

2001). Stoneberg et al. (1968) outlined a number of benefits and drawbacks related to the ensilage process (Table 7).

Table 7: Benefits and Drawbacks of Ensiled Storage

	Benefit	Drawback
Harvest	Extended harvest period	
	Grain/silage transport flexibility	
Storage	Long storage times	Bulky to store/handle
	Mechanization is possible	High equipment costs
		High losses possible
Feed Material	Maximum nutrient yield	Rapid emptying required
	Highly palatable	No readily available markets

Detailed research on the process of storing fresh forage material can be dated back as far as the 1800s (Nature 1885; Wrightson 1883), with continuous innovations over time. Silage categories were defined by moisture content by Noller & Thomas (1985): High Moisture (70% or greater), Wilted (60–70%), Low (40–60%).

The five major factors that affect silage quality, as outlined by Muck & Kung (2003), are: crop, harvest management, silo type, silo management and silage additives. Influential crop characteristics are related to available non-structural carbohydrates, buffering capacity, and moisture content. Kung (2001) provided three practical aspects for attaining good silage: rapid removal of air, rapid reduction in pH by lactic acid, and continued exclusion of oxygen during storage and feedout.

There are multiple designations for the steps in the process of ensilage (Noller & Thomas 1985; Collins & Owens 2003; Lemus 2010; Segler 2003). An aerobic phase occurs at the start of packing when oxygen is still present in the silo allowing continued aerobic respiration of plant cells and microbes, converting soluble sugars into carbon dioxide, water, and energy (Equation 1). This phase ceases when oxygen is exhausted or enzymes are inactivated by the reduction in pH, also when temperatures are reached in excess of 70°C (Henderson 1993). This phase can have excessive losses, which can be mitigated through adequate compaction, proper moisture content, rapid filling, smooth face, and a well-sealed silo (Collins & Owens 2003). Limiting time in this phase from a few hours to less than a day can reduce growth of spoilage microorganisms including yeasts, enterobacteria, and clostridia (Noller & Thomas 1985).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + energy$$

Equation 1: Aerobic Respiration (Henderson 1993) [Energy Loss: 100%]

As oxygen is depleted anaerobic microorganisms begin to proliferate leading to the fermentation phase, which ideally is entirely of homofermentative lactic acid bacterium following the Embden-Meyerhof-Parnas pathway (Equation 2) (McDonald et al. 1991). Heterofermentative bacteria produce a range of products including acetic acid (Equation 3), ethanol (Equation 4), carbon dioxide, and lactic acid (Collins & Owens 2003). Clostridia species can cause secondary fermentation of lactic acid to butyric acid (Equation 5), and enterobacteria can produce a mix of lactic and acetic acids (Collins & Owens 2003). This phase is characterized by a reduction in pH to between three and a half to five inhibiting microbial growth, lasting between seven and thirty days depending on concentrations of non-structural carbohydrates, moisture content, and bacterial concentrations (Collins & Owens 2003). Ammonia can be produced through proteolysis from clostridia species, but will generally halt when pH values drop below 5.5 (Noller & Thomas 1985).

$$C_6H_{12}O_6 \rightarrow 2(C_3H_6O_3)$$

Equation 2: Lactic Acid Fermentation (Noller & Thomas 1985) [Energy Loss: 2.89%]

$$3C_6H_{12}O_6 + 2H_2O \rightarrow 8H_2 + 6CO_2 + 2C_2H_4O_2 + 2C_4H_8O_2$$

$$C_6H_{12}O_6 + H_2O \rightarrow 2H_2 + 2CO_2 + C_2H_4O_2 + C_2H_6O$$

Equation 3: Acetic Acid Fermentation (Karadag & Puhakka 2010) [Energy Loss: 27.3%/19.93%]

$$C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$$

Equation 4: Ethanol Fermentation [Energy Loss: 2.27%]

$$2(C_3H_6O_3) \rightarrow C_4H_8O_2 + 2CO_2 + 2H_2$$

Equation 5: Butryic Acid Fermentation (Noller & Thomas 1985) [Energy Loss: 19.84%]

When pH stabilizes, the silage reaches the stability phase, which can persist for years as long as oxygen is excluded (Noller & Thomas 1985). Even during the stability phase reductions in protein content and changes in fermentation end products are observed over elongated storage times (Kung & Bedrosian 2010). Non-structural carbohydrates are the primary source of fermentative feedstock, though there is some cellulose (Henderson 1993) and hemicellulose (Kung 2001) converted.

Studies related to ensiled storage of bioenergy feedstocks focus primarily on sugar based crops, Sorghum (*Sorghum bicolor* (L.) Moench) [Egg et al. 1993; Meeske et al. 1993; Philipp et al. 2007; Schmidt et al. 1997], Sugar Beet (Beta vulgaris L.) [Zheng et al. 2011; Zheng et al. 2012], and Sugarcane (*Saccharum officinarum* L.) [Agblevor et al. 1994; Kim et al. 2010], and corn (*Zea mays* L.) [Shinners et al. 2011; Thomsen et al. 2008; Chen et al. 2012; Cui et al. 2012; Ren et al. 2007; Sun et al. 2011], more than other dedicated bioenergy feedstocks ([Maize, Rye, Clover Gass] Oleskowicz-Popiel et al. 2011; [Barley Straw, Triticale Straw/Hay, Wheat Straw, Cotton Stalk] Chen et al. 2007; [Switchgrsas, Reed Canarygrass] Digman et al. 2010; [Winter Rye, Rapeseed, Faba Bean] Petersson et al. 2007). Though ensiled storage is commonly a more expensive option than aerobic bale storage (Worley & Cundiff 1995), the potential for preprocessing (alteration of the biomass material to a more useful state) and availability of extractables makes it a promising storage technique for biobased chemical production (Schmidt et al. 1997).

There are several dedicated annual and perennial herbaceous lignocellulosic biomass feedstocks of national interest that can potentially be supplied over longer periods of time with storage through the ensilage process. Gill et al. (2014) showed that sorghums (*Sorghum bicolor* (L.) Moench) were a beneficial summer annual to the Southeast region, and the average yield in North Carolina was relatively high. In addition, three warm season perennial grasses Switchgrass (*Panicum virgatum* L.), Miscanthus (*Miscanthus x* *giganteous*), and Giant Reed (*Arundo donax* L.) were shown by Palmer et al. (2014) to have favorable yields in North Carolina. These biomass resources could potentially support developing renewable feestock use in the Southeast region that warrant further investigation in harvest management strategies. The objective of this work was to determine compositional change of biomass feedstocks during ensiled storage over time using lab scale ensilage bags for sorghum, switchgrass, miscanthus and giant reed.

3.2 Methodology

3.2.1 Physical Characteristics

All biomass feedstocks were harvested at the Williamsdale Biofuels Research Field Laboratory in either October of 2012 or March of 2013 (Wallace, NC 34.7622°N, 78.0995°W) (Table 8). Biomass samples were hand harvested then fed into a pull behind forage chopper (MH 90S, PZ Greenland) to produce uniformly chopped forage samples. A subsample was dried for a fresh initial biomass sample, with a subsample sent to NCDA for forage analysis (NCDA & CS 2014). Chopped samples were analyzed for bulk density using a standard for wood pellets (ASTM E 873-82). Two sets of sweet sorghum samples were produced at harvest to represent variations in management practices. The first sample set consisted of sorghum material stored in a pile overnight after harvest (approx. 24 hours) before ensilage treatment bags were constructed (classified as Pile), with the second sample set consisting of sorghum that was collected immediately after harvest, then stored in ensilage treatment bags (approx. 4 hours) (classified as Immediate).

Table 8: Biomass Feedstocks Used for Ensiled Storage

	Latin	Harvest Time
Sorghum 'M81E'	*Sorghum bicolor* (L.) Moench	Oct (Pile & Immediate)
Miscanthus	*Miscanthus x giganteou*	Oct
Switchgrass 'Alamo'	*Panicum virgatum* L.	Oct & Mar
Giant Reed	*Arundo donax* L.	Oct & Mar

Lab scale silage treatment bags were prepared of chopped material to mimic large scale bagged silos, which were chosen over jar ensiled methods to allow for greater uniform packing density (Johnson et al. 2004). Two hundred and fifty grams of fresh material was placed in a one gallon zip lock freezer bag. Air was evacuated with a standard shop vacuum, with additional air removed by sample compaction. The bag was then tightly wrapped with duct tape to eliminate light infiltration and increase packing density. The sample container was punctured to allow ventilation of volatile gaseous emissions to maintain packing density, then placed in a second plastic bag, vacuum sealed, and wrapped with rubber bands. Four replicates of each feedstock, harvest period, and sample handling methods were produced for four destructive sampling times, with temporal conditions beginning once pH stabilization was achieved (initial, 3 month, 6 month, and 12 month).

Stabilization ensilage bags were prepared in the same manner as the ensilage treatment bags to determine approximately when the ensilage process had stabilized for pH for each material. Eight sets of three replicates were produced for pH stabilization, which were tested biweekly for a month. pH was estimated using a pH meter on a slurry created by placing approximately three dry grams ($\pm$0.1 dry grams, utilizing initial moisture content of fresh biomass) of ensiled material in 100 mL of water for thirty minutes. The samples were considered stabilized when the pH dropped to 4 or when the pH stayed consistent over three sets of stabilization points. Control samples of 250 grams of fresh material of each feedstock and harvest period were maintained in cloth bags stored in rodent proof containers under ambient covered outdoor storage. These controls were tested in triplicate and sampled at the initial and twelve month treatment sampling times.

Ensilage bags were destructively sampled at each of the sampling periods. Any sample that was visually torn or punctured was not used, with additional stabilization samples used as a substitute. After removal of wet material for testing, excess material was placed in a drying oven at 45°C until dry weight stabilized, to determine moisture content. The low temperature was chosen to reduce caramelization of sugars in sweet sorghum samples, and limit loss of volatile fatty acids (Shen et al. 2011).

Dry matter losses were determined by comparing the final dry weight with the fresh biomass. An exception was made for March harvested switchgrass for use of the final biomass moisture content for both the final and initial moisture contents, as opposed to use of both final and fresh moisture contents, respectively. This was done to account for the natural variability in initial feedstock moisture content not captured by the aggregate moisture content of fresh biomass being used across all silage bags.

3.2.2 Volatile Fatty Acid Analysis

As each ensilage bag was destructively sampled, 50 grams of fresh material was removed, mixed with one hundred milliliters of deionized water, blended, and left in a refrigerator overnight. The sample was then passed through cheese cloth and the effluent was frozen for later analysis

A gas chromatograph (GC) was used to determine the following volatile fatty acids present in biomass effluent: Isobutyrate, Butyrate, and Valerate. Samples (1 ml) were centrifuged (21,000 x g, 10 minutes) and acidified using 20% meta-phosphoric acid (200 µl) to prepare for GC analysis. A capillary column (NUKOL 30 m) was used (4 ml/min, 11 psi, temperature program 4º/min from 100ºC to 130ºC) and analytes were measured using a flame ionization detector (FID) with detector and injector temperatures set at 270ºC and 270ºC, respectively.

A high performance liquid chromatograph was used to determine lactate and acetate concentrations in the effluent. Well mixed, thawed samples (2 ml) were centrifuged (20.8 x g, 10 min), then transferred to sample vials (1 ml) using filtered syringes with 0.2 µm nylon filters (Whatman 6768-1302) to remove additional particulates. The separation was performed with a Phenomenex Rezex ROA column (300 nm x 7.8 mm) at 50°C, with 0.8 ml/min 5mM sulfuric acid as the eluent, and analytes were quantified by refractive index detection (RID).

3.2.3 Detergent Fiber Analysis

Dried samples were ground in a Wiley knife mill (Thomas Scientific, Swedesboro, NJ) until material passed through a one millimeter screen. Dry matter was determined in duplicate with one gram of ground sample in a 105°C drying oven. - These samples were then used for ash determination in a 600°C muffle furnace until weight stabilized (~8 hours).

An ANKOM$^{200/220}$ fiber analyzer (Ankom Corp., Fairpark, NY) was used for detergent fiber analysis (Drewnoski & Poore 2012), modified from the assays developed by

Van Soest et al. (1991). Though this procedure was constructed to assess animal feed characteristics (Coblentz 2009; Hunhke 1990; Shinners et al. 2009) they have also been used to assess bioenergy feedstocks (Khanchi et al. 2009; Khanchi et al. 2010; Shinners et al. 2010; Shah et al. 2011). This method does relatively well for cellulose content but may overestimate hemicellulose values (Wiselogel et al. 1995). Samples were run in duplicate, half a gram per fiber bag, with sequential detergent extraction to determine structural carbohydrates (Figure 5). Alpha amylase was incorporated into Neutral Detergent Fiber (NDF) digestions to breakdown starch in the samples. Cellulose content was determined in an ANKOM DAISY (Ankom Corp., Fairpark, NY) with 72% sulfuric acid. After washes, samples were placed in acetone and blotted to increase drying, prior to drying in a forced air oven at 105°C. Lignin was determined by combustion in a muffle furnace at 600°C. Each set of samples were run with blanks and standards run in duplicate to incorporate a blank correction factor and to ensure that the digestions fell within the allowable range.

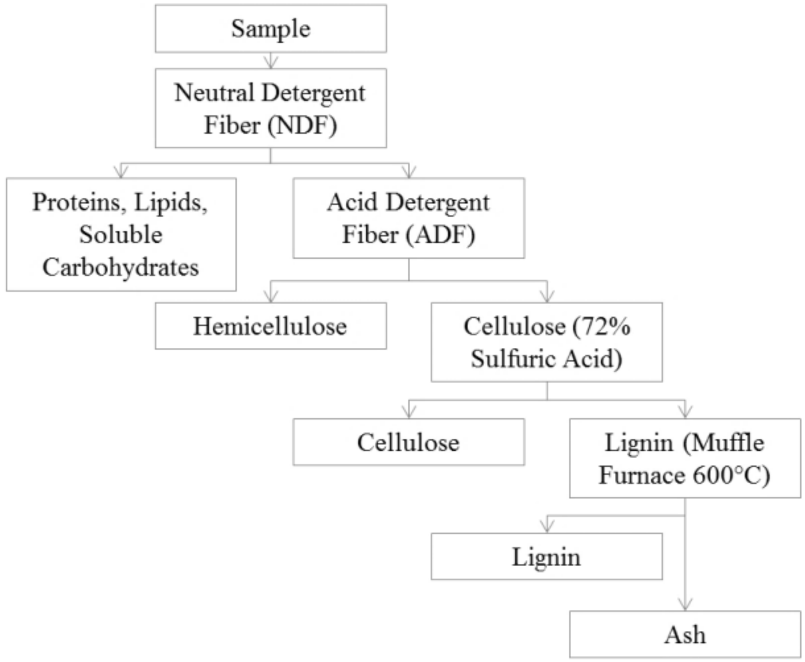


Figure 5: Detergent Fiber Analysis in Series

3.2.4 Statistical Analysis

The SAS environment was employed to determine statistical significance of parameters, using a significance level of $\alpha=0.05$. A set of generalized linear mixed models were employed using a normal distribution to determine least square means for determination of significance. Fixed factors of time (sample time), harvest/management (pile, immediate, harvest period), and species were used to evaluate the significance of proportional composition differences and dry matter loss. Pair-wise comparisons of the logarithmic differences in least means squares of dry matter loss were determined between each species and harvest/management treatment combinations.

3.3 Results & Discussion

3.3.1 Physical Characteristics

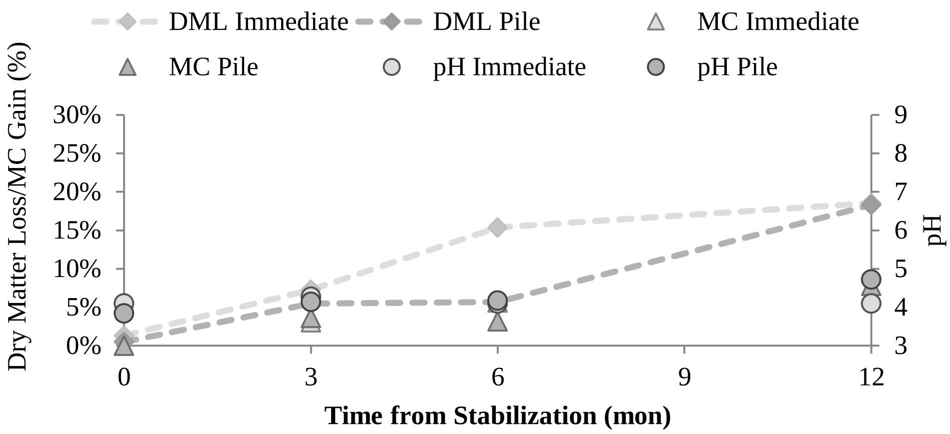
There was a distinctive difference in fresh biomass composition between management practices of harvested sweet sorghum (pile, immediate), and for harvest period in fresh perennial grasses (Table 9). The high soluble carbohydrate concentrations of sorghums (Table 9) support rapid microbial growth, resulting in either rapid stability of ensiled biomass or considerable reduction of soluble sugars when piled. The stability of sorghum is highly sensitive to microbial contamination, where a 50% drop in postharvest sugar content has been observed within four to six days (Eiland et al. 1983), with some additives demonstrating stabilization of sugar content during storage (Schmidt et al. 1997). Observed compositional differences in soluble carbohydrates, ash, and crude protein for these materials can have an effect on appropriate conversion technology utilized, logistical operations, and process operations at the biorefinery. Fresh moisture content and bulk density can also affect storage, transportation and handling operations of chopped biomass. Differences in moisture content between harvest period for switchgrass and soluble carbohydrates between management method for sweet sorghums may influence the ensilage process.

Table 9: Fresh Biomass Analysis (dry basis) (Analysis conducted by NCDA&CS forage laboratory)

	Sweet Sorghum		Switchgrass		Giant Reed		Miscanthus
Harvest	*Oct*	*Oct*	*Oct*	*Mar*	*Oct*	*Mar*	*Oct*
Management	*Pile*	*Immediate*					
Moisture Content (wet basis)	72.63%	72.02%	50.34%	10.90%	62.86%	52.05%	43.97%
Fresh BD (kg/m^3)		350.80	156.98	124.94	225.06	200.23	139.36
Extractives	35.60%	45.63%	18.51%	12.27%	30.36%	24.06%	19.36%
Crude Protein	5.85%	7.06%	4.47%	4.31%	10.78%	6.79%	5.24%
Soluble Carbohydrates	27.67%	36.93%	13.02%	7.32%	18.09%	16.47%	13.14%
Lipids	2.09%	1.64%	1.02%	0.63%	1.49%	0.79%	0.99%
Hemicellulose	17.52%	20.67%	25.64%	27.88%	23.19%	22.34%	23.64%
Cellulose & Lignin (by difference)	40.62%	28.00%	50.78%	57.09%	37.68%	47.09%	51.75%
Ash	4.02%	3.65%	3.47%	2.03%	5.82%	4.75%	3.64%
Minerals	2.24%	2.05%	1.60%	0.73%	2.95%	1.76%	1.61%
Calcium	0.18%	0.24%	0.26%	0.24%	0.41%	0.17%	0.31%
Phosphorus	0.17%	0.18%	0.13%	0.08%	0.12%	0.12%	0.14%
Sulfur	0.09%	0.10%	0.09%	0.07%	0.48%	0.21%	0.09%
Magnesium	0.20%	0.24%	0.16%	0.12%	0.19%	0.08%	0.15%
Sodium	0.00%	0.00%	0.01%	0.00%	0.01%	0.01%	0.00%
Potassium	1.59%	1.27%	0.93%	0.19%	1.72%	1.14%	0.89%
Copper	4 ppm	3 ppm	4 ppm	4 ppm	3 ppm	3 ppm	3 ppm
Iron	52 ppm	160 ppm	97 ppm	239 ppm	104 ppm	258 ppm	204 ppm
Manganese	30 ppm	24 ppm	52 ppm	56 ppm	9 ppm	11 ppm	77 ppm
Zinc	23 ppm	33 ppm	22 ppm	44 ppm	34 ppm	14 ppm	22 ppm

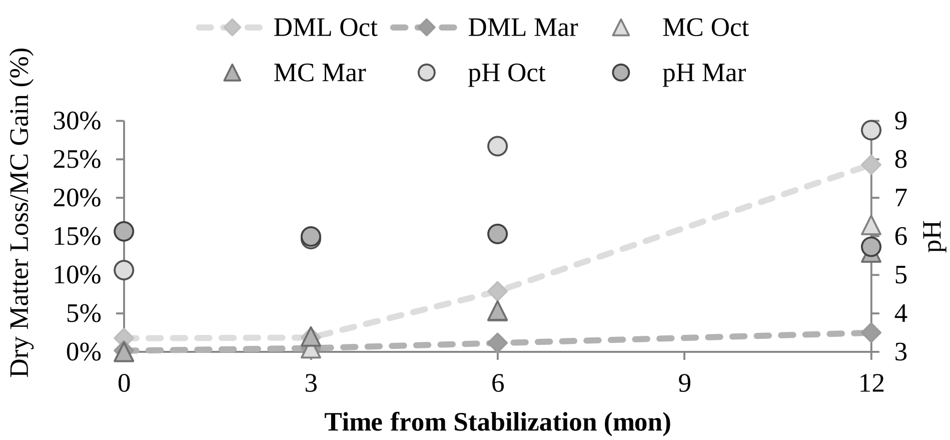
Moisture content increased over time in the ensilage treatment bags (Figure 6), which may be associated with respiration of easily accessible carbohydrates. Dry matter losses were found to increase over time as well (Figure 6), with perennial grasses low in soluble sugars and high in moisture content (Table 9) having the greatest losses over time. These dry matter changes were most likely associated with anaerobic respiration of spoilage microbes, but may also be associated with loss of volatile fatty acids during drying for determination of sample moisture content.

Figure 6: Physical Characteristics and Volatile Fatty Acids of Ensiled Biomass over Time [A. Sweet Sorghum (*Sorghum bicolor* (L.) Moench: Pile & Immediate Management), B. Switchgrass (*Panicum virgatum* L.: October & March Harvests), C. Giant Reed (*Arundo donax* L.: October & March Harvests), D. Miscanthus (*Miscanthus x giganteous*: October Harvest)] (Variables: Moisture Content (MC), Dry Matter Loss (DML), pH)



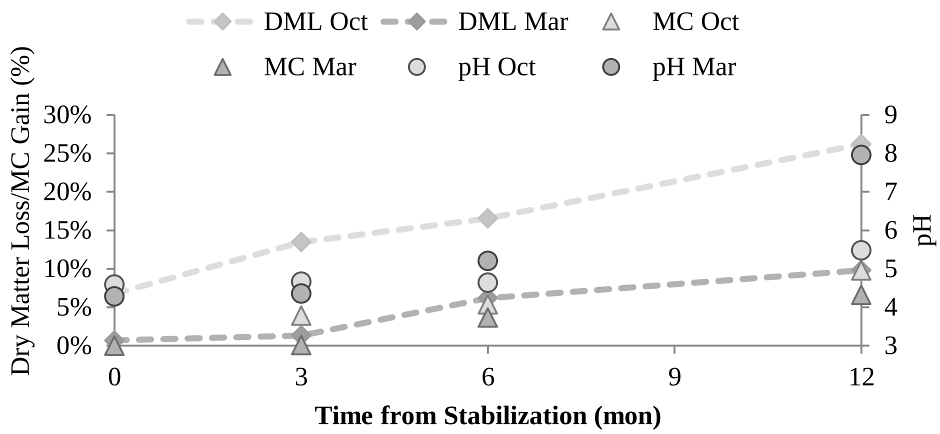
	Fresh (mg/ml)	Initial (mg/ml)	6 month (mg/ml)	12 month (mg/ml)
Lactate	1.89/**0.78**	1.39/**1.03**	1.28/**1.35**	1.41/**0.33**
Acetate	1.02/**0.76**	0.78/**0.92**	0.90/**0.55**	0.73/**0.71**
Iso-Butyrate	0/**0**	0/**0**	0/**0**	0/**0**
Butyrate	0/**0**	0/**0**	0/**0**	0.19/**0.17**
Valerate	0/**0**	0.02/**0**	0/**0**	0/**0**

A. Sweet Sorghum (Sorghum bicolor (L.) Moench*)* [Immediate/**Pile**]



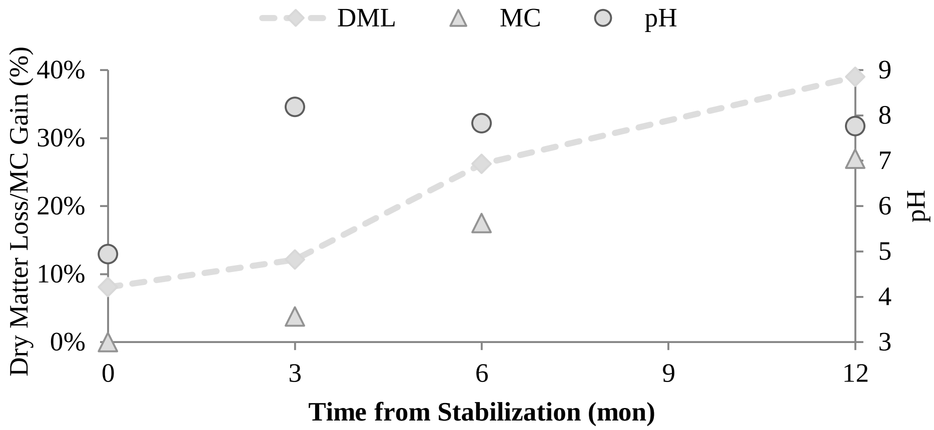
	Fresh (mg/ml)	Initial (mg/ml)	6 month (mg/ml)	12 month (mg/ml)
Lactate	0.13/**0**	0.16/**0**	0.04/**0**	0/**0**
Acetate	0.17/**0**	0.57/**0**	0.13/**0**	0/**0**
Iso-Butyrate	0/**0**	0/**0**	0/**0**	0/**0**
Butyrate	0/**0**	0/**0**	0/**0**	0/**0**
Valerate	0/**0**	0/**0**	0/**0**	0/**0**

B. Switchgrass (Panicum virgatum L.*)* [October/**March**]



	Fresh (mg/ml)	Initial (mg/ml)	6 month (mg/ml)	12 month (mg/ml)
Lactate	0.75/**0**	1.10/**1.63**	0.45/**0.43**	0/**0.33**
Acetate	0.43/**0**	1.21/**0.74**	1.86/**0.18**	0/**0.08**
Iso-Butyrate	0/**0**	0/**0**	0.02/**0**	0.01/**0**
Butyrate	0/**0**	0/**0**	0/**0**	0/**0**
Valerate	0/**0**	0/**0**	0/**0**	0/**0**

C. Giant Reed (Arundo donax L.*)* [October/**March**]



	Fresh (mg/ml)	Initial (mg/ml)	6 month (mg/ml)	12 month (mg/ml)
Lactate	0	0.43	0	0
Acetate	0.14	0.67	0	0
Iso-Butyrate	0	0	0	0
Butyrate	0	0	0	0
Valerate	0	0	0	0

D. Miscanthus (Miscanthus x giganteous) [October]

Dry matter loss (from fresh biomass) of sweet sorghum was relatively similar between the Immediate and Pile storage management strategies, with the exception of six months (Figure 6A) where the piled sorghum materials seemed to maintain a more stable ensiled condition. Gains in moisture content and changes in pH were similar at all time steps between the management strategies, and followed the trend of dry matter loss, especially the material from the Piled management strategy.(Figure 6A). Volatile fatty acid concentrations were higher in Immediate storage management treatments than Piled storage treatments, except at initial stabilization for acetate and six months for lactate (Figure 6A). This suggests that carbohydrates were available in sweet sorghum regardless of storage management strategy for proper ensilage, though the volatile fatty acid profiles may differ.

There was a major difference in dry matter loss between the October and March harvested switchgrass, with moisture content gains staying relatively similar (Figure 6B). October harvested switchgrass had greater pH values at six and twelve months, which may indicate the growth of spoilage microbes causing the increase in dry matter loss (Figure 6B). Detectable levels of volatile fatty acids were only found in the October harvested switchgrass, most likely due to the translocation and leaching of extractives during winter months minimizing availability of soluble energy sources and microbial activity in March harvested grasses (Figure 6B). These results suggest that greater losses may be observed over long periods of storage for October harvested switchgrass.

The rate of dry matter loss observed in giant reed treatments for the October and March harvest periods stayed relatively constant over time, with the October harvest showing greater losses (Figure 6C). Moisture content gains were relatively similar between the two harvests until twelve months, and pH also followed similar trends (Figure 6C). Volatile fatty acid concentrations fluctuated over time for both harvest periods for giant reed, suggesting that these may be metabolized, though few secondary fermentation products were detected (Figure 6C). The increase in dry matter loss for both harvest periods suggests that regardless of time of harvest giant reed will likely show increased losses over time.

Miscanthus showed elevated dry matter losses over time up to 40%, with pH following a similar trend, though moisture content gain showed some variation (Figure 6D). Volatile fatty acids were not detected after stabilization (Figure 6D), which may mean that extractives were metabolized through respiration or some other metabolic pathway.

The main effects of harvest, species, and time were found to be highly significant, with a p-value <0.0001 for dry matter loss. All species and harvest/management conditions appeared to fit a linear relationship of dry matter loss over time with an R^2 greater than 0.89 (Figure 6), though it would be reasonable to expect that with more time data points a logarithmic relationship could be observed. It can be assumed that dry matter losses after stabilization associated with spoilage microbes would follow a relationship similar to a growth curve, with an extended lag period due to the low pH values (Figure 6). Early competition for soluble carbohydrates and low populations may have limited proliferation of spoilage microbes prior to stabilization, resulting in this observed lag in the dry matter losses.

Though it could be inferred that a low pH anaerobic environment would be a good indicator of low dry matter loss, March harvested switchgrass low in moisture content and soluble carbohydrates (Table 9) showed elevated pH values and low dry matter loss (Figure 6B). This phenomenon was most likely related to the lack of easily accessible carbon for microbial proliferation, with the closed silage bag conditions ensuring the continuation of this preservation state. Log values of dry matter losses from each species were statistically compared for each sampling time (Table 10). For each sampling time dry matter loss from the March harvested giant reed and switchgrass were found to be significantly different, as was Miscanthus and sweet sorghum in October (Table 10). These differences may be related to the initial differences in fresh feedstock composition (Table 9) that directed the ensilage process, however the magnitude of these variations decreased over storage time.

Table 10: Comparison of Least Square Means of Absolute Log Dry Matter Losses of Ensiled Biomass Species over Time (positive value indicates that species 1 was greater than species 2)

Harvest	Species 1	Species 2	Initial	3 month	6 month	12 month
Oct	Giant Reed	Switchgrass	1.3611**	2.0989**	0.7834+	0.04823*
		Sweet Sorghum	2.5278**	0.8215*	0.5847+	0.4280+
		Miscanthus	-0.1911+	0.1325+	-0.4114+	-0.3962+
	Miscanthus	Sweet Sorghum	2.7189**	0.6889+	0.9960**	0.8241*
		Switchgrass	1.5522**	1.9664**	1.1948**	0.4444+
	Sweet Sorghum	Switchgrass	-1.1667**	1.2775**	0.1988+	-0.3798+
Mar	Giant Reed	Switchgrass	2.0312**	0.9869*	1.6832**	1.4538**

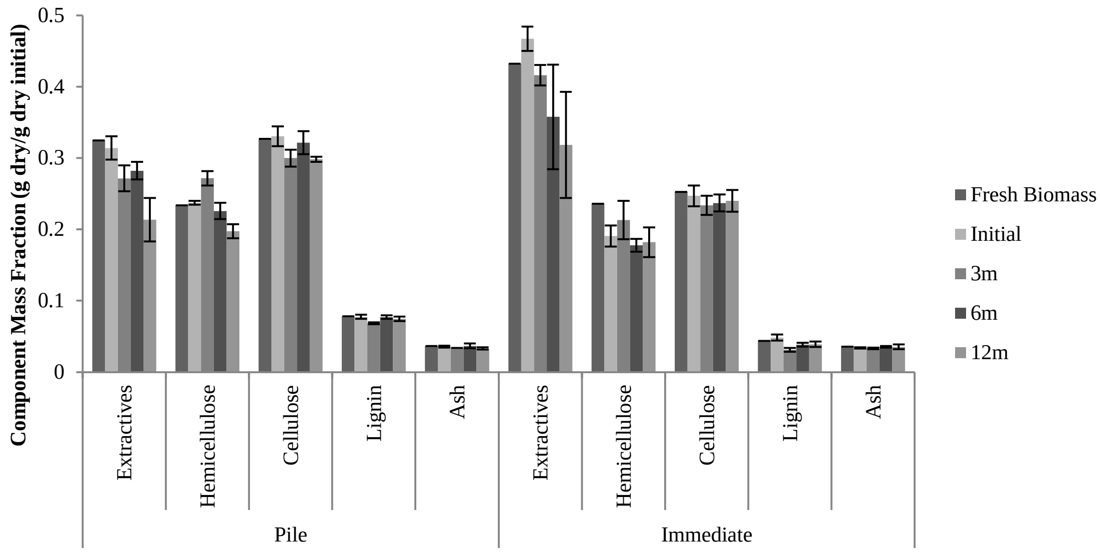
*+: p-value>0.05, *: p-value<0.05, **: p-value<0.01*

Trends in dry matter loss (Figure 6) were found to be similar to previously ensiled feedstocks (Collins & Owens 2003), as it related to fresh biomass composition (Table 9). The uncontrolled fermentation reactions occurring in nature can be complex and integrated, making it difficult to determine specific interactions during the ensilage process. Initial composition of biomass feedstocks (Table 9) had an effect on the ensilage process, as related to pH at time of stabilization (Figure 6). Increases in moisture content (Figure 6) can be associated with the respiration process (Equation 1) during metabolism of free sugars. The increased moisture content in combination with dry matter losses observed may also be associated with the loss of volatile fatty acids during the drying process, which can be misrepresented as water using gravimetric procedures. Some of the fermentation processes that occur during ensilage may require some of the water, such as acetic acid production (Equation 3), producing gases and volatile acids that can contribute to loss values measured. Both pH and moisture content are often assumed to be indicators of dry matter loss in ensiled biomass feedstocks (Figure 6), yet only moisture content followed a similar trend to the dry matter data collected (Figure 6).

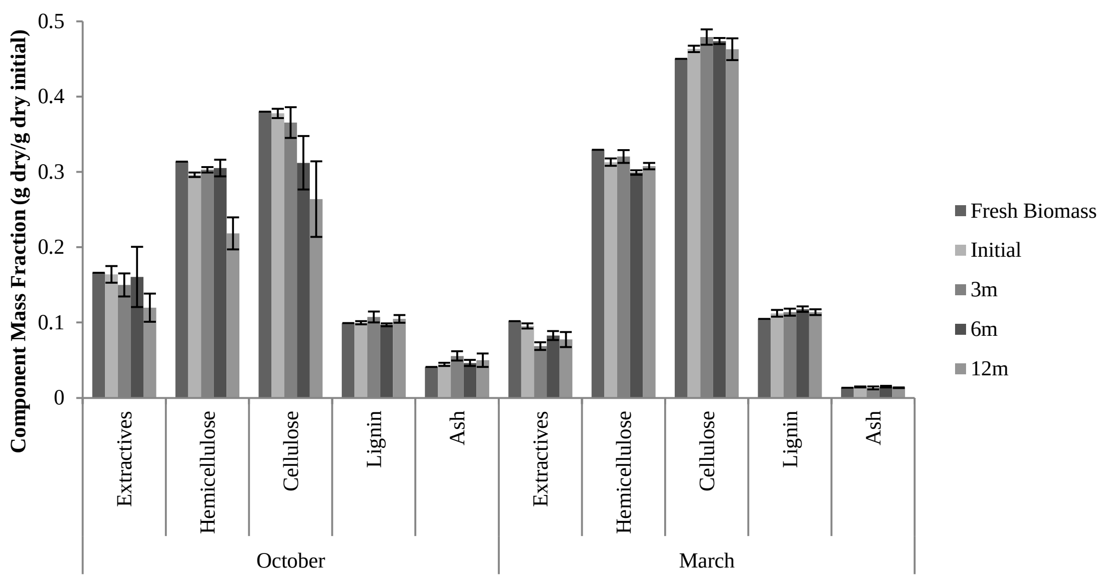
3.3.2 Detergent Fiber Analysis

A decline in extractives from fresh biomass composition was observed for all biomass feedstocks during ensiled storage, except switchgrass harvested in March which remained relatively stable (Figure 7). This was expected since native microbes will metabolize soluble sugars, proteins, and lipids more readily than structural carbohydrates. The low initial soluble carbohydrate concentration (Table 9) combined with the low moisture content of switchgrass during the March harvest excluded this source of readily available carbon for microorganisms, leading to a relatively stable feedstock in the silage treatment bags over time.

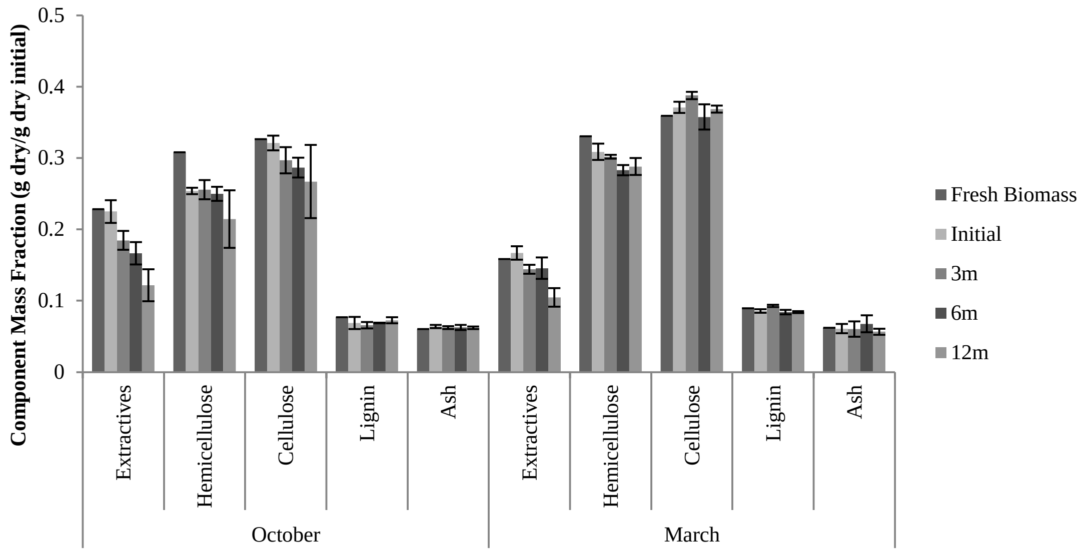
Figure 7: Absolute Change in Composition of Ensiled Biomass Treatments over Time [A. Sweet Sorghum, B. Switchgrass, C. Giant Reed, D. Miscanthus] (error bars represent one standard deviation) (extractives represents the NDF soluble fraction)



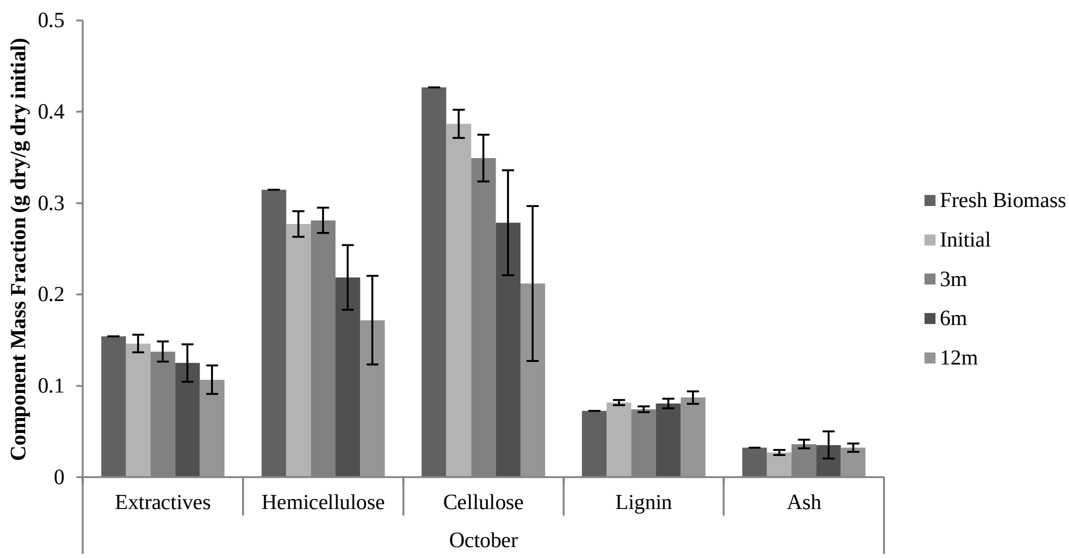
A. Sweet Sorghum, October Harvest (Pile & Immediate Management)



B. Switchgrass (October & March Harvests)



C. Giant Reed (October & March Harvests)



D. Miscanthus (October Harvest)

The proportion of ash and lignin was significantly affected by time for October harvests (Table 11), but when dry matter loss was taken into account they appear to be stable (**Error! Reference source not found.**), since ash consists of mineral components and lignin hich is a difficult complex of structural carbohydrates to metabolize (Appendix A lists the pairwise comparison of least means of the different smalls cale silage compositional changes over time). Miscanthus showed that time was a significant factor on the changes in all compositional proportions tested (Table 11), which is demonstrated by the absolute changes in composition shown in Figure 7D. October harvested perennial grasses displayed reductions in absolute cellulose over time (Figure 7B), with March harvested perennial grasses showing stability in cellulose (Figure 7B; Figure 7C) which may be attributed to the low initial extractives content in the March ensiled biomass (Table 9). Sweet sorghum showed stable cellulose content throughout the sampling period for both treatment conditions (Figure 7A), mostly a result of the effectiveness of the ensilage process creating a low stabilization pH (Figure 7) with early microbial activity on the initial high extractive content available (Figure 7A). October harvested perennial grasses showed increased variability in cellulose content during the storage period (Figure 7), which can be attributed to different primary and secondary fermentation pathways in each of the silage bags. This is also supported by the increases observed in moisture content and pH for these silage treatment bags (Figure 7). All perennial grasses, with October harvested species to a greater extent, showed reduction in hemicellulose over time (Figure 7). Similar to cellulose content reduction, loss of hemicellulose can be tied to the proliferations of spoilage microbes, of which increases in pH (Figure 7) and moisture content gains are inherent (Figure 7).

Table 11: Significant Change (p-value≤0.05) in Proportional Composition of Biomass from Stabilization to 12 Months of Storage [+: positive proportional difference, -: negative proportional difference]

		Extractives	Hemicellulose	Cellulose	Lignin	Ash
Oct	Switchgrass		+	+	-	-
	Giant Reed			+	-	-
	Miscanthus	-	+	+	-	-
	Sweet Sorghum (Immediate)		+			-
	Sweet Sorghum (Pile)		+		-	-
Mar	Switchgrass		+			
	Giant Reed					-

Primarily extractives showed the greatest absolute reduction over time in treatments, and some treatments displayed losses in hemicellulose and cellulose content (Figure 7). Ash and lignin remained constant over time for all treatments (Figure 7), which is consistent with ashes inability and lignin's difficulty to be metabolized. Lower moisture content material harvested in March showed little reduction in structural carbohydrates (Figure 7), and was related to the overall low dry matter losses observed during the storage period (Figure 7).

Ensiled sweet sorghum samples showed low dry matter losses (Figure 7), consistent pH values (Figure 7), and consistent levels of structural carbohydrates over time (Figure 7A). This relatively stable stored biomass condition can be linked to the soluble carbohydrate and moisture content levels being adequate for effective silage production in the sweet sorghum (Muck & Kung 2003). The high initial soluble carbohydrate levels (Table 9) provided ample carbon sources for microbial growth and acid production during the stability phase for both the pile and immediate management treatments. With the high throughput of large forage choppers some intermediate storage method may be required (such as piled management), resulting in deceases in soluble carbohydrates (Table 9) and depending on the length of intermediate storage time, and crop cultivar and maturity could potentially affect the quality of the ensilage process. Though soluble carbohydrate values were reduced in this study with the piled management sorghum treatments, the concentrations seemed to still be sufficient to ensure rapid ensilage and stabilized storage. Management methods of ensiled sweet sorghum was found to significantly affect dry matter loss (p-value < 0.0001), which may be associated with microbial proliferation during pile storage and loss of soluble carbohydrates and other extractives (Table 9).

Switchgrass harvested in March showed the lowest dry matter losses (Figure 7), as related to the very low moisture content and extractives present in the fresh biomass (Table 9). Ensilage reduces dry matter loss by rapidly creating a low pH anaerobic environment that inhibits many spoilage microbes. If the initial feedstock was already in a condition that would reduce microbial growth, which requires water and available sugars, storage in treatment bags simply reduced infiltration of water. Though giant reed harvested in March showed slightly higher dry matter losses than switchgrass (Figure 7). Besides a slight drop in hemicellulose, the structural carbohydrates stayed consistent over time as desired for giant reed (Figure 7C). This additional loss observed in giant reed was most likely related to the higher moisture content of the feedstock (Table 9). This suggests that late season harvests of giant reed can demonstrate lower moisture and soluble carbohydrate concentrations (Table 9) for rapid ensilage, but higher than required for dry material storage, similar to March harvested switchgrass. Depending on the year, it is difficult to get giant reed much lower than 50% moisture content at the point of harvest while standing in North Carolina. In addition, mowing of the crop can contribute to nutrients leaching out during field curing, especially after a rainfall event, and subsequent chopping with a pickup head can increase ash content.

All perennial grasses harvested in October demonstrated similar patterns of losses in hemicellulose and cellulose (Figure 7), which were slightly lower than optimal in moisture content and soluble carbohydrates for silage production (Muck & Kung 2003). Miscanthus demonstrated the highest loss in structural carbohydrates (Figure 7D), but had similar fresh biomass extractives at time of harvest to switchgrass in October (Table 9), suggesting that there were species specific characteristics that affected ensilage quality regardless of extractives.

Average values and coefficients of variation of structural carbohydrates, ash, extractives, and dry matter loss between treatment bags are shown in Appendix A (Appendix A 5 to Appendix A 11). An additional study examining perennial grasses harvested in the summer (a less mature crop) and ensiled had similar structural carbohydrate characteristics as crops presented here harvested in March (Appendix A 12), meaning that regardless of harvest strategy the ensilage characteristics of grasses is similar.

The high storage and production costs of silage operations make it a less attractive option for biomass feedstock storage operations, unless some value added products or processing can be achieved during storage. Corn silage production costs in North Carolina were estimated at approximately $120 per dry tonne by Benson & Green (2013), which is much higher than the production cost estimates for biomass feedstocks on a dry ton basis (Caffrey et al. 2014). To include value added chemical production or pre-processing steps, completing those operation(s) during storage may help to reduce this overall cost. Extraction of value added extractives during the steam explosion pre-treatment step of lignocellulosic ethanol production is possible, though subsequent extractions and purification are required.

Use of produced organic acids is also possible in methane production systems during water treatment operations of the facility. Forcing the fermentation process towards either beneficial chemical production or enhanced degradation of structural carbohydrates may require addition of additives to fresh biomass prior to storage, which is a normal operation of some silage operations today (Collins & Owens 2003).

A major issue with inclusion of ensiled storage into a biomass logistics system is the high moisture content and increased requirements for handling of loose material. Every time a piece of equipment is required for operations total costs of the supply system increase. Having to move the material from the field, pack it into storage structures, then unload it prior to transportation increases time, equipment usage, and space requirements. Added benefits of silage storage would need to alleviate these additional costs, such as the high ethanol production capacity of ensiled biomass feedstocks demonstrated in Oleskowicz-Popiel et al. (2011).

3.4 Conclusion

Ensiled storage of biomass feedstocks have been shown to perform similar to commonly ensiled forages, with similar compositional components affecting the process. Biomass feedstocks high in moisture content and soluble carbohydrates, sweet sorghums, and subsequently those low in moisture content and soluble carbohydrates, March harvested perennials, displayed the lowest dry matter loss during storage. Both of these are related to reduction in proliferation of spoilage microbes by limiting conditions suitable for metabolism of carbohydrates. Use of a silage storage system may be cost prohibitive for biomass feedstocks in the short term, but as systems are developed to produce high value co-products and use the silage fermentation process as a vessel for pre-processing of lignocellulosic materials competitiveness may increase.

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CHAPTER 4: BALED STORAGE OF BIOMASS FEEDSTOCKS IN NORTH CAROLINA

4.1 Introduction

There has been increased interest in use of herbaceous feedstocks for use in bioenergy production globally. With the requirement of year round operations of a biorefinery for economic production and limited harvest periods for feedstock collection some form and duration of storage is necessary. There are two primary forms of storage for forages that are commonly practiced today, bales and silage. In the baling methods, dry matter losses are typically higher at the point of harvest, while dry matter losses in silage tend to occur more during the actual storage period (Muck & Kung 2003).

Maintaining a uniform quality feedstock at a minimum cost is imperative for the growth of an emerging biobased economy (U.S. DOE 2009). Proposed feedstock supply systems mimic existing industrial operations (i.e. pulp & paper, grain, and forages), however modifications are required related to the high tonnage, quality characteristics, and low market value of biomass feedstocks. Other proposed systems include some form of preprocessing prior to delivery to a biorefinery (U.S. DOE 2009; U.S. DOE 2010). Storage can have a significant impact on biomass feedstock cost, quality, transportation requirements, scheduling of use, and various other factors (environmental impacts, conversion system, process design, etc.) that may affect bioenergy production systems. Reduction in biomass losses during storage can reduce total logistical costs (Mooney et al. 2012), and biomass feedstock production requirements, representing a major capital investment. The storage format adopted can have significant environmental impacts when operated on an industrial scale (Emery & Moiser 2012).

There are three categories of bales used in the animal feed industry: square, round, and big square. Square bales are formed so that a single adult can handle them manually, and are commonly stacked indoors for storage. Round bale technology was developed to allow water to be shed from hay during outdoor storage, and requires a bale spear or similarly specialized handling equipment. Use of the round baler has become the dominant form of hay production in North America (Rotz & Shinners 2003) due to reduced labor requirements (Collins & Owens 2003), lower production costs (Renoll et al. 1976), and ability for outdoor storage. Round balers can be split into two categories based on baling chamber: variable and fixed. A variable chamber creates a uniform compression of bales while fixed chambers will not start compression until the material has filled the chamber, thus creating a loose core and compressed outer layer (Cavalshini 1999). Big square balers have a higher field capacity than round balers (Lazarus 2014), producing a large bale that can reduce handling requirements and cube out transported loads.

The most common proposed types of baling operations for bioenergy feedstocks are round and big square, with the cost of baling increasing with yield for round bales and decreasing with yield for big square (4.5 to 18 dry Mg/ha, Round: $17 to $19.15/dry Mg, Square: $13.40 to $11.95/dry Mg) (Cundiff & March 1995). This is related to windrow size and characteristics of round balers creating lower density bales at greater yields, thus increasing costs (Cundiff & Marsh 1995). Additionally round balers need to stop to tie and discharge each bale while big square balers can tie bales as the pre-compression chamber is refilled. Regardless if storage is included Cundiff & March (1995) found that big square bales were 35% greater in cost than round at a 9 dry Mg/ha yield (Round: $19.91/dry Mg, Square: $26.80/dry Mg) .

Storage of bales depends on characteristics such as feedstock type, evaluation of total feedstock supply chain costs, quality constraints, storage duration, and availability of infrastructure and space. The shape of round bales allows for outdoor storage while square bales require covering of some type (Cundiff & Grisso 2008). For short term systems storage on pallets under a tarp can reduce dry matter loss, but any substantial amount of time may require some form of shelter (Mooney et al. 2012). Multiple types of wraps, storage surfaces, and coverage materials for round bales will affect storage cost and quality (Table 12). The primary focus of these storage configurations is the reduction of dry matter loss.

Table 12: Round Bale Storage Configurations

Coverage[1,2]	Wrap Material[1]	Storage Surface[2]
Shelter	Sisal Twine	Ground
None	Plastic Twine	Crushed Rock
Wrapped/Tube	Net Wrap	Pallets
Tarp	Breathable Film	
	Plastic Film	

[1](Shinners et al. 2010)
[2](Holmes 2004)

Moisture content at baling can have a significant effect on storage so for proper biomass production; a maximum of fifteen percent wet basis moisture content is recommended (Collins et al. 1997). Usually the more expensive storage techniques will yield a lower dry matter loss, though other characteristics need to be considered, such as value of the biomass material and how compositional changes during storage will affect conversion.

Both round and big square bale formats would need to be processed similarly prior to entry into the biorefinery throat, with bales being reduced to a uniform particle size after twine or wrap is removed. Compositional uniformity is an important factor for biorefinery operations, so weathered portions of outdoor stored bales may cause issues. It is possible to differentiate the highly weathered outer layer and base of round bales by unrolling the outer layer before entering the refinery (Shinners et al. 2010), however this may prove difficult to accomplish while a bale is intact. Big square bales are generally under some sort of structure or indoors, at a higher storage cost (Mooney et al. 2012), so the amount of weathered portions should be minimized.

Potential bioenergy feedstocks are commonly high yielding crops, which can affect baling operations by increasing windrow size and density, while creating challenges in handling with conventional equipment. Larger yields have been observed to cause interruptions in windrow pickup during baling (Freeland & Bledsoe 1988; Mislevy & Fluck 1992). Womac et al. (2012) designed a specialized pickup head that removed interruptions with high yielding switchgrass. Grisso et al. (2009) explained that tractor speed needs to be synchronized with windrow pickup, which requires experience for new operators in high yielding biomass feedstock production. Baling efficiency is directly related to windrow size and allowable forward speed, making yield a major issue in round baling operations (Srivastava et al. 2006). Other issues related to baling operations of bioenergy feedstocks may be entanglement of windrows (Womac et al. 2010; Coates & Lorenzen 1990), coarse stubble rupturing tires (Garland 2008), fines accumulation in extremely dry late season harvests (Womac et al. 2010; Buchs 2010), long coarse material snagging twine (Coates & Lorenzen 1990), and issues with formation of the bale core (Chapter 2).

Perennial grasses are similar to some woody crops in that they need to be planted once in a multiple year window, though herbaceous crops can be harvested annually. Garland (2008) explains that multiple harvests a year are possible for perennial grasses, but generally show similar yields to a single harvest system. These provide the opportunity for just in time harvest systems reducing the need for storage to periods outside the available harvest window for the grass. More commonly a single cut system has been proposed harvesting material after a killing frost to allow dry down and recycling of nutrients to soil (Garten et al. 2010). An additional added benefit of a late season harvest reported by Gorlitsky (2012) is the reduction of weeds that may alter the uniformity of biomass feedstocks. To provide year round feedstocks to a biorefinery requires complex harvest, transportation, and storage operations to be optimized (Judd et al. 2012). Research has been conducted on some species of biomass feedstocks (Table 13), but regional characteristics and management strategies can have a major effect (Huhnke 1993; Huhnke 1990). Three perennial grasses of interest in the Southeastern US are Switchgrass (*Panicum virgatum* L.), Miscanthus (*Miscanthus x giganteous*), and Giant Reed (*Arundo donax* L.).

Table 13: Dry Matter Losses of Uncovered Twine Wrapped Round Bales of Different Biomass Crops

Common Name	Scientific Name	Dry Matter Loss	Storage (mon)	Source
Reed Canarygrass	*Phalaris arundinacea* L.	14.9%	11.13 (334 days)	(Shinners et al., 2010)
Reed Canarygrass	*Phalaris arundinacea* L.	14.5%	9.77 (293 days)	(Shinners et al., 2010)
Switchgrass	*Panicum virgatum* L.	15.4%	9.77 (293 days)	(Shinners et al., 2010)
Switchgrass	*Panicum virgatum* L.	17.34%	6	(Khanach et al., 2010)
Switchgrass	*Panicum virgatum* L.	13%	12	(Sanderson et al., 1997)
Alfalfa	*Medicago sativa* L.	16.3%	4.77 (149 days)	(Shinners et al., 2009)
Alfalfa	*Medicago sativa* L.	22.9%	11.87 (356 days)	(Shinners et al., 2009)
Alfalfa	*Medicago sativa* L.	5.8%	7	(Huhnke, 1993)
Bermudagrass	*Cynodon dactylon* (L.) Pers.	12%	8	(Huhnke, 1990)
Sweet Sorghum	*Sorghum bicolor* (L.) Moench	8.2%	6	(Khanachi et al., 2009)
Sweet Sorghum	*Sorghum bicolor* (L.) Moench	18%	5	(Coble & Egg, 1987)

Switchgrass is a native warm season grass that has been described as a model bioenergy feedstock by Wright & Turhollow (2010), as a result of the large volume of research on the crop. This C_4 grass has been shown to be economically competitive with other proposed dedicated bioenergy crops (McLaughlin et al. 2002). Harvesting is accomplished with traditional hay equipment, with annual production of a mature stand yielding an average of six to eight dry tons per acre (Garland 2008).

A cross of *Miscanthus sacchariflorus* (Maxim.) Franch. and *Miscanthus sinesis* Anderss. produces the sterile hybrid miscanthus (*Miscanthus x giganteous*) (Greef et al. 1997). Establishment of a miscanthus stand requires transplanting of seedlings or rhizomes, with success depending on planting schedule and soil temperatures (Maughan et al. 2012). Harvest operations are similar to switchgrass, though some plot trials have shown increased yields for Miscanthus (Heaton et al. 2006), which may lead to more favorable economic returns since yield is closely associated with biomass feedstock profitability (Khanna et al. 2008).

Giant Reed (*Arundo donax* L.) is an emergent aquatic C_3 grass (Spencer et al. 2006) originating in Asia but has become widely distributed in Southern Europe, North Africa, the Middle East, Australia, and North/South America (Boose & Holt 1999). Planting is accomplished through either transplanting or propagation from shoot cuttings, since seed heads have been found to be sterile in North America (Decruyenaere & Hold 2005). Traits of invasiveness have been exhibited in giant reed as a result of its high productivity, propagation methods, and favor of aquatic ecosystems (Boose & Holt 1999).

The objective of this study was to determine changes in moisture content and composition over time in biomass feedstocks stored under different bale storage formats (Round, Big Square, Wrapped) and environmental conditions (Outdoor, Indoor) in North Carolina. This research goes beyond other past studies by determining North Carolina specific conditions and evaluating weathered and un-weathered bale portions for compositional change over time for multiple bale storage formats.

4.2 Methodology

4.2.1 Biomass Harvests & Storage Characteristics

Biomass feedstocks were grown at North Carolina State University's Williamsdale Biofuels Field Laboratory (Duplin County, NC 34.7622°N, 78.0995°W). Bale configurations analyzed were outdoor round (RO), outdoor fully wrapped round bales (RW), indoor big square, (BS), and indoor round (RI) on two separate harvest periods, October 2012 and

March 2013. The harvest times and bale configurations evaluated for switchgrass, miscanthus and giant reed are summarized in Table 14.

Table 14: Biomass Feedstocks, Bale Configurations, and Harvest Periods Analyzed

Biomass Feedstock	October Harvest	March Harvest
Miscanthus (*Miscanthus x giganteous*)	RO, RW, BS	
Switchgrass 'Alamo' (*Panicum virgatum* L.)	RO, RW, BS	RO, RW, RI
Giant Reed (*Arundo donax* L.)	RO, RW, BS	RO, RW, RI

During both harvests biomass feedstocks were cut with a John Deere mower conditioner, then baled by either a Case Silage Special round (5x4ft) or New Holland big square (3x3x7.5ft) baler. Six bales were formed for each storage format, harvest time, and species (Oct: 54 bales, Mar: 36 bales, 18 bales per species per harvest). Fully wrapped bales were formed and wrapped directly after baling with a McHale single bale wrapper using 1 mm white polyethylene stretch wrap.

Bales formed for outdoor round and indoor storage formats were field cured and harvested when moisture content was below 15% moisture content (wet basis), as determined by microwave (Griggs 2005), which was required for all October harvested biomass and giant reed in March. A basket type tedder was used during the October harvest for miscanthus and switchgrass to expedite drying; due to fear of mechanical damage giant reed was not tedded. It took approximately two weeks of field curing for the miscanthus and switchgrass, and nearly a month for the giant reed to drop below 20% moisture content (wet basis). The specific stand of giant reed was not yet mature (2 to 3 years since establishment) allowing baling of small diameter pliable stalks, though late season harvested giant reed would cause additional issues as the stand matures (Chapter 2).

Biomass harvested in October for use in big square bales was initially round baled for later square baling, due to equipment availability at time of biomass harvest. Bales were stored in a well-drained area under tarps for approximately one month prior to big square baling. For March harvested biomass round bales were stored indoors to evaluate if bale format would have an impact.

Outdoor bales were stored uncovered on the ground in a well-drained area, with at least three feet on all sides to avoid any bale to bale interactions. Storage uncovered, on the ground was used to evaluate the worst case scenario for storage losses (Saxe 2004). Indoor stored bales after formation of bale configuration were placed on pallets in a warehouse. Though it was not evaluated in this study, weather can have a major impact on outdoor stored bales, with high moisture and temperatures often encouraging increased microbial growth and related dry matter losses. Monthly precipitation and mean temperatures during storage of outdoor round and wrapped bales is presented in Table 15.

Table 15: Monthly Precipitation and Mean Temperatures during Storage Period (Williamsdale Biofuels Field Laboratory, Duplin County) (NC CRONOS 2014)

Month	Precipitation (cm)	Temperature (°C)
2012		
Oct	5.2	16.6
Nov	3.3	8.6
Dec	11.3	10.1
2013		
Jan	4.7	8.8
Feb	12.2	7.4
Mar	4.4	8.6
Apr	9.3	16.2
May	7	20.1
June	41.5	24.3
July	39.9	26
Aug	14.8	25.1
Sept	5.5	21.7
Oct	3.1	16.9
Nov	7.8	10.6
Dec	11.4	9.4
2014		
Jan	5.7	4.3
Feb	9.5	7.1
Mar	12.1	9.1

4.2.2 Physical Characteristics of Biomass Feedstocks Stored as Bales

A sample of fresh biomass material directly after harvest, but before baling, for each species and harvest period were sent to NCDA & CS for forage analysis (NCDA & CS 2014). Samples were collected from bales at five sampling periods: initial, 3 month, 6 month, 12 month, and 15 month. Sampling times were chosen to represent annual storage operations and the potential for some spill over from year to year, especially in the case of a high yielding year followed by a prospective lower yielding one.

Initial samples from all bales were taken after biomass was in its final bale format and storage configuration using an 45.72 cm (18 in) HMC hay probe (Hart Machine Co., Madras OR) across the cross section of each side of the bale at eight different locations (3 probes each), then combined into a composite sample. Fully wrapped bales were sampled prior to wrapping to ensure wrap integrity. Sampling locations were filled with spray foam insulation for outdoor round bales to limit the effect of sampling. At 3, 6, and 12 month sampling periods outdoor round and outdoor fully wrapped bales had weathered portions sampled using a 6.35 cm (2.5 in) hole saw at eight locations across the cross section. Core samples were then collected from those same points using a HPC hay probe, with replicate bales sampled shown in Table 16. Samples taken from the different locations within weathered portions and cores of a single bale were combined into composite samples representing the outer and inner cores samples, respectively. Outdoor fully wrapped round bales were treated differently in terms of sample replication to account for integrity of the bale wrap, since oxygen and water infiltration was possible after application of spray foam insulation and use of agricultural repair tape.

Table 16: Bales Sampled at Specified Sampling Periods

Format	Bale	Initial	3 month	6 month	12 month	15 month
RO	1-3	X	X	X	X	X
	4-5	X			X	
	6	X				X
RW	1-3	X	X	X		
	4-5	X		X	X	
	6	X			X	
BS/RI	1-3	X	X	X	X	
	4-5	X			X	
	6	X				X

Bales sampled were weighed at each of the sampling periods using a hanging scale with a fabricated harness to hold bales. Moisture content was determined by placing a cloth bag of known dry tare weight with collected composite samples into a 45°C drying oven until dry weight had stabilized. Dry matter loss was determined by change in dry matter over the sampling periods, with additional analysis included for integration of weathered (outer) and core (inner) samples of outdoor stored bales.

In an attempt to more accurately estimate the proportions of “weathered” and “core” bale sections, a single switchgrass outdoor round bale harvested in March of 2013 and stored outdoor for nine months was differentiated into sections and tested for moisture content of the sides, top, bottom, and core. The outer eight inches of material was removed with a chainsaw, put into cloth bags, and placed in a drying oven set to 45°C until weight had stabilized.

4.2.3 Detergent Fiber Analysis

Dried samples were ground in a Wiley knife mill (Thomas Scientific, Swedesboro, NJ) until material passed through a one millimeter screen. Dry matter was determined in duplicate with one gram of ground sample in a 105°C drying oven. - These samples were then used for ash determination in a 600°C muffle furnace until weight stabilized (~8 hours).

An ANKOM$^{200/220}$ fiber analyzer (Ankom Corp., Fairpark, NY) was used for detergent fiber analysis (Drewnoski & Poore 2012), modified from the assays developed by Van Soest et al. (1991). Though this procedure was constructed to assess animal feed characteristics (Coblentz 2009; Hunhke 1990; Shinners et al. 2009) they have also been used to assess bioenergy feedstocks (Khanchi et al. 2009; Khanchi et al. 2010; Shinners et al. 2010; Shah et al. 2011). This method does relatively well for cellulose content but may overestimate hemicellulose values (Wiselogel et al. 1995). Samples were run in duplicate, half a gram per fiber bag, with sequential detergent extraction to determine structural carbohydrates. Alpha amylase was incorporated into Neutral Detergent Fiber (NDF) digestions to breakdown starch in the samples. Cellulose content was determined in an ANKOM DAISY (Ankom Corp., Fairpark, NY) with 72% sulfuric acid. After washes, samples were placed in acetone and blotted to increase drying, prior to drying in a forced air oven at 105°C. Lignin was determined by combustion in a muffle furnace at 600°C. Each set of samples were run with blanks and standards run in duplicate to incorporate a blank correction factor and to ensure that the digestions fell within the allowable range.

4.2.4 Statistical Analysis

For each perennial grass species, the effects of harvest period (fixed effect, October and March), bale configuration (Round, Big Square, Wrapped), storage location (indoor, outdoor), sampling location (inner, outer) and storage time as a repeated measure (0, 3, 6, and 12 months) on moisture content and composition (cellulose, hemicellulose, lignin, extractives and ash) were analyzed using PROC MIXED in SAS® (Cary, NC) (RO- Round Outdoor, RI- Round Indoor, BS- Big Square, RW- Round Wrapped). Pairwise comparisons were made for all response variables using LS Means between bales stored indoors, inner and outer core samples for bale configurations stored outdoors, and over time for outdoor round bales for each species, A significance level of α=0.05 was used for the analysis.

4.3 Results & Discussion

4.3.1 Fresh Biomass Characteristics

Giant reed was found to have the greatest initial moisture content and proportion of extractives for both harvest periods compared to the other grasses (Table 17). The high moisture content could have been related to the structure of giant reed being less susceptible to physical conditioning during harvest, making dry down difficult, or potentially to growth cycle and timing of harvest. The fresh biomass characteristics for the perennial grasses at the different harvest periods (Table 17) provide a base case for comparison of composition changes in the bales during storage of the different storage formats and harvests. Moisture content of the crops was typically higher during the October harvest. Fractions of the different components (lignin, cellulose, hemicellulose, and extractives) measured for the three crops were similar during the October harvest as well, especially switchgrass and miscanthus. The switchgrass crop composition changed in greater proportions between the October and March harvest in comparison to changes observed for giant reed.

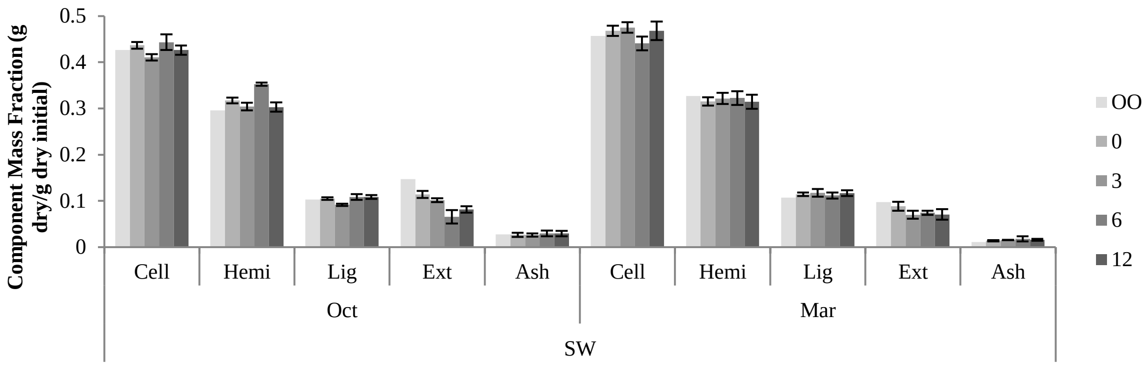
Table 17: Fresh Biomass Analysis (dry basis) (analysis conducted by NCDA&CS forage laboratory)

	Switchgrass		Giant Reed		Miscanthus
Harvest	*Oct*	*Mar*	*Oct*	*Mar*	*Oct*
Moisture Content (wet basis)	50.34%	10.90%	62.86%	52.05%	43.97%
Extractives	24.85%	14.3%	27.48%	28.81%	24.45%
Crude Protein	4.05%%	4.31%	6.21%	6.79%	3.78%
Soluble Carbohydrates	16.77%	7.32%	16.78%	16.47%	16.52%
Lipids	0.7%	0.63%	1.47%	0.79%	1.23%
Hemicellulose	22.41%	27.88%	23.14%	22.34%	21.07%
Cellulose & Lignin (by difference)	49.20%	43.21%	52.64%	54.90%	47.44%
Ash	3.34%	2.03%	3.02%	4.75%	2.92%
Minerals	1.50%	0.73%	1.33%	1.76%	1.34%
Calcium	0.26%	0.24%	0.22%	0.17%	0.37%
Phosphorus	0.12%	0.08%	0.09%	0.12%	0.08%
Sulfur	0.08%	0.07%	0.17%	0.21%	0.08%
Magnesium	0.17%	0.12%	0.10%	0.08%	0.16%
Sodium	0.01%	0.00%	0.00%	0.01%	0.00%
Potassium	0.84%	0.19%	0.72%	1.14%	0.64%
Copper	3 ppm	4 ppm	3 ppm	3 ppm	3 ppm
Iron	55 ppm	239 ppm	209 ppm	258 ppm	74 ppm
Manganese	103 ppm	56 ppm	30 ppm	11 ppm	26 ppm
Zinc	37 ppm	44 ppm	15 ppm	14 ppm	15 ppm

4.3.2 Indoor Stored Bale Characteristics

Indoor round bales harvested in March and big square bales harvested in October were found not to be significantly different for the grasses at each sampling period by pairwise comparison (p-value >0.05), except for giant reed initially (p-value<0.0001). This was probably related to differences in initial moisture content of the material being harvested in October versus March (Table 17), which within the first three months likely equilibrated, minimizing observed differences. Absolute changes in composition of indoor stored bales, as shown in Figure 8 appeared to remain relatively stable. Pairwise comparisons were made between each bale format within each sampling period.

Figure 8: Absolute Composition and Difference in Least Square Means of Biomass Components of Indoor Stored Bales Harvested in October (Big Square) and March (Round) for Each Sampling Period [A. Switchgrass (*Panicum virgatum* L.), B. Giant Reed (*Arundo donax* L.), C. Miscanthus (*Miscanthus x giganteous*)] (error bars represent one standard deviation) [Cell:cellulose, Hemi: hemicellulose, Lig: lignin, Ext: Extractives, OO: fresh biomass] (-: negative relationship between round indoor and big square bales, +: positive relationship between round indoor and big square bales)

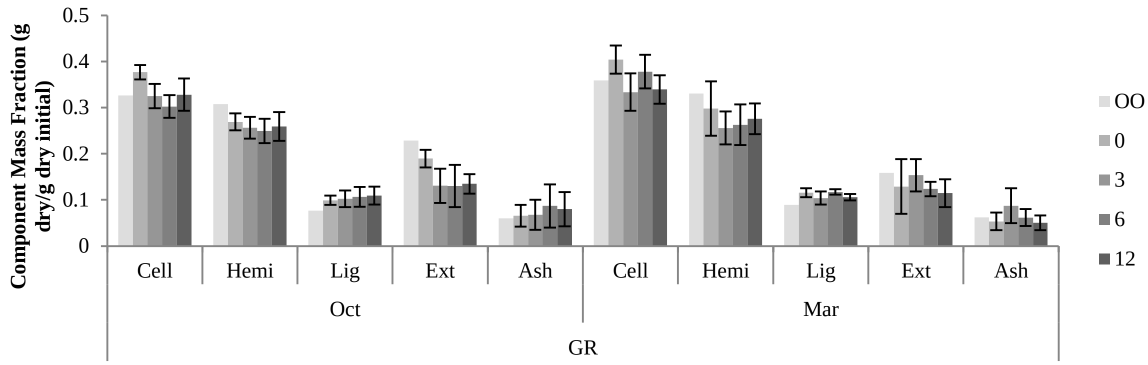


Difference in Least Square Means of Structural Components and Moisture between Round Indoor and Big Square Bales at Each Sampling Period

	Cellulose	Hemicellulose	Lignin	Extractives	Ash	Moisture Content
Initial	0.03122*	-0.00230+	0.009317+	-0.02547*	-0.01277**	-0.05775+
3 month	0.03759*	-0.01004+	0.02116**	-0.03575*	-0.01299**	-0.04052+
6 month	0.02398+	-0.02548*	0.009023+	0.01398+	-0.01153*	-0.02567+
12 month	0.02692+	-0.00197+	0.004951+	-0.01338+	-0.01639**	-0.00637+

*+: p-value>0.05, *: p-value<0.05, **: p-value<0.01*

A. Switchgrass (Panicum virgatum L.*)*

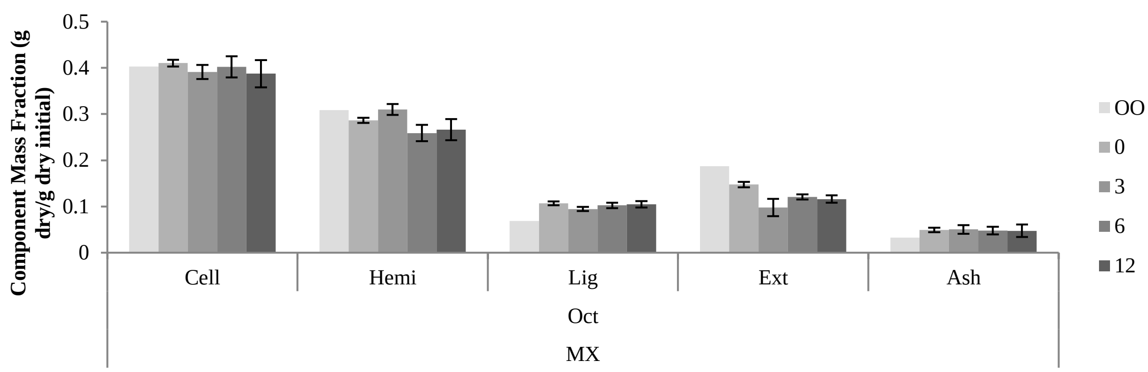


Difference in Least Square Means of Structural Components and Moisture between Round Indoor and Big Square Bales at Each Sampling Period

	Cellulose	Hemicellulose	Lignin	Extractives	Ash	Moisture Content
Initial	0.02708+	0.02918+	0.01649+	-0.06050**	-0.01225+	0.2598**
3 month	-0.00537+	-0.00218+	-0.00612+	0.002414+	-0.01723+	0.01448+
6 month	0.05999*	0.007883+	0.001320+	-0.03051+	-0.03272+	-0.01941+
12 month	0.02119+	0.02834+	0.000736+	-0.02109+	-0.02734+	-0.00253+

*+: p-value>0.05, *: p-value<0.05, **: p-value<0.01*

B. Giant Reed (Arundo donax L.*)*



C. Miscanthus (Miscanthus x giganteous)

Giant reed did not show statistically significant differences in proportional composition between indoor big square and round bales, except in extractives initially and at six months in cellulose (Figure 8). Switchgrass showed some statistically significant differences in proportional composition changes over time within each harvest period between bale formats stored indoors. Cellulose and extractives differences were observed initially and at 3 months, while lignin and hemicellulose showed significant differences at 3 and 6 months, respectively (p-value <0.05). Proportional ash contents were statistically lower at all sampling periods for indoor square bales than indoor round bales (Figure 8).

All indoor stored perennial grass bale formats displayed the greatest proportions of cellulose and hemicellulose (approximately 30%), and low lignin, extractives, and ash (Figure 8). On average, extractives showed the greatest absolute losses over time (Figure 8), which represent the proportion of the crops with the easiest digestible carbon sources for growth of natural microflora.

4.3.3 Comparison of Core & Weathered Fractions of Outdoor Stored Bales

Moisture content of the weathered (outer) and core (inner) samples collected were found to be significantly different at specific sampling periods, except for a few instances at 3 months and 6 months for round bales and wrapped bales stored outdoors (Table 18; Table 19). Observed differences as expected were most likely related to weather conditions increasing the moisture content of the weathered portion, especially in bales with poor thatching patterns, allowing infiltration and evaporation of moisture from the weathered portion. Generally the weathered portion was found to have higher moisture content than the core samples. Since the presented data only represents proportional changes it is difficult to infer any absolute changes in parameters, and that limitation is tied to the variability in moisture throughout the bale weathered and core portions and the inability to make a reasonable estimation of the dry matter content of the bale, in whole or part with the various samples taken.

Table 18: Outdoor Round Bales Differences in Least Mean Squares for Weathered & Core Samples (difference in composition mass fraction on a dry matter basis) (-: negative relationship between weathered and core samples, +: positive relationship between weathered and core samples)

	Harvest	Month	Cellulose	Hemicellulose	Lignin	Extractives	Ash	Moisture Content
Giant Reed	Oct	3	0.02007+	-0.00102+	-0.00788+	-0.02076+	0.01067+	-0.1909**
		6	0.1091**	0.01772+	-0.04033**	-0.08433**	-0.00109+	-0.4159**
		12	0.1896**	0.08157**	-0.09964**	-0.1051**	-0.06687**	-0.3931**
Switchgrass	Oct	3	-0.01079+	-0.00591+	-0.01424+	0.01771+	0.01064*	-0.3025**
		6	-0.00888+	-0.00191+	-0.01516*	0.008628+	0.01474**	-0.3128**
		12	0.06939**	0.01979*	-0.01375*	-0.07939**	0.003952+	-0.3541**
Miscanthus	Oct	3	0.005084+	0.006973+	-0.02742*	0.02782+	-0.013+	-0.4840**
		6	0.08729**	0.02879*	-0.06932**	-0.02789+	-0.01941+	-0.5256**
		12	0.1731**	0.06336**	-0.1139**	-0.06479**	-0.05758**	-0.4882**
Giant Reed	Mar	3	0.05457*	-0.00327+	-0.00268+	-0.03989+	-0.00974+	-0.3407**
		6	0.1379**	-0.00346+	-0.06531**	-0.06051*	-0.00968+	-0.2514**
		12	0.1677**	0.04209*	-0.09443**	-0.08154**	-0.03461+	-0.3440**
Switchgrass	Mar	3	0.02049+	0.004946+	0.001318+	-0.02271+	-0.00186+	-0.2748**
		6	-0.00535+	0.02949*	-0.01356+	-0.01022+	0.001823+	-0.08177+
		12	0.04452**	0.01692+	-0.01118+	-0.04844**	-0.00163+	-0.2674**

*+: p-value>0.05, *: p-value<0.05, **: p-value<0.01*

Table 19: Outdoor Wrapped Bales Differences in Least Mean Squares for Weathered & Core Samples (difference in composition mass fraction on a dry matter basis) (-: negative relationship between weathered and core samples, +: positive relationship between weathered and core samples)

	Harvest	Month	Cellulose	Hemicellulose	Lignin	Extractives	Ash	Moisture Content
Giant Reed	Oct	3	-0.01760+	-0.00683+	0.001650+	0.003243+	0.01421+	-0.09010+
		6	0.03960+	-0.00985+	-0.00813+	-0.01614+	-0.00728+	-0.2033**
		12	0.1233**	0.03877+	-0.02984**	-0.07528**	-0.05168*	-0.3737**
Switchgrass	Oct	3	-0.02054+	-0.01612+	0.02108**	0.005895+	0.007772+	0.1807**
		6	0.05667**	-0.02615**	-0.00642+	-0.01288+	-0.01155*	-0.07275+
		12	0.1180**	0.01407+	-0.04061**	-0.06204**	-0.02755**	-0.3430**
Miscanthus	Oct	3	-0.05020**	-0.00754+	0.02367*	-0.04316*	0.07387**	0.2152**
		6	0.07365**	0.02007*	-0.01173+	-0.05722**	-0.02473+	0.05155+
		12	0.08345**	0.03250**	-0.04683**	-0.03337+	-0.03240+	-0.3171**
Giant Reed	Mar	3	-0.05984*	-0.0200+	-0.00946+	0.06179*	0.02102+	-0.04404+
		6	0.07983**	0.03649*	-0.02247*	-0.07722**	-0.02116+	-0.3300**
		12	0.1451**	0.04091+	-0.04494**	-0.08411**	-0.04341*	-0.3780**
Switchgrass	Mar	3	0.003905+	-0.01238+	0.001707+	0.002796+	0.000313+	-0.1007+
		6	0.007642+	-0.00233+	-0.00334+	-0.00693+	0.002587+	-0.1257**
		12	0.02168+	-0.00197+	0.000076+	-0.01652+	0.000395+	-0.1996**

*+: p-value>0.05, *: p-value<0.05, ** p-value<0.01*

Both the outdoor round and fully wrapped bales showed an increase in the number of compositional parameters showing significant difference between the weathered and core samples within each sampling period as storage time increased (Table 18; Table 19), indicating the increased time contributed to changes in structural components. Miscanthus had the greatest number of significant differences between the weathered and core samples for both bale types (Table 18; Table 19). Cellulose had the greatest number of significant differences between weathered and core samples for both outdoor round and wrapped bales of the different grasses from both harvest periods, with values generally being higher in proportion in the core samples (Table 18; Table 19).

The statistical differences observed between weathered and cores samples of the round bales stored outside, reinforces the common finding that bales show non-uniform gradients in moisture and composition over time throughout the material. This makes estimates of dry matter losses and overall composition very difficult. Methods for testing hay lots focus primarily on use of sharp implements over a random number of bales (Kinder & Shewmaker 2011), but does not focus on the variability that is inherent between the core and weathered portions of the bale that are not accurately accounted for using bale core sampling equipment. Some estimates could be made to determine the extent of the weathered portion of a bale (Collins et al. 1997), with which a dry matter loss could be estimated if weathered and core samples were collected. This can incorporate a large amount of uncertainty and variability in this type of analysis. For example if a 700 lb five foot diameter round bale with a harvest moisture content of 15% (wet basis) weighed 675 lb after 6 months, with core and weathered sample moisture contents at 15% and 40% (wet basis), respectively, then estimating a weathered layer at 2 inches (13% weathered) compared to 6 inches (36% weathered) would result in a 7.2% and 15.6% dry matter loss, respectively. This wide range of dry matter loss estimates based on assumed weathered fractions limit the confidence in these types of calculations for outdoor stored large round bales. This reinforces the need to measure weathered fraction gradients in bales more closely if accurate dry matter determinations are desired.

Handling bales of different consistencies at a biorefinery could involve differentiation of the bales to unwrap the weathered portion, most likely for heat and power production, with the core portion used for chemical production. An important aspect of measuring composition of stored bales is demonstrating to conversion facilities how the biomass feedstock changes over time however, the current method of taking composite core samples of outdoor stored bales does not properly represent the bale as a whole, making absolute changes difficult to accurately measure and variations throughout the bale impossible to effectively capture.

4.3.4 Differentiated Switchgrass Bale

When an entire switchgrass bale was differentiated to determine how the moisture content varied, it was determined that the bottom of the bale contained the majority of the water (Table 20), both in the samples taken and the entire bale. During this sampling period the weathered portion was found to be lower in moisture content than the core, which seems counter intuitive and different in comparison to other bale data collected as part of this intensive treatment study. Since the weathered portion only represented the outer two inches of the bale using a hole saw, the actual weathered section, and the majority of the moisture, was present beyond this point (Table 20). The difference in the hole saw and differentiated bale moisture contents was most pronounced in the bottom of the bale, with hole saw and differentiated bale samples at 14.33% and 44.23% moisture content (wet basis), respectively (Table 20). Weather conditions could have had an effect on this occurrence as could the thatching pattern of specific species, which can inhibit infiltration of moisture but can also limit evaporation of moisture once it becomes trapped.

Table 20: Differentiated Switchgrass Outdoor Bale Moisture Content (9 months of storage)

	Weathered Sample	**Core Sample**		**Whole Bale**[1]	
	Moisture Content (wet basis)	*Moisture Content (wet basis)*	*Moisture Content (wet basis)*	*Moisture Content (Proportion)*	*Volume (proportion)*
Top	9.96%	18.92%	17.5%	7.95%	8.83%
Sides	14.07%	18.87%	38.67%	32.95%	21.21%
Bottom	14.33%	30.84%	44.23%	52.27%	16.18%
Core			8.45%	6.81%	53.78%

[1]Whole Bale Moisture Content (wet basis): 30.34%

The proportion of moisture in the weathered and core samples taken, as described in the methodology, did not match the proportional volume in each section of the whole bale sampled and dried as large differentiated sections (Table 20), especially in the bottom and core of the bale. To create a composite sample of this specific bale, additional samples would need to be collected from the bottom portion, though weather would most likely be a major factor in some of these variations that would need accounted for. For this specific sample the moisture results from samples collected from the bottom portion of the bale happened to be similar to the moisture of the entire bale with all masses compiled however, this is likely not a common trend in sampling as we observed in the other bales collected and sampled .

Though only a single outdoor stored round bale was evaluated to generate the data in Table 20, it can be inferred that fully wrapped bales may have similar trends, since moisture present in the bale at time of storage may translocate to the bottom portion of the bale during storage, pooling at the bottom of the bale increasing moisture content of that portion. This evaluation shows that production of composite samples from bale core samplers, although more intensive than tradition practices as completed in this study, may not adequately represent moisture content of an entire bale, affecting reliable quantification of absolute composition changes.

With the gradients and variability observed between core and weathered portions, a more robust method for sampling bales other than those outlined in Kinder & Shewmaker (2011) may be required for bioenergy feedstocks. Consistency of moisture and composition can be major factors that affect the process design and operations of a biorefinery, especially as these facilities begin to focus on multiple end products from the same biomass source. With some proposed biomass feedstock purchase plans being based on dry matter content, and with biorefineries primarily focused on conversion of specific biomass components, an accurate method for determination of these characteristics over the storage period is important. Potentially including regionally specific weather and drainage factors over storage time, accounting for the thatching pattern of each of the potential biomass feedstocks, in conjunction with specific sampling locations along the biomass lot may better characterize these properties. Additional research focused on total and differentiated bale composition over time can help determine these factors.

4.4 Conclusion

This study found that there were significant differences in composition and moisture content between the weathered and core samples within outdoor stored bales. Indoor storage of bales showed constant moisture content after an initial stabilization period, allowing for lower absolute changes in composition of key components of the feedstock, including cellulose. The current methodology of bale sampling of outdoor stored bales presented in this study may not adequately represent moisture and composition of the bales, limiting assessment of overall bale consistency over time. This establishes a need for additional research to evaluate whole bale changes and determine how composite samples and weather factors can be included into the bale sampling process.

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CHAPTER 5: PREDICTIVE MODEL FOR CROPLAND CONVERSION TO BIOMASS FEEDSTOCKS: A CASE STUDY OF THE THREE MAJOR REGIONS OF NORTH CAROLINA

5.1 Introduction

Inclusion of bioenergy into the US energy portfolio can have positive environmental, political, economic, and societal implications. The need for increased production of domestic energy sources in the United States was emphasized with the Energy Infrastructure and Security Act (EISA) of 2007, which called for an increase in renewable energy including those produced from terrestrial biomass sources (U.S. House 2007). In the U.S., biofuels (ethanol and biodiesel) have increased dramatically throughout the 21st century, in 2011 accounting for 22.1% of renewable energy production, with renewable sources accounting for 11.8% of total US energy production (U.S. DOE 2012). Multiple conversion technologies exist for biomass sources split into biochemical and thermochemical methods, both having related benefits and drawbacks.

Bioenergy feedstocks can be split into several different categories (Figure 9), with primary sources related to forestry and agricultural practices. Each of these categories may be associated with different production and conversion technologies. The Billion Ton Study (U.S. DOE 2005) and subsequent update (U.S. DOE 2011a) highlighted the importance of dedicated herbaceous biomass feedstocks for the emerging biobased economy. The favorable climatic conditions of the Southeastern United States show it to be a potentially large contributor of dedicated herbaceous feedstocks (U.S. DOE 2011a).

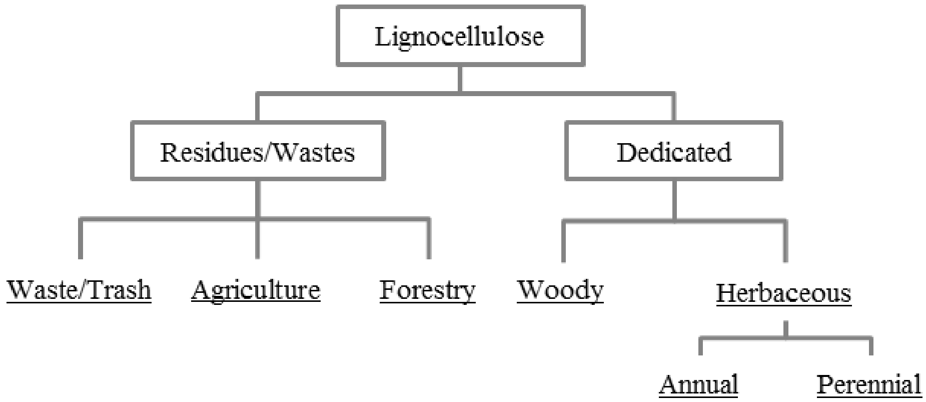


Figure 9: Lignocellulosic Bioenergy Feedstock Categories

Dedicated herbaceous biomass feedstocks are commonly split into either perennial grasses or annual crops. A list of associated benefits and drawbacks of perennial and annual herbaceous biomass feedstocks are shown in Table 21. Both of these categories are harvested annually, with the major difference being planting schedule, where annual crops require yearly planting and perennials are set on some multi-year replanting schedule. To ensure compositional uniformity it is important to set some defined replanting schedule for perennial grasses, since grasslands can commonly become infested with nuisance plants like crabgrass (*Digitaria sanguinalis* (L.) Scop.) (Green et al. 2006). Annual crops allow for inclusion of biomass feedstocks into multiple year rotation strategies (such as tobacco or sweet potato), reduce grower risk to single years, allow annual incorporation of updated seed stock, and can incorporate winter annual crops improving economic conditions. The rate of production of a mature crop also provides greater opportunities for annual biomass feedstocks to be modified, through breeding or genetic improvements, more rapidly for optimal biomass production characteristics.

Table 21: Comparison of Perennial and Annual Dedicated Herbaceous Biomass Feedstocks

	Perennial	Annual
Establishment	Single establishment for multiple years	Annual establishment required
	Establishment failure may take a year to determine, very costly	Rapid determination of failure, replanted same year
	High initial investment	Annual investment
Yield	Annual ramp up in yield to full maturity	Annual full yields
Crop Improvements	Wait until next replanting	Best seed planted annually
Winter Cover	No winter cover	Can be incorporated
Annual Field Rotation	Field dedicated for multiple years	Can fit into traditional field rotations
Soil Carbon	Large soil carbon accumulation from roots	Reduced soil carbon accumulation
Time Requirement	Reduced annual field operations	Similar operations to traditional agricultural products
Nutrient Requirement	Some nutrients recycled annually	Similar nutrient removal to forages

Three warm season perennial grasses of interest in the southeast US are: Switchgrass (*Panicum virgatum* L.), Miscanthus (*Miscanthus x giganteous*), and Giant Reed (*Arundo donax* L.). Switchgrass is a native grass referred to by Wright & Turhollow (2010) as the model bioenergy feedstock, leading to its use by the U.S. Department of Energy for comparison of other biomass feedstocks. Miscanthus (*Miscanthus x giganteous*) is a hybrid between *Miscanthus sacchariflorus* (Maxim.) Franch. and *Miscanthus sinesis* Anderss., which the genus originated in tropical/subtropical regions (Greef et al. 1997).Giant reed is thought to have originated in Asia propagating through rhizomes and canes (West et al. 2014), and has shown some characteristics of invasiveness (Boose & Holt 1999).

Sorghum is an annual biomass feedstock of interest for the southeast U.S., which has been demonstrated in a regional set of yield trials to have beneficial yields (Gill et al. 2014).

Categories of sorghum are commonly forage, grain, sweet and more recently, biomass, which are designated by product end use (Whitfield et al. 2012). There are multiple benefits of sorghum including short maturity window, high yield, drought tolerance, nutrient use efficiency, favorable production on marginal soils, and functional use of existing agricultural equipment for production (Köppen et al. 2009). Two potential winter annual crops that could be incorporated with sorghum cultivars are barley (*Hordeum vulgare* L.) and rape/canola (*Brassica napus* L.), though most winter annual crops can fit within this rotation. Barley is a common grain crop with existing markets and the potential for use in bioenergy production, both grain (Griffey et al. 2010) and straw (Han et al. 2013). Rapeseed is an oilseed with existing edible food and lubricant markets, and is a major biodiesel feedstock in Europe (Zentková & Cvengrošová 2013).

With the high capital investment required for bioenergy production facilities, determination of available feedstock is incredibly important. U.S. DOE (2002) found that a 10,000 MT/day Iowa biorefinery utilizing corn stover would require a collection radius of 56 (35), 72 (45), and 169 (105) kilometers (miles) for 100%, 50%, and 10% cropland inclusion, respectively. The collection radius has a major impact on hauling charges from \$6.71 to \$15.51 per metric ton (\$6.09 to \$14.07 per short ton) for 0 to 24 (0 to 15) and 80 to 161 (50 to 100) kilometers (miles), respectively (U.S. DOE 2002). This leads to a theoretical maximum for economies of scale at a cropland inclusion rate of 10% for a facility above 8,000 MT/day as a result of increases in logistical operations, offsetting the cost savings from facility operations (U.S. DOE 2002). To avoid the issues of indirect land use change (Searchinger et al. 2008), marginal cropland (Dale et al. 2010) and unconventional land areas

(Mayer 2012) have been proposed for production of biomass feedstocks, but these areas commonly have lower yields than productive cropland. Babcock & Iqbal (2014) have shown that outside of developing countries, increases in crop production are accomplished by intensive not extensive practice. This is especially prevalent in industrialized countries, such as the U.S. and EU members, where total cropland is diminishing (Deininger et al. 2011). Current production of dedicated bioenergy feedstocks in the Southeast U.S. is limited, mostly because the significant investments in viable biorefinery facilities have not been established. The ability to establish prediction methods for potential cropland conversion from traditional agricultural products to biomass feedstocks would be beneficial to biorefinery and economic development in different regions globally.

The objectives of this study were to construct a predictive model to determine cropland conversion from traditional agricultural products to bioenergy feedstocks, using a probabilistic equation based on agricultural margins, and demonstrate the usefulness of this method with case studies of an individual county within each of the three major regions of North Carolina (Coastal Plain, Piedmont, Mountains). Uncertainty analysis within each case study was included to determine variability within the model from each parameter.

5.2 Methodology

5.2.1 Yield Determination

Traditional agricultural product yields were determined by soil type and county (in North Carolina) using the NCSU Soil Science Department's Realistic Yield Expectations (Crouse 2003). With ArcGIS (ESRI Redlands, CA), 2003 soil survey (USDA 2014a) and

2013 cropland cover (USDA 2014b) were used to determine the acreage of selected North Carolina crops (Table 22) and soil types for specific counties of interest, Duplin (Coastal Plain), Granville (Piedmont) and Henderson (Mountains). Since data was not available for sweet potato yields by soil type in North Carolina, proportional tobacco yields were used for a soil type (Leon Sand, Duplin County) yielding the average state tobacco yields (USDA 2013) to create a yield ratio for other soil types. A ten percent coefficient of variation was used for traditional agricultural products, and winter bioenergy rotational crops in the analysis.

Table 22: Proportion of Land Area by Agricultural Product (2013)

Code[1]	**Crop**	**Duplin (Coastal Plain)**	**Granville (Piedmont)**	**Henderson (Mountains)**
	Total Area[2]	213,050 ha	139,000 ha	97,150 ha
1	Corn	9.42%	1.03%	3.52%
2	Cotton	2.05%	0.10%	0.00%
4	Soybean	0.43%	0.03%	0.00%
5	Sorghum	4.91%	0.92%	0.68%
10	Peanut	0.72%	0.00%	0.00%
11	Tobacco	0.55%	0.10%	0.01%
21	Barley	0.04%	0.00%	0.00%
24	Wheat	0.48%	1.31%	0.00%
26	Dbl Crop WinWht/Soybean	7.91%	0.69%	0.01%
36	Alfalfa	0.00%	0.00%	0.01%
37	Other Hay/Non Alfalfa	5.16%	4.01%	4.80%
46	Sweet Potato	0.15%	0.00%	0.00%
60	Switchgrass	0.00%	0.00%	0.00%
61	Fallow/Idle Cropland	5.13%	7.55%	0.51%
176	Grassland/Pasture	0.81%	10.51%	3.95%
225	Dbl Crop WinWht/Corn	0.00%	0.02%	0.00%
235	Dbl Crop Barley/Sorghum	0.00%	0.00%	0.00%
236	Dbl Crop WinWht/Sorghum	0.17%	0.05%	0.00%
237	Dbl Crop Barley/Corn	0.00%	0.03%	0.00%
238	Dbl Crop WinWht/Cotton	0.00%	0.00%	0.00%
239	Dbl Crop Soybean/Cotton	0.00%	0.00%	0.00%
241	Dble Crop Corn/Soybean	0.00%	0.00%	0.00%
254	Dbl Crop Barley/Soybean	0.00%	0.00%	0.00%
	Total Agricultural Area[2]	162,000 ha	110,900 ha	90,300 ha

[1]Code represents the grid code given in the USDA (2014b)
[2]Total area of counties may not be exact due to raster format of data within ArcGIS, transformation of data, and geodetics

The most accessible publically available bioenergy crop yields and coefficients of variation for North Carolina were used for perennial grasses (Palmer et al. 2014) and canola (George et al. 2010). For sorghum yields an unpublished variety trial conducted at the NCSU Biofuel's Field Lab (Duplin County, NC 34.7622°N, 78.0995°W) on favorable sorghum cultivars was used. The highest observed dry matter yield from this trial was used as an average yield for sorghum (Sugar T), with standard deviation calculated using the top four yielding cultivars (Table 23). This was deemed appropriate since only the best yielding cultivars would be considered for large scale cultivation. Using the specific soil types these trials were conducted on, ratios were established between similar crops where extensive data already exists in databases. For perennial grasses fescue was used in the Mountains, bermudagrass in the Coastal Plain, and an average between the two for the Piedmont. Sorghum yields were considered proportional to sorghum in the Mountains, sorghum sudan in the Coastal Plain, and an average of the two in the Piedmont. Wheat was used to proportionally determine the yield of canola in all regions. For example the average canola yield (averaged across varieties and years) used for Duplin County (Goldsboro Loamy Sand, representative slope) was 2.47 tonne/ha (36.8 bu/ac), while wheat in the same county and soil type had a realistic yield expectation of 4.37 tonne/ha (65 bu/ac) (Crouse 2003). To predict the yield of canola in Duplin County on Pantego Loam (representative slope) where wheat has a realistic yield expectation of 4.04 tonne/ha (60 bu/ac), a ratio of 4.04:4.37 would be used, giving a predicted yield of canola at 2.28 tonne/ha (33.97 bu/ac).

Table 23: Sorghum 2013 Cultivar Trial (Wallace, NC [Goldsboro Loamy Sand, Duplin County])

Cultivar	MC (wet basis)	Yield (dry tonne/ha)
ES 5140	63%	15.18
EJ 7282	63%	17.03
ES 5155	64%	16.89
Sugar T	67%	20.09

5.2.2 Agricultural Product Margins

Traditional agricultural product enterprise budgets were used from the NCSU Department of Agricultural and Resource Economics (Bullen & Weddington 2012a; Bullen & Weddington 2012b; Bullen 2013a; Bullen 2013b; Bullen & Jordan 2013a; Bullen & Jordan 2013b; Bullen & Dunphy 2012a; Bullen & Dunphy 2012b; Bullen & Fisher 2013a; Bullen & Fisher 2013b; Bullen & Fisher 2013c; Bullen & Weddington 2012c; Bullen & Weddington 2012d; Bullen & Little 2013; NCSU 2014; Green & Benson 2013a; Green & Benson 2013b; Green & Benson 2013c; Green & Benson 2013d), using the most updated budgets provided. When multiple management systems for the crops were provided (e.g. till and no-till) the values were averaged. These budgets were used to determine average fixed and variable production costs for the various crops shown in Table 22. Virginia peanuts were assumed throughout the state, due to profitable margins, and tobacco production practices were divided between the coastal plain and piedmont, with piedmont operations assumed to be half hand harvested and half machine harvested.

Bioenergy enterprise budgets were constructed with best publically available data (Appendix C), and knowledge from variety trials at NCSU. All perennial crops were assumed to be on a ten year replanting schedule, using big square bales stored for a maximum of six months on a gravel pad in tarped piles. This harvest and storage method was selected to reduce transportation costs by cubing out loads (U.S. DOE 2009) and allows for low dry matter losses using the lowest cost storage method (Saxe 2004). Annual yields used accounted for losses during storage and a three year yield maturity required for perennial grasses (50%/75%/100%). Giant Reed was assumed to be forage chopped with a specialized willow harvester outlined in Buchholz & Volk (2011) to alleviate the potential of invasiveness. Traditional and minimum tillage operations were assumed to be evenly used throughout the production area, since depending on soil type and production methods management strategies vary. Rapeseed costs were determined using the ratio of canola to wheat costs shown in Atkinson et al. (2006) with the current wheat enterprise budget (Bullen & Weddington 2012c; Bullen & Weddington 2012d).

Agricultural product prices were determined from USDA (2013) for average prices in North Carolina. Sorghum was priced at 95% the value of corn on a weight basis, as has been done in contracts by Murphy Brown (MB 2012). The value of pastures was based on two thirds of the dry matter yields of hay, with this assumption accounting for management strategy variations between hay and pasture operations, such as stubble height requirements. Canola was valued from 2013 Canadian prices (CC 2014), after converting to US dollars. Biomass was valued on a dry ton basis, after taking into account cellulose content. Primary price of cellulose was determined using a 37% cellulose content of switchgrass (Lee et al. 2007) rather than a set value for biomass on a dry tonnage basis. The coefficient of variation of switchgrass cellulose content was used for all biomass feedstocks in this analysis. A coefficient of variation for agricultural product yields of ten percent was also used for this analysis.

5.2.3 Cropland Conversion Probability

After agricultural product and biomass feedstock margins were determined, a probabilistic function was constructed to determine cropland conversion. Three categories of land managers were assumed to exist: those that would convert as long as the profit margin was positive, a linear increase in probability from proportional margins with existing profits to double margins, and a maximum probability regardless of increases in margins above twice the existing current profits. There are positive benefits of converting to a bioenergy feedstock including guaranteed annual contracts reducing land manager risk, increases in soil carbon from perennial crop (Liebig et al. 2008), diversification of crop production, and some land managers may wish to contribute to advancing an emerging bioeconomy. As profits begin to grow beyond that of existing agricultural products land managers will continue to convert cropland. Due to the high capital costs of specialized agricultural operations (combines, cotton pickers, etc.) there would be some maximum probability of converting cropland, regardless of increases in profit. Additionally some land managers would leave cropland in traditional agricultural products for similar reasons which may include: variability in agricultural products can produce high profits at a risk, annual crop rotations of high value products may limit annual use, and traditional products provide a certain level of reassurance to many producers. For this analysis, a minimum and maximum probability of converting land use practices of one and twenty five percent, respectively, was chosen, with a linear increase from proportional to double profits from current agricultural product (Figure 10).

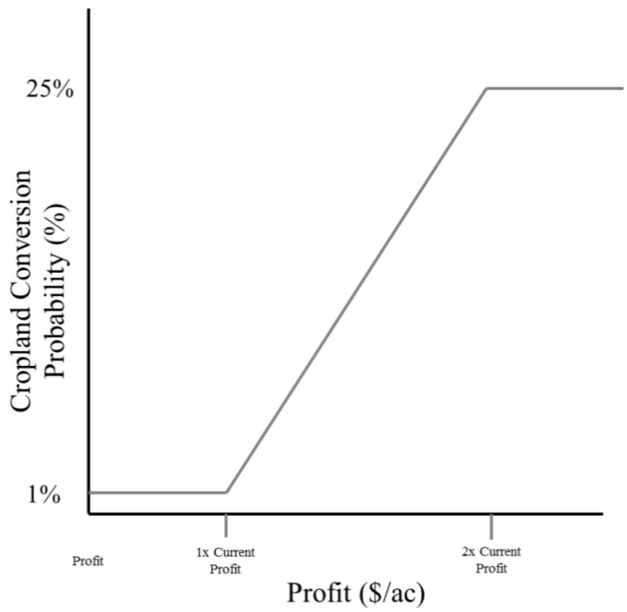


Figure 10: Cropland Conversion Probability Function

Using the soil type (USDA 2014a), cropland cover (USDA 2014b), the probability function and the calculated margins (Section 5.3.3), the total converted acreage of each soil type within the specified counties was calculated, taking into account yield with variable cost. This probability was used as a proportion of land converted, since as the dataset size increases probability can be used as an estimate of proportion.

5.2.4 North Carolina Case Study with Uncertainty Analysis

A case study using the predictive model was constructed for the three major regions of North Carolina, with a single representative county selected in each: Coastal Plain (Duplin), Piedmont (Granville), and Mountains (Henderson). Each of these counties contained a research station with biomass feedstock data, allowing for greater comparison between soil types. Spatial data for these counties was used to evaluate the acreage that would convert to biomass feedstocks production.

An uncertainty analysis was conducted for each case study using a single parameter sensitivity analysis method. Coefficients of variation of ten percent were used for traditional agricultural crops and available data for biomass feedstock yields and switchgrass cellulose content. An average biomass feedstock value of $71.65 per dry tonne ($65 per dry ton) was used, with a higher price of $82.67 ($75) and lower of $60.63 per dry tonne ($55 per dry ton). U.S. DOE (2002) used a feedstock price of $33.07 per dry tonne ($30/dry ton), with further updated research efforts showing increase to $64.82/dry tonne ($58.80/dry ton) (Humbird et al. 2011). Glassner et al. (1998) evaluated corn stover costs in Iowa determined a cost of $39.30 per dry tonne ($35.70/dry ton) for a low yield scenario, common for sloped terrain, and $34.76 per dry tonne ($31.60/dry ton) for higher yields, which was commonly selected by most farmers. U.S. DOE (2002) using life cycle analysis from Oak Ridge National Laboratory found a cost of $62 per dry tonne ($56/dry ton) after accounting for fertilizer inputs, transportation, baling/staging, and a farmer premium of 18% ($11.16/dry tonne, $10.08/dry ton). An increase in price per dry tonne was deemed adequate since this analysis used dedicated bioenergy feedstocks, not agricultural residues. A baseline for the uncertainty analysis was produced using average values, then best and worst case scenarios two standard deviations above and below the mean for each parameter. This resulted in either an increase or decrease in the predicted acreage converted from the estimated average acreage. Each individual parameter was subsequently increased and decreased by two standard deviations to determine the sensitivity of each.

5.3 Results & Discussion

5.3.1 Yield Determinations

Yield ratios for bioenergy crops were usually lower than one, showing that yield trials were conducted on productive soils in the regions. County specific yield average and coefficients of variation for each bioenergy feedstock are shown in Table 24, disregarding zero values associated with some soil types that were not suitable for production.

Table 24: County Average Biomass Feedstock Yields across Soil Types (dry tonne per hectare)

	Duplin		Granville		Henderson	
	Mean	CoV	Mean	CoV	Mean	CoV
Switchgrass	14.1	0.23	12.1	0.25	13.2	0.21
Miscanthus	14.6	0.23	10.6	0.25	12.7	0.21
Giant Reed	19.7	0.23	13.6	0.25	16.67	0.21
Sorghum	14.9	0.25	15.9	0.34	15.0	0.23
Barley (straw)	4.5	0.20	4.1	0.31	4.3	0.19
Barley (grain)	1.9	0.20	1.7	0.31	1.8	0.19
Canola (grain)	1.9	0.20	1.2	0.31	1.1	0.19

5.3.2 Agricultural Product Margins

Bioenergy feedstock enterprise budgets were constructed for each of the bioenergy feedstocks, summarized in Table 25. Establishment costs for perennial grasses were low because they were annualized over the ten year life span, with annual maintenance costs accounting for yearly operations. Sorghum and giant reed harvest prices were high related to use of large self-propelled forage choppers, with giant reed using a specialized header. Storage costs were slightly higher in the barley due to a higher proportion of the annual yield of biomass delivered, since barley straw does not have a multi-year ramp up period. Differences in transportation costs were related to bulk density, biomass format, and moisture content of the different crops. Detailed enterprise budgets are shown in the Appendix C.

Table 25: Annual Bioenergy Enterprise Budget Values (See Appendix C for full budgets)

	Establishment ($/ha)	Maintenance ($/ha)	Harvest ($/ha)	Storage ($/dry tonne)	Transport ($/dry tonne)	Delivered Biomass Yield	Grain Transport ($/tonne)
Sorghum	$459.76		$130.50		$4.56	100%	
Barley	$633.48		$195.06	$1.69	$2.94	97%	$5.51
Switchgrass	$44.18	$289.41	$81.12	$1.60	$2.94	90%	
Miscanthus	$122.42	$289.41	$81.12	$1.60	$2.94	90%	
Giant Reed	$122.42	$289.41	$179.99		$1.93	90%	

Values shown in Table 25 were calculated using existing equipment cost information from Lazarus (2009) and Lazarus (2014) using field capacity and equipment information from major commodity crop production in Minnesota, with the intent of modeling costs for the nth field. Though establishment equipment costs are probably relatively similar, depending on seeding rates, a major difference may be related to harvesting operations. With higher biomass crop yields compared to hay, and additional wear on equipment of the larger diameter rigid stems, actual field operations may be considerably more expensive. The higher yields of biomass crops compared to hay may reduce field efficiency, especially for round balers that must stop to bind and discharge each bale. Larger diameter more rigid stems of biomass feedstocks can increase wear of equipment, reducing equipment lifetime and increasing maintenance costs. The values in Table 25 did not account for land value since the commodity enterprise budgets utilized also did not account for this value, which would have raised per hectare costs by $207.57 annually for non-irrigated cropland in North Carolina ($84 per acre) (USDA 2015).

5.3.3 Cropland Conversion Probability

Estimated yield and enterprise budget parameters were applied to the produced set of equations (Equation 6; Equation 7; Equation 8), and related variables (Table 26) to estimate cropland conversion probability, and subsequently converted area. This can be used for a range of feedstocks, land areas, parameters, and bioenergy production technologies. Though this was specifically designed for bioenergy, this equation can be used for any cropland conversion to determine land availability. It is also possible to update the probability function depending on specific information from land managers on requirements for conversion.

$$P_{C,B} = \left(Y_{C,B} * Pr_{C,B}\right) - \left[F_{C,B} + \left(Y_{C,B} * V_{C,B}\right)\right]$$
$$Pr_B = \left[Pr_{dry} * \frac{1}{Cell_{SW}}\right] * Cell_B$$

Equation 6: Profitability of Agricultural Products

$$if\ 0 < P_B < P_C, Prob = 1\%$$

$$if\ P_C \leq P_B \leq 2P_c, Prob = \left[\frac{0.24}{P_C} P_B\right]\%$$

$$if\ 0 < P_C\ \&\ 2P_C < P_B, Prob = 25\%$$

$$if\ P_C < 0\ \&\ \frac{1}{2}P_C < P_B, Prob = 25\%$$

Equation 7: Probability of Cropland Conversion

$$CA = \sum Prob * A(Soil, Crop)$$

Equation 8: Total Area of Cropland Converted to Biomass Feedstock Production

Table 26: Probabilistic Cropland Conversion Equation Variables (Equation 6; Equation 7; Equation 8)

C:	Current Crop	F:	Fixed Cost ($/hectare)	CA:	Converted Area (hectare)
B:	Biomass Feedstock	V:	Variable Cost ($/tonne)	A:	Area (hectare)
P:	Profit ($/hectare)	Cell:	Cellulose Content (SW-model switchgrass) (%)	Pr	Price ($/tonne)
Y:	Delivered Yield (tonne/hectare)			Prob:	Conversion Efficiency (%)

For example data from Duplin County for corn and switchgrass (Table 27) on blanton Sand, 1 to 6 percent slope (BnB) and pantego loam, 0 to 1 percent slope (PnA) soil types showed a total area converted to bioenergy crop production at 15.39 hectares (38.04 acre) (Equation 9).

Table 27: Example Data for Profit Based Cropland Conversion (Duplin County)

	Corn [C] (15.5% MC)	Switchgrass [B] (dry)
Fixed Cost [F] ($/ha)	$979.90	$414.72
Variable Cost [V] ($/tonne)	$12.20	$4.54
Cellulose Content [Cell] (%)	NA	40.34%
Price [Pr] ($/tonne)	$192.90	$82.67
Delivered Yield [Y]		90% annual yield
BnB [Soil] (tonne/ha)	4.46	12.21
PnA [Soil] (tonne/ha)	10.17	13.87
Area (A)		
BnB [Soil] (ha)	56.0	NA
PnA [Soil] (ha)	139.3	NA

Biomass Feedstock Cost

$$\left[\$82.67\ (Pr_{DT}) * \frac{1}{0.37\ (Cell_{SW})}\right] * 0.4034\ (Cell_B) = \$90.13\ (Pr_B)$$

Blanton Sand, 1 to 6 % slope (BnB)

$$\big(4.46(Y_C) * \$192.90(Pr_C)\big) - [\$979.90(F_C) + (4.46(Y_C) * \$12.20(V_C)] = -\$173.98\ (P_C)$$

$$\big(12.21(Y_B) * \$90.13(Pr_B)\big) - [\$414.72(F_B) + (12.21(Y_B) * \$4.54(V_B)] = \$630.33\ (P_B)$$

$$-\$86.99\ \left(\frac{1}{2} P_C\right) < \$630.33(P_B), Prob_{BnB} = 25\%$$

Pantego Loam, 0 to 1 % slope (PnA)

$$\big(10.17(Y_C) * \$192.90(Pr_C)\big) - [\$979.90(F_C) + (10.17(Y_C) * \$12.20(V_C)] = \$820.70\ (P_C)$$

$$\big(13.87(Y_B) * \$90.13(Pr_B)\big) - [\$414.72(F_B) + (13.87(Y_B) * \$4.54(V_B)] = \$772.41\ (P_B)$$

$$0 < \$772.41\ (P_B) < \$820.70\ (P_C), Prob_{PnA} = 1\%$$

Converted Land Area

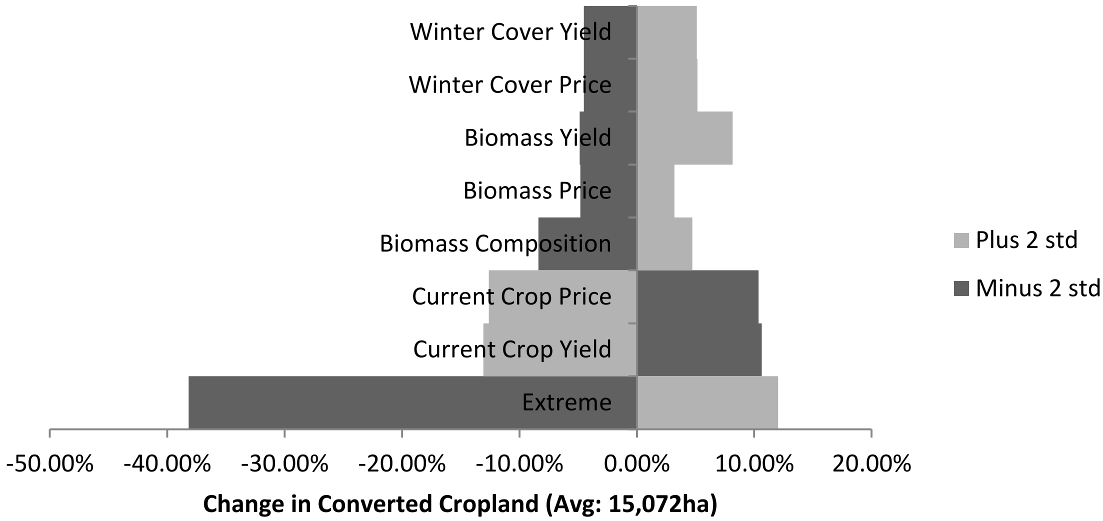
$$[0.25(Prob_{BnB}) * 56(A_{BnB})] + [0.01(Prob_{PnA}) * 139.3(A_{PnA})] = 15.39(CA)$$

Equation 9: Profit Based Cropland Conversion Equation Example

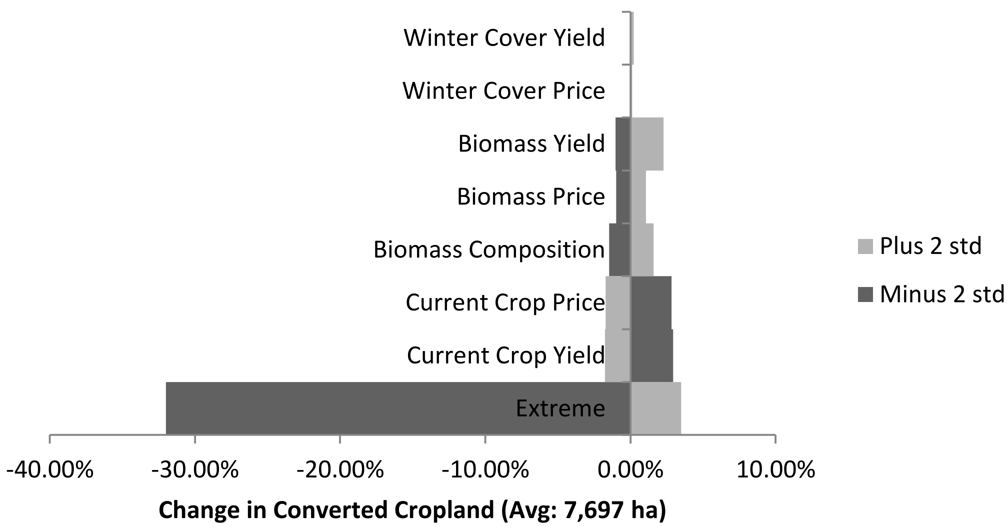
5.3.4 North Carolina Case Study with Uncertainty Analysis

Using average parameter values, the model predicted that a considerably higher amount of land would be converted from current crop production in Duplin County (15,072 ha) than either Granville (7,697 ha) or Henderson (2,117 ha) (Figure 11). These values make some sense since Duplin County has more than 1.5 and 2.5 times the area in production of selected crops (Table 22) compared to Granville and Henderson counties, respectively. For all selected counties the combination of parameters in the extreme negative case (e.g. lower yields, low cellulose composition, low prices) showed drastic decreases in converted cropland, but considerably smaller gains when all parameters were similarly increased (Figure 11). This suggests that the average parameter values already have set the probability function near its maximum value, so increasing these parameters would not entice many additional land managers to convert their cropland. For single parameters, modifications in the current crop price and yield had the greatest effect on cropland conversion probabilities (Figure 11).

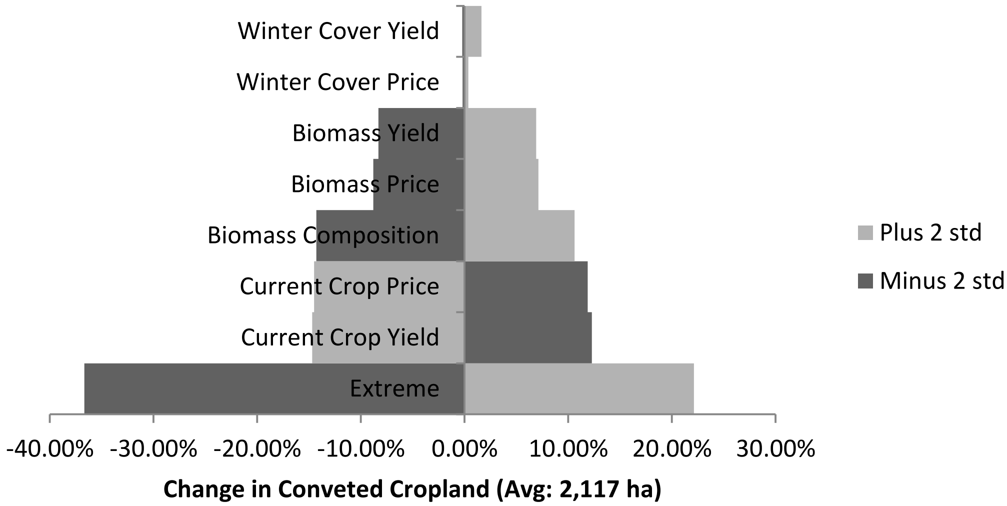
Figure 11: Variation in Converted Cropland to Biomass Feedstocks using Average Values for Parameters [A. Duplin County, NC (Coastal Plain), B. Granville County (Piedmont), C. Henderson County, NC (Mountains)]



A. Duplin County, NC (Coastal Plain)



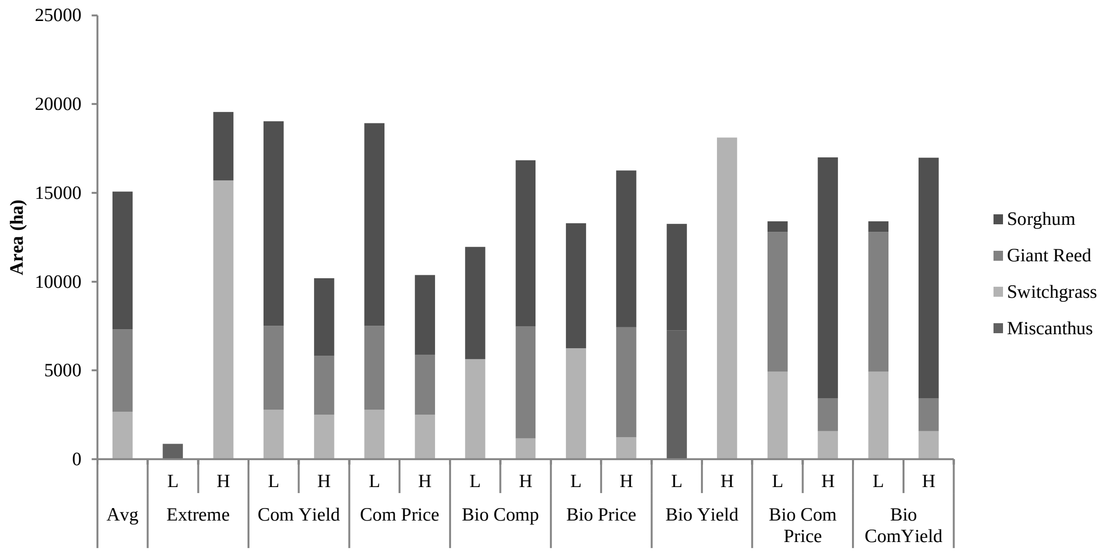
B. Granville, NC (Piedmont)

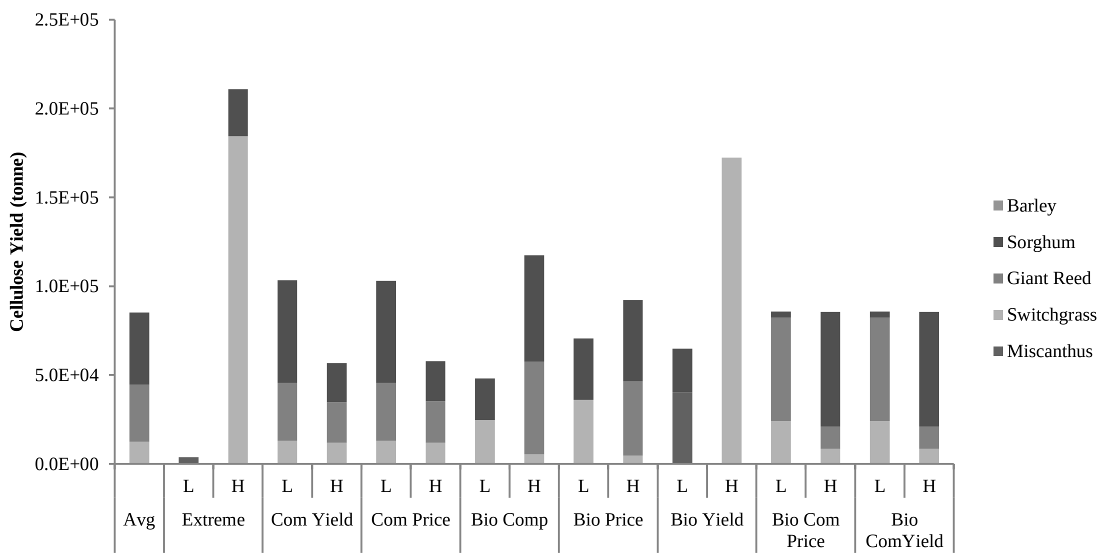


C. Henderson, NC (Mountains)

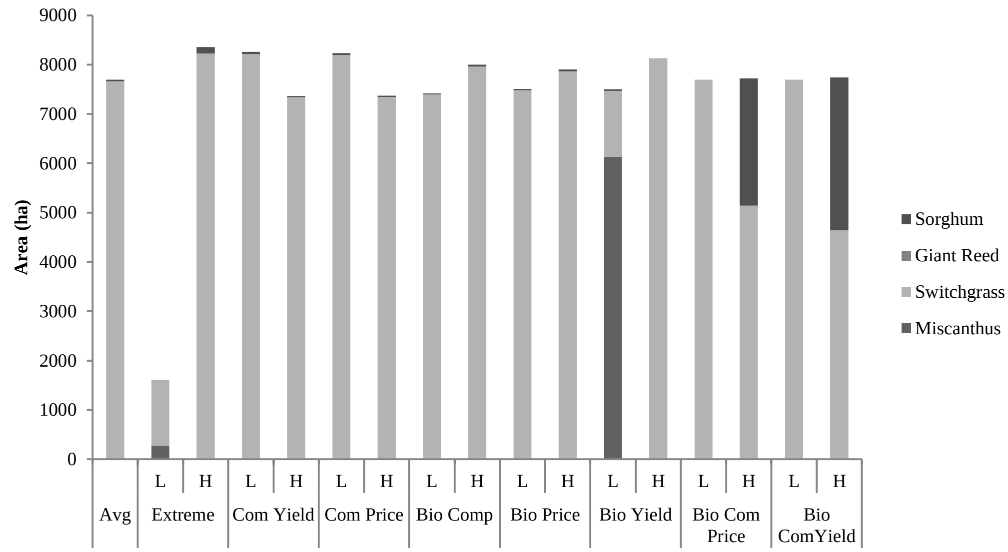
Variations in the selected parameters also had an effect on the mix of biomass feedstocks adopted and cellulose yield from each specific county (Figure 11). The model indicated that for Granville County of the area converted the bioenergy feedstock that would be grown was almost entirely switchgrass (Figure 11B), while Duplin County (Figure 11A) and Henderson County (Figure 11C) generally had a mix of sorghum and switchgrass as the feedstocks adopted. Some giant reed was included in Duplin County (Figure 11A) and miscanthus only was selected as part of the extreme low case and when biomass yields were reduced in Duplin and Granville Counties (Figure 11A; Figure 11B). Inclusion of giant reed was most likely related to its high yield capacity in the Coastal Plain Region and miscanthus was commonly not selected by the model because of its high establishment cost compared to switchgrass (Table 25). Inclusion of miscanthus in poor bioenergy yield situations was likely tied to its low yield standard deviation (Palmer et al. 2014). Predicted cellulose production values for each county was primarily from adoption of perennial grasses because of their greater cellulose content compared to sorghum (Chapter 3). The added soluble carbohydrate concentration of sorghums and an integrated soluble sugar animal feed system was not included in this model, which could alter the economics and overall feedstock value. To put cellulose yield into context, a 75 million liter nameplate facility using a feedstock that is 37% cellulose (Lee et al. 2007) with a dry tonnage conversion of 322 liters per dry tonne (U.S. DOE 2011b) would require approximately 86,000 tonnes of cellulose annually (assuming no storage or handling losses). This would mean that using average parameter values, Duplin County could produce enough feedstock to supply an entire 75 million liter facility, and under the best case parameters it could produce feedstock for more than two and a half facilities of similar capacity (Figure 12A).

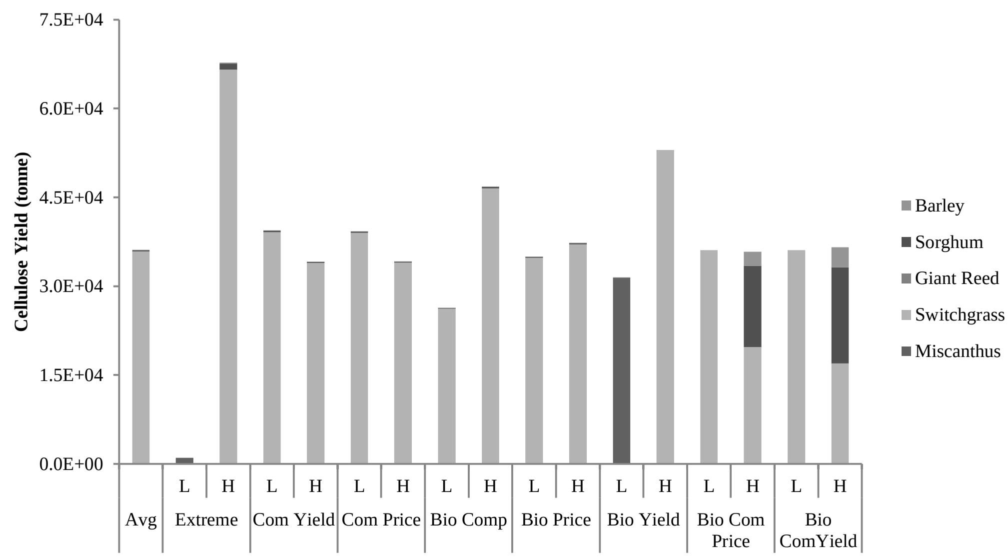
Figure 12: Variation in Biomass Feedstock Production and Cellulose Yield across Parameters of Interest [A. Duplin County, NC (Coastal Plain); B. Granville County, NC (Piedmont); C. Henderson County, NC (Mountains)] [L: - 2σ, H: +2 σ]



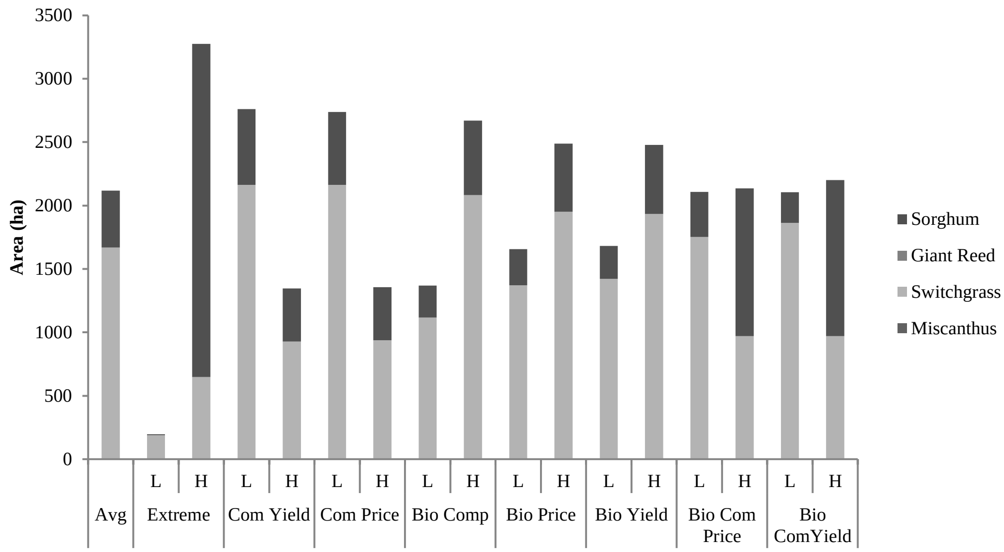


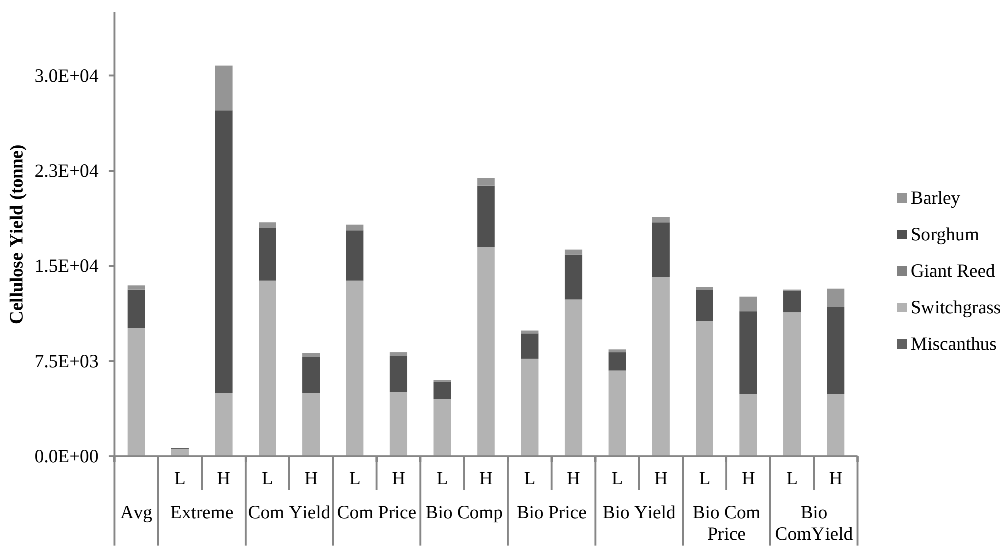
A. Duplin County, NC (Coastal Plain)





B. Granville County, NC (Piedmont)





C. Henderson County, NC (Mountains)

For all scenarios in the Coastal Plain, canola was found to be the winter crop of choice with sorghum, while in the Piedmont barley was usually selected. Though barley does assist with the economics for production it does not contribute a large amount of cellulosic material as part of the to excess straw collected (Figure 12C). Henderson County was split between the two with the majority of sorghum production land area using a barley winter cover, though some soil types showed beneficial yields to justify canola (Table 28).

Table 28: Proportion of Winter Cover with Sorghum in Henderson County (Mountains)

	Low		**High**	
	Canola	Barley	Canola	Barley
Average	11%	89%	11%	89%
Extreme	81%	19%	8%	92%
Commodity Yield	9%	91%	11%	89%
Commodity Price	9%	91%	11%	89%
Cellulose Content	19%	81%	9%	91%
Bioenergy Price	17%	83%	10%	90%
Bioenergy Yield	19%	81%	10%	90%
Bioenergy Commodity Price	14%	86%	4	96%
Bioenergy Commodity Yield	20%	80%	4^	96%

The number of crop types shown in Table 22 was reduced to those that were at least ten percent of the converted area in at least one of the counties (Figure 13), using average parameter values within the model. In Granville and Henderson Counties cropland associated with grassland and hay production was the primary type converted to biomass feedstocks, while in Duplin County profitability was observed over a greater number of traditional agricultural products, with the greatest proportions being tied to corn, hay and grassland (Figure 13). When the proportion of total land area converted from current use for each of the selected agricultural products in a county were taken into account there was a high percentage of hay, grassland, and fallow land converted (Table 29). This was a result of all of these land areas being related to the average price of hay, which is commonly undervalued. NCSU (2008) provided a range of prices for hay production after accounting for all operations and storage losses between \$180 to \$245 per dry tonne, which was considerably higher than the \$143 per dry tonne (\$121/tonne, at 15% MC) average sales price for hay in North Carolina (USDA 2013). The calculation done by NCSU (2008) did not account for additional benefits of hay production, such as nutrient removal from animal production operations, which can favorably alter the system economics .

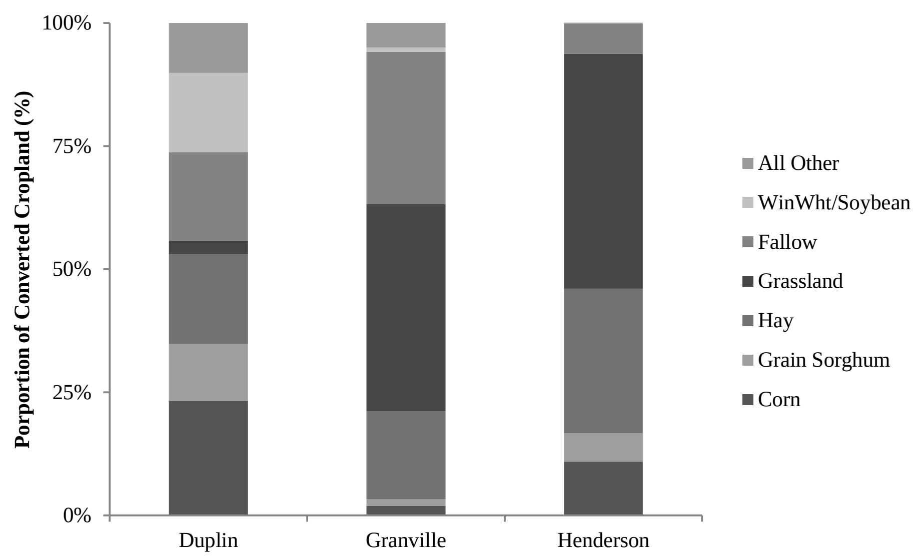


Figure 13: Proportion of Total Converted Land by Selected Current Agricultural Product

Table 29: Proportion of Total Current Cropland Converted to Biomass Feedstocks

	Duplin	Granville	Henderson
Corn	17%	10%	6%
Grain Sorghum	18%	4%	21%
Hay	23%	24%	15%
Grassland	24%	23%	25%
Fallow	24%	23%	25%
WinWht/Soybean	14%	2%	21%

5.4 Conclusion

Through use of the North Carolina case study the model has shown its usefulness to potential biorefinery facility planners by providing an estimate of cropland converted from traditional agricultural products to biomass feedstock production. The enterprise budgets used functioned as expected, with cash crops like tobacco, cotton, and sweetpotato showing low cropland conversions (Appendix C). Use of soil type to determine realistic yield provided flexibility for the model to be used over many different land areas and provide meaningful estimates for a range of feedstocks to be produced in each region (Figure 12). Uncertainty analysis showed that the different land areas displayed differing parameter sensitivity, with average values being near the higher end of the probability function and the combination of factors in the worst case showing drastically reduced conversion of cropland (Figure 12).

A major limitation to this modeling approach is data availability. Increased information from land owners on what is required for cropland conversion and use of more detailed cropland cover information can produce more accurate results, which can be accomplished through surveys of local areas. It may also be best to set a minimum field size that is required for conversion, such as one hectare, to allow for optimal logistical operations if harvest equipment is to be moved between locations. Use of multiple years of data would allow for determination of which fields would be best suited for conversion to a perennial biomass crop, and implement a multi-year rotational schedule that may allow for annual biomass crop production. Multi-year rotational schedules are common in many cash crops to disrupt the life cycle of pests and diseases, diversify products, and promote soil health.

In 2012 the data derived from the billion ton update (U.S. DOE 2011a) found that at a biomass price of $66 per dry tonne ($59.87 per dry ton) Duplin County had 28 to 56 thousand dry tonnes of agricultural biomass available (30.86 to 61.73 thousand dry tons), while Granville and Henderson would produce between 0 and 4 thousand dry tonnes (0 and 4.4 thousand dry tonnes), including residues (U.S. DOE 2014). By 2022 this was estimated to increase to between 60 and 150 thousand dry tonnes for Duplin County (66.1 and 165.3 thousand dry tons), and agricultural biomass in Granville and Henderson Counties was estimated to increase to between 0 and 25 thousand dry tonnes (0 and 27.6 thousand dry tons) (U.S. DOE 2014). Using standard cellulose content for model switchgrass at 37% (Lee et al. 2007) the developed model estimates total biomass produced in Duplin, Granville, and Henderson at 30, 12, and 4 thousand dry tonnes annually respectively (33.1, 13.2, 4.4 thousand dry tons), using average parameters. The discrepancy between the reported values and those calculated by U.S. DOE (2014) may be due to this model only focusing on dedicated bioenergy feedstocks, not accounting for crop residues that may increase total availability. The inclusion of residues, and specific system parameters, need to be addressed when data from this modeling exercise are used outside of the specific parameters of the analysis.

The results of this modeling approach showed that switchgrass is the primary feedstock of choice when profitability is taken into account for the selected counties, with some sorghum included (Figure 12). Use of this modeling approach is not limited to biomass feedstocks, but can be used for determination of cropland conversion potential or determination of profitability for land managers for other agricultural crops.

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CHAPTER 6: BIOMASS FEEDSTOCK LOGISTICS OPTIMIZATION: CASE STUDY FOR NORTH CAROLINA

6.1 Introduction

In the U.S. the major feedstocks for biofuel production come from agricultural commodity crops, which have been historically grown as food and animal feed products (corn-grain based ethanol and soybean oil based biodiesel) (U.S. EPA 2011). This has spurred a debate, known commonly as Food vs. Fuel, over the sustainability of using these crops for energy production. One option for bioenergy production that provides an alternative to use of these commodity crops are lignocellulosic sources, including dedicated energy crops, residues, and waste products (both forestry and agricultural products). A revised set of renewable fuel standards was set in EISA 2007 (U.S. Cong 2007) that call for the production of 102.21 billion liters per year (27 billion gallons per year) by 2022 with 60.56 billion liters per year (16 billion gallons per year) coming from lignocellulosic sources (U.S. DOE 2011a). Currently the production of biofuels from lignocellulosic sources is constrained to a handful of second generation facilities utilizing corn stover as a feedstock in the Midwest.

Since limited data was available on a national scale to determine the possibility of reaching these lignocellulosic feedstock goals an update to the 2005 Billion Ton Study (U.S. DOE 2005) was conducted, the 2011 Billion Ton Update (U.S. DOE 2011a). Under the baseline scenario using a $66.14 per dry tonne purchase price ($60 per dry ton), modeling found that by 2022 dedicated energy crops would account for 33.72% of the 546.13 million dry tonnes (602 million dry tons) of potential feedstock sources (U.S. DOE 2011a). Using the high yield scenario this would increase to between 47.95% and 55.90% of potential resources, or 371.95 to 511.65 million dry tonnes nationally (410 to 564 million dry tons) (U.S. DOE 2011a). Dedicated energy crop classifications are based on herbaceous or woody biomass materials grown under intensive management practices specifically to produce energy.

Conversion of lignocellulosic feedstocks to biofuels is an area still under development and optimization, and is listed as one of the seven board action areas by the Biomass Research and Development Board (BR&DB 2008). Due to the infancy of the technology and economies of scale it is currently not feasible to consider conversion of lignocellulosic feedstocks directly to biofuels at farm scale, thus requiring logistical operations to accommodate production of material for an off-site biorefinery, a facility producing products from biological sources. "Economies of scale" refers to the general idea that as total output of an industrial operation increases, the price per unit decreases. As the size of a biorefinery, increases, the non-feedstock costs decrease while feedstock costs increase as a result of transportation and handling costs (U.S. DOE 2002). Using a ten percent cropland inclusion assumption for corn stover (*Zea mays* L.) as a feedstock, the U.S. National Renewable Energy Laboratory (NREL) found a corn stover biorefinery located in Iowa below 2,000 dry tonnes per day of feedstock (1814.4 dry tons/day) (approx.: $0.36/liter or $1.38/gallon minimum ethanol sales price) is cost prohibitive primarily because of non-feedstock costs, yet a plant above 10,000 dry tonnes per day (approx.: $0.35/liter or $1.32/gallon) loses out on cost savings by expanded scale related increased transportation costs (U.S. DOE 2002). A reduction in biomass logistics costs can potentially have major impacts on the minimum ethanol sales price, necessary to increase profitability of a biorefinery.

Biomass logistics encompasses operations form the harvest of lignocellulosic feedstocks to the point of feeding the material into the throat of the biorefinery. Additionally, logistics is listed by the Biomass Research and Development Board as an action area (BR&DB 2008). Some of the operations of biomass logistics include: harvest & collection, storage, transportation & handling, and pre-processing. Depending on the specific feedstock, biorefinery operations, and region among other site specific characteristics, different logistic operations may be warranted. This may mean specialized harvest operations, densification of feedstocks, pre-processing of the feedstock prior to arrival at the biorefinery, or an array of other options. The most important aspect of these systems is that a uniform feedstock is delivered on a regular schedule to the biorefinery at the lowest cost possible. In most cases the biomass logistics system will change most readily due to the feedstock being utilized by the biorefinery.

A wide range of parameters including feedstock types, transportation methods, modeling boundaries, and research scopes have been used to model biomass logistics chains. Resop et al. (2011) used a geographic information system to set uniformly spaced storage sites to determine the least cost storage and transportation costs for baled perennial grasses. This was then improved by Judd et al. (2012) using a solution to a traveling salesmen problem to optimally set storage location in an effort to optimize mobile processing and handling equipment. The Integrated Biomass Supply Analysis and Logistics (IBSAL) model was created to investigate the entire feedstock logistics chain from seed to biorefinery

(Kumar & Sokhansanj 2007). Less computationally intensive modeling of these logistics chains have been developed with focus on feedstock characteristics more than optimization of logistics chains, similar to work by Worley & Cundiff (1991). The Uniform Format Bioenergy Feedstock Supply System was designed by the U.S. DOE to handle biomass feedstocks similarly to agricultural commodity crops (U.S. DOE 2009). Similar to the IBSAL model, researchers at the University of Illinois at Urbana-Champaign have developed the BioFeed model that is directly targeted for the state of Illinois (Shastri et al. 2011; Shastri et al. 2012). Simulation models have been developed to treat biomass feedstocks similar to existing agricultural crops such as: cotton (Ravula et al. 2008), sugarcane (Cundiff & Grisso 2008), and wood products (Cundiff et al 2004). Even multi-echelon modeling approaches have been implemented to model the complex biomass logistics chains for bioenergy production (An et al. 2011). Each of these systems optimizes their formats, generally by cost, for a particular portion of the bioenergy production pathway, not the entire system.

The objective of this analysis was the construction of a model to site a potential biorefinery, determine cropland conversion to biomass feedstocks, estimate required price to meet plant needs, and evaluate harvest system operations. A case study was completed for three potential biorefinery sites in North Carolina representing the three major regions of the state: Mountains, Piedmont, and Coastal Plain. This approach differs from other studies of logistical operations by incorporating two potential feedstocks and harvest systems that may be implemented concurrently, allowing for increased equipment utilization and incorporation of biomass feedstocks into existing agricultural crop rotations in the Southeast.

6.2 Biomass Logistics Operations

6.2.1 Computational Analysis

Modeling of these systems was performed in the MatLab environment (Mathworks: Natick, MA) utilizing the MatLog logistical toolset developed at North Carolina State University by Dr. Michael Kay (Kay 2014). Data from ArcGIS (ESRI: Redlands, CA) was transferred to MatLab for analysis as a comma delineated text file, which was converted to a structure for use in MatLab.

6.2.2 Heuristic Biorefinery Siting

Potential locations for biorefinery facilities were determined using a heuristic to minimize the number of sites for analysis in the developed model (Table 30). Since a biorefinery is an industrial operation requiring extensive infrastructure locating a facility near a medium sized city would be beneficial. The city would need to be large enough to provide infrastructure requirements of the facility but small enough to reduce nuisance issues related to logistical operations, such as increased tractor trailer traffic, loose biomass material appearing on roadsides, and twenty-four hour operations of the supply chain. Density of agricultural land is an important parameter to consider within a given radius of the facility, especially since the closer the feedstocks are produced the lower the logistical complexity and costs. This is related to both feedstock availability and community acceptance of agricultural operations. Finally it is important to consider characteristics of the potential area for available workforce and to place facilities within an economically depressed rural area. Siting a facility in these areas can lead to additional government and community support of the potential biorefinery, as well as ensuring that adequate personnel trained in the required fields are available for operations.

Table 30: Biorefinery Siting Heuristic Parameters

	Min	Max	Parameters	Source
City Size	10k	50k	Population	USDA (201)
Natural Land	25%	100%	Cultivated Crops, Hay/Pasture, Shrub/Scrub, Barren Land, Herbaceous	U.S. DOI (2014) (within 80.47 kg (50 mi))
Regional Data	Multiple	Multiple	Employment Status, Occupation, Poverty	U.S. BOC (2014) (county specific)

6.2.3 Feedstock & Harvest System Selection

The feedstock supply chain for a biorefinery includes complex interconnected operations combining feedstock production, biomass logistics, and biorefinery facility operations. To reduce complexity of these systems a plantation style production system may be employed, where the biorefinery would operate large farms surrounding the biorefinery or specified storage locations. This would require large land and equipment investments, while diverting focus from conversion facility optimization. It is more likely that the conversion facility would contract local land managers to produce feedstocks, allowing individuals knowledgeable in field operations and owning agricultural equipment to focus on feedstock production. This shift in production system will create a disaggregated set of fields that would complicate biomass logistics operations required.

Complexity of the logistics system would shift focus overly from conversion facility operations, which may necessitate the inclusion of a third entity to optimize logistical operations. Use of the term biomass logistics in this case would include harvest, storage, and transportation operations spanning from standing biomass feedstocks to delivery at the biorefinery. This scenario creates a three party system of land managers, biomass logistics operations, and the conversion facility allowing each to include experts in the individual areas that can optimize operations.

North Carolina crop selection investigations found a combination of Switchgrass (*Panicum virgatum* L.) and Sorghum (*Sorghum bicolor* (L.) Moench) production to be profitable (Chapter 5). Switchgrass can be harvested and stored annually from the same field, while sorghum can be integrated with other annual cash crops on a multi-year crop rotation. As a winter annual with sorghum, rapeseed (*Brassica napus* L.) was selected to include as a food and feed product, though other winter annuals are possible.

Sorghum necessitates harvesting with a forage chopper and canola with a combine. Switchgrass on the other hand can be harvested in round bale, square bale, or a forage chopper with a pickup head either in the fall or winter. It is possible to use a multi-harvest system for switchgrass extending the harvest period, but it may increase cost significantly. Using average feedstock production values for Duplin County (Chapter 5), a comparison of harvest systems can be made (Table 31). In-field transportation included loading/unloading (4 bales every 15 minutes, to account for field aggregation) and transportation using a bale mover (16.1 kilometers (10 miles) at 88.5 kilometer per hour (55 miles per hour), holding 16 bales per load). Storage was modeled for outdoor crushed gravel pads covered with tarpaulins to reduce cost and dry matter losses, with tarpaulins and gravel pads found to be slightly higher in dry matter loss than indoor storage, but considerably lower than uncovered outdoor (Saxe 2004) (Chapter 4: Outdoor Round Bale- 14% dry matter loss, Indoor Square

Bale- 4.25% dry matter loss). Transportation combined loading of bales, transportation for 80.47 kilometers (50 miles), and unloading at the conversion facility, with a telehandler used for bales and a truck dump for forage chopped material (using measured bulk densities from Chapter 3).

Table 31: Comparison of Biomass Harvest Systems for Duplin County, NC

	Fixed [$/ha] ($/ac)	Harvest [$/ha] ($/ac)	Field Transport [$/ha] ($/ac)	Storage [$/ha/yr] ($/ac/yr)	Transportation [$/ha 80.47 km] ($/ac 50 mi)	Final [$/ha] ($/ac)	Unit [$/dry tonne] ($/dry ton)
Switchgrass							
Round Bale	$334 ($135)	$73.52 ($29.75)	$108.55 ($43.93)	$1.21 ($0.49)	$314.24 ($127.17)	$831.11 ($336.34)	$46.35 ($42.05)
Square Bale	$334 ($135)	$81.12 ($32.83)	$90.05 ($36.44)	$40.45 ($16.37)	$226.18 ($91.53)	$771.39 ($312.17)	$38.44 ($34.87)
Forage(fall)	$334 ($135)	$129.04 ($52.22)			$203.07 ($82.18)	$665.70 ($269.40)	$31.76 ($28.81)
Forage (winter)	$334 ($135)	$129.04 ($52.22)			$147.08 ($59.52)	$608.87 ($246.40)	$29.09 ($26.39)
Sorghum	$460 ($186)	$130.50 ($52.81)			$173.02 ($70.02)	$763.14 ($308.83)	$38.00 ($34.47)

Values for perennial grasses are averaged across fall and winter harvests
Sorghum a fall only harvest
(See Appendix C for enterprise budget citations)

Values shown in Table 31 were calculated using existing equipment cost information from Lazarus (2009) and Lazarus (2014), using field capacity and equipment information from major commodity crop production in Minnesota, with the intent of modeling costs for the n^{th} field. Though establishment equipment costs are probably relatively similar, depending on seeding rates, a major difference may be related to harvesting operations. With the high biomass crop yields compared to hay and additional wear on equipment of the larger diameter rigid stems actual field operations may be considerably higher. The higher yields of biomass crops compared to hay may reduce field efficiency, especially for round balers that must stop to bind and discharge each bale. Larger diameter more rigid stems of biomass feedstocks can increase wear of equipment, reducing equipment lifetime and increasing maintenance costs. The values in Table 31 did not account for land value since the majority of commodity enterprise budgets also did not account for this value, which would have raised per hectare costs by $207.57 annually for non-irrigated cropland in North Carolina ($84 per acre) (USDA 2015).

Though sorghum shows a higher production cost than some of the other systems the inclusion of a winter annual crop would decrease the unit price of sorghum to $30.91 per dry tonne ($28.04 per dry ton) (Atkinson et al. 2006), at a $302.77 per tonne canola price ($8.24 per bushel). Additionally this would allow the inclusion of an annual summer crop into other cash crop rotations, increasing land availability while reducing initial land manager investment. This demonstrates that the lowest cost system would include forage chopping switchgrass in the winter and sorghum in the fall, moving the supply chain closer to a just in time system, while producing big square bales over the same time period, which would be stored to allow year round supply availability. When storage is removed from the values calculated in Table 31 square bales continue to be more profitable than round, with forage chopping operations being the most profitable, similarly when transportation and the combination of both are excluded. Ensiled storage was not included because it would increase the cost of forage chopped switchgrass to $51.83 and $49.19 per dry tonne ($47.02 and $44.62 per dry ton) for fall and winter harvests respectively, and sorghum to $58.95 per dry tonne ($53.47 per dry ton), using transportation and filling/packing values from Benson et al. (2013). These additional costs may be worthwhile in conversion processing; however, the boundaries of the model end at the biorefinery throat and do not capture the potential benefits of ensiled storage.

A set of harvest systems was constructed to reduce safety stocks, increase utilization of capital intensive specialized equipment, and increase utilization of just in time operations (Figure 14). The same fleet of self-propelled forage choppers could be used for both sorghum and forage chopped switchgrass, just changing the pickup head between crops to provide biomass for immediate use at the biorefinery. Baling the specific fields within the harvest window (Figure 14) will create a safety stock of bales during just in time operations and create a stock of bales to be used for the following six months to ensure year round operations of the conversion facility. Generally, two week to one month maintenance down time is incorporated for similar large industrial facilities, which can be scheduled prior to the harvest period corresponding to the lowest level of storage. The storage sites would be emptied on a first in first out method, creating a uniform storage time of approximately six months for all bales ensuring uniform removal operations at storage sites.

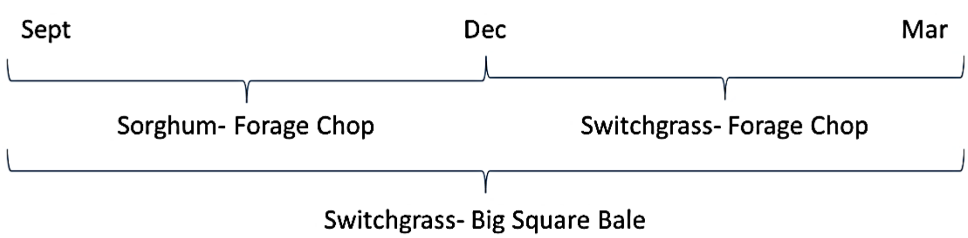


Figure 14: Biomass Feedstock Harvest System Proposed for Analysis

Though the harvest periods shown in Figure 14 may consist of multiple months the actual working days are significantly lower, depending on weather and soil moisture levels. Using a probabilistic method accounting for weather and soil moisture across representative Oklahoma counties Hwang et al. (2009) determined the number of working days for mowing and baling switchgrass (Table 32). Depending on the standing crop moisture content baling may occur directly after mowing, without the need for any additional field curing. In North Carolina well drained sandy soils in the Coastal Plain may allow additional working days, while the poorly drained clay soils of the Piedmont may reducing working days.

Table 32: Working Days for Mowing and Baling of Switchgrass across representative Oklahoma counties (Hwang et al. 2009) (95% probability level)

	Total Days	**Mowing**		**Baling**	
		Low	*High*	*Low*	*High*
Sept-Nov	91	42 (46%)	55 (60%)	38 (42%)	57 (63%)
Dec-Feb	90[1]	23 (26%)	31 (34%)	31 (34%)	55 (61%)

[1]Common year, non-leap year

Inclusion of barley (*Hordeum vulgare* L.), in place of canola on sorghum fields, would allow utilization of the big square balers during barley harvest, May through June, for straw that can serve as an additional lignocellulosic feedstock. This may increase just in time operations, further reducing storage requirements. As a result of the high cost of barley production (Chapter 5) and low primary product value it was not included, though further analysis and system optimization may increase profitability and potential incorporation into this harvest system model with sorghum.

6.2.3 Prediction of Cropland Conversion to Biomass Feedstocks

A probabilistic profit based cropland conversion method was used to determine potential biomass feedstock production locations (see Chapter 5 for methodology). Yield data was used for the county where the potential conversion facilities were located, using North Carolina realistic yield expectations (Crouse 2003) for average and standard deviation values across soil types. Potential feedstock production fields were determined using a fifty mile radius from possible conversion facilities (based on the centroid of each field to facility location) using NASS cropland cover data (USDA 2014) in ArcGIS. After using a normal random variable to determine yield variation in each field a uniform random variable was used to determine if a field converted to biomass feedstock production, after using the prescribed probabilistic equation in Chapter 5 for conversion probability.

Total feedstock requirements were determined for a 75.71 million liter cellulosic ethanol facility (20 million gallon) that uses an 354.68 liter per dry tonne conversion rate (85 gallon per dry ton) (U.S. DOE 2011b), or approximately 585.13 dry tonnes per day (645 dry tons). Safety stock included yield variability and storage losses, with other safety stock issues being alleviated by feedstock harvest schedule (Figure 14). A price of $33.07 per dry tonne ($30 per dry ton) was initially used, and if available feedstock did not equal the requirements for each of the categories then the price was raised by $1.10 per dry tonne ($1 per dry ton) until enough feedstock was available. This method accounts for profit above breakeven costs for both existing agricultural products and biomass feedstocks; though this does not represent the actual price that would most likely be paid by the conversion facility for the feedstock. These sites were used as the potential feedstock production locations.

Site selection criteria followed the highest cost transportation method first until feedstock requirement was filled, followed by the following crop and harvest group. This means that if forage chopped sorghum was the most expensive to transport on a $ per dry tonne-kilometer basis, feedstock production sites closest to the conversion facility would be allocated to sorghum production until annual tonnage requirements were fulfilled, then the next most expensive transportation method would evaluate remaining potential sites. Only a single year of cropland cover was used for this analysis to determine conversion related to profitability, so the multi-year nature of perennial grasses (i.e. switchgrass) would need to be evaluated over multiple years to determine if a given land parcel would convert to production. Use of a single year to determine profitability was deemed adequate for this analysis since the objective was to demonstrate use of the proposed logistical system, not to determine specific production locations. Since specific quantities of feedstock are required for each harvest and feedstock combination, a defined area was required. This method determined which potential feedstock and harvest combination would be produced at each location, choosing feedstock order by transportation cost in $ per dry tonne-kilometer.

6.2.4 Biomass Storage Operations

Storage site location configurations can be split into three categories: centralized, dissipated, and decentralized. Centralized would require all material to be stored at a central storage location for use at the conversion facility, most likely near the facility. For the six months of feedstock required to operate outside the harvest range (Figure 14), excluding safety stock, approximately 130,000 dry tonnes of feedstock would be required (118,000 dry tons). If each 0.9x0.9x2.3 m (3x3x7.5 ft) big square bale of switchgrass weighed 340 kilograms (750 pounds) at 15% moisture content (wet basis) that would mean storage of around 370,000 bales, or almost 708 thousand m^3 (25 million ft^3). For a 9.1 meter (30 foot) tall stack (10 bales) this would require approximately 7.7 hectares (19 acres), or closer to 16.2 hectares (40 acres) accounting for lanes for use in handling and as fire breaks. The large requirement of contiguous land area for the centralized storage method makes it unreasonable, with multiple smaller storage yards allowing for use of marginal or low value land areas and reducing the risk of a single localized catastrophic event impacting stored biomass material. Additionally a single storage location with one entry point would require increased handling requirements as stored material is removed, or movement of the staging area requiring additional travel distance across the storage yard.

A dissipated storage location method would require each individual field to have a co-located storage yard for harvested feedstocks. For a 4.05 hectare (10 acre) field at 17.93 tonnes per hectare yield (8 dry ton per acre) a storage area for 250 bales would be approximately 93 square meters (1000 square feet). Though this is a reasonable storage area a proper site in each individual field may be difficult to locate, as well as an annual payment to the land manager for use of that land. If all fields were 4.05 hectares (10 acres) there would be around 1500 storage sites that would need to be managed and a proper transportation network maintained, which would greatly increase the complexity of the supply chain and require many partial loads to either be shipped to the conversion facility or taken to the next storage location to complete the load.

A combination of these methods would be the decentralized system where multiple storage sites are produced in a wheel and spoke system to store material from multiple farms.

This would reduce the size of each of the storage sites and reduce the complexity of the logistics network. An alternative location allocation heuristic was utilized to determine the location of ten optimally located storage yards for the developed model. These sites would use a storage method that involved crushed gravel to allow drainage and use of tarpaulins to reduce weathering, minimized total storage cost and dry matter loss (Saxe 2004).

6.3 Case Study for Regions of North Carolina

6.3.1 Biorefinery Siting Heuristic

For this analysis three cities were chosen across North Carolina to represent the three major regions of the state: Lenoir (Mountains), Sanford (Piedmont), and Kinston (Coastal Plain (Table 33). These regions represent different cropland densities and current agricultural crop production, both of which may influence selection of prospective fields for biomass feedstock production, and subsequently the supply chain configuration.

Table 33: Selected North Carolina Biorefinery Location Site Parameters (US Census Bureau 2010; NLCD data & TIGER database)

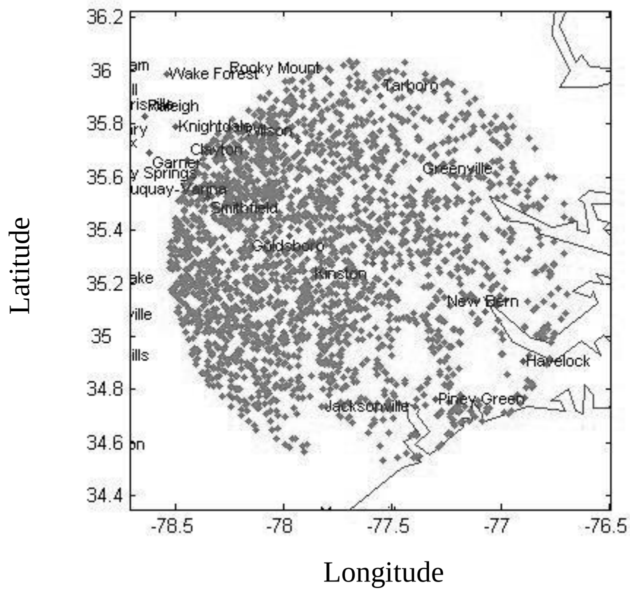
	Kinston (Coastal Plain)	**Sanford (Piedmont)**	**Lenoir (Mountains)**
City Size	21,677	28,094	18,228
Natural Land Density	45.6%	34.1%	25.9%
Economically Depressed County (DP3)			
Employment Status			
In Labor Force (VC05)	60%	60.5%	65.6%
Unemployed (VC13)	9.1%	10.5%	9.8%
Occupation			
NatResources/Construction/Maintenance (VC44)	13.9%	12.3%	11.5%
Production/Transport/Handling (VC45)	19.3%	27.4%	22.9%
Industry			
Ag/Forestry/Fish&Hunt/Mining (VC50)	3.5%	1.1%	1.5%
Construction (VC51)	7.9%	7.5%	8.1%
Manufacturing (VC52)	17.6%	27.7%	26.6%
Transport/Warehouse/Utilities (VC55)	3.5%	5.2%	3.4%
Income and Benefits			
<10,000 (VC75)	13.6%	9.3%	8.9%
10,000 to 14,999 (VC76)	9.3%	9.5%	6.1%
15,000 to 24,999 (VC77)	14.5%	14.6%	12.7%
25,000 to 34,999 (VC78)	14.7%	14%	11.3%
35,000 to 49,999 (VC79)	15%	14.5%	16.5%
Families/People Below Poverty Line (VC156)	18%	12%	11.6%

6.3.2 Cropland Conversion to Biomass Feedstocks & Storage Operations

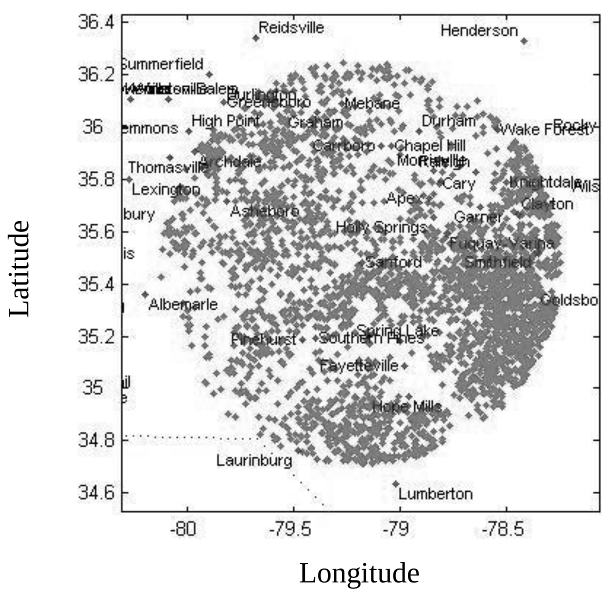
All of the potential biorefinery locations had a large number of fields greater than one acre within an 80.47 kilometer radius (50 mile) (130 to 180 thousand fields for each of the selected sites). From analysis in Chapter 5, it was decided to reduce the cropland cover areas of interest to those currently in corn, grain sorghum, winter wheat/soybeans, hay, fallow, and grasslands. Enterprise budgets for each of these were used to determine profitability (Bullen & Weddington 2012a; Bullen & Weddington 2012b; NCSU 2014; Bullen & Dunphy 2012a; Bullen & Dunphy 2012b; Bullen & Weddington 2012c; Bullen & Weddington 2012d; Green & Benson 2013a; Green & Benson 2013b; Green & Benson 2013c; Green & Benson 2013d), including average realistic yield expectations (Crouse 2003) for each county with a normal random variable to account for variability among soil types. Using a uniform random number generator, if the probability function (Chapter 5) was less than the number generated the field was likely to convert to production of a biomass feedstock.

All of the potential sites showed adequate feedstock at a purchase price of $33.07 per dry tonne ($30 per dry ton). This should not be used as the actual purchase price for feedstocks since due to the large number of fields, inclusion of a one percent inclusion rate for profitability (even if current crops are greater), and low value assigned for hay and grassland production the model may be overestimating available field acreage at the given price point. What it does do is give an idea of how the biomass production sites would be dissipated and provides a method for simplifying logistical operations within this system. This also reduced the number of potential sites from the initial number of sites in the 80.47 kilometer radius (50 mile) (which was over one hundred thousand for each potential biorefinery location) to between 2400 and 5100 (Figure 15). The coastal plain region showed the least number of potential sites, while the mountains showed the highest. This could be related to the number of initial sites, size of each field, and profitability of the current agricultural products.

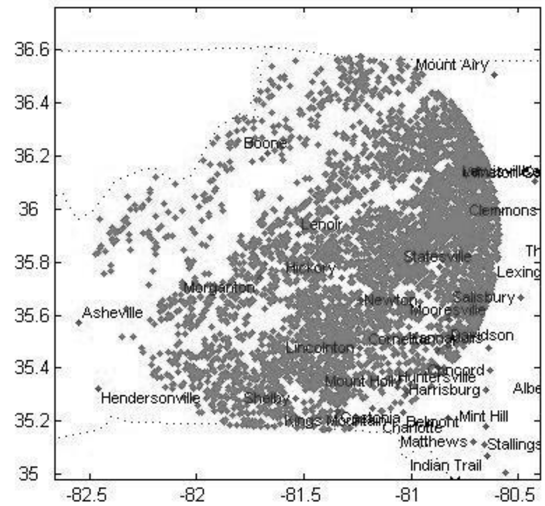
Figure 15: Potential Feedstock Production Locations [A. Kinston, B. Sanford, C. Lenoir]



A. Kinston



B. Sanford



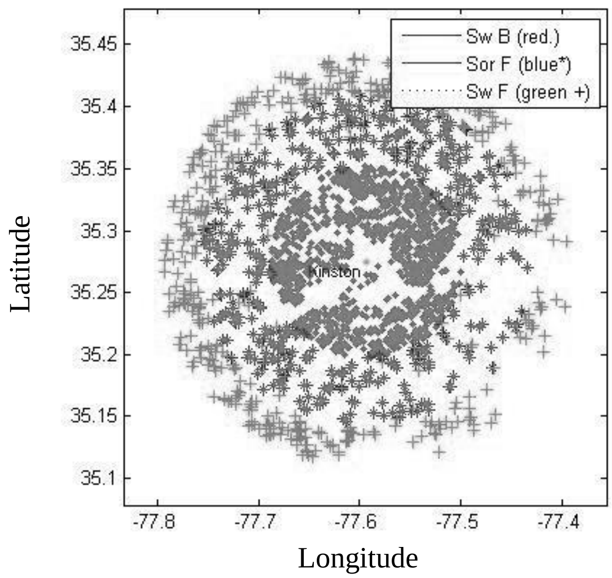
Latitude

Longitude

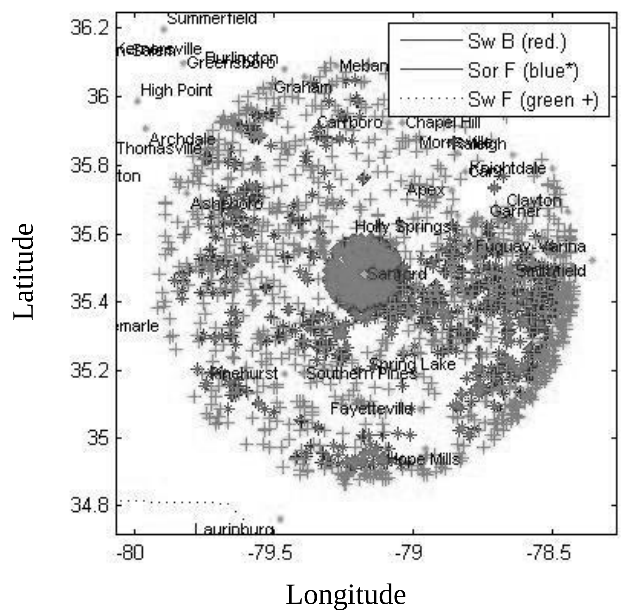
C. Lenoir

Converting feedstock transportation cost to $ per dry tonne-kilometer from $ per hectare (Table 31), and removing loading and unloading, the total cost of sorghum, switchgrass forage, and switchgrass square bales was $0.10, $0.10, and $0.03 per dry tonne kilometer ($0.14, $0.14, and $0.05 per dry ton-mile), respectively. This leads to a priority of feedstock production sites by radial distance from the conversion facility in order of: switchgrass square bales, sorghum forage chopped, and switchgrass forage chopped. Feedstock production sites were selected from the closest point moving radially in order of transportation cost priority, and removes sites that were already selected (Figure 16).

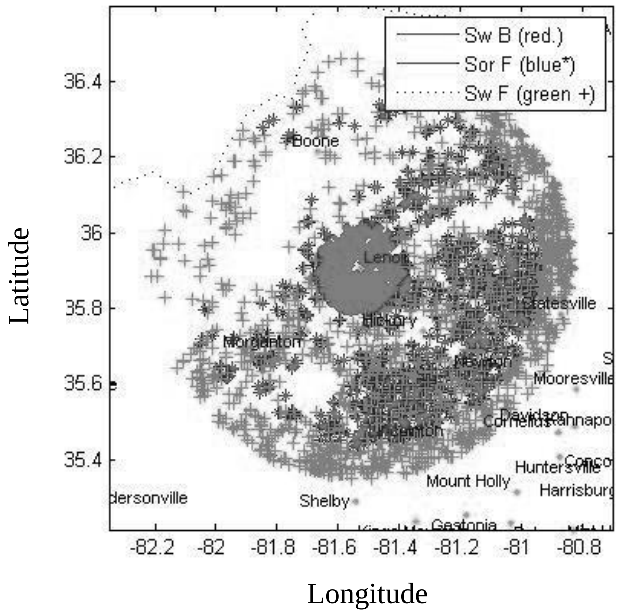
Figure 16: Select Feedstock Production Locations [A. Kinston, B. Sanford, C. Lenoir]



A. Kinston



B. Sanford



Sw B (red.)
Sor F (blue*)
Sw F (green +)
36.4
36.2
36
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Latitude
-82.2
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-81.6
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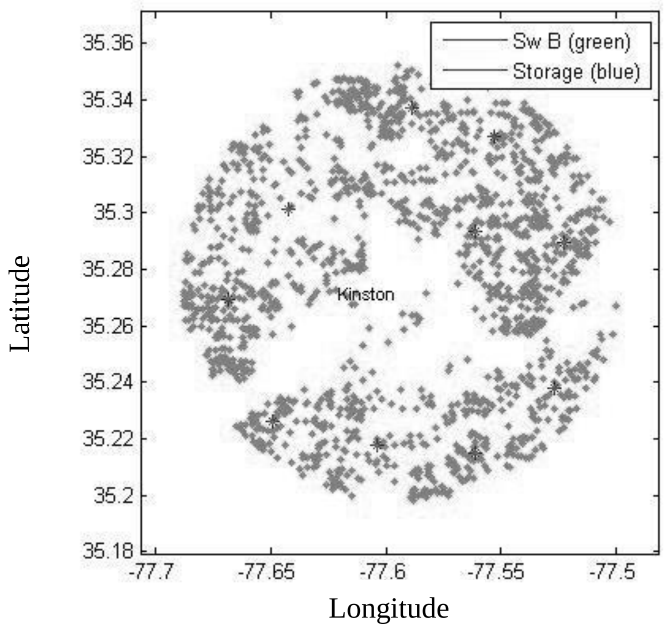
-81.2
-81
-80.8
Longitude
Boone
Statesville
Mooresville
Mount Holly
Harrisburg
Shelby
Gastonia

C. Lenoir

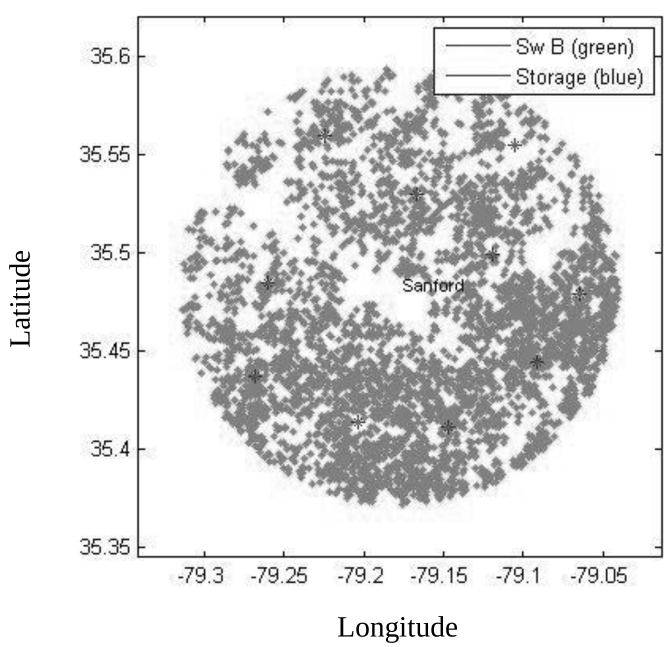
The farthest distance for all of the feedstock systems was for forage chopped switchgrass, which had a farthest location of 69.2, 18.4, 62 kilometers (43, 11.4, and 38.5 miles) for Sanford, Kinston, and Lenoir, respectively. The allocation of feedstocks for Sanford (Figure 16B) was not as defined as Lenoir (Figure 16C) or Sanford (Figure 16A). This was related to many locations in the Piedmont showing favorable economics with switchgrass and not sorghum (as seen in Chapter 5). All potential biorefinery locations locate switchgrass bale operations closely to the conversion facility, reducing transportation from storage yards and complexity of the supply chain. Kinston (Figure 16A) seemed to differ in feedstock allocation, but this can be tied to the small feedstock production radius and high cropland cover in the area (Table 33).

Radial area of the baled switchgrass was considerably smaller than the total area at 13.4, 8.5, and 13.5 kilometers (7.7, 5.3, and 8.4 miles) for Sanford, Kinston, and Lenoir, respectively. This created a very tight radial area to determine optimal storage locations, making many combinations of storage yard locations close to optimal. It is still advisable to have multiple storage locations that are spread about the area of collection to reduce risk and allow for use of dissipated low value land area. If an alternative location allocation procedure is used (Cooper 1964) a set number of storage locations can be set, with yield of each selected location used as a weighting factor. The single 16.2 hectare (40 acre) location determined seemed overly excessive but breaking this up into ten 1.6 hectare (4 acre) storage locations would make the system simpler to optimize (Figure 17).

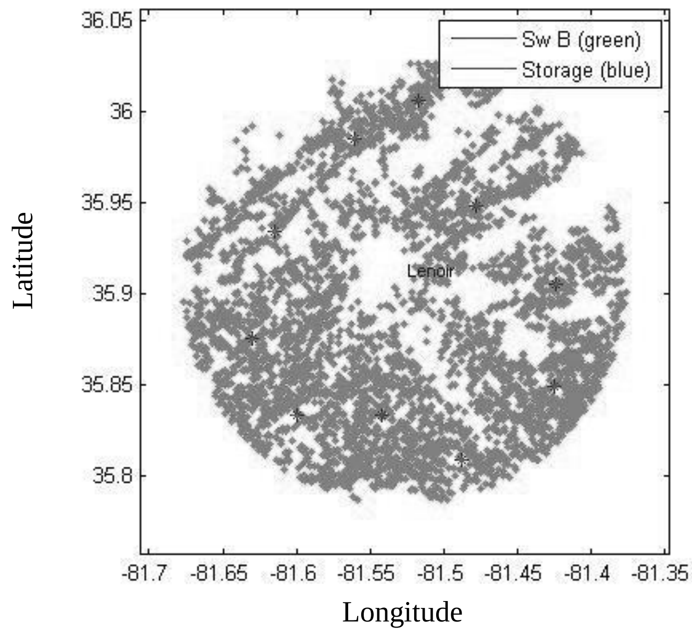
Figure 17: Optimized Feedstock Storage Yard Locations [A. Kinston, B. Sanford, C. Lenoir]



A. Kinston



B. Sanford



Sw B (green)
Storage (blue)
Lenoir
36.05
36
35.95
35.9
35.85
35.8
-81.7
-81.65
-81.6
-81.55
-81.5
-81.45
-81.4
-81.35
Latitude
Longitude

C. Lenoir

Siting storage as closely to these optimized sites as possible will reduce in-field transportation costs and help ensure that equal proportions of material will be taken to each storage site. Average distance from conversion facility to storage site was 8.4, 6.4, and 9.5 kilometers (5.2, 4, and 5.9 miles) to facilities in Sanford, Kinston, and Lenoir, respectively. This modeled distance means that even with inclement weather, transportation may be possible, though a small storage facility would still be required at the conversion facility for day to day operations, further reducing the size and possibly the number of decentralized storage yards.

Results of this case study show the benefits of siting a refinery in the Coastal Plain region of North Carolina, because of the high proportion of agricultural land and high productivity of the region. For all potential locations siting perennial grass storage yards near the facility shows benefits, while just in time operations could be placed farther from the central location.

The above outlined approach differs from others in that it includes multiple feedstocks and multiple harvest systems, instead of assuming a single feedstock harvested in a single format to supply a conversion facility. This method allows selected feedstock production locations to be sited by transportation unit cost, which reduces the total area in which each of the feedstocks is produced. This compartmentalizes logistical optimization into set regions of the total area, allowing the potential for near optimal solutions to be realistic. The shift to just-in-time supply chain management reduces storage requirements, corresponding storage losses, and safety stock requirements, reducing total feedstock requirements of the system. On a larger scale it allows each individual entity or business unit to optimize operations within their own area of expertise (feedstock production, logistical operations, and conversion operations), while allowing for full utilization of capital intensive specialized equipment.

6.5 Conclusion

Logistical operations of biomass supply chains can be incredibly complex with many different factors that need to be evaluated for optimal operations, with a large number of disassociated production sites on defined harvest schedules which must feed a conversion facility operating continually year round (with the exception of a short maintenance period). This model provides a method for determination of potential biorefinery locations, and proposes a multi-crop multi-harvest system for increased just in time operations, while accounting for production costs.

Optimization of the feedstock supply chain is an important aspect of biorefinery operations that can have a major impact on economical operations. This is especially important for biomass since the material is low value, low bulk density, and required at a constant rate for year round operations. Though this specific model used data from North Carolina the practical applications can be applied to produce a conceptual biomass supply system for any site with reasonable data available, to assist the emerging biomass based industry evaluate different operations. Using multiple feedstock and harvest systems allows for increased just in time operation, decreasing storage requirements and increasing equipment utilization.

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APPENDICES

Appendix A: Chapter 3

Appendix A 1: Pairwise Comparison of Least Square Means of Sweet Sorghum (Sorghum bicolor (L.) Moench) Small Scale Silage Compositional Changes over Time [Immediate & Pile Storage]

	Immediate					Pile				
	Ext	**Hemi**	**Cell**	**Lig**	**Ash**	**Ext**	**Hemi**	**Cell**	**Lig**	**Ash**
Int to Fresh	**-0.05061+**	**0.006693+**	**0.02590+**	**0.02365+**	**0.01147+**	**-0.01402+**	**-0.01042+**	**0.006194+**	**0.001250+**	**-0.00012+**
Int to 3 mon	**-0.06771***	**-0.04686****	**0.02627+**	**0.03377***	**0.01128+**	**0.02332+**	**-0.00360+**	**0.01581+**	**0.007197+**	**0.000537+**
Int to 6 mon	**-0.03804+**	**0.001155+**	**-0.00312+**	**0.02189+**	**0.004838+**	**0.01125+**	**0.01444+**	**-0.00773+**	**-0.00215+**	**-0.00252+**
Int to 12 mon	**0.004827+**	**0.02198***	**0.01566+**	**-0.01664+**	**-0.03251****	**0.04439+**	**0.02866****	**0.02022+**	**-0.05815****	**-0.02844****
12 mon to Fresh	**-0.05544+**	**-0.01528+**	**0.01025+**	**0.04029+**	**0.04398***	**-0.05841+**	**-0.03908+**	**-0.01402+**	**0.05940***	**0.02832+**
12 mon to 3 mon	**-0.07254****	**-0.06883****	**0.01062+**	**0.05040****	**0.04376****	**-0.02108+**	**-0.03227***	**-0.00441+**	**0.06534****	**0.02898****
12 mon to 6 mon	**-0.04286+**	**-0.02082+**	**-0.01878+**	**0.03652****	**0.03735****	**-0.03314+**	**-0.01423+**	**-0.02795+**	**0.05600****	**0.02592***
3 mon to Fresh	**0.01710+**	**0.05355***	**-0.00037+**	**-0.01012+**	**0.000198+**	**-0.03733+**	**-0.00682+**	**-0.00961+**	**-0.00595+**	**-0.00065+**
3 mon to 6 mon	**0.02968+**	**0.04801****	**-0.02940+**	**-0.01188+**	**-0.00644+**	**-0.01206+**	**0.01804+**	**-0.02354+**	**-0.00935+**	**-0.00306+**
6 mon to Fresh	**-0.01257+**	**0.005538+**	**0.02903+**	**0.001763+**	**0.006635+**	**-0.02527+**	**-0.02485+**	**0.01393+**	**0.003399+**	**0.002408+**

*+: p-value>0.05, *: p-value<0.05, ** p-value<0.01*

Appendix A 2: Pairwise Comparison of Least Square Means of Switchgrass (Panicum virgatum L.) Small Scale Silage Compositional Changes over Time [October & March Harvests]

	Oct					Mar				
	Ext	**Hemi**	**Cell**	**Lig**	**Ash**	**Ext**	**Hemi**	**Cell**	**Lig**	**Ash**
Int to Fresh	**-0.01288+**	**-0.01024+**	**0.01301+**	**0.005675+**	**0.004442+**	**-0.00566+**	**-0.01003+**	**0.009533+**	**0.005360+**	**0.000777+**
Int to 3 mon	**0.000423+**	**-0.00529+**	**0.02069+**	**-0.00461+**	**-0.01121+**	**0.02712+**	**-0.00269+**	**-0.02176+**	**-0.00374+**	**0.001066+**
Int to 6 mon	**-0.02104+**	**-0.02792***	**0.05431***	**-0.00047+**	**-0.00488+**	**0.01245+**	**0.01667+**	**-0.01956+**	**-0.00874+**	**-0.00082+**
Int to 12 mon	**-0.03652+**	**0.02583***	**0.07769****	**-0.04397****	**-0.02302****	**-0.02450+**	**0.02245***	**0.008484+**	**-0.00604+**	**-0.00040+**
12 mon to Fresh	**0.02364+**	**-0.03608+**	**-0.06468+**	**0.04965+**	**0.02746+**	**0.01884+**	**-0.03248+**	**0.001049+**	**0.01142+**	**0.001173+**
12 mon to 3 mon	**0.03695+**	**-0.03112***	**-0.05700***	**0.03936****	**0.01181+**	**0.05163+**	**-0.02514+**	**-0.03025+**	**0.002297+**	**0.001462+**
12 mon to 6 mon	**0.01548+**	**-0.05375****	**-0.02338+**	**0.04350****	**0.01814+**	**0.03695+**	**-0.00578+**	**-0.02804+**	**-0.00271+**	**-0.00043+**
3 mon to Fresh	**-0.01330+**	**-0.00496+**	**-0.00768+**	**0.0.01029+**	**0.01565+**	**-0.03279+**	**-0.00734+**	**0.03130+**	**0.009118+**	**-0.00029+**
3 mon to 6 mon	**-0.02146+**	**-0.02263+**	**0.03362+**	**0.004141+**	**0.006332+**	**-0.01468+**	**0.01936+**	**0.002208+**	**-0.00500+**	**-0.00189+**
6 mon to Fresh	**0.008159+**	**0.01768+**	**-0.04130+**	**0.006144+**	**0.009322+**	**-0.01811+**	**-0.02670+**	**0.02909+**	**0.01412+**	**0.001599+**

*+: p-value>0.05, *: p-value<0.05, ** p-value<0.01*

Appendix A 3: Pairwise Comparison of Least Square Means of Giant Reed (Arundo donax L.) Small Scale Silage Compositional Changes over Time [October & March Harvests]

	Oct					Mar				
	Ext	**Hemi**	**Cell**	**Lig**	**Ash**	**Ext**	**Hemi**	**Cell**	**Lig**	**Ash**
Int to Fresh	**-0.02670+**	**-0.02702+**	**0.02896+**	**0.01258+**	**0.01218+**	**0.001075+**	**-0.01832+**	**0.009589+**	**0.004927+**	**0.002727+**
Int to 3 mon	**-0.01194+**	**-0.01453+**	**0.01266+**	**0.01345+**	**0.000361+**	**0.01334+**	**0.006295+**	**-0.02411+**	**0.000496+**	**0.003981+**
Int to 6 mon	**0.002148+**	**-0.01857+**	**0.01216+**	**0.006687+**	**-0.00243+**	**0.004161+**	**0.01041+**	**-0.01220+**	**0.004737+**	**-0.00711+**
Int to 12 mon	**0.006862+**	**0.01490+**	**0.051153***	**-0.04158****	**-0.03172****	**0.01203+**	**0.009322+**	**0.01614+**	**-0.01682+**	**-0.02067***
12 mon to Fresh	**-0.03356+**	**-0.04193+**	**-0.02257+**	**0.05416***	**0.04390***	**-0.01095+**	**-0.02764+**	**-0.00655+**	**0.02175+**	**0.02340+**
12 mon to 3 mon	**-0.01880+**	**-0.02943***	**-0.03888+**	**0.05503****	**0.03208****	**0.001317+**	**-0.00303+**	**-0.04025+**	**0.01731+**	**0.02465***
12 mon to 6 mon	**-0.00471+**	**-0.03347****	**-0.03937+**	**0.04826****	**0.02929****	**-0.00787+**	**0.001091+**	**-0.02834+**	**0.02156+**	**0.01356+**
3 mon to Fresh	**-0.01476+**	**-0.01250+**	**0.01631+**	**-0.00087+**	**0.01182+**	**-0.01227+**	**-0.02461+**	**0.03370+**	**0.004431+**	**-0.00125+**
3 mon to 6 mon	**0.01409+**	**-0.00404+**	**-0.00049+**	**-0.00676+**	**-0.00279+**	**-0.00918+**	**0.004119+**	**0.01191+**	**0.004241+**	**-0.01109+**
6 mon to Fresh	**-0.02885+**	**-0.00845+**	**0.01680+**	**0.005893+**	**0.01461+**	**-0.00309+**	**-0.02673+**	**0.02179+**	**0.000190+**	**0.009834+**

*+: p-value>0.05, *: p-value<0.05, ** p-value<0.01*

Appendix A 4: Pairwise Comparison of Least Square Means of Miscanthus (Miscanthus x giganteous) Small Scale Silage Compositional Changes over Time [October Harvest]

	Oct				
	Ext	**Hemi**	**Cell**	**Lig**	**Ash**
Int to Fresh	**-0.00415+**	**-0.00156+**	**-0.01021+**	**0.01582+**	**0.000113+**
Int to 3 mon	**-0.00651+**	**-0.00714+**	**0.01894+**	**0.003639+**	**-0.00893+**
Int to 6 mon	**-0.02041+**	**0.01755+**	**0.04196+**	**-0.02290+**	**-0.01619+**
Int to 12 mon	**-0.05443***	**0.04520****	**0.1102****	**-0.06932****	**-0.03161****
12 mon to Fresh	**0.05028+**	**-0.04677***	**-0.1204****	**0.08514****	**0.03172+**
12 mon to 3 mon	**0.04792+**	**-0.05234****	**-0.09122****	**0.07296****	**0.02267***
12 mon to 6 mon	**0.03402+**	**-0.02765***	**-0.06820****	**0.04642****	**0.01541+**
3 mon to Fresh	**0.002360+**	**0.005572+**	**-0.02915+**	**0.01218+**	**0.009045+**
3 mon to 6 mon	**-0.01390+**	**0.02469***	**0.02302+**	**-0.02654+**	**-0.00726+**
6 mon to Fresh	**0.01626+**	**-0.01911+**	**-0.05217+**	**0.03872+**	**0.01631+**

*+: p-value>0.05, *: p-value<0.05, ** p-value<0.01*

Appendix A 5: Sweet Sorghum (Sorghum bicolor (L.) Moench) Small Scale Silage Average Composition and Dry Matter Loss, Immediate Storage

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**		**DM Loss**	
	Avg	*CoV*	*Avg*	*CoV*	*Avg*	*CoV*	*Avg*	*CoV*	*Avg*	*CoV*	*Avg*	*CoV*
Pre	3.55%		23.61%		25.26%		4.38%		43.20%			
Initial	3.44%	0.02	19.29%	0.06	25.01%	0.04	4.90%	0.07	47.37%	0.05	0.27%	0.09
3 mon	3.57%	0.03	22.92%	0.08	25.22%	0.05	3.37%	0.08	44.91%	0.05	0.36%	0.87
6 mon	4.03%	0.03	19.77%	0.07	26.48%	0.08	4.32%	0.11	45.40%	0.09	3.03%	0.61
12 mon	4.35%	0.07	22.38%	0.03	29.68%	0.10	4.82%	0.14	38.76%	0.11	3.44%	0.10
Initial Control	6.38%	0.02	26.93%	0.02	31.63%	0.04	9.21%	0.02	25.84%	0.07		
Final Control	12.74%	0.08	16.13%	0.05	21.75%	0.11	13.19%	0.06	36.19%	0.07		

Appendix A 6: Sweet Sorghum (Sorghum bicolor (L.) Moench) Small Scale Silage Average Composition and Dry Matter Loss, Pile Storage

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**		**DM Loss**	
	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Pre	3.64%		23.38%		32.68%		7.84%		32.47%			
Initial	3.58%	0.03	23.85%	0.01	33.21%	0.04	7.79%	0.04	31.57%	0.05	0.41%	0.20
3 mon	3.58%	0.01	28.73%	0.03	31.71%	0.03	7.24%	0.02	28.73%	0.07	0.48%	0.13
6 mon	3.88%	0.06	23.93%	0.02	34.07%	0.01	8.18%	0.02	29.94%	0.03	1.61%	0.18
12 mon	4.06%	0.04	24.17%	0.03	36.56%	0.04	9.14%	0.06	26.06%	0.09	2.77%	0.27
Initial Control	3.70%	0.02	24.31%	0.01	33.41%	0.01	8.19%	0.04	30.39%	0.04		
Final Control	9.69%	0.09	18.75%	0.05	24.22%	0.21	19.96%	0.35	27.38%	0.13		

Appendix A 7: Switchgrass (Panicum virgatum L.) Small Scale Silage Average Composition and Dry Matter Loss, October Harvest

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**		**DM Loss**	
	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Pre	4.10%		31.35%		38.01%		9.92%		16.61%			
Initial	4.53%	0.05	30.14%	0.02	38.46%	0.01	10.17%	0.02	16.70%	0.06	0.74%	0.03
3 mon	5.66%	0.11	30.86%	0.00	37.25%	0.05	10.95%	0.08	15.28%	0.10	0.68%	0.02
6 mon	5.03%	0.07	33.12%	0.02	33.88%	0.11	10.54%	0.03	17.43%	0.24	2.21%	0.09
12 mon	6.46%	0.18	29.18%	0.01	36.11%	0.07	13.54%	0.11	14.71%	0.07	8.41%	0.40
Initial Control	4.56%	0.37	30.58%	0.03	40.45%	0.05	10.92%	0.04	13.49%	0.10		
Final Control	7.18%	0.04	25.93%	0.03	26.36%	0.03	16.46%	0.02	24.06%	0.07		

Appendix A 8: Switchgrass (Panicum virgatum L.) Small Scale Silage Average Composition and Dry Matter Loss, March Harvest

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**		**DM Loss**	
	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Pre	1.24%		32.82%		45.34%		10.63%		9.98%			
Initial	1.46%	0.05	31.35%	0.02	46.41%	0.01	11.24%	0.04	9.56%	0.04	0.03%	0.47
3 mon	1.24%	0.06	31.79%	0.01	48.61%	0.01	11.62%	0.02	6.74%	0.07	0.11%	0.23
6 mon	1.51%	0.08	30.27%	0.01	47.91%	0.01	11.92%	0.03	8.38%	0.07	0.51%	0.09
12 mon	1.42%	0.05	31.48%	0.01	47.63%	0.02	11.93%	0.03	7.53%	0.12	0.94%	0.59
Initial Control	1.37%	0.05	32.87%	0.01	44.98%	0.01	10.31%	0.13	10.47%	0.10		
Final Control	1.63%	0.24	26.76%	0.14	42.19%	0.15	11.47%	0.06	17.95%	0.59		

Appendix A 9: Giant Reed (Arundo donax L.) Small Scale Silage Average Composition and Dry Matter Loss, October Harvest

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**		**DM Loss**	
	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Pre	6.04%		30.79%		32.67%		7.67%		22.83%			
Initial	6.87%	0.05	27.22%	0.01	34.41%	0.02	7.39%	0.14	24.11%	0.05	0.94%	0.04
3 mon	7.22%	0.04	29.54%	0.01	34.30%	0.04	7.59%	0.03	21.35%	0.07	0.86%	0.08
6 mon	7.50%	0.03	29.95%	0.01	34.35%	0.04	8.26%	0.04	19.94%	0.07	1.47%	0.07
12 mon	7.94%	0.03	29.51%	0.02	36.82%	0.03	9.33%	0.04	16.41%	0.10	4.23%	0.59
Initial Control	7.76%	0.07	29.26%	0.04	37.10%	0.02	11.00%	0.03	14.89%	0.07		
Final Control	13.48%	0.05	22.73%	0.02	21.15%	0.03	18.19%	0.02	24.45%	0.02		

Appendix A 10: Giant Reed (Arundo donax L.) Small Scale Silage Average Composition and Dry Matter Loss, March Harvest

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**		**DM Loss**	
	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Pre	6.23%		33.05%		35.93%		8.95%		15.84%			
Initial	5.80%	0.03	31.53%	0.01	37.21%	0.03	8.69%	0.02	16.77%	0.07	0.17%	0.17
3 mon	6.46%	0.14	30.68%	0.01	39.02%	0.02	9.35%	0.02	14.49%	0.04	0.63%	0.25
6 mon	7.70%	0.13	29.93%	0.02	37.62%	0.05	8.81%	0.02	15.94%	0.11	2.24%	0.14
12 mon	6.06%	0.04	31.59%	0.02	40.85%	0.02	9.29%	0.05	12.21%	0.05	2.65%	0.13
Initial Control	6.98%	0.11	31.42%	0.01	36.26%	0.01	10.54%	0.03	14.80%	0.02		
Final Control	11.63%	0.03	28.10%	0.03	27.81%	0.05	13.52%	0.02	18.94%	0.13		

Appendix A 11: Miscanthus (Miscanthus x giganteous) Small Scale Silage Average Composition and Dry Matter Loss, October Harvest

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**		**DM Loss**	
	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Pre	3.21%		31.45%		42.66%		7.25%		15.43%			
Initial	3.09%	0.01	30.44%	0.03	41.42%	0.03	8.77%	0.05	16.28%	0.04	1.42%	0.55
3 mon	3.99%	0.10	32.10%	0.03	40.09%	0.05	8.50%	0.04	15.31%	0.07	2.56%	0.63
6 mon	3.79%	0.14	30.24%	0.02	38.43%	0.02	10.47%	0.14	17.07%	0.10	5.87%	0.55
12 mon	5.90%	0.10	27.88%	0.06	31.77%	0.14	15.95%	0.15	18.49%	0.19	13.00%	0.50
Initial Control	3.59%	0.17	32.82%	0.03	41.04%	0.02	8.73%	0.01	13.81%	0.06		
Final Control	7.91%	0.24	24.83%	0.04	25.47%	0.08	17.22%	0.03	24.57%	0.03		

Appendix A 12: Fresh Biomass & Stabilization Compositions of Summer Small Scale Silage

Biomass samples were harvested at the NCSU Williamsdale Biofuels Field Laboratory (Wallace, NC) in July utilization the same equipment as earlier harvests. Ensilage bags were assembled in the same manner and the same detergent fiber method was employed as other small scale silage samples (see Chapter 3).

	Ash		**Hemicellulose**		**Cellulose**		**Lignin**		**Extractives**	
	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Sw (FB)	4.81%		33.69%		41.51%		7.97%		12.01%	
Sw (0)	5.47%	0.03	32.36%	0.02	42.23%	0.01	8.56%	0.02	11.38%	0.06
GR (FB)	4.67%		30.05%		40.33%		8.54%		16.41%	
GR (0)	5.33%	0.04	29.01%	0.01	43.35%	0.01	9.89%	0.03	12.42%	0.02
Mx (FB)	3.00%		32.64%		43.36%		7.97%		13.02%	
Mx (0)	3.57%	0.04	31.07%	0.02	44.69%	0.01	8.25%	0.05	12.41%	0.04

Appendix A 13: SAS code used for statistical analysis of ensilage composition

Composition

```
options ls=95 nodate nocenter formdlim="+" ps=1000;

data one;
   length species2 $3;
   array rvec{8} Ash Hemicellulose Cellulose Lignon Extractives mc ph
dml;
   array rname{8} $9
("Ash","Hemicellulose","Cellulose","Lignon","Extractives","MC","PH","DM
L");
   infile "ensilage.txt" dsd firstobs=2;
   input  species $ harvest $ mgmt $ control $ breakage $ time $
Replicate $ j1 Ash Hemicellulose Cellulose Lignon Extractives j2 MC PH
DML;
   hs=catx("-",harvest,species);
   logph=log(ph);
```

```
   logdml=log(dml);
   if mgmt=" " then mgmt="I";
   if species="SS" then do;
      if mgmt="I" then species2="SSI";
      else if mgmt="P" then species2="SSP";
   end;
   else species2=species;
   do i = 1 to 8;
      y=rvec{i}; response=rname{i};
      output;
   end;
run;
data one; set one; if harvest="Jul" then delete; run;
proc print; var species mgmt species2;run;
proc sort data=one;
   by response;
run;
proc glimmix data=one;
   by response;
   where response not in ("MC","PH","DML");
   class time harvest species mgmt control breakage hs species2;
   *model y = harvest|species time  harvest*species*time / outp=two;
   model y = harvest|species2 time  harvest*species2*time;
   *lsmeans species*time(harvest)/slice=harvest;
   lsmeans species2*time*harvest/slicediff=harvest*time;
   ods output lsmeans=lsm;
run;
symbol value=dot;
proc print data=lsm;title "lsm"; run;
proc sort data=lsm;
   by response harvest;
run;
proc gplot data=lsm;
   by response harvest;
   plot estimate * time=species2;
run;
endsas;
proc gplot data=two; plot resid*pred=harvest;run;
endsas;
proc print data=lsm(obs=100);run;
symbol value=dot;
proc gplot data=lsm;
   plot estimate*time=hs;
run;
endsas;

proc sort data=one;
   by hs time;
run;
proc gplot data=one;
```

```
   by hs ;
   plot dml*logph=time;
run;
```

Composition & Time

```
options ls=95 nodate nocenter formdlim="+" ps=1000;

data one;
   length species2 $3;
   array rvec{8} Ash Hemicellulose Cellulose Lignon Extractives mc ph
dml;
   array rname{8} $9
("Ash","Hemicellulose","Cellulose","Lignon","Extractives","MC","PH","DM
L");
   infile "ensilage.txt" dsd firstobs=2;
   input  species $ harvest $ mgmt $ control $ breakage $ time $
Replicate $ j1 Ash Hemicellulose Cellulose Lignon Extractives j2 MC PH
DML;
   hs=catx("-",harvest,species);
   logph=log(ph);
   logdml=log(dml);
   if mgmt=" " then mgmt="I";
   if species="SS" then do;
      if mgmt="I" then species2="SSI";
      else if mgmt="P" then species2="SSP";
   end;
   else species2=species;
   do i = 1 to 8;
      y=rvec{i}; response=rname{i};
      output;
   end;
run;
data one; set one; if harvest="Jul" then delete; run;
proc print; var species mgmt species2;run;
proc sort data=one;
   by response;
run;
proc glimmix data=one;
   by response;
   where response not in ("MC","PH","DML");
   class time harvest species mgmt control breakage hs species2;
   *model y = harvest|species time  harvest*species*time / outp=two;
   model y = harvest|species2 time  harvest*species2*time;
   *lsmeans species*time(harvest)/slice=harvest;
   lsmeans species2*time*harvest/ slice=harvest*species2
slicediff=harvest*species2;   *time effects;
   lsmeans species2*time*harvest/ slice=species2*time;
*harvest effects;
   ods output lsmeans=lsm;
```

```
run;
endsas;
symbol value=dot;
proc print data=lsm;title "lsm"; run;
proc sort data=lsm;
   by response harvest;
run;
proc gplot data=lsm;
   by response harvest;
   plot estimate * time=species2;
run;
endsas;
proc gplot data=two; plot resid*pred=harvest;run;
endsas;
proc print data=lsm(obs=100);run;
symbol value=dot;
proc gplot data=lsm;
   plot estimate*time=hs;
run;
endsas;

proc sort data=one;
   by hs time;
run;
proc gplot data=one;
   by hs ;
   plot dml*logph=time;
run;
```

Ensilage

```
options ls=95 nodate nocenter formdlim="+" ps=1000;

data one;
   infile "ensilage.txt" dsd firstobs=2;
   input  species $ harvest $ mgmt $ control $ breakage $ time $
Replicate $ j1 Ash Hemicellulose Cellulose Lignon Extractives j2 MC PH
DML;
   hs=catx("-",harvest,species);
   logph=log(ph);
   logdml=log(dml);
run;
proc glimmix data=one;
   class time harvest species mgmt control breakage hs;
   *model logdml = harvest harvest*time species(harvest)
species*time(harvest)/outp=two;
   model logdml = harvest|species time  harvest*species*time;
   *lsmeans species*time(harvest)/slice=harvest;
   lsmeans species*time*harvest/slicediff=harvest*time;
   ods output lsmeans=lsm;
```

```
run;
symbol value=dot;
proc sort data=lsm;
   by harvest;
run;
proc gplot data=lsm;
   by harvest;
   plot estimate * time=species;
run;
endsas;
proc gplot data=two; plot resid*pred=harvest;run;
endsas;
proc print data=lsm(obs=100);run;
symbol value=dot;
proc gplot data=lsm;
   plot estimate*time=hs;
run;
endsas;

proc sort data=one;
   by hs time;
run;
proc gplot data=one;
   by hs ;
   plot dml*logph=time;
run;
```

Appendix B: Chapter 4

Appendix B 1: Switchgrass (Panicum virgatum L.) Bales Average Composition Over Time, October Harvest

	Bales	Extractives		Hemicellulose		Cellulose		Lignin		Ash	
		Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Big Square Bale											
Pre											
Initial	1 to 6	11.41%	0.06	31.73%	0.02	43.67%	0.02	10.51%	0.03	2.68%	0.17
3 month	1 to 3	10.88%	0.02	32.55%	0.01	43.94%	0.01	9.82%	0.04	2.80%	0.13
6 month	1 to 3	6.59%	0.22	35.26%	0.01	44.34%	0.04	10.85%	0.06	2.96%	0.21
12 month	1 to 5	8.58%	0.08	31.92%	0.02	44.92%	0.01	11.45%	0.05	3.12%	0.19
15 month	6	7.48%		31.35%		46.64%		11.53%		2.99%	
Round Outdoor											
Pre											
Initial	1 to 6	12.55%	0.10	30.29%	0.01	44.27%	0.02	10.06%	0.06	2.83%	0.16
Inner											
3 month	1 to 3	10.43%	0.18	30.58%	0.03	45.90%	0.02	10.26%	0.08	2.83%	0.30
6 month	1 to 3	7.83%	0.17	34.47%	0.02	44.35%	0.02	10.45%	0.06	2.91%	0.27
12 month	1 to 5	9.18%	0.10	31.13%	0.02	45.54%	0.01	10.99%	0.06	3.16%	0.18
15 month	6	6.27%		31.80%		47.60%		11.72%		2.61%	
Outer											
3 month	1 to 3	8.86%	0.06	31.44%	0.02	46.28%	0.01	11.67%	0.05	1.74%	0.17
6 month	1 to 3	7.17%	0.11	34.93%	0.02	44.54%	0.03	11.96%	0.04	1.40%	0.65
12 month	1 to 5	17.10%	0.25	29.20%	0.07	38.62%	0.10	12.36%	0.06	2.72%	0.28
15 month	6	14.19%		28.34%		39.95%		13.08%		4.44%	
Wrapped Round											
Pre											
Initial	1 to 6	15.25%	0.11	32.32%	0.04	38.91%	0.02	8.07%	0.03	5.45%	0.05
Inner											
3 month	1 to 3	14.93%	0.03	31.98%	0.03	39.28%	0.01	8.13%	0.10	5.68%	0.07
6 month	4 to 5	10.63%	0.03	33.05%	0.02	41.65%	0.02	8.95%	0.02	5.72%	0.05
12 month	6	9.68%		32.66%		41.73%		9.95%		5.99%	
Outer											
3 month	1 to 3	15.66%	0.16	33.02%	0.01	36.78%	0.08	8.14%	0.10	6.40%	0.11
6 month	4 to 5	8.97%	0.15	35.74%	0.01	41.22%	0.01	8.32%	0.04	5.75%	0.10
12 month	6	12.81%		31.73%		39.58%		9.67%		6.20%	
Spoiled											
Inner											
6 month	1 to 3	13.20%	0.03	28.27%	0.04	39.91%	0.01	11.47%	0.07	7.15%	0.07
12 month	4 to 5	14.49%	0.01	26.70%	0.01	38.16%	0.03	12.60%	0.02	8.05%	0.11
Outer											
6 month	1to 3	17.06%	0.08	30.47%	0.07	28.26%	0.13	14.31%	0.10	9.90%	0.14
12 month	4 to 5	20.25%	0.15	25.91%	0.02	28.36%	0.10	15.66%	0.02	9.82%	0.01

Appendix B 2: Switchgrass (Panicum virgatum L.) Bales Average Composition Over Time, Spring Harvest

	Bales	Extractives		Hemicellulose		Cellulose		Lignin		Ash	
		Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Big Square Bale											
Pre											
Initial	1 to 6	8.87%	0.11	31.50%	0.03	46.79%	0.02	11.44%	0.03	1.41%	0.10
3 month	1 to 3	7.02%	0.12	32.16%	0.04	47.52%	0.02	11.74%	0.07	1.55%	0.02
6 month	1 to 3	11.56%	0.03	33.33%	0.02	45.56%	0.01	11.56%	0.03	1.86%	0.27
12 month	1 to 5	7.20%	0.19	31.91%	0.04	47.45%	0.02	11.83%	0.04	1.61%	0.13
15 month	6	8.57%		30.77%		47.02%		11.93%		1.71%	
Round Outdoor											
Pre											
Initial	1 to 6	11.20%	0.13	33.34%	0.03	40.86%	0.02	10.37%	0.04	4.23%	0.04
Inner											
3 month	1 to 3	11.60%	0.06	29.47%	0.02	40.84%	0.02	13.29%	0.02	4.80%	0.05
6 month	1 to 3	11.76%	0.13	29.37%	0.01	40.24%	0.05	13.41%	0.03	5.22%	0.03
12 month	1 to 5	12.79%	0.13	29.17%	0.03	39.17%	0.04	14.03%	0.04	4.83%	0.04
15 month	6	9.77%		30.22%		42.23%		12.94%		4.84%	
Outer											
3 month	1 to 3	15.70%	0.20	29.82%	0.05	35.41%	0.07	13.77%	0.06	5.31%	0.17
6 month	1 to 3	17.92%	0.10	29.74%	0.02	26.47%	0.14	20.15%	0.07	5.73%	0.13
12 month	1 to 5	21.08%	0.08	24.87%	0.05	22.36%	0.06	23.41%	0.05	8.28%	0.21
15 month	6	21.45%		25.40%		23.17%		23.91%		6.06%	
Wrapped Round											
Pre											
Initial	1 to 6	21.51%	0.09	31.29%	0.05	32.05%	0.04	7.77%	0.03	7.39%	0.39
Inner											
3 month	1 to 3	18.50%	0.20	29.51%	0.04	34.12%	0.09	10.06%	0.09	7.81%	0.16
6 month	4 to 5	17.98%	0.51	28.97%	0.05	33.47%	0.10	9.00%	0.01	10.58%	0.39
12 month	6	19.03%		31.99%		33.74%		9.48%		5.76%	
Outer											
3 month	1 to 3	14.73%	0.24	29.68%	0.06	35.35%	0.15	12.13%	0.13	8.10%	0.28
6 month	4 to 5	16.44%	0.01	29.71%	0.07	34.72%	0.03	10.47%	0.12	8.65%	0.21
12 month	6	17.14%		34.30%		33.82%		9.49%		5.25%	
Spoiled											
Inner											
6 month	1 to 3	14.84%	0.14	27.11%	0.07	37.71%	0.03	12.09%	0.02	8.25%	0.16
12 month	4 to 5	15.54%	0.22	27.31%	0.11	34.96%	0.02	12.88%	0.03	9.30%	0.01
Outer											
6 month	1to 3	29.88%	0.09	19.44%	0.08	20.89%	0.09	15.89%	0.06	13.91%	0.19
12 month	4 to 5	25.50%	0.05	23.80%	0.08	20.29%	0.02	17.93%	0.08	12.48%	0.17

Appendix B 3: Giant Reed (Arundo donax L.) Bales Average Composition Over Time, October Harvest

	Bales	Extractives		Hemicellulose		Cellulose		Lignin		Ash	
		Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Big Square Bale											
Pre											
Initial	1 to 6	18.96%	0.10	26.88%	0.07	37.67%	0.04	9.92%	0.10	6.57%	0.36
3 month	1 to 3	14.60%	0.18	29.23%	0.11	37.09%	0.09	11.58%	0.08	7.50%	0.42
6 month	1 to 3	14.61%	0.25	28.64%	0.12	34.86%	0.15	12.11%	0.13	9.78%	0.52
12 month	1 to 5	14.76%	0.10	28.49%	0.09	36.12%	0.09	11.95%	0.09	8.68%	0.44
15 month	6	13.03%		32.01%		40.44%		10.75%		3.77%	
Round Outdoor											
Pre											
Initial	1 to 6	21.17%	0.03	28.66%	0.01	38.20%	0.01	8.01%	0.06	3.95%	0.09
Inner											
3 month	1 to 3	11.06%	0.02	32.12%	0.01	42.36%	0.02	10.00%	0.01	4.46%	0.12
6 month	1 to 3	9.06%	0.15	33.34%	0.02	42.15%	0.03	10.84%	0.04	4.60%	0.09
12 month	1 to 5	11.36%	0.14	32.01%	0.02	41.44%	0.05	10.49%	0.07	4.70%	0.12
15 month	6	10.87%		30.45%		42.38%		11.92%		4.38%	
Outer											
3 month	1 to 3	13.21%	0.10	31.28%	0.06	39.95%	0.05	10.44%	0.07	5.12%	0.11
6 month	1 to 3	17.58%	0.14	30.62%	0.03	30.84%	0.01	14.53%	0.04	6.43%	0.14
12 month	1 to 5	21.94%	0.11	23.81%	0.16	22.48%	0.16	20.37%	0.13	11.39%	0.67
15 month	6	21.95%		26.52%		26.23%		19.13%		6.17%	
Wrapped Round											
Pre											
Initial	1 to 6	24.77%	0.04	28.55%	0.04	31.55%	0.03	5.61%	0.04	9.53%	0.25
Inner											
3 month	1 to 3	18.61%	0.07	28.23%	0.03	32.35%	0.05	8.65%	0.06	12.26%	0.27
6 month	4 to 5	19.89%	0.08	27.99%	0.02	32.94%	0.03	8.94%	0.07	10.25%	0.08
12 month	6	20.41%		26.02%		30.81%		8.05%		14.70%	
Outer											
3 month	1 to 3	19.20%	0.15	28.18%	0.05	31.53%	0.01	9.08%	0.07	12.01%	0.12
6 month	4 to 5	18.67%	0.08	28.58%	0.01	31.28%	0.10	9.02%	0.07	12.44%	0.30
12 month	6	21.67%		26.79%		31.01%		9.46%		11.07%	
Spoiled											
Inner											
6 month	1 to 3	19.13%	0.38	25.55%	0.06	32.07%	0.15	10.00%	0.10	13.26%	0.15
12 month	4 to 5	19.02%	0.02	22.99%	0.04	33.46%	0.06	11.45%	0.01	13.08%	0.26
Outer											
6 month	1 to 3	23.28%	0.14	25.69%	0.09	24.07%	0.15	11.72%	0.12	15.23%	0.18
12 month	4 to 5	28.32%	0.06	17.88%	0.01	18.58%	0.13	14.33%	0.09	20.89%	0.02

Appendix B 4: Giant Reed (Arundo donax L.) Bales Average Composition Over Time, Spring Harvest

	Bales	Extractives		Hemicellulose		Cellulose		Lignin		Ash	
		Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Big Square Bale											
Pre											
Initial	1 to 6	12.91%	0.50	29.80%	0.21	40.37%	0.08	11.57%	0.09	5.35%	0.40
3 month	1 to 3	16.44%	0.23	27.36%	0.13	35.71%	0.12	11.15%	0.15	9.34%	0.43
6 month	1 to 3	13.16%	0.17	27.77%	0.13	40.02%	0.04	12.43%	0.05	6.62%	0.35
12 month	1 to 5	12.96%	0.27	31.10%	0.11	38.27%	0.07	11.97%	0.04	5.70%	0.32
15 month	6	11.91%		32.66%		39.00%		11.35%		5.08%	
Round Outdoor											
Pre											
Initial	1 to 6	11.20%	0.13	33.34%	0.03	40.86%	0.02	10.37%	0.04	4.23%	0.04
Inner											
3 month	1 to 3	11.60%	0.06	29.47%	0.02	40.84%	0.02	13.29%	0.02	4.80%	0.05
6 month	1 to 3	11.76%	0.13	29.37%	0.01	40.24%	0.05	13.41%	0.03	5.22%	0.03
12 month	1 to 5	12.79%	0.13	29.17%	0.03	39.17%	0.04	14.03%	0.04	4.83%	0.04
15 month	6	9.77%		30.22%		42.23%		12.94%		4.84%	
Outer											
3 month	1 to 3	15.70%	0.20	29.82%	0.05	35.41%	0.07	13.77%	0.06	5.31%	0.17
6 month	1 to 3	17.92%	0.10	29.74%	0.02	26.47%	0.14	20.15%	0.07	5.73%	0.13
12 month	1 to 5	21.08%	0.08	24.87%	0.05	22.36%	0.06	23.41%	0.05	8.28%	0.21
15 month	6	21.45%		25.40%		23.17%		23.91%		6.06%	
Wrapped Round											
Pre											
Initial	1 to 6	21.51%	0.09	31.29%	0.05	32.05%	0.04	7.77%	0.03	7.39%	0.39
Inner											
3 month	1 to 3	18.50%	0.20	29.51%	0.04	34.12%	0.09	10.06%	0.09	7.81%	0.16
6 month	4 to 5	17.98%	0.51	28.97%	0.05	33.47%	0.10	9.00%	0.01	10.58%	0.39
12 month	6	19.03%		31.99%		33.74%		9.48%		5.76%	
Outer											
3 month	1 to 3	14.73%	0.24	29.68%	0.06	35.35%	0.15	12.13%	0.13	8.10%	0.28
6 month	4 to 5	16.44%	0.01	29.71%	0.07	34.72%	0.03	10.47%	0.12	8.65%	0.21
12 month	6	17.14%		34.30%		33.82%		9.49%		5.25%	
Spoiled											
Inner											
6 month	1 to 3	14.84%	0.14	27.11%	0.07	37.71%	0.03	12.09%	0.02	8.25%	0.16
12 month	4 to 5	15.54%	0.22	27.31%	0.11	34.96%	0.02	12.88%	0.03	9.30%	0.01
Outer											
6 month	1to 3	29.88%	0.09	19.44%	0.08	20.89%	0.09	15.89%	0.06	13.91%	0.19
12 month	4 to 5	25.50%	0.05	23.80%	0.08	20.29%	0.02	17.93%	0.08	12.48%	0.17

Appendix B 5: Miscanthus (Miscanthus x giganteous) Bales Average Composition Over Time, October Harvest

	Bales	Extractives		Hemicellulose		Cellulose		Lignin		Ash	
		Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV	Avg	CoV
Big Square Bale											
Pre											
Initial	1 to 6	14.74%	0.04	28.64%	0.02	41.03%	0.02	10.67%	0.04	4.92%	0.10
3 month	1 to 3	10.34%	0.18	32.88%	0.03	41.44%	0.01	10.02%	0.02	5.32%	0.17
6 month	1 to 3	12.94%	0.02	27.77%	0.01	43.20%	0.01	10.98%	0.01	5.12%	0.13
12 month	1 to 5	12.61%	0.06	28.85%	0.02	42.05%	0.03	11.40%	0.05	5.10%	0.22
15 month	6	14.93%		27.18%		38.74%		12.63%		6.52%	
Round Outdoor											
Pre											
Initial	1 to 6	16.20%	0.04	29.46%	0.01	40.89%	0.02	9.61%	0.02	3.84%	0.04
Inner											
3 month	1 to 3	10.18%	0.06	35.05%	0.01	41.56%	0.01	8.92%	0.02	4.29%	0.04
6 month	1 to 3	13.06%	0.09	29.73%	0.01	43.10%	0.03	10.30%	0.02	3.81%	0.05
12 month	1 to 5	12.94%	0.07	29.43%	0.01	42.93%	0.03	10.48%	0.03	4.22%	0.12
15 month	6	12.63%		29.08%		42.12%		11.83%		4.35%	
Outer											
3 month	1 to 3	7.52%	0.23	34.09%	0.04	40.98%	0.04	11.87%	0.02	5.54%	0.31
6 month	1 to 3	15.97%	0.13	26.58%	0.01	34.29%	0.04	17.45%	0.02	5.71%	0.07
12 month	1 to 5	19.39%	0.04	23.07%	0.07	25.67%	0.07	21.88%	0.13	9.99%	0.16
15 month	6	17.72%		23.53%		31.66%		20.97%		6.11%	
Wrapped Round											
Pre											
Initial	1 to 6	17.62%	0.15	34.37%	0.03	35.68%	0.03	5.77%	0.08	6.56%	0.59
Inner											
3 month	1 to 3	9.98%	0.37	36.13%	0.03	34.44%	0.09	5.34%	0.18	14.12%	0.52
6 month	4 to 5	16.57%	0.09	31.54%	0.03	39.92%	0.02	6.84%	0.01	5.13%	0.01
12 month	6	22.08%		32.32%		34.57%		5.83%		5.20%	
Outer											
3 month	1 to 3	15.44%	0.28	35.74%	0.06	36.88%	0.04	5.11%	0.17	6.84%	0.14
6 month	4 to 5	17.59%	0.01	31.83%	0.06	38.69%	0.02	6.86%	0.07	5.03%	0.11
12 month	6	17.50%		29.35%		33.24%		5.65%		14.26%	
Spoiled											
Inner											
6 month	1 to 3	14.30%	0.13	29.85%	0.05	39.78%	0.01	8.48%	0.04	7.59%	0.25
12 month	4 to 5	17.40%	0.19	27.49%	0.10	37.63%	0.08	9.34%	0.02	8.14%	0.28
Outer											
6 month	1 to 3	23.89%	0.08	26.05%	0.04	27.19%	0.1	11.97%	0.09	10.90%	0.10
12 month	4 to 5	22.98%	0.14	25.82%	0.09	29.65%	0.13	13.25%	0.19	8.30%	0.04

Appendix B 6: SAS code used for statistical analysis of bale composition

Bale

```
options ls=115 nodate nocenter formdlim="+" ps=1000;

data one;
   array rvec{6} Ash Hemicellulose Cellulose Lignon Extractives MCw ;
   array rname{6} $9
("Ash","Hemicellulose","Cellulose","Lignon","Extractives","MCw");
   infile "bale.txt" dsd firstobs=2;
   input  Species $ Harvest $ Storage $ Location $ Spoilage $ Period $
Time $ Replicate $ j2 Ash Hemicellulose Cellulose Lignon Extractives j2
MCw BaleWeight;
   sl=catx("-",storage,location);
 do i = 1 to 6;
      y=rvec{i}; response=rname{i};
      output;
   end;
```

```
run;


proc sort data=one; by species response; run;
proc mixed data=one method=type3;
   where replicate ne "OO" and time ne "15";
   by species response;
   class species harvest storage location time replicate sl;
   *model mcw = harvest|storage|location|time;
   *model mcw = harvest*sl harvest*sl*time;
   model y = harvest*storage*location storage*location*time
harvest*storage*location*time;
   random replicate(storage*location*harvest);
   *lsmeans harvest|storage|location|time/e;
   *lsmeans harvest*sl harvest*sl*time;
   lsmeans harvest*storage*time*location/slice=(harvest*storage*time)
diffs;
   ods output slices=slslices diffs=diffs;
run;
proc print data=slslices; title "storage-location slices"; run;
proc sort data=diffs;  by response species effect harvest storage time;
run;
proc print data=diffs; title "inner vs outer";
   where harvest=_harvest and storage=_storage and location ne
_location and time = _time;
run;
proc print data=diffs; title "time1 vs time2";
   where harvest=_harvest and storage=_storage and location=_location
and time ne _time;
run;
```

__Round Indoor vs. Big Square Indoor__

```
options ls=115 nodate nocenter formdlim="+" ps=1000;

data one;
   array rvec{6} Ash Hemicellulose Cellulose Lignon Extractives MCw ;
   array rname{6} $9
("Ash","Hemicellulose","Cellulose","Lignon","Extractives","MCw");
   infile "bale.txt" dsd firstobs=2;
   input  Species $ Harvest $ Storage $ Location $ Spoilage $ Period $
Time $ Replicate $ j2 Ash Hemicellulose Cellulose Lignon Extractives j2
MCw BaleWeight;
   sl=catx("-",storage,location);
   do i = 1 to 6;
      y=rvec{i}; response=rname{i};
      output;
   end;
```

```
run;



proc sort data=one; by species response; run;
proc mixed data=one method=type3;
   where replicate ne "OO" and time ne "15";
   by species response;
   class species harvest storage location time replicate sl;
   *model mcw = harvest|storage|location|time;
   *model mcw = harvest*sl harvest*sl*time;
   model y = harvest*storage*location storage*location*time
harvest*storage*location*time/outp=two;
   random replicate(storage*location*harvest);
   *lsmeans harvest|storage|location|time/e;
   *lsmeans harvest*sl harvest*sl*time;
   lsmeans harvest*storage*time*location/slice=(harvest*storage*time)
diffs;
   ods output slices=slslices diffs=diffs;
run;
proc print data=slslices; title "storage-location slices"; run;
proc sort data=diffs;  by response species effect harvest storage time;
run;
data diffs; set diffs; sig05=(probt <= .05);
proc print data=diffs; title "diffs";
   where harvest ne _harvest and location=_location and location="I"
and (storage in ("BS","RI")) and (_storage in ("BS","RI")) and
time=_time;
run;
proc gplot data=two;
   by species response;
   plot resid*pred=harvest;
run;
```

Appendix C: Chapter 5

Appendix C 1: Sorghum (Sorghum bicolor (L.) Moench) Production Inputs & Enterprise Budget

	Quantity	Unit	Cost ($/ac)
Establishment (Traditional)			
Tandem Disk	2	Acre	$21.74
Field Cultivator	1	Acre	$6.42
Fertilizer Spreader	1	Acre	$3.78
Superphosphate (44-46%) (P)	88.89	Lb	$27.60
Muriate of Potash (60-62%) (K)	65.57	Lb	$19.70
Limestone, spread	160	Lb	$4.53
Row Planter	1	Acre	$11.44
Seed	2.1	Lb	$17.85
Boom Sprayer	1	Acre	$3.78
Glyphosate	0.375	Gal	$10.05
2,4-D	0.25	Gal	$5.23
32% Nitrogen Solution (N)	250	Lb	$52.00
Trad. Establishment ($/ac)			$184.12
Establishment (Min-Til)			
Boom Sprayer	2	Acre	$7.56
Glyphosate	0.75	Gal	$20.10
Fertilizer Spreader	1	Acre	$3.78
Superphosphate (44-46%) (P)	88.89	Lb	$27.60
Muriate of Potash (60-62%) (K)	65.57	Lb	$19.70
Limestone, spread	160	Lb	$4.53
Min-Til Planter	1	Acre	$15.82
Seed	2.1	Lb	$17.85
Boom Sprayer	1	Acre	$3.78
Glyphosate	0.375	Gal	$10.05
2,4-D	0.25	Gal	$5.23
32% Nitrogen Solution (N)	250	Lb	$52.00
Min-Til Establishment:			$188.00
Total Establishment (50-50 Trad/Min-Til) ($/ac)			$186.06
Harvest			
Forage Harvester	1	Acre	$42.10
High Dump	0.5	Acre	$10.71
Total Harvest ($/ac)			$52.81
Transportation			
Tractor Trailer	30	Mile	$4.14
Transportation Total ($/dry ton)			$4.14

Appendix C 2: Barley (Hordeum vulgare L.) Production Inputs & Enterprise Budget

	Quantity	Unit	Cost ($/ac)
Establishment (Traditional)			
Tandem Disk	2	Acre	$21.74
Field Cultivator	1	Acre	$6.42
Fertilizer Spreader	1	Acre	$3.78
Superphosphate (44-46%) (P)	122.22	Lb	$37.95
Muriate of Potash (60-62%) (K)	24.59	Lb	$7.39
Limestone, spread	245	Lb	$6.93
Calcium Sulfate (23/19%) (S)	105.26	Lb	$11.74
Conventional Drill	1	Acre	$13.78
Seed	105	Lb	$29.09
Boom Sprayer (Pre)	1	Acre	$3.78
Glyphosate	0.375	Gal	$10.05
Boom Sprayer (Post)	1	Acre	$3.78
Harmony	0.5	Oz	$10.16
Fertilizer Spreader	1	Acre	$3.78
Urea (44-46%) (N)	272.22	Lb	$87.66
Trad. Establishment ($/ac)			$258.02
Establishment (Min-Til)			
Boom Sprayer	2	Acre	$7.56
Glyphosate	0.75	Gal	$20.10
Fertilizer Spreader	1	Acre	$3.78
Superphosphate (44-46%) (P)	122.22	Lb	$$37.95
Muriate of Potash (60-62%) (K)	24.59	Lb	$7.39
Limestone, spread	245	Lb	$6.93
Calcium Sulfate (23%/19%) (S)	105.26	Lb	$11.74
Min-Til Drill	1	Acre	$24.78
Seed	105	Lb	$29.09
Boom Sprayer (Post)	1	Acre	$3.78
Harmony	0.5	Oz	$10.16
Fertilizer Spreader	1	Acre	$3.78
Urea (44-46%) (N)	272.22	Lb	$87.66
Min-Til Establishment:			$254.69
Total Establishment (50-50 Trad/Min-Til) ($/ac)			$256.36
Harvest			
Combine	1	Acre	$33.33
Grain Cart	1	Acre	$21.42
Rotary Mower	1	Acre	$12.10
Large Rectangular Baler	1	Acre	$12.09
Total Harvest ($/ac)			$78.94
Storage			
Pad & Tarp (2.75% DM Loss)	6	Month	$1.57
Storage ($/Dry Ton)			$1.57
Transportation			
Tractor Trailer (grain)	35	Miles	$0.05
Tractor Trailer (straw)	30	Miles	$2.67
Transportation ($/bu)			$0.05
Transportation ($/dry ton)			$2.67

Appendix C 3: Switchgrass (Panicum virgatum L.) Production Inputs & Enterprise Budget

	Quantity	Unit	Cost ($/ac)
Establishment (Traditional)			
Tandem Disk	2	Acre	$21.74
Field Cultivator	1	Acre	$6.42
Conventional Drill	1	Acre	$13.78
Seed	8	Lb	$80.00
Boom Sprayer	1	Acre	$3.78
Glyphosate	0.375	Gal	$10.05
Cimarron (Ally)	0.0115	Gal	$6.07
Trad Establishment ($/ac)			$141.84
w/20% Failure			$170.21
Establishment (Min-Til)			
Boom Sprayer (Burndown)	2	Acre	$7.56
Glyphosate	0.75	Gal	$20.10
Min-Til Drill	1	Acre	$24.78
Seed	8	Lb	$80.00
Boom Sprayer (Pre)	1	Acre	$3.78
Glyphosate	0.375	Gal	$10.05
Cimarron (Ally)	0.0115	Gal	$6.07
Min-Til Establishment ($/ac)			$152.34
w/20% Failure			$182.81
Total Establishment (50-50 Trad/Min-Til)			$176.51
Annual Establishment			
5 Year Cost	1	Acre	$35.30
Annual Yield Proportion			85%
10 Year Cost	1	Acre	$17.65
Annual Yield Proportion			93%
20 Year Cost	1	Acre	$8.83
Annual Yield Proportion			96%
Annual Maintenance			
Fertilizer Spreader	1	Acre	$3.78
Superphosphate (44-46%) (P)	88.89	Lb	$27.60
Muriate of Potash (60-62%) (K)	131.15	Lb	$39.41
Urea (44-46%) (N)	133.33	Lb	$42.93
Limestone, spread	120	Lb	$3.40
Total Annual Maintenance ($/ac)			$117.12
Harvest			
Mower Conditioner	1	Acre	$14.22
Hay Rake	1	Acre	$6.52
Large Rectangular Baler	1	Acre	$12.09
Total Harvest ($/ac)			$32.83
Storage			
Pad & Tarp (2.75% DM Loss)	6	Month	$1.57
Total Storage ($/dry ton)			$1.57
Transportation			
Tractor Trailer	30	Mile	$2.67
Total Transportation ($/dry ton)			$2.67

Appendix C 4: Miscanthus (Miscanthus x giganteous) Production Inputs & Enterprise Budget

	Quantity	Unit	Cost ($/ac)
Establishment			
Tandem Disk	2	Acre	$21.74
Field Cultivator	1	Acre	$6.42
Potato Planter	1	Acre	$42.61
Rhizomes	4,047	#	$404.70
Boom Sprayer	1	Acre	$3.78
Glyphosate	0.375	Gal	$10.05
Cimarron (Ally)	0.0115	Gal	$6.07
		Total Establishment ($/ac)	$495.37
Annual Establishment			
5 Year Cost			$99.07
		Annual Yield Proportion	85%
10 Year Cost			$49.54
		Annual Yield Proportion	93%
20 Year Cost			$24.77
		Annual Yield Proportion	96%
Annual Maintenance			
Fertilizer Spreader	1	Acre	$3.78
Superphosphate (44-46%) (P)	88.89	Lb	$27.60
Muriate of Potash (60-62%) (K)	131.15	Lb	$39.41
Urea (44-46%) (N)	133.33	Lb	$42.93
Limestone, spread	120	Lb	$3.40
		Total Annual Maintenance ($/ac)	$117.12
Harvest			
Mower Conditioner	1	Acre	$14.22
Hay Rake	1	Acre	$6.52
Large Rectangular Baler	1	Acre	$12.09
		Total Harvest ($/ac)	$32.83
Storage			
Pad & Tarp (2.75% DM Loss)	6	Month	$1.57
		Total Storage ($/dry ton)	$1.57
Transportation			
Tractor Trailer	30	Mile	$2.67
		Total Transportation ($/ac)	$2.67

Appendix 5C: Giant Reed (Arundo donax L.) Production Inputs & Enterprise Budget

	Quantity	Unit	Cost ($/ac)
Establishment			
Tandem Disk	2	Acre	$21.74
Field Cultivator	1	Acre	$6.42
Potato Planter	1	Acre	$42.61
Rhizomes	4047	#	$404.70
Boom Sprayer	1	Acre	$3.78
Glyphosate	0.375	Gal	$10.05
Cimarron (Ally)	0.0115	Gal	$6.07
Total Establishment ($/ac)			$495.37
Annual Establishment			
5 Year Cost	1	Acre	$99.07
Annual Yield Proportion			85%
10 Year Cost	1	Acre	$49.54
Annual Yield Proportion			93%
20 Year Cost	1	Acre	$24.77
Annual Yield Proportion			96%
Annual Maintenance			
Fertilizer Spreader	1	Acre	$3.78
Superphosphate (44-46%) (P)	88.89	Lb	$27.60
Muriate of Potash (60-62%) (K)	131.15	Lb	$39.41
Urea (44-46%) (N)	133.33	Lb	$42.93
Limestone, spread	120	Lb	$3.40
Total Maintenance ($/ac)			$117.12
Harvest			
Willow Harvester	1	Acre	$72.84
Total Harvest ($/ac)			$72.84
Transportation			
Tractor Trailer	30	Mile	$1.75
Total Transportation ($/dry ton)			$1.75

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Appendix D: Chapter 6

Appendix D 1: Biomass Logistics Model Pseudo Code

Data Entry

Commodity Info: Code, Fixed, Variable, Price, Fixed 2, Variable 2, Price 2

1-Corn, 4- Grain Sorghum, 26- Dbl WinWht/Soybean, 61- Fallow/Idle, 176- Grassland/Pasture, 37- Other Hay

Biomass Info: Fixed, Storage, Transport, Price

Sorghum, Canola, Switchgrass (fall sq, win sq, fall for, win for)

Yields and Std: Piedmont (Yld, Std), Coastal Plain (Yld, Std), Mountains (Yld, Std)

Commodity and Biomass

Create Matrices

Convert Structures to Matrices

Puts farm centroid and area data into a matrix (date from ArcGIS)

Adds columns to the centroid and area matrices

Adds Yield Coefficient, Crop Profit, Biomass Profit, Normal Random Probability, Distance, Inclusion of Biomass (by type)

Current Crop Profit

Determine the profit of the current crop being produced on each farm

All unlisted crops are considered to have infinite profit

Biorefinery Information

Uses NCCITY function to determine lat long of potential biorefinery locations

Determines safety stock of each of the potential feedstock configurations

Determines total material requirements for each of the potential biorefinery sites

Distance from Biorefinery

Determines distance from farms to biorefinery sites (DISTS function)

Biomass Feedstock Costs

Biomass price starts at $30 per dry ton

Determines if biomass crops make more money than current commodity crop

If not enough feedstock is produced to meet need price increase by $1

Reruns all potential farms to determine inclusion, until requirement met

Plot Potential Feedstock Sites

Removes farms that are not included

Uses PPLOT to create a figure of potential farms and biorefinery site

Selection of Farms by Feedstock

Distances of included farms are ordered by distance from potential biorefinery site

Closest farms are set as switchgrass square bales, if they are profitable

Next closest are set as switchgrass forage, if they are profitable

Lastly sorghum is included, if profitable

Each of the biomass types needs to be filled to make it work

Plot Selected Farms

Use a PPLOT to plot which farms are changed to which biomass type

Shows farms, biomass produced, and potential biorefinery

Selection of Storage Locations

Uses the ALA function for baled biomass to determine storage sites

10 storage sites was selected which are weighted by yield

PPLOT is used to show storage sites with baled biomass locations