5-2020

Biomass Potential in Sustainable Aviation Fuel Development: Switchgrass Production Optimization and Carinata Oilseed Enterprise Viability Analysis

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Recommended Citation

Robertson, Kevin Alan, "Biomass Potential in Sustainable Aviation Fuel Development: Switchgrass Production Optimization and Carinata Oilseed Enterprise Viability Analysis. " Master's Thesis, University of Tennessee, 2020.
https://trace.tennessee.edu/utk_gradthes/5592

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I am submitting herewith a thesis written by Kevin Alan Robertson entitled "Biomass Potential in Sustainable Aviation Fuel Development: Switchgrass Production Optimization and Carinata Oilseed Enterprise Viability Analysis." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural and Resource Economics.

Burton C. English, Major Professor

We have read this thesis and recommend its acceptance:

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(Original signatures are on file with official student records.)

Biomass Potential in Sustainable Aviation Fuel Development: Switchgrass Production Optimization and Carinata Oilseed Enterprise Viability Analysis

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Kevin Alan Robertson
May 2020

Acknowledgements

I would like to thank my major professor, Dr. Burton C. English, for his encouragement and mentorship throughout this process. I would not have made it to the finish line without him. I will always look back on my experiences at the University of Tennessee fondly and it is due, in large part, to him. I would also like to thank my other committee members: Dr. Chris Clark, Dr. Jada Thompson, and Dr. Kimberly Jensen for their tireless efforts in the brainstorming as well as editing portion of this process. Thank you to Jamey Menard who played a considerable role in research and sanity support. A special thank you to Dr. Jim Larson who never ceased to take time out of his day to help mentor me through this program; thanks for believing in me. Thank you to Dr. Katryn Pasaribu who helped me through many early struggles in graduate school as well as provided an excellent budget template with the help of Dr. Evan Markel and Umama Rahman. I would also like to take a moment and give a special thank you to each of the faculty and staff members here at the university who have provided so much help and support to me. Specifically, Mrs. Dora Pratt, Mrs. Amy Cooley, Mrs. Julie Daughtry, Dr. Chris Boyer, Dr. Aaron Smith, and Dr. Carlos Trejo-Pech. Thank you to my girlfriend, Katy Smith, who has been a constant rock of encouragement and love from start to finish. Last but not least, an enormous thank you has to be given to my family: my parents Kevin and Dana Robertson, and grandparents Jim and Shirley Robertson and James and Lavonne Smith who have each been with me through the highs and lows of the master's program and always provide endless love and support throughout all my endeavors.

Abstract

Global trends are moving toward more renewable fuel supply systems for the aviation industry. The adoption of biomass as a renewable energy source is growing alongside the industry as a whole. The goal of this study is to ascertain whether Tennessee has potential to be a leading producer of energy crops in the United States for sustainable aviation fuel production. The first chapter of this thesis provides an introductory overview of the research topics. The purposes of this study are twofold. First, to provide a farm-gate analysis of the perennial crop switchgrass using microeconomic and econometric methods to determine profitability for producers and a biorefinery when varying nitrogen (N) fertilizer. Second, provide a budgeting analysis and stochastic simulation for the financial returns from producing the oilseed crop Carinata to be grown in Tennessee for refinement into Sustainable Aviation Fuel (SAF). Regarding the second study, switchgrass has proven to be economically viable through other experiments and research done at the University of Tennessee. This study seeks to discover a linkage between N fertilizer application during the crop management stage and final biofuel conversion at the biorefinery. Though there is not a secured market for switchgrass in Tennessee, both the producer and refinery show potential for positive profit margins when optimized methods are adopted. The results of the Carinata farm-level enterprise budget include calculations of breakeven analysis and stochastic simulation of yield, cost, and profit for three Environmental Policy Integrated Model (EPIC) yield scenarios including Tennessee, frost tolerant, and documented yields. The

final chapter of this thesis offers concluding comments and suggestions for further research.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The aviation industry has been around for more than a century in the United States. The very first flight spanned a mere 21 miles in distance. Today, the industry is on track to record over 30.4 billion miles annually, which is ten times the distance from Earth to Neptune (ICAO, 2017). This high-traffic trend is unlikely to decrease in the foreseeable future. The increase in miles flown is due, primarily, to population growth as well as a more globalized world where airline travel is heavily relied upon for business and leisure. Many countries, including the United States, are pushing for renewable aviation fuel systems to be implemented for environmental purposes. The International Civil Aviation Organization (ICAO) has set a target of net CO_2 emissions of the international aviation sector at the average of 2019-2020 levels for the coming years of 2021-2035. Though any reduction effort is positive, this still may fall short of the Paris Agreement goal of a 1.5 Celsius degree global temperature decrease by 2050 (Michielin, 2019). The International Coalition for Sustainable Aviation (ICSA) is urging the adoption of the Enhanced Climate Mitigation Targets and Levers for International Aviation which secures "zero climate impact" by 2050 (Michielin, 2019). The pathway to this effort is outlined by technology advancements for fuel efficiency as well as the adoption of biofuels replacing fossil fuels effective immediately.

This study explores the potential for two very different crops to aid in mitigating one common problem in the renewable energy sector: economically efficient biofuel feedstocks. Specifically, in the first study, the farm-gate analysis of the perennial crop switchgrass is broken down using both microeconomic as well as econometric methods to determine profit maximizing nitrogen (N) fertilizer applications for both the producer as well as the biorefinery. The second study evaluates the financial enterprise potential for the oilseed crop Carinata to be grown in Tennessee for refinement into Sustainable Aviation Fuel (SAF) using budgeting techniques and stochastic simulation.

Chapter two considers the optimization methods of minimization and maximization for ash content and yield respectively when varying nitrogen (N) fertilizer application rates on switchgrass for a biofuel feedstock. The factors of ash and yield are initially considered separately because they tailor to different links along the supply chain. While producers may be focused on producing higher switchgrass yields per acre, the thermochemical biorefinery must also consider ash content of the feedstock, with lower ash content being more desirable for refinement. This is because ash in the raw feedstock plays a negative role in the refining process. It creates a char-like residue inside the combustion chamber which, subsequently, increases the cost of refinery cleanup and reduces the overall efficiency of the refining process. Switchgrass yield in literature such as Hong et. al (2014) exhibits increases in yield at a decreasing rate in response to N fertilizer application. Ash content decreases at a decreasing rate in response to N fertilizer application. Therefore, information regarding N application rates which are optimal across the production and conversion of switchgrass into biofuels is needed information. In order to conduct the analysis, profit maximizing assumptions must be made. In addition, a potential incentive program mitigation effort is evaluated. Previous literature has analyzed yield response to N application as well as ash content response to N application. The contribution of this paper will be to jointly show the effect on the biorefinery's conversion ratio when ash content and yield are considered. Agronomically, switchgrass provides desirable traits of heartiness and durability in less than optimal conditions. This is due to a well-developed root system of up to 10 feet deep and a highly efficient photosynthetic system (Brodowska et al., 2018).

The purpose of chapter three is to provide an enterprise budget and producer profitability analysis of growing *Brassica carinata* as an energy cover crop in Tennessee and to be marketed through a supply chain to produce sustainable aviation fuel (SAF). Palisade's @RISK software is used to develop profit margin probabilities for the cover crop enterprise given three different yield scenarios. The results from this analysis will provide Tennessee farmers insight about future cover cropping options as technology advances and the financial feasibility of introducing Carinata onto their own farms.

Brassica carinata is a part of the mustard family and due to its waxy leaves and deep rooting abilities it provides farmers with an excellent candidate for a winter cover crop (Seepaul et al., 2016) Carinata implemented as a cover crop adds important environmental benefits as well as potential for a third revenue source for a two-year crop rotation. Carinata has a 40% oil content and is proven to grow successfully in the warmer climates of the southern region with relatively low herbicide and fertilizer input requirements. This potential cropping solution provides a groundbreaking settlement of the food versus fuel argument typically involved with growing fuel. Within this study, a break-even analysis is conducted to determine both price and yield sensitivity for producers. Moreover, a stochastic simulation of three yield scenarios is conducted to determine the probabilities of breakeven given each scenario.

CHAPTER 2: OPTIMAL NITROGEN APPLICATION RATES WHEN NITROGEN APPLICATION INFLUENCES SWITCHGRASS QUANTITY AND QUALITY

Abstract

The supply of economically efficient biofuel feedstocks is increasing due to the demand growth for bioenergy. The focus of this project is on the use of switchgrass feedstock being further refined through pyrolysis methods to create an avenue of Sustainable Aviation Fuel (SAF) supply in Tennessee. Switchgrass (*Panicum virgarum* L.) is a perennial bunchgrass native to North America with traits suitable for biofuel production. This study analyzes how N fertilizer application rates influence producer and biorefinery profitability. First, a partial budgeting profitability analysis is conducted for this cropping enterprise at the farm-gate level without considering downstream implications of ash content. At the biorefinery level, higher ash content as a percentage of the feedstock decreases biorefinery fuel output (Ou et al., 2018). Results show farm-gate profit is maximized when N fertilizer is applied 47 lbs./acre, while biorefinery profit is maximized when N is applied at 114 lbs./acre. Given this information, lower ash could lead to premium prices being paid to producers if higher quality feedstock were to be demanded as part of an integrated industry approach.

2.1 Introduction

Biofuel production and use in the United States is hindered by an inconsistent market and relatively low crude oil prices (Tyner, 2015). Government intervention, through policy decisions, is the backbone of biofuel production and consumption. For example, the United States Department of Agriculture (USDA) is helping enforce President Donald Trump’s October biofuels agreement titled the Higher Blends Infrastructure Incentive Program (HBIIP). This policy finalizes more than 15 billion gallons of ethanol and 2.43 billion gallons of biodiesel to enter the market in 2020 (2020). However, the true catalyst of change in the biofuels industry will occur when fossil fuel based oil prices rise as they did during the 2008 recession when a barrel of crude oil was going for over $120 (Tyner, 2008). For now, however, the market in Tennessee for switchgrass feedstock is essentially nonexistent due to the lack of a biorefinery. However, Tennessee has the potential to be a major supplier, along with the entire Southeastern United States if the market for second generation biofuels expands in the future (Larson et al., 2010).

With respect to the agriculture industry, there is a common conflict between producing food or fuel. It is true that biofuel feedstocks are competing with traditional row-crop land. However, switchgrass provides a unique solution to this problem. Switchgrass (*Panicum virgarum* L.) is a native bunchgrass to the United States that has been researched and implemented into biofuels production operations for many years. Agronomically, switchgrass is hearty perennial grass with erect stems and a rooting depth of up to 10 feet deep (Brodowska et al., 2018). Due to the biological nature of the perennial grass, it can be grown on marginal lands where other crops would turn subordinate yields and provide lower net returns. For example, secondary land on many farms could easily be transitioned from the Conservation Reserve Program (CRP) or idle acres to switchgrass production.

This study assumes a strict net return maximizing throughout supply chain. At the farm-gate, this includes farmers making optimal cropping decisions such as which crop to plant and when. Beyond making a cropping decision, producers also make decisions on how much fertilizer, maintenance practices, and when to harvest. The management practice that will be modeled and examined in this study is the application of N fertilizer. N application is of particular interest since, while it can increase switchgrass yields, higher applications rates could also reduce price paid per unit of switchgrass. This is because N application can contribute to ash content in the conversion process which is less desirable to conversion facilities. Hence, higher N rates likely bring a price discount.

Previous research suggests that feedstock yield is a function of N. Thus, at the farm gate level, revenue and costs are a function of N and producers can be expected to choose the net return maximizing level of N. However, previous research also suggests that N influences ash content, which influences the costs of converting Switchgrass to biofuel. Thus, N influences both quantity and quality of switchgrass. Given the differences in conversion costs associated with differences in Switchgrass quality (i.e., ash content), higher quality Switchgrass could be expected to command a higher price. Thus, the effect on both yield and ash content (i.e., quality) should be taken into consideration in determining optimal N application rate.

The expected results of this project are that as N fertilizer application rate increases, cellulose and hemicellulose content, as a percentage of the plant, will increase at a decreasing rate. These results are expected to be similar to Hong et al. (2014) and Mulkey et al. (2006). Additionally, ash content is expected to decrease at a decreasing rate. This is probable because, as found in Lemus et al. (2008), ash content as a percentage of the plant begins to decrease steadily with additional N fertilizer application. Net returns for the biorefinery is also a function of an Environmental Protection Agency (EPA) subsidy or renewable identification number (RIN). A RIN is a number assigned to each gallon of biofuel at creation to stay with it until it ends its lifecycle at a blending facility or other obligated party. Assigned by the EPA, it adds additional revenue to the biorefinery as an incentive to pay producer higher rates for these crops as well.

Beyond this project, the goal of biofuels and alternative energy research is to develop an economically efficient renewable energy source to lessen the global dependency on fossil fuels for a more environmentally sustainable future. The specific objective of this research project is to

1.) use microeconomic methods to optimize N application on switchgrass during management practices for both the producer as well as the bio-refinery. This objective is accomplished using operations research methods to model fuel conversion rates measuring oven dry tons (ODT) of switchgrass being thermochemically refined to biofuel (gallons) to model an increase in ash content leading to a lower biofuel yield;

2.) build upon literature-derived knowledge of the relationship between yield and N and econometrically model a relationship between N application and ash content. If the findings of this research prove the need for switchgrass producers to be concerned with the quality as well as quantity of feedstock;

3.) yield (dry tons/acre) and ash content (%) will be incorporated into the biorefinery conversion ratio to potentially show a relationship between N fertilizer application rate and fuel conversion. Finally, discuss the possibility of a premium price being paid or incentive program put in place by the biorefineries as part of an integrated supply chain.

An incentive program for the producer is the Biomass Crop Assistance Program (BCAP) which is sponsored by the Farm Service Agency (FSA) and was established under the Food, Conservation, and Energy Act of 2008 (Peterson, 2008). The outlay of this incentive program included a dollar-for-dollar payment matching system where costs of collection, harvest, storage, and transportation would be afforded to producers up to $45 per ton. The only qualification or limitation to this program was the biomass must be delivered to a qualified facility. Meaning, a refinery may be interested in incentivizing switchgrass grown using a specific N fertilizer rate and, if qualifications are met, additional or all input costs could be incurred by the refinery (Peterson, 2008).

2.2 Review of Literature

2.2.1 Background on Biofuels

Biomass contains stored energy, and there are three general methods to release that energy: burning, bacterial decay, and conversion to liquid or gas fuels. Biofuel is an example of that biomass being converted into liquid or gas fuels and serves as an alternative for liquid fossil fuels in the transportation sector (Hinrichs and Kleinbach, 2013).

There are two different types or “generations” of biofuels. Generation 1 biofuels are made from the sugars or vegetable oils from traditional food crops such as corn or soybeans; while generation 2 primarily refers to non-food biomass such as switchgrass, non-edible oils, or wood pellets in the creation of advanced fuels. Generation 1 biofuels are typically blended with traditional fossil fuel to ensure proper combustion in transportation vehicles. Commonly, their mixture with petroleum has a legal maximum. Legislation under the Carter Administration in the late 1970’s made the first steps toward biofuel initiatives. Blenders that mixed 10% ethanol with gasoline received a $0.50 tax break per gallon produced (Christensen and Lausten, 2014). Generation 2 fuels provide an umbrella term that many biofuels produced for which switchgrass as well as various non-food oilseed crops are categorized.

2.2.2 Bioenergy and Environmental Impacts

The Renewable Fuel Standard (RFS) was created under the Energy Policy Act of 2005 as an amendment to the Clean Air Act (CAA). The Energy Independence and Security Act of 2007 (EISA) further amended the CAA by creating production volume requirements extending to 2022. This production statue shows the increased dependence on cellulosic biofuel (D3) in expectation of reaching the 36-billion-gallon target in 2022. When this litigation was initially written, there was no volume standard for this fuel type. The overall primary component of renewable fuel was renewable biofuel (D6) (US EPA, 2015). However, by the target year, the anticipated production of cellulosic biofuel is nearly half of the objective gallons of production. This can be seen visually in Figure 2.1 (Sikarwar et al., 2017). Carbon savings also play a key role in the development and use of biofuels. As seen in Figure 2.2, cellulosic fuels composed of cellulose, hemicellulose, and lignin provide a 60% reduction in Greenhouse Gas (GHG) emissions. This metric was calculated against 2005 petroleum baseline as mandated by the EISA. The only caveat to this mandate is the "grandfathered" refineries which began biofuel production prior to 2007 (US EPA, 2015). Research from the National Academies of Science (2016), Engineering, and Medicine has shown that the use of sustainable alternative jet fuels (SAJF) alleviate net life-cycle carbon emissions in comparison to standard fossil fuels because they reclaim carbon previously in the biosphere during feedstock production.

Two primary lignocellulosic ethanol production methods are in use today: biochemical and thermochemical conversion. "Biochemical conversion involves hydrolysis and fermentation while thermochemical conversion involves gasification catalytic synthesis" (Mu et al., 2010). Both of these conversion technologies prove similar in fuel yield. Additionally, as shown in Mu et al. (2010), biochemical conversion appears to do better in greenhouse gas emissions. However, thermochemical refinement has significantly less direct, indirect, and life cycle water consumption. For the sake of this project, the focus will be on thermochemical refinement only.

There are two common approved pathways for converting the feedstock into usable fuel. One form is a process known as gasification. This method requires a controlled oxygen chamber to heat small feedstock particles at high temperatures to create synthesis gas (syngas). This syngas is composed mostly of dihydrogen and carbon monoxide which is further refined into liquid chemicals though Fischer Tropsch (FT) processing to produce hydrocarbon molecules from which viable bio-jet fuel is extracted. The second common pathway is pyrolysis or "fast pyrolysis" which involves grinding or cutting the feedstock into small particles and heating it to high enough temperatures for a few seconds to create a bio-oil for further processing. Due to its potential usage of pre-existing oil refineries, switchgrass as a feedstock, and its higher efficiency for production, pyrolysis is the pathway assumed in this study. To begin the fast pyrolysis refinement, first the feedstock must be dried. The switchgrass post field drying has a moisture content between 15% and 45% (Ou et al., 2018). The drying involved at the refinery reduces the moisture content of the feedstock to a maximum of 7% to ensure proper combustion (Ou et al., 2018). After the drying process, fast pyrolysis conversion can begin. A detailed visual depiction of the thermochemical pathway is presented in Figure 2.3.

Thermochemical refinement, when utilizing fast pyrolysis, involves heating the switchgrass feedstock indirectly to temperatures of 500° C with a control on oxygen and other gasses. This process will result in the feedstock being converted into fixed carbon (char) and gas. The char is the ash chemical component of the feedstock being separated from the combustible gasses. The vapors produced are condensed into a bio-oil which goes to the upgrading process for further hydro-processing and final distillation (Ou et al., 2018).

The char from the fast pyrolysis reaction is primarily composed of ash. Further, ash is also comprised of many earth alkali metals and metallic oxides. As found in

González-Vázquez et al. (2018), switchgrass ash has 44.2% concentrations of SiO_2 which is not harmful in thermochemical conversion. However, there are also significant levels of more limiting elements such as K_2O and CaO with total composition of 20.7% and 14.1%, respectively (González-Vázquez et al., 2018).

2.2.3 Relevant Literature on Switchgrass Yield and Ash Content

Yield response to N fertilizer application has been estimated in a number of different ways. Much of the literature only takes the yield response to fertilizer into consideration, however. For example, Hong et al. (2014) analyzed the means and used interaction variables of year x N and location x N to show yield variation in 5 separate states: Oklahoma, New York, South Dakota, Virginia, and Iowa. This study stopped short of using response functions as in Boyer et al. (Boyer et al., 2012). By using the quadratic, quadratic-plus-plateau, linear response plateau, and the linear response stochastic plateau, the study was able to model incremental variation in yield when slight alterations were made to N fertilizer application. Additionally, this study looked at West Tennessee farm land across a seven-year period and four separate test plot sites each with differing characteristics (i.e. upland slope with well-drained soil). Similarly, Seepaul et al. (2016) analyzed yield response to varying N fertilizer application rates in Raymond, Mississippi. In contrast, however, it considered harvest timing (i.e. pre and post senescence). Interaction variables were also included in this study similar to Hong et al. which measured year x harvest interaction effects. The statistical methods used by Seepaul et al. (2016) can be summarized by basic regression analysis. Advanced response functions were not utilized as in Boyer et al.(2012). The Seepaul et al. (2016) paper did analyze ethanol yield, however, fell short of exploring the effect of ash content on ethanol yield.

Kenney et al. (2013), explored the negative attributes of higher ash content where pyrolysis conversions were performed. The study found less than 1% ash to be preferred due to the impairment on catalysts and slag formation during the combustion process. Additionally, the study revealed that switchgrass with higher ash content creates excess conversion cost and maintenance requirements in thermochemical refinement. The concluding comments on ash explain the best management practices to reduce the ash including: feedstock selection, fractionation, and removal of entrained soil. What this study did not consider was the effect of N fertilizer on chemical composition of the plant; specifically, ash. As discussed in Gonzalez et al. (2012), higher ash content decreases the Net Present Value (NPV) of bio-refineries in analysis of break-even analysis.

Edmunds et al. (2018) analyzed thermochemical conversion looking specifically at biomass characterization of switchgrass and pine residue blends. This study highlighted that the switchgrass was of a high ash content (1.3%) while the pine was much lower. The results of the study showed that ash content was not strongly correlated with pyrolysis product yields. However, some of the organics in the study showed high significance. The conclusion of this study emphasized the need for understanding the chemical composition of the feedstock beyond just quality. Meaning, knowing the specific concentrations of alkali and alkaline Earth metals contained within the ash is more important than ash content as a percentage of biomass to final fuel production yield estimation (Edmunds et al., 2018).

Ou et al. (2018) completed a study analyzing the impacts of feedstock properties such as ash contend, moisture content, and carbon content on fast-pyrolysis biorefinery fuel conversion. The process fuel conversion model assumed in the study was based on previous research by Jones et al. (2013). The ash content in the study ranges from 1-7% and is shown to decrease biofuel yield, excess electricity from turbines, and final hydrocarbon yield in higher concentrations. Moisture content effects the pre-pyrolysis steps because prior to refinement, the feedstock must be dried to no higher than 7% moisture. Therefore, the higher the starting moisture, the longer the drying duration and more expensive it is to prepare for refinement. Carbon content in conjunction with ash content affect fast pyrolysis biofuel yields and composition of the subsequent bio-oil (Ou et al., 2018).

In Ou et al. (2018), the biorefinery facility is assumed to have a capacity of 2000 metric tons or 2204.6 short tons of feedstock per day year-round. This study sequentially held ash, moisture, and carbon constant to estimate the impact of each variable on biofuel yield. Specifically, at a 1% ash content and holding moisture and carbon constant, biofuel yield is 30.2 gallons per ton of feedstock input. Whereas, at 5% ash content with the same assumptions, biofuel yield decreased to 26.0 gallons per ton of feedstock input (Ou et al., 2018).

This study seeks to discover the effect on the optimal N fertilizer application rate when quality, as measured in this case by ash content, as well as quantity is considered in the decision-making process. Thus, one contribution of this study is to show the potential value of a more sophisticated approach to feedstock production that incorporates the effect of production practices on conversion-relevant qualitative attributes. Yield measured in dry tons per acre will be studied alongside ash content as a percentage of biomass and will be incorporated into the biorefinery conversion ratio to potentially show the relationship between N fertilizer application rate and fuel conversion and optimal N application rates for both the producer as well as biorefinery.

2.3 Conceptual Framework

2.3.1 Maximizing Net Returns

This study assumes strict net return maximization at the farm-gate and refinery level. Meaning, utility is solely derived from net returns. This study also assumes the only operational costs of production at the farm level are fertilizer costs. For the integrated industry biorefinery, the only operational costs are transportation and N fertilizer. Therefore, net returns is a more accurate term than profit. The economic concept behind net returns maximization means that a farmer will produce a crop if the net returns can be modeled as follows:

Model 2.1

$$NR_{Farm} = P(N) * Y(N) - C(N)$$

where net returns (*NR*) are maximized subject to gross returns (price (*P*) times yield (*Y*)) less the operational costs (*C*).

When defining this for the producer, *P* is potentially a function of *N* if a premium or discount were to be paid to producers based on feedstock quality characteristics. The switchgrass yield is a function of N application. Cost (*C*) in this model is a function of N application. This objective is achieved with net returns maximization which is only a function of switchgrass yield, price, and assumed operational costs. However, for the biorefinery, there is an added layer of complexity.

Model 2.2

$$NR_{Refinery} = P * FY(S(N), Ash\ (N)) - C(Trans)$$

where net returns (*NR*) are maximized subject to gross returns (price (*P*) times fuel yield (*FY*)) less the operational costs (*C*).

When defining this for the biorefinery, *P* is the price received per gallon of biofuel. FY is the quantity of gallons produced per dry ton of switchgrass feedstock input which makes it a function of switchgrass quantity (*S*) as well as ash content (*Ash*), which are both functions of N application. Cost (*C*) of the biorefinery is a function of transportation (*Trans*) in dollars per ton.

Quantity of incoming feedstock is important, however, so is the quality. The quality of feedstock is a function of total ash, moisture, and carbon content of switchgrass (Ou et al., 2018). For the purpose of this study, moisture and carbon will be held constant and ash content will be allowed to vary. In Ou et al. (2018), the quality factors were analyzed and only ash content proved to be significant in affection conversion yield.

The economic theory behind profit maximization stems from the assumption that all firms are in pursuit of achieving the largest economic profits possible. Therefore, a firm will choose a combination of inputs and outputs that maximize the difference between total revenues and its economic costs; assuming a perfectly competitive market system. This theory is rooted in a "marginal" concept. Meaning, if a firm is able to increase inputs by one unit and profits also increase, there is no incentive not to do so. Firms will then continue to increase inputs until an additional input increases profits at a level equal to zero. In summation, a firm will always seek to maximize economic profits by incurring marginal revenues that are equal to marginal costs (Nicholson and Snyder, 2012).

2.4 Data and Methods

2.4.1 Data Description

Extensive experiments were conducted at the University of Tennessee's Research and Education Center in Milan, Tennessee (35°56/N, 88°43/W) on Alamo Switchgrass from 2004-2014. The data is representative of the impact of four different levels of N fertilizer in pounds per acre on yield measured in dry tons per acre, chemical composition as a percentage of the plant make up, and waste minerals or ash content as a percentage of switchgrass plant. For the purpose of this project, analysis will be limited to N fertilizer's impact on yield and ash content. Tables 2.1 and 2.2 show the descriptive statistics including mean, standard deviation, minimums and maximums of switchgrass when N fertilizer is varied. Additionally, Figures 2.3 and 2.4 visually show the minimum and maximum averages for each N rate.

Harvest data collected for this study was obtained in years 2006, 2008, 2010, 2012, and 2013. The plots utilized for the study are abbreviated by field N21 and 212. Field 212 is characterized with a well-drained Grenada silt loam soil type with no slope in an upland position of site. Field N21 remains similar with a well-drained Vicksburg silt loam soil type and no slope, and positioned in a flood plain. Throughout the course of the experiments, rainfall, temperature, and weather are constants given plot location and proximity. Nitrogen fertilizer was applied to sub plots in both field N21 and 212 with rates ranging from 0, 60, 120, and 180 pounds per acre. The source of the N is ammonium nitrate (NH_4NO_3). Each of these treatments was applied annually. According to Mooney et al. (2009) switchgrass requires very little P and K, however, 80 pounds of P_2O_5 and K_2O were applied per acre annually. Harvest occurred once per year, post senescence, with samples tested for moisture content in a forced air oven.

2.4.2 Analysis of Variance

The Analysis of Variance (ANOVA) model is included in this study to reflect both yield and ash content variability. This type of model helps capture uncertainty aspects and visually represent the effects of N fertilizer at each application rate. The N fertilizer application rate was applied to Alamo switchgrass at rates of 0, 60, 120, and 180 pounds per acre annually. To model the fixed effects of each N rate, an ANOVA model is utilized and shown in functional form as:

Method 2.1

$$S = \propto + \sum_{i=1}^{k=4} \beta_i X_i + \varepsilon$$

Given the nature of the objective, there are two similar models used. First, a model with the dependent variable of switchgrass yield in dry tons per acre, represented as *S*, is regressed onto the independent variables represented as *X* of N rate *i* 1 through 4 to analyze the variation of yield when this input is altered. Parameter estimates are represented in the model with the Greek letter *β*. Additionally, the ε represents the random error.

Method 2.2

$$Ash = \propto + \sum_{i=1}^{k=4} \delta_i X_i + \varepsilon$$

Method 2.2 with the dependent variable of switchgrass ash content as a percentage of plant composition, is regressed onto the independent variables represented as X of N fertilizer rate i 1 through 4 to estimate the variation in ash content when the input variable is altered. The parameter estimate is represented in the model with the Greek letter δ. Additionally, the ε is placed in the model to allow for random error.

2.4.3 Response Functions

To construct a model that would estimate the parametric relationship of the dependent variable and independent variables, model selection had to be conducted. Similar to Boyer et al. (2012), techniques such as the log likelihood ratio (LLR) test as well as the Akaike Information Criterion (AIC) or adjusted (AICC) and Bayesian Information Criterion (BIC) fit statistics are applied to ensure accurate estimation. The models tested include the quadratic response function (QRF) (see Table 2.3), mixed quadratic response function (MQRF) (see Table 2.4), linear response plateau (LRP) (see Table 2.5) and the mixed linear response plateau (MLRP) (see Table 2.6). When comparing the AIC, AICC, and BIC, the lower values indicate a better statistical fit for the data. With respect to comparing models that include or exclude year random effects, the LLR test is used. If LLR of model 1 less LLR of model 2 is greater than the X^2 statistic of 3.84, then the mixed model is preferred. The results of this testing showed the mixed effect models being stronger given year random effects being accounted for. With respect to biofuel yield, however, no year random effects are present. Thus, only the LRP and QRF models were estimated. Based on the results of AIC, BIC, and LLR testing, the QRF function fit the data best. Conclusively, the MQRF model was estimated as the most statistically powerful in predicting switchgrass yield and ash content while the QRF model proved the best at predicting biofuel yield conversion. For the response functions estimating biofuel yield, the mixed models showing year random effects are excluded. This is because no year to year variation is accounted for in the data.

As in Boyer et al., the MQRF estimates a model in Method 2.3 showing the relationship between N fertilizer application and switchgrass yield (2012). The purpose of this model is to simulate a curve experiencing decreasing or increasing returns to scale. This can be seen in functional form as follows:

Method 2.3

$$S = \beta_0 + \beta_1 N + \beta_2 N^2 + v + \varepsilon$$

where S represents the quantity of switchgrass in dry tons per acre, β represents the parameter estimates from the regression, and N is N fertilizer application rate in pounds per acre. Due to the nature of chemical composition and yield variability between year to year due to changes in weather, harvest timing, and other situational effects; random effects are included in the MQRF. These are assumed to be unrelated to the independent variables and independent of the error term. This is represented in the v term in the quadratic equation and the ε picks up random error within the model. Boyer et al. used the quadratic response function to model the yield response to N fertilizer application (2012). The results of the yield impact are to be considered for this paper to serve as a quantity of switchgrass at the farm-gate level in dry tons per acre.

The QRF is applied to convert estimates from Ou et al. (2018) point estimates into function form. Similar to the estimations shown in Ou et al. (2018), ash content (Ash), moisture content (Moist), and carbon content (Carbon) are modeled to determine a relationship between these variables and biofuel yield in gallons. In the study each of these explanatory variables was separately held constant at a median value. For the sake of this study, each will be included in the model, however, assumed values of moisture and carbon content are held constant (see Table 2.12). This method can be seen represented in Method 2.4 below:

Method 2.4

$$FY = \phi_0 + \phi_1 Ash + \phi_2 Ash^2 + \phi_3 Moist + \phi_4 Moist^2 + \phi_5 Carbon + \phi_6 Carbon^2$$

The purpose of this model is to estimate the effect of marginal increases in ash content on biofuel yield. *FY* represents the fuel yield in gallons, ϕ represents the parameter estimates, *Ash* is the composition of switchgrass being made up of ash, *Moist* is the moisture content, and *Carbon* is the carbon content all represented as a percentage.

A literature contributing MQRF will be estimated for the effect of N fertilizer application on ash content in switchgrass. If Method 2.4 provides significant results, then Method 2.5 will provide a previously unknown link between N application and ash content of switchgrass. This provides supports the resulting relationship between N application and biofuel yield at the refinery as well as different optimal N application rates for both the producer and refinery. The modeling can be seen as follows:

Method 2.5

$$Ash = \delta_0 + \delta_1 N + \delta_2 N^2 + v + \varepsilon$$

The purpose of this model is to estimate the effect of marginal increases in ash content on biofuel yield. Ash represents ash content as a percentage of biomass, δ represents the parameter estimates, and N is the nitrogen fertilizer application in pounds per acre. Similar to the previous response functions, chemical composition and yield variability between year to year due to changes in weather, harvest timing, and other situational effects justifies including random effects in the function. These are assumed to be unrelated to the independent variables and independent of the error term. This is represented in the v term in the quadratic equation and the ε picks up random error within the model.

Given the lack of a market for switchgrass in Tennessee, prices of the feedstock must be assumed. A techno-economic analysis (TEA) is used to assume the linked switchgrass feedstock price ($/dry short ton) and the price of the subsequent biofuel ($/gallon) using pyrolysis refinement methods. Based on this TEA, switchgrass price is assumed to be $80.00 per dry short ton (Brandt and Garcis-Perez, 2019). Additionally, the related biofuel price is assumed to be $6.27 per gallon (Brandt and Garcis-Perez, 2019). The price of N fertilizer is assumed to be $2,920 per short ton which converts to $1.46 per pound (NASS, 2019). Transportation costs are included in the partial budgeting model to analyze the effects of distance between the farm and the biorefinery on optimal N application rates. Larson et al. (2015), who estimated the per ton cost of switchgrass being transported from farm to biorefinery as $11.95. This estimate is based on a 37.5 mile assumed distance and an average rate of speed of 50 miles per hour. The semi-truck and trailer used in the estimates has a capacity of 36 large round bales totaling an average of 13 tons per trip.

The biorefinery assumed in this study is replicated from Ou et al. (2018) for facility capacity as well as controls for ash content, moisture, and carbon. Ou et al. (2018) assumed a feedstock capacity of 2,204.6 short ton of feedstock per day. Assuming the facility runs 365 days per year, the total feedstock processing capacity is 804,687.4 short tons per year. This is then converted into a gallons per short ton of switchgrass based on quality and subsequent quantity in tons. The Ou et al. (2018) study separately controlled for each potential limiting input of ash, moisture, and carbon. Considering the objective of this study, both moisture and carbon content are held constant at 35% and 46%, respectively, when predicting biofuel yield. When varying ash content from zero to five percent, biofuel yield ranges from 33.02 to 25.96 gallons per short ton, respectively (see Table 2.12). The fuel price paid to the biorefinery for their final output is assumed to be $2.68 per gallon (Lynd et al., 2017).

The base case of the switchgrass farmer in this analysis is considered “naïve” toward the effects of ash content. This is because the producer does not receive a higher price for quality-considered product. Therefore, to maximize net returns, the optimal N fertilizer application is only a function of quantity or yield (S). Differing from the statistical analysis, now both the costs of N and transportation are included. Building upon the NR function given in Model 2.1, the equation for the farmer can be written as follows:

Equation 2.1

$$NR_{Farm} = P_S * (\beta_0 + \beta_1 N + \beta_2 N^2) - P_N * N$$

where the price paid to producers (P_S) is multiplied by the regression equation showing the impact of N fertilizer on switchgrass yield (*S*) less the fertilizer price (P_N) multiplied by the fertilizer quantity (*N*). This equation provides the net returns level associated with a variable quantity of N fertilizer application.

Equation 2.2 and 2.3 are the first order condition (FOC) of Equation 2.1 with respect to N then solved for the optimal N application for the farmer (N^*_{Farm}). These equations can be seen below:

Equation 2.2

$$\frac{\partial NR}{\partial N} = P_S * (\beta_1 + 2\beta_2 N) - P_N = 0$$

Thus,

Equation 2.3

$$N^*_{Farm} = -\frac{\beta_1 P_S - P_N}{2\beta_2 P_S}$$

The result of the optimal N application rate for the farmer is 47 lbs./acre when fertilizer and transportation costs are included in the decision-making process. This is much lower than the initial N application estimated under the yield maximum criteria which showed 124 lbs./acre being optimal. Now, marginal revenue equals marginal cost.

With respect to the biorefinery, Equation 2.4 (see below) implements Equation 2.1 as the feedstock quantity (*S*), however, also includes Method 2.4 to show decreasing biofuel yield (*FY*) and Method 2.5 to show connect N fertilizer application and ash content. Ultimately, this allows the net returns equation (Equation 2.4) to encompass the goal of this project by making the connection between N application at the farm-level and biorefinery net returns. Given that the biorefinery is seeking to maximize net returns by considering both the quantity and quality of the switchgrass feedstock input, the base net returns function discussed in Model 2.1 is also adapted for this entity as follows:

Equation 2.4

$$
\begin{aligned}
NR_{Refinery} = P_Y & \\
& * (\beta_0 + \beta_1 N + \beta_2 N^2)\big[\phi_0 + \phi_1(\delta_0 + \delta_1 N + \delta_2 N^2) \\
& + \phi_2(\delta_0 + \delta_1 N + \delta_2 N^2)^2 + \phi_3(35) + \phi_4(35)^2 + \phi_5(46) + \phi_6(46)^2\big] \\
& - P_N * N - Trans * (\beta_0 + \beta_1 N + \beta_2 N^2)
\end{aligned}
$$

where the price received for the finished biofuel product per gallon (P_Y) is multiplied by the MQRF to model switchgrass yield (*S*) which is multiplied onto the QRF for biofuel yield (*FY*). Since the effect of N on moisture and carbon content is assumed constant, the intercept value of the function shows the relationship of the two constant variables on the fuel conversion yield. Embedded in this function is the MQRF modeling the effect of N fertilizer on ash content (*Ash*). This is reduced by the cost of transportation in dollars per ton (*Trans*) multiplied by the feedstock yield (*S*). This model shows the ultimate effect of both quantity of switchgrass and quality of switchgrass being refined into biofuel. Solved using Maple software, the optimal N rate ($N^*_{Refinery}$) is derived.

Equation 2.5

$$\begin{aligned}\frac{\partial NR}{\partial N} = {} & P_Y(\beta_0 + N\beta_1 + N^2\beta_2)(\phi_0 + \phi_1(\delta_0 + N\delta_1 + N^2\delta_2) + \phi_2(\delta_0 + N\delta_1 + N^2\delta_2)^2 \\ & + 35\phi_3 + 1225\phi_4 + 46\phi_5 + 2116\phi_6) \\ & + P_Y(\beta_0 + N\beta_1 + N^2\beta_2)\big(\phi_1(2N\delta_2\delta_1) \\ & + 2\phi_2(\delta_0 + N\delta_1 + N^2\delta_2)(\delta_1 + N^2\delta_2)\big) - P_N N - Trans(2N\beta_2 + \beta_1) = 0\end{aligned}$$

where,

Equation 2.6

$$\begin{aligned}N^*_{Refinery} = {} & 6\beta_2\delta_2^2 P_Y\phi_2 + \left(5P_Y\beta_1\phi_2\delta_2^2 + 10\beta_2\phi_2\delta_1\delta_2\right) \\ & + \left(4P_Y\beta_0\phi_2\delta_2^2 + 8\beta_1\phi_2\delta_1\delta_2 + 8\beta_2\delta_0\delta_2\phi_2 + 4\beta_2\delta_1^2 P_Y\phi_2 + 4\beta_2\delta_2 P_Y\phi_1\right) \\ & + \big(6P_Y\beta_0\phi_2\delta_1\delta_2 + 6\beta_1\delta_0\delta_2 P_Y\phi_2 + 3\beta_1\delta_1^2 P_Y\phi_2 + 6\beta_2\delta_0\delta_1 P_Y\phi_2 \\ & + 3\beta_1\delta_2 P_Y\phi_1 + 3\beta_2\delta_1 P_Y\phi_1\big) \\ & + \big(4\beta_0\delta_1\delta_2 P_Y\phi_2 + 2\beta_0\delta_1^2 P_Y\phi_2 + 4\beta_1\delta_0\delta_1 P_Y\phi_2 + 2\beta_2\delta_0^2 P_Y\phi_2 \\ & + 2\beta_0\delta_2 P_Y\phi_1 + 2\beta_1\delta_1 P_Y\phi_1 + 2\beta_2\delta_0 P_Y\phi_1 + 2\beta_2 P_Y\phi_0 + 70\beta_2 P_Y\phi_3 \\ & + 2450\beta_2 P_Y\phi_4 + 92\beta_2 P_Y\phi_5 + 4232\beta_2 P_Y\phi_6 - 2Trans\beta_2\big) \\ & + 2\beta_0\delta_0\delta_1 P_Y\phi_2 + \beta_1\delta_0^2 P_Y\phi_2 + \beta_0\delta_1 P_Y\phi_1 + \beta_1\delta_0 P_Y\phi_1 + \beta_1 P_Y\phi_0 \\ & + 35\beta_1 P_Y\phi_3 + 1225\beta_1 P_Y\phi_4 + 46\beta_1 P_Y\phi_5 + 2116\beta_1 P_Y\phi_6 - Trans\beta_1 \\ & - P_N\end{aligned}$$

shows the optimal N application preferred by the integrated industry biorefinery considering the quality and quantity of the biofuel feedstock in the decision-making process.

2.5 Results

The results of this analysis show the profitability of both the farmer as well as the biorefinery. Beginning this results section is the statistical methods conclusions. These parlay into the net returns equations presented in Equations 2.1 and 2.4. Regarding the naïve producer, they are not considering the downstream effects of ash content at the biorefinery. Thus, they only seek to maximize net returns by applying the optimal level of N fertilizer application, considering costs of the inputs and transportation, to maximize net returns. With respect to the biorefinery, maximized net returns are realized by implementing ash content as a limiting factor in fuel production. Then, the link between N fertilizer application and ash content is included. By doing so, the biorefinery, though not directly connected to production, has a unique optimal N application rate to maximize net returns.

2.5.1 Statistical and Econometric Analysis

The descriptive statistics for switchgrass ash content when varying N fertilizer in 60 pound per acre increments show the means decreasing from 2.56, 2.21, 2.11, and 2.11 for applications of 0, 60, 120, and 180, respectively (See Table 2.1). This provides evidence to warrant further analysis because ash content has a decreasing response to N fertilizer application. With respect to the means of yield, the values are increasing from 5.73, 7.72, 7.64, and 6.84 tons per acre with increases of N fertilizer applications of 0, 60, 120, and 180, respectively (see Table 2.2). Yield shows a positive response to N fertilizer application.

The results of the Analysis of Variance (ANOVA) model for ash content mirror that of the descriptive statistics means with statistically significant results (see Table 2.7). The intercept value is a placeholder for the 0 pounds per acre application and its value is 2.557 percent of the total plant composition. The parameter estimates that follow is -0.347, -0.443, -0.448 for 60, 120, and 180 pounds per acre of N fertilizer. The minimum of these values, of course, is 2.11% ash content. This shows a decreasing response of ash content when N fertilizer application increases (see Figure 2.5). The results of the ANOVA model when applied to switchgrass yield show similar results to the descriptive statistics means values with statistically significant results (see Table 2.8). The intercept value is a placeholder for the 0 pounds per acre N application and its value is 5.725 dry tons per acre. The parameter estimates are 0.997, 1.916, and 1.116 for N applications of 60, 120, and 180 pounds per acre respectively (see Figure 2.6) This provides a maximum value of 7.687 tons per acre.

The mixed quadratic model for yield had an intercept value of 5.643 dry tons per acre which represents the yield when 0 pounds of N fertilizer are applied. The β_1 value is 0.03 and the β_2 value is -0.00012. The statistical maximum derived from the response function shows a yield of 7.466 dry tons per acre (see Table 2.9). Thus, yield will have a "Ո-Shape" allowing for a maximum to be achieved with the marginal increases of yield with increases in N fertilizer (see Figure 2.7).

The results of the quadratic response function estimating biofuel yield (*FY*) at the biorefinery in gallons per short ton considering ash, moisture, and carbon content of switchgrass had an intercept value of 100.6 which represents the yield holding all variables constant. The ϕ_1 value representing ash content had a highly statistically significant result of -9.509. The ϕ_2 also showed significant results representing the ash squared term with a value of 1.042. Contrary to the ash content findings, neither the moisture nor carbon content proved to have statistically significant results on biofuel yield. Therefore, leading to a conclusion that ash content is a limiting factor for biofuel conversion when thermochemical conversion is used. The ϕ_3 parameter estimate for moisture is -0.0007 and the ϕ_4 parameter estimate is 0.000012. Both of these estimates will be held constant at the assumed moisture content of 35%. The ϕ_5 parameter estimate for carbon is -1.178 and the ϕ_6 parameter estimate is 0.0022. Both of these estimates will be held constant at the assumed carbon content of 46%. These estimates, along with the rest of the model results, can be seen in Table 2.10. A graphical representation of this model can be seen in Figure 2.8.

The mixed quadratic model estimating N application's effect on ash content started with an intercept value of 2.544 percent of plant composition represents applying 0 pounds of N fertilizer per acre. The β_1 value is -0.007 and the β_2 value is 0.000024. The results of this function show a statistical minimum ash content of 2.078% of total feedstock (see Table 2.11). Given these results, a "U-shaped" curve is derived showing the marginal decrease in ash content when N fertilizer application increases (see Figure 2.9).

Based on the results of the statistical methods, a maximum as well as a minimum can be derived for yield and ash content, respectively. When N fertilizer is applied at a rate of 140 pounds per acre, ash content to reaches a minimum of 2% of total biomass.

Additionally, switchgrass yield is maximized at 7.5 dry tons per acre when 124 pounds per acre of N fertilizer is applied.

2.5.2 Farm-Gate Profitability

Implementing the optimal N application derived in Equation 2.3 of 47 lbs./acre, the net returns less cost equates to $472.87 per acre paid to the farmer. Total fertilizer costs equal $68.62 per acre. At this optimal N rate, the switchgrass yield (S) is estimated to be 6.77 dry tons per acre. Additionally, the ash content of the feedstock is estimated to be 2.28%. The optimal N rate differs from the yield maximizing N application of 124 pounds per acre which pays the producer a total net returns of $416.26 per acre when they apply N at 124 lbs./acre. At the yield maximizing N rate, total fertilizer cost equals $181.04 per acre. Considering these results do not account for the effect of ash content downstream in the supply chain, the N application is much lower than what will be desired at the biorefinery. This is because, as the results of Method 2.5 suggested, ash content decreases when a greater N is applied. Therefore, the results presented in 2.5.3 differ from what is optimal at the farm-gate.

2.5.3 Biorefinery Profitability

When the integrated industry biorefinery is seeking to minimize ash content of incoming feedstock as a percentage of the biomass, the optimal N rate is 139 lbs./acre. This application only considers ash content and therefore does not consider the limiting effects of this higher N rate on switchgrass yield (S) and the subsequent decrease in biofuel yield. When both factors are considered simultaneously, the resulting optimal N application for the biorefinery is 114 lbs./acre. This result considers the effects of ash content on the biofuel conversion while simultaneously accounting for the highest quantity possible being received. When N is applied at 114 lbs./acre the switchgrass yield (*S*) is estimated to be 7.46 dry tons per acre. Additionally, the ash content of the feedstock is estimated to be 2.09%. The biofuel conversion yield (*FY*) is estimated to be 27.98 gallons per short ton with net returns of $3,729.39 per ton. Contrary to the farm-gate analysis, the costs of higher N rate and transportation are not absorbed in the model. Therefore, this estimate provides a higher yield in dry tons per acre. It can be seen that ash content and its limiting effects on biofuel yield (*FY*) are strongly considered because ash content only decreased 0.25% when over tripling the quantity of N fertilizer. Though this does not sound highly limiting, consider that only the decrease of 0.19% in ash content and a 0.69 dry ton per acre increase in raw feedstock input leads to a 0.31 gallons/ton increase in biofuel output. The reason this effect resulted the way it did is because reducing ash content does not imply a higher cost to the biorefinery, yet it increases the entity's output.

Essentially, four separate optimal N application rates exist; each accomplishing a different goal and having a unique effect on switchgrass yield in dry tons per acre, ash content as a percentage, farm-gate profitability, and biorefinery profitability. Switchgrass yield in dry tons per acre is maximized at 124 pounds per acre N application, while an N application of 47 pounds per acre leads to farm-gate net returns maximization. Biorefinery net returns are maximized when N is applied at 114 pounds per acre, and ash content is minimized at an N application of 139 pounds per acre. Table 2.13 shows the effect of each N application on the above outcomes.

The resulting optimal N applications open the conversation for the possibility of an incentive program to be implemented. This incentive could come in many forms; however, the effect is simple: mitigate costs for the farmer to apply higher N fertilizer. The first possible incentive could come as an integrated industry is created. Where, instead of considering ash content as an externality, it becomes part a single decision-making entity. This could be modeled after other similar circumstances such as the poultry industry. In this business, often the broiler houses are erected to standard company guidelines and exact feed/water ratios are provided. By doing so, this eliminates the guess work for the farmer and standardizes the quality of birds being raised. If this were to be applied to the switchgrass and biofuel industry in Tennessee, the structure may look similar. Where farmers provide soil samples of prospective land for propagation, then optimal N applications are set to be applied with the result of a consistent feedstock delivered to the biorefinery.

A second opportunity would be having a benefit/penalty system in place at the refinery. Switchgrass quality tests could be conducted upon feedstock arrival at the biorefinery. Considering a certain criterion that the refinery is seeking to achieve, a premium may be paid for switchgrass with a lower ash content. Conversely, a penalty may be applied where the producer’s feedstock is discounted because of a higher ash content.

A third, and final, option is a simple subsidy or cost relief program. Given that a farmer maximizes net returns when they apply 47 lbs./acre of N, and the biorefinery maximizes its net returns at a N application of 114 lbs./acre, the total cost of applying double the amount of fertilizer to meet specifications at the biorefinery increases costs at the farm level. Specifically, at 47 lbs./acre the total fertilizer cost of $68.62 per acre and at 114 lbs./acre the total fertilizer cost of $166.44 per acre. This means a per acre subsidy of $97.82 could be paid to the farmer for complying with quality specifications.

2.6 Conclusion

Ash content from biomass feedstock is important to conversion facilities due to increased cellulosic ethanol yield in gallons per short ton when ash content is lower as a percentage of plant composition. Hence, it is likely that conversion facilities may pay discounted prices for feedstocks that have higher ash content. A contributor to this ash content occurs due to N fertilizer application on the feedstock crop.

This study uses parts of an enterprise budget for switchgrass being grown in Tennessee for further refinement into SAF. Econometric analysis methods were used to determine the effects of N fertilizer application on ash content, switchgrass yield at the farm gate, and, subsequently, biofuel yield. The price of switchgrass paid to the farmer is assumed to be $80.00 per dry ton and N fertilizer cost is $1.46 per pound. Biofuel price paid to refineries is assumed to be $6.27.

Net returns are shown to be a function of quantity, as well as quality of the feedstock being produced when being refined into SAF. Nitrogen fertilizer application is shown through econometric methods to have a statistically significant relationship between switchgrass yield as well as ash content. By varying the N application and assessing profitability at both the farm-gate and biorefinery level, the link between final fuel conversion and management practices is demonstrated.

This study assumes that producers operate under the goal of net returns maximization. Therefore, net returns are only a function of quantity produced less operational costs of N purchase and application along with transportation of the feedstock to the biorefinery. This can be thought of as a farm-gate net returns maximization level N application because, at the farm, the producer is ignoring the effects of ash content on biofuel yield. Whereas, the biorefinery net returns function considers ash content and fuel conversion rates associated with a variable N application rate.

At the farm-gate level the switchgrass yield is maximized at 124 lbs./acre of N fertilizer and ash content is minimized at 139 lbs./acre. When seeking to maximize net returns, however, the optimal N application is 47 lbs./acre which provides a yield of 6.77 dry tons per acre with an ash content of 2.28% of total biomass. At the optimal N rate, cost of N purchase and application total $68.62 per acre. The farmer net returns is, thus, estimated at $472.87 per acre. Conclusively, there is no reason for a farmer to consider ash content or quality in the decision-making process of growing switchgrass.

For the biorefinery, it has been shown that a higher ash content does decrease biofuel yield. Additionally, it has been shown by this study that an increased N application during management practices decreases ash content in switchgrass at harvest. This being considered, the optimal N rate to maximize net returns for the biorefinery is 114 pounds per acre which provides a biofuel yield of 27.98 gallons per short ton of feedstock input. The transportation costs, estimated to be $11.95 per ton, are also considered in determining this optimal N rate. At this N application, the switchgrass yield at the farm gate is 7.46 dry tons per acre and the ash content is 2.09%. If a farmer were to abide by this application standard, the N cost would be $166.44 per acre. Consequently, this would reduce farmer net returns by $42.83 per acre. The difference in N application costs paid by farmers opens the discussion of how a biorefinery could incentivize switchgrass producers to consider quantity and quality of switchgrass in their decision making.

Three possible subsidy or cost-relief programs are discussed. The first of these incentives would be an integrated industry. Under this scenario, ash content is no longer considered an externality, but it becomes part a single decision-making entity. This could be modeled after other similar circumstances such as the poultry industry. The goal of this program would be to standardize the efficiency and quality of switchgrass being produced. The second scenario would be having a benefit/penalty system in place at the refinery. The quality of the switchgrass could be tested upon feedstock arrival at the biorefinery. Considering a certain criterion that the refinery is seeking to achieve, a premium may be paid for switchgrass with a lower ash content. Conversely, a penalty may be applied where the producer's feedstock is discounted because of a higher ash content. The final program could be a simple subsidy. This scenario would be modeled as a cost-relief program to cover the increase in cost associated with applying N fertilizer at 114 lbs./acre instead of 47 lbs./acre. This incentive would be paid by the biorefinery directly to the farmers for complying with recommended growing practices.

The limitations of this study include a lack of a complete enterprise budget from which to draw a multi-faceted cost scenario. Further research could include this dynamic budgeting approach which may provide a different optimal N fertilizer application for both the farm as well as biorefinery. The biorefinery did not have a complex budget tied to production costs, either. Therefore, it is difficult to assume the optimal N application estimated at the refinery is totally accurate. An extension of this research would be to include both of these budgets and determine the optimal N application throughout the supply chain. Another continuation of this study would be to model the interaction of moisture and carbon content in relation to N fertilizer application. If significant results occur, then allow these variables to be implemented without being held constant. Another continuation is to determine an economically efficient cost-relief program for the biorefinery and work backwards to estimate the impact of that program on the farmer.

Appendices

Tables

Table 2.1: Descriptive statistics for Alamo Switchgrass ash content when varying nitrogen fertilizer (N) application (lbs./acre)

N	Mean	Std. Dev	Minimum	Maximum
0	2.56	0.58	0.63	4.41
60	2.21	0.59	0.47	4.01
120	2.11	0.46	1.08	3.58
180	2.11	0.61	0.80	3.76

Table 2.2: Descriptive statistics for Alamo Switchgrass yield (tons/acre) when varying nitrogen fertilizer (N) application (lbs./acre)

N	Mean	Std. Dev	Minimum	Maximum
0	5.73	2.06	1.44	11.35
60	6.72	2.38	2.65	15.40
120	7.64	2.26	2.87	14.60
180	6.84	3.04	0.07	14.30

Table 2.3: Statistical tests for model selection for the quadratic response function (QRF)

Test	Ash Content	Switchgrass Yield	Biofuel Yield
AIC	757.7	2226.1	254.7
AICC	757.8	2234.1	257.3
BIC	774.1	2234.2	272
LL	374.9	1125.4	119.4

Table 2.4: Statistical tests for model selection for the mixed quadratic response function (MQRF)

Test	Ash Content	Switchgrass Yield	Biofuel Yield
AIC	706.6	2127.3	--
AICC	706.8	2127.4	--
BIC	704.7	2125.3	--
LL	348.3	1058.7	--

Table 2.5: Statistical tests for model selection for the linear response plateau function (LRP)

Test	Ash Content	Switchgrass Yield	Biofuel Yield
AIC	802.6	2241.3	414.3
AICC	802.6	2241.4	415.8
BIC	819.0	2258.0	427.3
LL	397.3	1116.7	201.2

Table 2.6: Statistical tests for model selection for the mixed linear response plateau function (MLRP)

Test	Ash Content	Switchgrass Yield	Biofuel Yield
AIC	758.7	2136.6	--
AICC	758.8	2136.7	--
BIC	756.8	2134.6	--
LL	392.4	1063.3	--

Table 2.7: Parameter estimates and significance for the ANOVA of ash content (% of biomass) of Alamo switchgrass when varying nitrogen fertilizer (N) application rates (lbs./acre)

Parameter	Parameter Estimate	Significance Level
Intercept	2.557	<0.0001
N60	-0.347	<0.0001
N120	-0.443	<0.0001
N180	-0.448	<0.0001

Table 2.8: Parameter estimates and significance for the ANOVA of Alamo switchgrass yield (dry tons/acre) when varying nitrogen fertilizer (N) application rates (lbs./acre)

Parameter	Parameter Estimate	Significance Level
Intercept	5.725	<0.0001
N60	0.997	0.0018
N120	1.916	<0.0001
N180	1.116	0.0005

Table 2.9: Parameter estimates and significance level for mixed quadratic response function for yield (dry tons/acre) in Alamo switchgrass

Parameter	Estimate	Significance Level
Intercept	5.643	0.0006
N	0.030	<0.0001
N2	-0.00012	<0.0001

Table 2.10: Parameter estimates and significance level for quadratic response function for biofuel yield (gallons) considering ash, moisture, and carbon content (% of biomass) in Alamo switchgrass

Effect	Estimate	Significance
Intercept	154.79	0.1561
Ash	-9.5087	<0.0001
Ash^2	1.0416	<0.0001
Moisture	-0.0007	0.9953
Moisture^2	0.000012	0.9949
Carbon	-1.1779	0.7984
Carbon^2	0.002188	0.9644

Table 2.11: Parameter estimates and significance level for mixed quadratic response function ash content (% of biomass) in Alamo switchgrass

Parameter	Estimate	Significance Level
Intercept	2.544	<0.0001
N	-0.007	<0.0001
N2	0.000024	0.0006

Table 2.12: Parameter estimates for biofuel yield (gallons/short ton) when varying ash content (% of biomass) and holding moisture, and carbon content constant (% of biomass)

Ash	Moisture	Carbon	Biofuel Yield
0	35	46	33.02
1	35	46	30.24
2	35	46	28.14
3	35	46	26.73
4	35	46	26.01
5	35	46	25.96

Table 2.13: Estimates of switchgrass yield (dry tons/acre), farm-gate profit ($/acre), biorefinery profit ($/ton), and ash content (% of biomass) when four optimal N rates (lbs./acre) are applied

	Nitrogen Fertilizer Application (lbs./acre)			
	47	114	124	139
Yield (dry tons/acre)	6.77	7.46	7.47	7.44
Farm-Gate Profit ($/acre)	472.87	430.04	416.26	391.98
Biorefinery Profit ($/ton)	3,428.25	3,729.39	3,722.48	3,686.42
Ash Content (% of biomass)	2.28	2.09	2.08	2.07

Figures

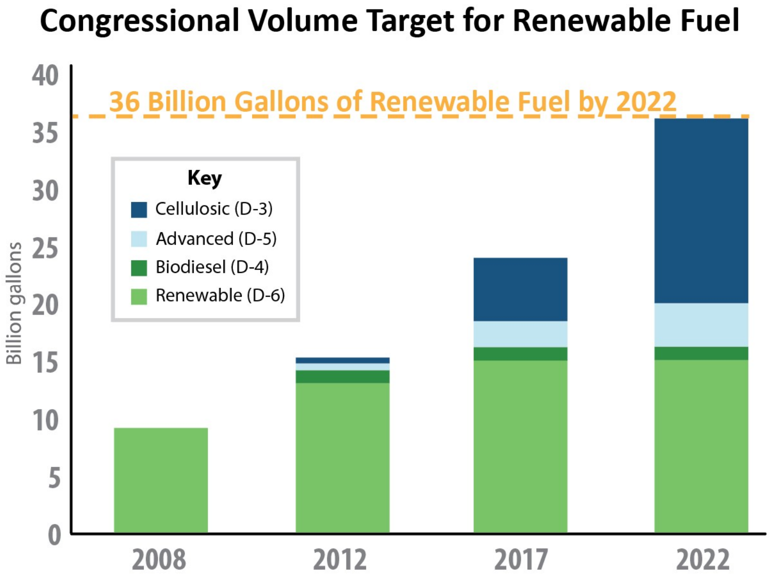


Figure 2.1: Breakdown of biofuel production provided the 2007 Energy Independence and Security Act from inception to target 2022

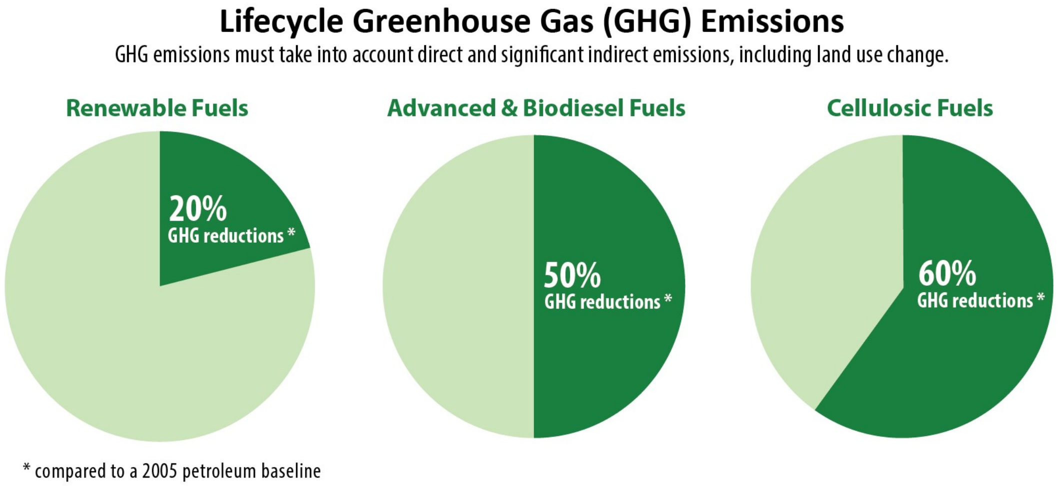
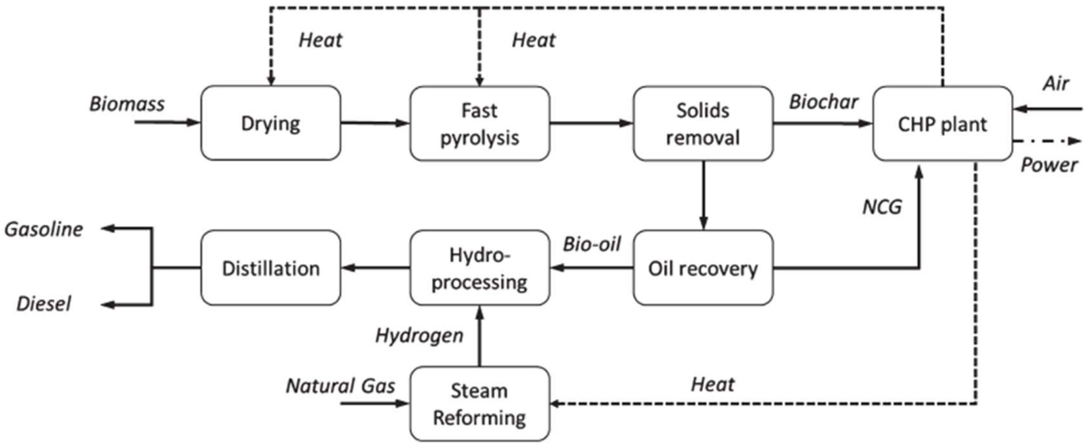


Figure 2.2: Breakdown of Greenhouse Gas (GHG) Emission reduction when utilizing renewable, advanced and biodiesel, and cellulosic fuels.



Modified from (Ou et al., 2018)

Figure 2.3: Visual representation of the schematic thermochemical pathway from switchgrass feedstock to biofuel

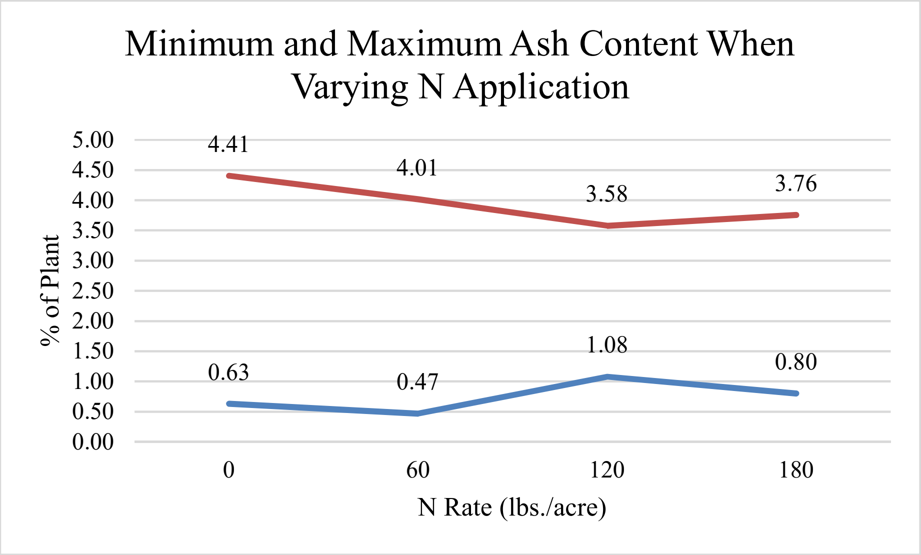


Figure 2.4: Graph showing the difference in average highest and lowest ash content (%) in Alamo switchgrass when varying Nitrogen fertilizer application (lbs./acre).

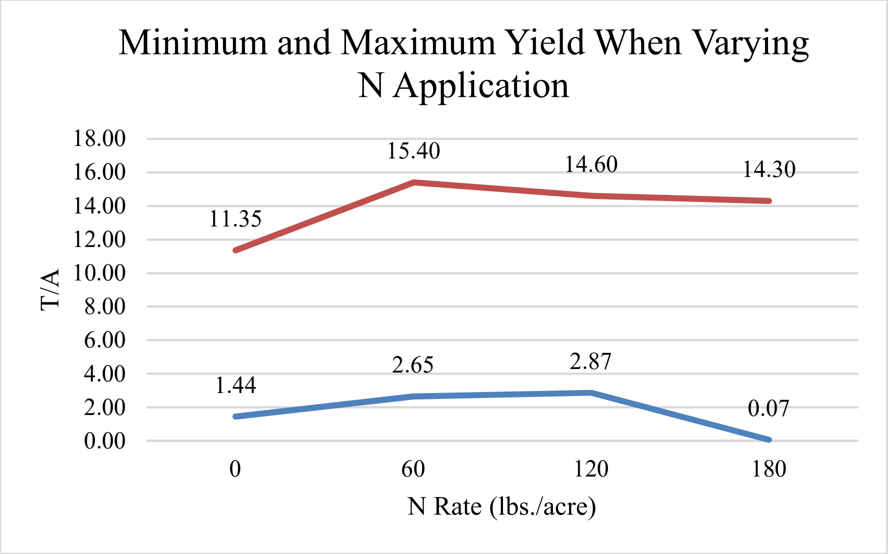


Figure 2.5: Graph showing the difference in average highest and lowest yield (tons/acre) in Alamo switchgrass when varying Nitrogen fertilizer application (lbs./acre).

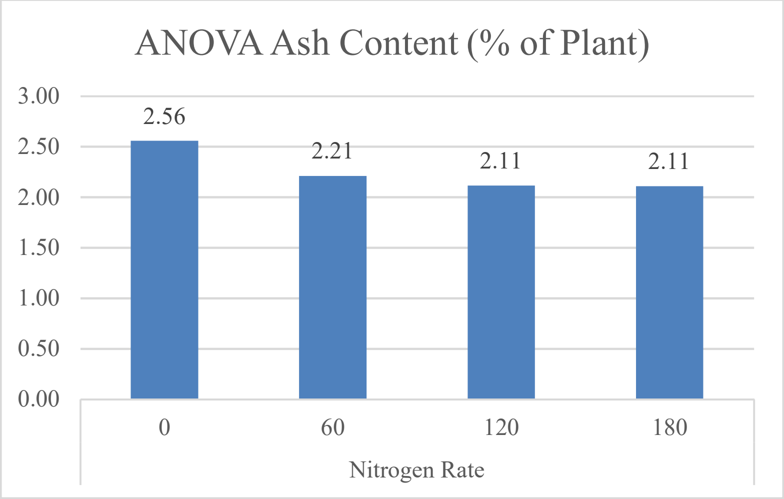


Figure 2.6: Analysis of Variance bar graph showing the decreasing percentage of ash content in Switchgrass as Nitrogen fertilizer application increases (lbs./acre)

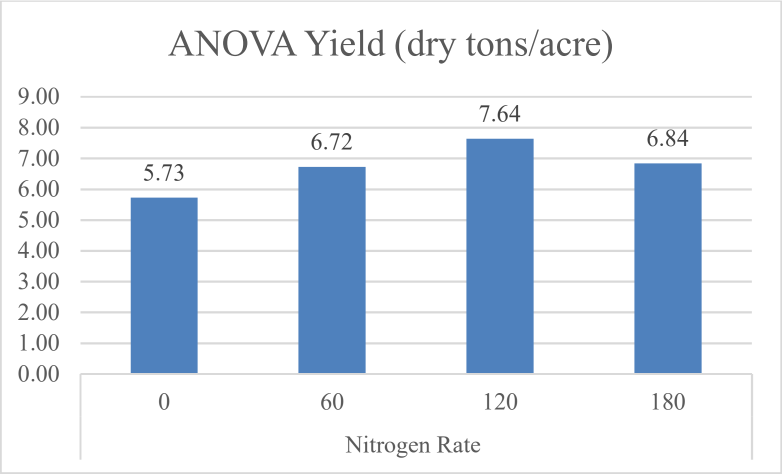


Figure 2.7: Analysis of Variance bar graph showing the increasing yield of Switchgrass as Nitrogen fertilizer application increases (lbs./acre) with an apparent maximum

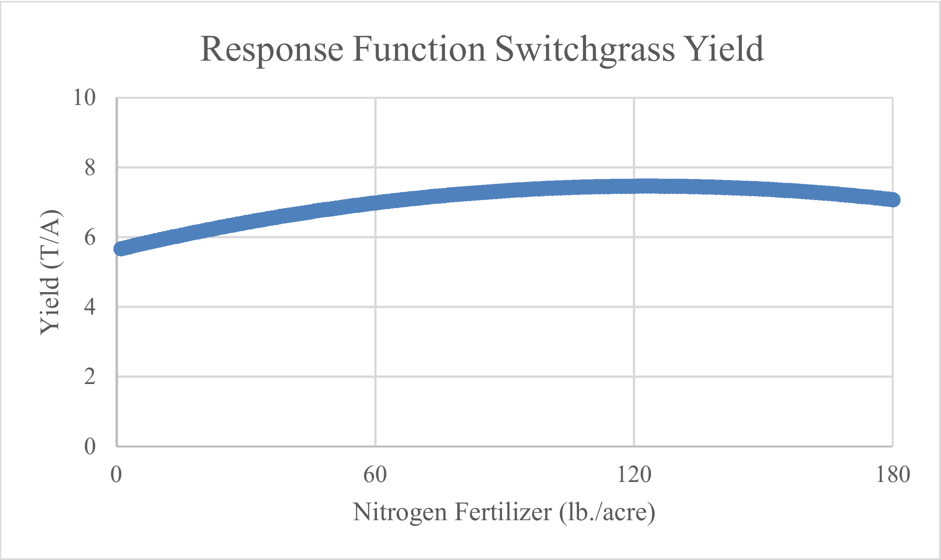


Figure 2.8: Graph showing increasing yield (dry tons/acre) as nitrogen fertilizer application increases (lbs./acre)

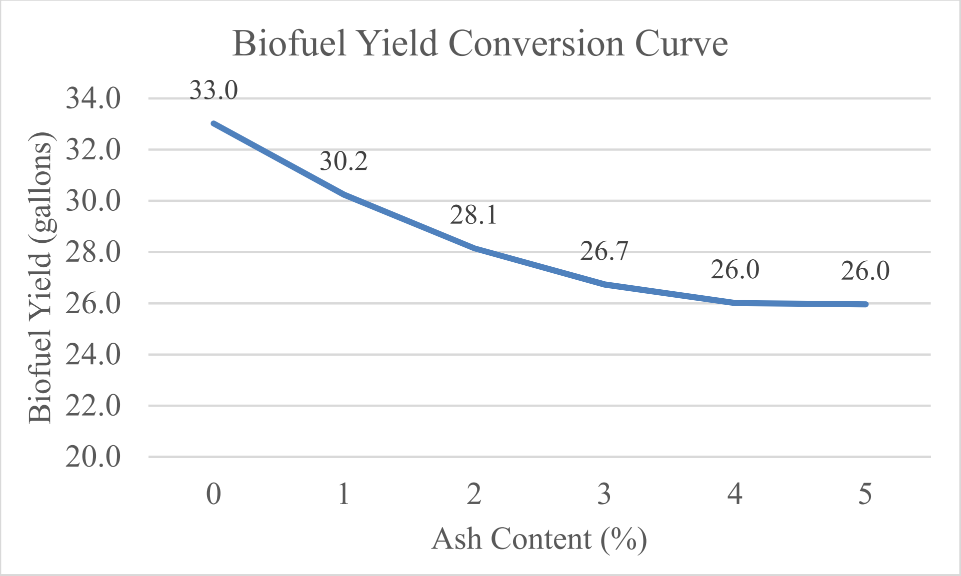


Figure 2.9: Graph showing decreasing biofuel yield conversion (gallons/short ton) as ash content increases (% of biomass)

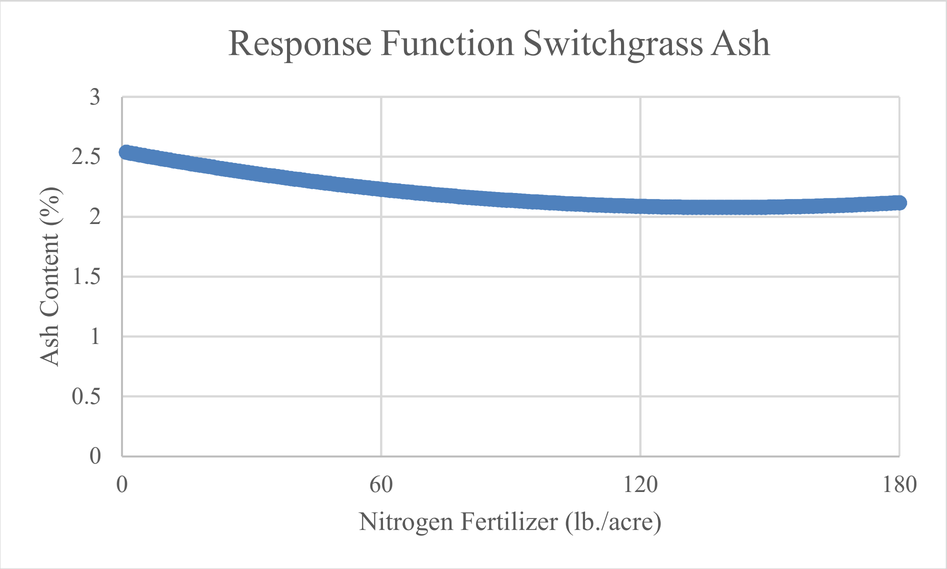


Figure 2.10: Graph showing decreasing ash content (%) as nitrogen fertilizer application increases (lbs./acre)

CHAPTER 3: A STOCHASTIC ANALYSIS OF CARINATA OILSEED ENTERPRISE VIABILITY AS SUSTAINABLE AVIATION FUEL

Abstract

The growth of bioenergy as a renewable fuel source will likely increase demands for efficient biofuel feedstocks that are multipurposed and economically viable for producers and processors. Carinata (*Brassica carinata* A. Braun) is an example of a feedstock that is high yielding oilseed that can be combined with other production cycles, creating a potential source for additional revenue for producers. The objective of this study is to analyze the economic feasibility of growing Carinata in Tennessee as a feedstock for conversion into sustainable aviation fuel (SAF). The hypothetical supply chain consists of producers growing the oilseed and selling it to crushing facilities, which create an unrefined oil and sell it to a biorefinery for production of SAF and various co-products. A profit, risk, and break-even analysis for the crop enterprise is conducted at the farm-level. Considering the only documented Carinata cover crop yields have come from Florida, and given the geographical constraints of Carinata, due to frost damage and colder winter season temperatures, three separate yield scenarios are estimated. The Environmental Policy Integrated Model (EPIC) is implemented to give a clearer understanding of Tennessee, frost tolerant, and documented yield scenarios in the state. Palisade's @RISK software is used to generate stochastic simulation of a triangular distribution of each yield category and the risk associated with variant prices and yield combinations.

3.1 Introduction

Carbon dioxide (CO_2) is believed to be the largest contributor to greenhouse gas (GHG) emissions and consequently to global climate change (Martínez-Zarzoso and Maruotti, 2011). Reducing these carbon emissions are critical to meeting the Paris Agreement of 1.5 degrees Celsius decrease in global temperature (Michielin, 2019). The International Civil Aviation Organization (ICAO) has targeted net CO_2 emissions of the global aviation sector at the average of 2019-2020 levels for the years of 2021-2035. The International Coalition for Sustainable Aviation (ICSA) is urging the adoption of the Enhanced Climate Mitigation Targets and Levers for International Aviation which secures "zero climate impact" by 2050 (Michielin, 2019). The inclusion of SAF provides additional reductions due to carbon negative emissions from oilseed-based biofuels (Tilman, Hill, and Lehman, 2006).

In the United States, more liquid fuel is consumed annually than any other nation worldwide. In 2008, some 19.4 million barrels per day (Ferraro, 2010). With respect to the aviation sector, emissions from these fuels are immense. In 2010, it was reported that 448 megatons (Mt) of CO_2 equivalents was emitted into the atmosphere from aircraft alone. Estimations based on flight trends indicate that by 2020 this will have increased to 682-755 Mt (IRENA, 2017).

Enacted January 1, 2019, all aircraft are mandated to comply with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and report annual CO_2 emissions (IATA, 2017). The International Civil Aviation Organization (ICAO), alongside the greater aviation sector, is pushing toward reduction of carbon emissions to

2005 levels (considered carbon neutral growth) by the year 2050. (Mulvaney et al., 2019). With the continual growth and expansion of online shopping and a globalized world, cargo shipments will likely increase into the foreseeable future. With global concern rising and a continued push for reduction in GHG emission requirements for airlines, the reduction can be met in total or in part with SAF. The National Academies of Science, Engineering, and Medicine research has proven that the use of sustainable alternative jet fuels (SAJF) alleviate net life-cycle carbon emissions in comparison to standard fossil fuels because they simply reclaim carbon previously in the biosphere to generate the fuel (2016).

One potential feedstock to meet the regional needs of a regional aviation biofuels industry is Carinata (*Brassica carinata* A. Braun) or “Ethiopian Mustard”, which is an oilseed crop similar to Canola. Carinata’s viability to be grown as a cover crop in the west Tennessee region allows producers to diversify crop rotations with potential for both livestock feed as well as a feedstock in the production of SAF. Hence, Carinata could serve a dual role as a cover crop as well as a feedstock for SAF. Research shows that no-till farming practices in conjunction with cover crop implementation provide increased organic matter in the soil, reductions in soil erosion, and increasing water holding capacity (Roberts et al., 1998). Knowing this, many farmers prefer to use cover crops in their standard rotations. Hence, many farmers are already aware of cover cropping benefits. Therefore, if agriculturists already have an incentive to plant a cover crop, and if profitability measures are proven, it could easily become a third source of revenue in a two-year crop cycle.

Regarding the biological composition of the crop, Carinata is high in erucic and linoleic acid which aid in biofuel conversion (Cardone et al., 2003). This characteristic renders it unusable as a food oil, however, makes it a prime candidate for drop-in fuels. The crop at maturity will reach heights of 4-5 feet and have a similar profile to that of Canola (Seepaul et al., 2019). Additionally, its deep rooting depth and heavy waxy leaves provide protection from drought as well as variable temperatures to a certain degree (Seepaul et al., 2019). This makes Carinata a potential candidate for propagation in November with plans of harvest in May in Tennessee. The only concern for the crop to be grown in the state is the issue of frost damage, which occurs after prolonged periods of cold temperatures. However, the extent of the damage is highly dependent upon the crop growth stage and duration in hours of below certain temperatures. See Tables 3.11, 3.12, and 3.13 for a detailed breakdown from the University of Florida assessing frost tolerance of Carinata. Assuming temperatures stay warm enough during the crop's early life, there will be little yield loss suffered (Mulvaney et al., 2018).

Currently, Carinata has no recorded yields in Tennessee. Therefore, yield must be simulated based on a similar crop profile. Per insight from Leyton (2020) at Texas A&M, EPIC modeling of Carinata yields were estimated for this study using a Canola crop profile. These estimates are derived for west Tennessee, specifically, due to higher concentrations of corn and soybean rotations. The first yield scenario will be estimated using the recommended crop profile and simulated Tennessee weather patterns to estimate Carinata yield in Tennessee. The second scenario uses the same assumptions as the first, however, applies central Alabama weather patterns as a proxy for a simulated “frost tolerant” variety. Central Alabama was chosen as the location for weather estimates for this scenario because frost is less likely to occur during winter months. Though a frost tolerant variety exists, no yield data has been officially recorded or researched to our knowledge. Therefore, similar to Tennessee estimations, the frost tolerant variety must be simulated as well. The final scenario applies Florida panhandle weather patterns to the same crop assumptions. Assuming canola to be an accurate proxy for Carinata and considering the close similarity of these estimates to documented yields in Florida trials, the model validates that colder weather is the leading cause of yield loss for Carinata.

There is potential for increased farm revenue from propagation and harvest of Carinata in Tennessee if yields are high enough to offset breakeven costs. Carinata oilseeds contain a robust 40% oil content on average, which is twice that of soybeans (Mulvaney et al., 2019). Test plots of this jet fuel crop in Canada using optimal seeding rate returns average yields of 1,644 pounds per acre (Eric Johnson, 2014). In Canada, however, it was not grown as a cover crop. In Florida, yield has a recorded average of 1,933 pounds per acre (Mulvaney et al., 2019).

The economic viability of Carinata being grown in Tennessee is yet to be determined. However, using agronomic and economic data from the literature for studies performed in the Southeastern United States, estimates of profitability can be provided. We hypothesize that it would be profitable for Tennessee producers to grow a frost tolerant variety of Carinata. This hypothesis is derived from similar studies on comparable crops such as Camelina and Pennycress (Rahman et al., 2018; Trejo-Pech et al., 2019). This research is part of a larger project seeking to analyze three bio-based aviation fuel crops for the University of Tennessee's portion of the Aviation Sustainability Center (ASCENT) commitment. One of these studies, led by Dr. Carlos O. Trejo-Pech at the University of Tennessee Institute of Agriculture (UTIA), analyzed the Pennycress supply chain under similar conditions and price points. The research showed positive profit margins at both the farm-gate level as well as for the crushing facility. Additionally, Umama Rahman's third chapter of her master's thesis analyzed the viability of Camelina to be utilized as SAF. Her studies show similar results to Dr. Trejo-Pech in that positive profits were estimated.

The objective of this study is to assess the producer's prospective enterprise profitability of growing Carinata for SAF production in Tennessee. This objective will be accomplished using the following steps:

1) develop a farm-level budget taking into consideration expenses such as establishment, management, and harvest to determine revenue and cost structures for the enterprise;
2.) develop a farm-gate level sensitivity analysis of farm-gate breakeven;
3.) use EPIC to model yield combinations for Tennessee and the frost tolerant variety given differing weather patterns as the growing acres move north; and
4.) use Palisade's @RISK software to develop a stochastic budgeting model for Carinata yield and determine probabilities of positive or negative net returns given the three different yields.

3.2 Review of Literature

3.2.1 Background on Biofuels

Biofuel is an abbreviation for biomass fuel, and it has been around for thousands of years. Biofuels, as a whole, are an alternative to petroleum-based liquid transportation fuels which are commonly associated with crops such as corn, sugar cane, and soybeans (Ferraro, 2010). However, biomass-based fuel such as wood and peat when burned created the first known use of these renewable fuel sources by early humans (Reisser and Reisser, 2019). What exactly is biomass? Defined generally, it pertains to stored solar energy found in three common forms: 1) solid biomass fuels or feedstocks such as wood chips; 2) liquid biofuels produced from solid biomass through chemical or biological conversion; and 3) gaseous fuels produced by high temperatures and pressure processing (Hinrichs and Kleinbach, 2013). Over time, these fuels became less about providing a heat source for comfort and food preparation, and more about transportation.

There is a need for advanced biofuels in the transportation sector, especially for use as aviation fuel. There are multiple types of biofuels available for production today. Most commonly; Generation 1 biofuels are comprised of fuels made from oils and sugars. Corn based ethanol as well as oilseed fuel are examples of this fuel type. Generation 2 fuels are primarily composed of non-food biomass such as switchgrass or woody feedstock. Further specification reveals that under the Environmental Protection Agency (EPA) approved pathways for biofuels, oilseed cover crops for jet fuel are classified as either D3 or D5 advanced fuels (US EPA, 2015). The designation of D3 or D5 specifically affects the RIN valuation which could provide more or less EPA subsidies for the biorefinery.

3.2.2 Environmental Impact

Growing concern regarding global warming and climate change are spurring rising demand for biofuels. This important and potentially dangerous issue facing the planet can, in part, be mitigated by a reduction in CO_2 being released into the atmosphere. Therefore, carbon savings play a key role in the development and use of biofuels. As seen in Figure 3.3, these advanced D5 fuels offer a 50% reduction in Greenhouse Gas (GHG) emissions. This metric was calculated against 2005 petroleum baseline as mandated by the EISA. Much of the aviation industry including plane manufacturers, airlines, and industry associations have committed to carbon neutral growth by the year 2020. Advancements in technology creating more efficient aircraft, airports, and optimized navigational systems have a potential to reduce these emissions by 1.5% (IRENA, 2017). This, however, is not enough. True carbon-neutral growth will be nearly impossible without the use of renewable and reliable bio-jet fuel. This can be seen visually in Figure 3.2 as developed by the Air Transport Action Group.

There is a new trend that is spurring from the consumer sector of the industry that is showing individuals choosing not to fly on aircrafts due to remorse of harmful environmental impacts. This trend is termed “flight shame” and is growing as more people become aware of their carbon footprint. However, with the growing globalized population, airline travel is not on a downward trend soon. Biofuels in the aviation sector could be part of the solution. The Committee on Propulsion and Energy Systems to

Reduce Commercial Aviation Carbon Emissions (2016) has shown through recent research that the use of sustainable alternative jet fuels (SAJF) alleviate net life-cycle carbon emissions in comparison to standard fossil fuels because they reclaim carbon previously in the biosphere to generate the fuel.

3.2.3 Economic Feasibility of Oilseeds for SAF

An important and potential agent in making bio-based aviation fuel is the use of oilseed crops such as Pennycress, Camelina, and for the purpose of this study, Carinata. Each of these varieties have an especially high oil yield and fatty acid content making them excellent crops in consideration of biofuel production (Seepaul et al., 2019). Economic analysis of these crops is important to determine producer profitability.

Recent research from the University of Tennessee by Dr. Trejo-Pech and others (2019) studied the cost and profitability of Pennycress oilseeds for SAF in the Southern United States. The findings from the study show that the breakeven variable cost of Pennycress to be grown, harvested, and transported is \$0.08/lb. and a crushing facility is able to pay up to \$0.108/lb. This means that there is a profit margin maintaining a 12.5% annual return. The total cost through the supply chain to the biorefinery is between \$0.38-0.49/lb. Thus, making costs slightly above the NPV= 0 goal. The authors make the following three suggestions: produce more bio-oil for an increased capacity, decrease the oilseed costs, or if the crushing facility were to pay less than \$0.108 then there would also exist a profitable margin.

Similar to Carinata, Camelina sativa is an oilseed crop in the Brassicace family that is also commonly known as “gold-of-pleasure” (NRCS, 1983). This crop is very similar to Carinata in that there are common traits regarding seed size as well as oil content. Additionally, it has been researched in much of the Southeast and in Canada for its potential as a winter-season cover crop. Rahman et al. (2018) studied the potential of Camelina as a feedstock for renewable jet fuel across the entire United States. With respect to the farm-gate economic analysis in her study, she found that Camelina has an estimated $123.31 per acre in variable cost and a total fixed cost of $33.04 per acre. Additionally, the return above all variable and fixed expenses totaled $136.80 per acre. Breakeven analysis showed that the breakeven yield was estimated at 560 pounds per acre when the market price remained constant at $0.28 per pound. The breakeven price when yield remained constant at 1050 pounds per acre was $0.12 per pound. Therefore, she estimated that Camelina grown in Tennessee exhibits profitable margins at the producer level.

Diniz et al. (2018) researched the techno-economic feasibility of Carinata, Camelina, and Jatropha using capital budgeting techniques such as NPV, IRR, and Payback Period. In addition, she stochastically simulated each of these metrics. The conclusion of this research is that Camelina performed the best under their scenario and Carinata was second best. The results of this study showed Carinata jet fuel facilities having a 99.9% probability of loss. This study bypassed the farm level and ran economic analysis on the facilities that refine the raw oil into jet, naphtha, LPG, and diesel through HEFA refinement. Therefore, the purpose of including this study is to show similar stochastic probability analysis procedures that will be used at the farm-level to determine profitability for Carinata in Tennessee.

3.3 Conceptual Framework

3.3.1 Defender vs. Challenger

The optimal decision becomes evaluating tradeoffs in profitability generated from current land use (defender) and that which can be realized with a different crop such as Carinata (challenger). It is assumed that the producer seeks to maximize profits and make decisions to maximize expected net returns. Pairwise comparisons are made between the defender (*D*) and the challenger (*C*) by analyzing the profitability of each. The economic concept behind profit maximization means that a farmer will produce a crop if the net returns can be modeled as follows:

Model 3.1

$$NR = P * Y - OC$$

where net returns (*NR*) are maximized subject to price (*P*) and yield (*Y*) less the operational costs (*OC*).

The growing practices considered in this study include using Carinata as a rotational winter-season cover crop to potentially add a third revenue stream over the course of a two-year cropping cycle. Moreover, the defender practice includes only a rotation of corn and soybeans (corn-soybean) over this time. The challenger practice would include corn, Carinata, and soybeans (corn-Carinata-soybeans) and have separate net returns (NR_C). If the defender practice, then that will be the optimal cropping selection for the farmer. Conversely, if the challenger practice estimates are higher, the same is true (Mooney, Larson, English, & Tyler, 2012).

A modification of the generic Model 3.1 allows for the defender cropping to be represented as the following equation:

Model 3.2

$$NR_D = P_{Corn} * Y_{Corn} + P_{Soy} * Y_{Soy} - OC_{Corn} - OC_{Soy}$$

where net returns for the defender (NR_D) are a function of corn price (P_{Corn}), soybean price (P_{Soy}), corn yield (Y_{Corn}), soybean yield (Y_{Soy}), corn operations costs (OC_{Corn}), and soybean operations costs (OC_{Soy}).

A further modification of Model 3.1 includes the challenger net returns model where the Carinata cover crop is included. The equation for this can be seen as follows:

Model 3.3

$$NR_C = P_{Corn} * Y_{Corn} + P_{Soy} * Y_{Soy} + P_{Car} * Y_{Car} - OC_{Corn} - OC_{Soy} - OC_{Car}$$

where the net returns are calculated for the challenger cropping practice with the same notation for Model 3.2 but now included are the Carinata price (P_{Car}), Carinata Yield (Y_{Car}), and Carinata operations cost (OC_{Car}). In summation of the modeling, the producer will choose the challenger cropping practice which uses Carinata as a winter season cover crop if $NR_C > NR_D$ based on all yields, prices, and operations costs for each crop (Mooney et al., 2012). Government subsidies exist to incentivize cover crop implementation; however, they are not accounted for in this study.

3.4 Methods

For this enterprise analysis, it is assumed that the farm equipment must be purchased in order to plant, manage, harvest the oilseed. This assumption is made because, in Tennessee, oilseeds are not traditionally utilized as a winter cover crop. Thus, some farmers may not have the equipment necessary for full scale operation. The tool utilized in this study to evaluate the profit margins and economic feasibility of Carinata grown as an oilseed crop in Tennessee is an enterprise budget. Using estimated assumptions on fixed and variable costs for the production, management, and harvest of similar oilseed crops in the Southeastern United States will provide an evaluation of profit maximization and margins for the crop. Farmers are often faced with difficult decisions come planting time. It is important for producers to understand the potential benefits and opportunity costs associated with each cropping decision.

EPIC yield modeling was involved in this study because the true yield data does not exist for Tennessee. The only documented yields using Carinata as a cover crop have come from Florida which has warmer winter weather patterns. Expert agronomic insight per Leyton (2020) at Texas A&M, the crop profile is comparably similar to Canola varieties. West Tennessee is the region assumed in the study due to The planting density of 200 plants per m^2 assumed in the model is based on optimal results from Florida research (Mulvaney et al., 2019). Tennessee yield estimates were generated under these assumptions. The frost tolerant variety was estimated by applying Alabama weather patterns to the model using the same cropping assumptions. Finally, these cropping assumptions are paired with Florida panhandle weather patterns. The resulting estimates from this modeling show almost identical results as the Florida field trial documented in literature. Thus, validating the model and showing weather as a determining factor of

Carinata yield outcome, assuming accurate EPIC estimates based on the canola proxy for Carinata.

3.4.1 Farm-Gate Breakeven Analysis

Carinata is not commercially grown, thus, yield, production inputs, and total production costs are not known with certainty for Tennessee. Three separate enterprise production budgets for the no-till planting, maintenance, and harvest of Carinata in Tennessee as an energy crop were developed. The goal of this analysis is to determine the minimum price at which the farmer will breakeven (profit=0). The price value of $0.108 per pound that is used in the budget comes from the Markel et al. (2018) which studied Pennycress oilseed and determined this is the maximum price that a crushing facility could pay for the harvested oilseed and breakeven assuming a 12.5% return on investment. The price that the farmer receives needs to be between their breakeven and the value the crush facility can afford to pay. Therefore, this price is reduced to $0.105 per pound to allow a narrow margin for the crush facility. Additionally, transportation is excluded from the farm-gate analysis, so a $0.01 per pound is reduced from this as well. Therefore, the assumed price used in this assessment is $0.095 per pound.

Three yield scenarios are evaluated in this study. The baseline Tennessee yield assumed in the budget is 919 pounds per acre. This average value is estimated from the EPIC model using the crop profile and Tennessee weather patterns, as aforementioned. An improved “frost tolerant” yield scenario is estimated using the same profile and assumptions with Alabama weather patterns . The frost tolerant average yield was predicted at 1,602 pounds per acre. The documented yield scenario average estimate is

1,933 pounds per acre. To see the complete yield summary, see Table 3.14. Machinery purchase and schedules of operation was developed from University of Tennessee Canola budgets (Smith et al., 2018). The equipment's efficiency, maintenance, speed, and useful life was estimated using American Society of Agricultural and Biological Engineers (ASABE) standards (ASABE, 2009). The machinery costs included depreciation, interest, repair and maintenance, ultra-low sulfur diesel fuel, oil, filter, lubrication factors, taxes, insurance, and housing. These metrics were found from the Energy Information Administration (EIA), ASABE requirements, and UT Field Crop Budgets (ASABE, 2009; EIA, 2020; Smith et al., 2018). The diesel fuel price was calculated over a 10-year average using EIA data then reduced by the agricultural fuel discount from the Tennessee Department of Transportation (TDOT) to a final value of $3.18 per gallon. The establishment, maintenance, and harvest costs of Carinata include machine and operator labor hours as derived from the United States Department of Labor H2A hourly operator rate of $11.19 per hour (2018).

Due to the variability of this crop's inputs, associated budgeting costs will vary among differing yields (Tennessee, frost tolerant, and documented), market prices, pest management, fertilizer/herbicide applications, and planting/harvest techniques to capture possible scenarios. A one-way sensitivity analysis is created for the documented yield scenario by allowing one parameter to change at a time while holding all others constant at their respective baseline value. The results of this analysis are given visually in Figure 3.1 as a tornado diagram. All assumed yields, production practices, and associated costs are presented in Table 3.1.

3.4.2 Stochastic Yield Simulation

The risk and uncertainty of growing Carinata in Tennessee comes from unknown yields. Many of the Carinata cover-crop trials have been done in the deep southern regions of the United States where the crops are exposed to a lower potential for frost damage and freezing temperatures. Given the lower and upper bound assumptions, the one-way sensitivity analysis (Figure 3.1) shows yield as the most sensitive variable in determining if a producer will breakeven off of their investment to grow Carinata. Stochastic simulation and Monte Carlo sampling is used to model yields and probability of profit measures. Hardaker et al. (2015) explain the importance of stochastic simulation when variables have uncertain values and are best modeled with continuous probability distributions. Monte Carlo sampling is also used to converge a stable distribution by random sampling and modeling the iteration output.

A Probability Density Function (PDF) is used in this study to model the uncertainty of Carinata yields in Tennessee. A PDF can be modeled normally with a bell-shaped distribution depicting the most unlikely values toward the tails and the mode or most likely values toward the middle of the curve. A special type of PDF can be represented as a triangular distribution when only the minimum, maximum, and mode values are known. The minimum, average, and maximum EPIC yield estimates 696, 919, and 1488 pounds per acre, respectively, for Tennessee. The frost tolerant scenario resulted in minimum, average, and maximum EPIC yield estimates of 1127, 1602, and 2448 pounds per acre, respectively. Finally, the documented scenario uses literature-derived minimum, average, and maximum yields of 1462, 1933, and 3127 pounds per acre, respectively. To view these yield variations, see Table 3.14.

The randomized component of Palisade's @RISK software completes one hundred thousand iterations to fill in the gaps between these points. Equation 3.1 depicts the functional form of the triangular distribution PDF as $f(x)$, where *x* denotes the uncertain quantity, *a* represents the minimum, *b* represents the maximum, and *m* for the mode.

Equation 3.1

$$f(x) = \frac{2(x-a)}{(b-a)} * (m-a), x \leq m$$

$$f(x) = \frac{2(b-x)}{(b-a)} * (b-m), x > m$$

Some of the benefits of this distribution in decision analysis are simple graphs that can be generated and easily understood. However, due to a difficulty of ensuring the total area under the curve equals one, as the laws of probability mandate, these distributions can be complex to manage. A potential solution that allows for ease of interpretation as well as convenient mathematical depiction is the Cumulative Distribution Function (CDF). The Cumulative Distribution Function allows for incremental dissemination along each point of the curve. Equation 3.2 depicts the functional form of the triangular distribution CDF as $F(x)$, where *x* denotes the uncertain quantity, *a* represents the minimum, *b* represents the maximum, and *m* for the mode.

Equation 3.2

$$F(x) = \frac{(x-a)^2}{(b-a)} * (m-a), x \leq m$$

$$F(x) = 1 - \frac{(b-x)^2}{(b-a)} * (b-m), x > m$$

The squared term on the graphical curve of this model to take an S-shape where the inflection point corresponds with the mode of the PDF. This method predicts probabilities of profitable yields, positive net returns, and manageable cost combinations.

A PDF and CDF of production costs and profit margins are estimated in addition to Carinata yield. Production costs include seed, establishment, fertilizer, herbicide, and harvest costs in dollars per pound. Transportation is excluded from this study because the consideration is only at the farm-gate level, which is reflected in the budget analysis. Profit margins are represented in dollars per pound and are also simulated using PDF and CDF across the stochastic yield distribution.

3.5 Results

3.5.1 Farm-Gate Cost Analysis

First, the financial cost analysis for the Tennessee specific yields of Carinata is discussed. Given this yield scenario, the gross revenue of production is $87.33 per acre. Budgeting results show an estimated total variable cost of $119.62 per acre with total fixed cost equaling $33.96. The estimated return above all variable expenses is -$32.29 while the return above all expenses is -$66.24 per acre.

To calculate these values, EPIC estimated average yield of 919 pounds per acre and a seeding rate of 5 pounds per acre is used. The assumed price is constant at $0.095

per pound. The breakeven price, given the yield of 919 pounds per acre, is $0.13 per pound (see Table 3.4). EPIC estimated this average yield based on a Canola crop profile and weather variations in west Tennessee. It can be assumed that these exact metrics can change regionally. This is due to changes in input costs as well as yield differences given warmer or cooler regions. The breakeven yield, given the price of $0.095 per pound, is 1,259 pounds per acre (see Table 3.5). To see a budget summary of Carinata being grown in Tennessee with estimated Tennessee yields, see Table 3.15.

Table 3.8 shows the two-way profitability analysis when varying yield in 250 pound per acre increments as well as price in 20% increments given the Tennessee scenario. The summary results of this table show poor profit margin estimates with multiple combinations of prices and quantities being below the respective breakeven threshold. This shows the profitability margins for Carinata in Tennessee as being questionable. Since little is truly known about the reaction of this crop in the state, the triangular distributed yields are stochastically modeled to estimate profitability further.

Second, the financial analysis for the frost tolerant Carinata yields are discussed. Given this yield scenario, the gross revenue of production is $152.15 per acre. Budgeting results show an estimated total variable cost of $119.62 per acre with total fixed cost equaling $33.96. The estimated return above all variable expenses is $32.53 per acre while the return above all expenses is -$1.43 per acre.

EPIC predicted a yield of 1,602 pounds per acre given a seeding rate of 5 pounds per acre to calculate these values. The assumed price is assumed $0.095 per pound as a baseline. The breakeven price, given the yield of 1,602 pounds per acre, is $0.075 per pound (see Table 3.6). Conversely, the breakeven yield, given the price of $0.095 per pound, is 1,259 pounds per acre (see Table 3.7). EPIC estimated this average yield based on Alabama weather variations in a moderate area between Tennessee and Florida. It can be assumed that these metrics can change regionally. This is due to variable input costs as well as yield differences across multiple regions. To see a budget summary of Carinata with estimated frost tolerant yields, see Table 3.16.

Table 3.9 shows the two-way profitability analysis when varying yield in 250 pound per acre increments as well as price in 20% increments given the frost tolerant scenario. The summary results of this table show profit margin estimates with combinations of prices and quantities being above the respective breakeven threshold. This, again, shows the profitability margins for Carinata in Tennessee as being questionable considering the frost tolerant variety is not currently available. As previously justified, the triangularly distributed yields are stochastically modeled for the frost tolerant variety to further estimate profitability.

Third, the financial analysis for the documented yield scenario of Carinata is discussed. Given this yield scenario, the gross revenue of production is $183.64 per acre. Budgeting results show an estimated total variable cost of $119.62 per acre with total fixed cost equaling $33.96. The estimated return above all variable expenses is $64.02 while the return above all expenses is $30.06 per acre.

To calculate these values, an expected yield of 1,933 pounds per acre and a seeding rate of 5 pounds per acre is used. The assumed price is $0.095 per pound. The breakeven price, given the yield of 1,933 pounds per acre, is $0.062 per pound (see Table

3.2). Conversely, the breakeven yield, given the price of $0.095 per pound, is 1,259 pounds per acre (see Table 3.3). It can be assumed that these exact metrics can change regionally. This is due to changes in input costs as well as yield differences across multiple regions. To see a summary of the Carinata budget for Tennessee given the documented yield scenario, see Table 3.17.

Triangular distributions are applied to oilseed yield and the variable expenses of seed price, establishment costs, transportation, harvest cost, fertilizer costs, and herbicide. The one-way sensitivity analysis further shows the variability of profit margins represented in Figure 3.1 as a tornado diagram. The lower and upper bounds are listed in Table 3.1 and the footnote explains the origin of the data. As expected, oilseed yield proves to be the strongest contributing factor in Carinata's net returns. If there were to be an increase in yield, it would lead to an increase in profits. Subsequently, if yields were to decrease, the opposite effect would be observed. Additionally, the seed price as well as establishment cost also have a significant impact on net returns. Similar to yield, when input seed prices rise, the profitability will decrease.

Table 3.10 shows a two-way profitability analysis when varying yield in 250 pound per acre increments as well as price in 20% increments. The summary results of this table show higher potential profit margin estimates with multiple combinations being above the respective breakeven price and yield.

3.5.2 Stochastic Yield Simulation

The results of the stochastic simulation of yield using Palisade's @RISK software for Carinata being grown in Tennessee provide two analysis tools. One being the PDF and the other being the CDF. The CDF is used primarily for probability determination because of the curve that is represented. The PDF shows the density of that probability in a chart. The results of the Carinata simulations show that yield is a significant factor when discussing profitability. Additionally, the variability of yield predictions showed the current scenario Tennessee yields being the worst-case scenario. The literature yields from Florida studies served as the best-case scenario, yet short of reality. Finally, the frost tolerant variety that was estimated shows potential for this crop to be integrated in the traditional crop rotations in Tennessee; pending the widespread release of the frost tolerant brassica seed.

The results of the PDF and CDF of Carinata that is harvested at the Tennessee estimated yield per pound average of 919 per acre has a 90% probability of being between 700 and 1,490 pounds per acre (see Figure 3.4 and 3.5). The minimum yield recorded in the simulation was 551 pounds per acre with a maximum of 1,698 pounds per acre. This means, given the breakeven yield occurring at 1,259 pounds per acre, there is only a 21.5% probability of yield surpassing the breakeven benchmark. Conversely, there is a 78.5% probability that yield will not be high enough for a producer to breakeven. Therefore, given this yield simulation and an assumed market price, it can be said with very little confidence that a producer in Tennessee wishing to implement Carinata as a cover crop between rotational corn and soybeans will harvest the required yield to breakeven on his/her investment.

When analyzing the production cost of Carinata at the farm-gate level using the current Tennessee yields, the results are less than optimistic. The CDF curve shows a 2%

probability that cost of production ($/lb.) will be less than or equal to the assumed market price of $0.095. Thus, there is a highly likely 98% probability that cost will exceed gross revenue (see Figure 3.6 and 3.7). With respect to profit margins, the Tennessee yields performed similarly. At the same probability of 2%, profits are greater than or equal to zero. Conversely, there is a 98% probability of negative returns (see Figure 3.8 and 3.9). Concluding, there is only a 2% chance of a producer breaking even off his/her investment to grow Carinata given the simulated Tennessee yields and costs of production.

With respect to the PDF and CDF simulation conducted on Carinata that is harvested at the average frost tolerant yield of 1,602 pounds per acre, there is a 90% probability of yield being between 1,130 and 2,490 pounds per acre (see Figure 3.10 and 3.11). The minimum yield recorded in the simulation was 856 pounds per acre with a maximum of 2,835 pounds per acre. This means, given the breakeven yield occurring at 1,259 pounds per acre, there is a 90% probability of yield surpassing the breakeven benchmark. Therefore, given this yield simulation and an assumed market price, it can be said with relative confidence that a producer in Tennessee wishing to implement Carinata as a cover crop between rotational corn and soybeans will harvest at least the minimum yields required to breakeven on his/her investment.

When analyzing the production cost of Carinata at the farm-gate level using the frost tolerant yields, the results are promising as well. The CDF curve shows a 67% probability that cost of production ($/lb.) will be less than or equal to the assumed market price of $0.095. Thus, there lies a 33% probability that cost will exceed revenue (see Figure 3.12 and 3.13). With respect to profit margins, the frost tolerant yields performed well. At the same probability of 67%, profits are greater than or equal to zero. Conversely, there is a 33% probability of negative returns. In summary, there is a 67% chance of a producer breaking even off his/her investment to grow Carinata under this scenario.

Based on the results of the PDF and CDF simulation, Carinata that is harvested at the documented average yield per pound of 1,933 per acre average has a 90% probability of being between 1,400 and 2,460 pounds per acre (see Figure 3.16 and 3.17). The minimum yield recorded in the simulation was 1,160 with a maximum of 2,706. This means, given the breakeven yield occurring at 1,259 pounds per acre, there is a 99% probability of yield surpassing the breakeven benchmark. Conversely, there is only a 1% probability of yield being less than or equal to the breakeven. Therefore, given this yield simulation and an assumed market price, it can be said with a high level of confidence that a producer in Tennessee wishing to implement Carinata as a cover crop between rotational corn and soybeans will harvest at least the minimum yields required to breakeven on his/her investment.

When analyzing the production cost of Carinata at the farm-gate level using the literature yields, the results are promising as well. The CDF curve shows an 87% probability that cost of production ($/lb.) will be less than or equal to the assumed market price of $0.095. Thus, there is a low, 13%, probability that cost will exceed revenue (see Figure 3.18 and 3.19). With respect to profit margins, the literature yields performed well. The estimated probability that profits are greater than or equal to 0 is 87%. Conversely, there is a 13% probability of negative returns (see Figure 3.20 and 3.21).

Concluding, there is an 87% chance of a producer breaking even off their investment to grow Carinata in Tennessee if documented yields are realized.

3.6 Conclusion

In total, this study utilized crop enterprise budgets with variable yield combinations derived from EPIC results along with @RISK software to derive yield, cost, and profit probabilities of implementing Carinata as a winter-season cover crop in Tennessee. The enterprise budget is based on a market price of $0.095 and three yield scenarios: 919, 1,602, and 1,933 pounds per acre for Tennessee, frost tolerant, and documented Florida yields, respectively. The seeding rate concluded at 5 pounds per acre with a planting density of 200 per m^2. Additionally, Carinata boasted a high oil content of 40% at harvest. The results of the budget analysis show net returns of -$66.24, -$1.43, and $30.06 per acre for the Tennessee, frost tolerant, and documented yields, respectively.

The results of the tornado diagram represented net returns being affected by fluctuating variables such as yield, seed cost, establishment, and harvest cost. The concluding results of this figure show that yield is the most significant variable in securing positive net returns.

The two-way profitability tables are presented to show the importance of yield and price combination scenarios. The current Tennessee yield distribution showed the most negative profits. Conversely, the literature-based Florida yields given the same prices, showed promising results in profitability. The frost tolerant yields also showed promise given that many of the price and quantity combinations were above the breakeven benchmark.

The EPIC modeling was used in this study to estimate Carinata yields as potential growing acres move north. Given, the only true recorded yields come from Florida. The model predicted the yields almost to the exact pounds per acre as to what was recorded in Florida. This validated that the model worked in picking up weather patterns given different regions. The Tennessee estimated yields were quite low ranging from 696 pounds per acre to 1,488 per acre a minimum and maximum, respectively. The most likely value being 919 pounds per acre, which was below the breakeven yield calculated in the budget. This is believed to be due in large part to the model penalizing Carinata for the colder winter temperatures. The frost tolerant variety is modeled after EPIC model variation in Alabama. This estimation provided a range of 1,127 to 2,488 as a minimum and maximum, respectively. The most likely value being 1,602 which was above the breakeven yield mark estimated in the budget analysis.

The probability density function and cumulative distribution function were also used to assess the probability of earning a profit given the three different yield scenarios. The Tennessee specific yield performed poor showing only a 21.5% chance of yield being high enough to breakeven. 90% of the yield estimated in the model fell between 700 and 1,490 pounds per acre. The maximum value is slightly over 200 pounds per acre higher than the breakeven value of 1,259. Additionally, there was a 98% chance that a producer would incur negative profit margins. The frost tolerant yields showed somewhat promising results. Under this scenario there was a 90% probability of yield falling between 1,130 and 2,490 pounds per acre. Thus, a 90% chance of yields being above the breakeven benchmark. Profit margins showed a 67% probability of at least breaking even off of the investment to grow Carinata with a 33% chance of incurring a loss. Finally, the literature-derived documented yield provided the strongest results which concluded with a 99% probability of yield being above the breakeven mark and an 87% probability of at least breaking even. Though this result is highly positive, it is also reflecting a best-case scenario with little likelihood of occurring given the current outlook of yield and weather in the state of Tennessee.

While these projections are encouraging, currently in Tennessee, the crop price is simply non-existent, and furthermore, the crop is not agronomically prepared for more northern winters. However, as demand for SAF increases, there is likely to be a push for higher prices demanded. As government mandates begin taking affect, it is likely that the market price will continue to increase. This could, in part, be enough to offset the relatively low yields estimated in Tennessee. With the finalization of a frost tolerant variety being made available, however, Carinata has potential to be incorporated as a part of a two-year cropping cycle and be profitable in Tennessee based off this analysis.

This study has several limitations. One of which being that Carinata yield is still, largely, unknown in Tennessee. The EPIC estimates used in this study simulate reality, however, they do not fully represent reality. Current research is being done at both the Milan, Tennessee and Spring Hill, Tennessee Research and Education Centers with Carinata, Camelina, and Pennycress. True yield estimates will be recorded from this agronomic study for further analysis. Another limitation to this study is the variability of the budgeting assumptions from farm to farm which potentially could raise or lower profits on a subjective basis. This study considers corn-carinata-soybeans. A further step in this research could be to assess cotton-carinata-soybeans which could prove to be more profitable for producers. Additionally, given the agronomic limitations of Carinata, this could prove to be more beneficial for yields as well. This study also does not take into consideration a loss on soybean yield due to later planting. A continuation of this research could include the actual recorded Tennessee yields from 2019-2020 using the same budgeting assumptions. Additionally, considering the yield loss on soybeans and estimating that decrease into the two-year cropping cycle would be an extension of this research.

Appendices

Tables

Table 3.1: Data and assumptions for breakeven and one-way analysis of field Carinata oilseed farm-level production costs when considering variable expenses

Item	Baseline	Lower Bound	Upper Bound
Carinata Seed ($/acre) [1]	$ 20.00	$ 8.00	$ 40.00
Establishment ($/acre) [2]	$ 31.29	$ 10.00	$ 37.55
Fertilizer ($/acre) [3]	$ 40.30	$ 0.00	$ 48.36
Herbicide ($/acre) [4]	$ 27.50	$ 0.00	$ 33.00
Harvest ($/acre) [5]	$ 25.84	$ 20.67	$ 31.00
Transportation ($/acre) [6]	$ 25.45	$ 20.36	$ 30.54
Oilseed Yield (lb./acre) [7]	1932.91	1546.33	2319.49

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[1] Base seeding at 5lb./acre (Mulvaney et al., 2019)Lower Bound seeding rate is 2lb./acre (Hossain et al., 2018). Upper bound seeding rate is 10lb./acre (AgMRC, 2018); (Johnson, 2014).

[2] Carinata is assumed to be established in late October with baseline assumptions of a no-till grain drill from establishment calculations; lower bound from aerial seed rate (Markel et al. 2018); upper bound is an assumed 20% deviation increase possibility.

[3] Fertilizer lower bound assumes no application while; baseline represents the total quantity of fertilizer: 40 lbs. Nitrogen, 30 lbs. of Phosphorous, and 20 lbs. of sulfur. Nitrogen application is used in two separate applications in 20 lb. increments (Mulvaney et al., 2019); upper bound is a 20% increase in deviation above base value.

[4] Herbicide lower bound assumes no application (Trejo-Pech et al. 2019); baseline from establishment of 1 pint/acre; upper bound is a 20% increase in deviation above baseline

[5] Carinata is assumed to be harvested in May. Both lower and upper bounds are 20% deviations above and below the baseline.

[6] Transportation is assumed to be 100-mile round trip from the farm to the crushing facility. The lower and upper bounds are 20% deviations above and below the baseline.

[7] Documented yields from the University of Florida (Mulvaney et al., 2019); the lower and upper bounds for this parameter are assessed from the same study’s minimum and maximum values.

Table 3.2: Breakeven analysis results for Carinata when varying Tennessee yield and holding price constant

Yield (lbs.)	Variable Cost ($/lb.)	Total Specified Costs ($/lb.)
439	$ 0.27	$ 0.35
599	$ 0.20	$ 0.26
759	$ 0.16	$ 0.20
919	**$ 0.130**	**$ 0.167**
1079	$ 0.11	$ 0.14
1239	$ 0.10	$ 0.12
1399	$ 0.09	$ 0.11

Table 3.3: Breakeven analysis results for Carinata when varying price and holding Tennessee yield constant

Price ($/lb.)	Yield (lbs./acre)	Total Specified Costs (lbs.)
$ 0.03	4125	5296
$ 0.05	2345	3011
$ 0.07	1639	2104
$ 0.095	**1259**	**1617**
$ 0.12	1022	1313
$ 0.14	861	1105
$ 0.16	743	954

Table 3.4: Breakeven analysis results for Carinata when varying frost tolerant yield and holding price constant

Yield (lbs.)	Variable Cost ($/lb.)	Total Specified Costs ($/lb.)
1122	$ 0.11	$ 0.14
1282	$ 0.09	$ 0.12
1442	$ 0.08	$ 0.11
1602	**$ 0.075**	**$ 0.096**
1762	$ 0.07	$ 0.09
1922	$ 0.06	$ 0.08
2082	$ 0.06	$ 0.07

Table 3.5: Breakeven analysis results for Carinata when varying price and holding frost tolerant yield constant

Price ($/lb.)	Yield (lbs./acre)	Total Specified Costs ($/lb.)
$ 0.03	4125	5296
$ 0.05	2345	3011
$ 0.07	1639	2104
$ 0.095	**1259**	**1617**
$ 0.12	1022	1313
$ 0.14	861	1105
$ 0.16	743	954

Table 3.6: Breakeven analysis results for Carinata when varying literature-derived yield and holding price constant

Yield (lbs.)	Variable Cost ($/lb.)	Total Specified Costs ($/lb.)
1453	$ 0.08	$ 0.11
1613	$ 0.07	$ 0.10
1773	$ 0.07	$ 0.09
1933	**$ 0.062**	**$ 0.079**
2093	$ 0.06	$ 0.07
2253	$ 0.05	$ 0.07
2413	$ 0.05	$ 0.06

Table 3.7: Breakeven analysis results for Carinata when varying price and holding literature-derived yield constant

Price ($/lb.)	Yield (lbs./acre)	Total Specified Costs (lbs.)
$ 0.03	4125	5296
$ 0.05	2345	3011
$ 0.07	1639	2104
$ 0.095	**1259**	**1617**
$ 0.12	1022	1313
$ 0.14	861	1105
$ 0.16	743	954

Table 3.8: Two-Way profit/loss table showing Tennessee yield (lb./acre) variation in 250 lb. increments response to price ($/lb.) changes in 20% increments

		Price ($/lb.)				
		$ 0.06	$ 0.08	**$ 0.095**	$ 0.11	$ 0.13
TN Yield (lb./acre)	169	$ 109.97	$ 106.75	$ 103.54	$ 100.32	$ 97.10
	419	$ 95.72	$ 87.75	$ 79.79	$ 71.82	$ 63.85
	669	$ 81.47	$ 68.75	$ 56.04	$ 43.32	$ 30.60
	919	$ 67.22	$ 49.75	$ 32.29	$ 14.82	$ 2.65
	1169	$ 52.97	$ 30.75	$ 8.54	$ 13.68	$ 35.90
	1419	$ 38.72	$ 11.75	$ 15.21	$ 42.18	$ 69.15
	1669	$ 24.47	$ 7.25	$ 38.96	$ 70.68	$ 102.40

Table 3.9: Two-Way profit/loss table showing frost tolerant yield (lb./acre) variation in 250 lb. increments response to price ($/lb.) changes in 20% increments

		Price ($/lb.)				
		$ 0.06	$ 0.08	**$ 0.095**	$ 0.11	$ 0.13
Frost Tolerant Yield (lb./acre)	852	$ 71.08	$ 54.90	$ 38.72	$ 22.54	$ 6.36
	1102	$ 56.83	$ 35.90	$ 14.97	$ 5.96	$ 26.89
	1352	$ 42.58	$ 16.90	$ 8.78	$ 34.46	$ 60.14
	1602	$ 28.33	$ 2.10	$ 32.53	$ 62.96	$ 93.39
	1852	$ 14.08	$ 21.10	$ 56.28	$ 91.46	$ 126.64
	2102	$ 0.17	$ 40.10	$ 80.03	$ 119.96	$ 159.89
	2352	$ 14.42	$ 59.10	$ 103.78	$ 148.46	$ 193.14

Table 3.10: Two-Way profit/loss table showing literature-derived yield (lb./acre) variation in 250 lb. increments response to price ($/lb.) changes in 20% increments

		Price ($/lb.)				
		$ 0.06	$ 0.08	**$ 0.095**	$ 0.11	$ 0.13
Documented Yield (lb./acre)	1183	$ 52.19	$ 29.71	$ 7.23	$ 15.24	$ 37.72
	1433	$ 37.94	$ 10.71	$ 16.52	$ 43.74	$ 70.97
	1683	$ 23.69	$ 8.29	$ 40.27	$ 72.24	$ 104.22
	1933	$ 9.44	$ 27.29	$ 64.02	$ 100.74	$ 137.47
	2183	$ 4.81	$ 46.29	$ 87.77	$ 129.24	$ 170.72
	2433	$ 19.06	$ 65.29	$ 111.52	$ 157.74	$ 203.97
	2683	$ 33.31	$ 84.29	$ 135.27	$ 186.24	$ 237.22

Table 3.11: Cumulative hours below differing temperature thresholds that cause slight frost damage to Carinata

Temperature	Cumulative Hours Below
32° F (0°C)	61.8
25°F (-3.9°C)	19.3
20°F (-6.7°C)	3.5
15°F (-9.4°C)	0.0

*Adapted from University of Florida Research by Dr. Mike Mulvaney on Carinata Frost Damage (2018)

Table 3.12: Cumulative hours below differing temperature thresholds that cause moderate frost damage to Carinata

Temperature	Cumulative Hours Below
32° F (0°C)	61.8
25°F (-3.9°C)	19.3
20°F (-6.7°C)	3.5
15°F (-9.4°C)	0.0

*Adapted from University of Florida Research by Dr. Mike Mulvaney on Carinata Frost Damage (2018)

Table 3.13: Cumulative hours below differing temperature thresholds that cause severe frost damage to Carinata

Temperature	**Cumulative Hours Below**
32° F (0°C)	196.8
25°F (-3.9°C)	63.8
20°F (-6.7°C)	14.5
15°F (-9.4°C)	0.0

*Adapted from University of Florida Research by Dr. Mike Mulvaney on Carinata Frost Damage (2018)

Table 3.14: Carinata literature-derived, Tennessee, frost tolerant, and Florida yields (lbs./acre) simulated using EPIC

	Literature-Based Yield	Tennessee Yield	Frost Tolerant Yield	Florida Weather Yield
	(lbs./acre)	(lbs./acre)	(lbs./acre)	(lbs./acre)
Average	1932	919	1602	1928
Maximum	3127	1488	2488	3001
Minimum	1462	696	1127	1458

Table 3.15: Summary of enterprise budget for Carinata in Tennessee with Tennessee estimated yield representing harvest quantity

Field Carinata Brassica: Tennessee Yield

	Unit	Quantity	Price	Total
Revenue			**Gross Revenue ($/Acre)**	
Carinata[1]	lbs.	919	$ 0.095	$ 87.33
			Total Revenue	**$ 87.33**
Variable Expenses				
Seed[1]	lbs.	5	$ 4.00	$ 20.00
Fertilizer[2]	Acre	1	$ 40.30	$ 40.30
Chemical[2]	Acre	1	$ 27.50	$ 27.50
Repair & Maint.[3]	Acre	1	$ 14.33	$ 14.33
Fuel, Oil, & Filter[3]	Acre	1	$ 11.46	$ 11.46
Operator Labor[3]	Acre	1	$ 5.14	$ 5.14
Machinery cost- Seed Drill #3	Acre	1	$ 0.12	$ 0.12
Crop Insurance[5]	Acre	1	$ -	$ -
Operating Interest[6]	Acre	1	$ 0.77	$ 0.77
Other Variable Cost	Acre	1	$ -	$ -
			Total Variable Expenses	**$ 119.62**
			Return Above Variable Expenses	**$ (32.29)**
Fixed Expenses				
Machinery[3]				
Capital Recovery	Acre	1	$ 23.66	$ 23.66
Other Fixed Machinery Cost	Acre	1	$ -	$ -
Taxes, Housing, & Insurance	Acre	1	$ 10.30	$ 10.30
Other Fixed Costs	Acre	1	$ -	$ -
			Total Fixed Expenses	**$ 33.96**
			Return Above All Specified Expenses	**$ (66.24)**

Table 3.16: Summary of enterprise budget for Carinata in Tennessee with frost tolerant estimated yield representing harvest quantity

Field Carinata Brassica: Frost Tolerant Yield

	Unit	Quantity		Price		Total
Revenue				**Gross Revenue ($/Acre)**		
Carinata [1]	lbs.	1602	$	0.095	$	152.15
				Total Revenue	**$**	**152.15**
Variable Expenses						
Seed [1]	lbs.	5	$	4.00	$	20.00
Fertilizer [2]	Acre	1	$	40.30	$	40.30
Chemical [2]	Acre	1	$	27.50	$	27.50
Repair & Maint. [3]	Acre	1	$	14.33	$	14.33
Fuel, Oil, & Filter [3]	Acre	1	$	11.46	$	11.46
Operator Labor [3]	Acre	1	$	5.14	$	5.14
Machinery cost- Seed Drill #3	Acre	1	$	0.12	$	0.12
Crop Insurance [5]	Acre	1	$	-	$	-
Operating Interest [6]	Acre	1	$	0.77	$	0.77
Other Variable Cost	Acre	1	$	-	$	-
				Total Variable Expenses	**$**	**119.62**
				Return Above Variable Expenses	**$**	**32.53**
Fixed Expenses						
Machinery [3]						
Capital Recovery	Acre	1	$	23.66	$	23.66
Other Fixed Machinery Cost	Acre	1	$	-	$	-
Taxes, Housing, & Insurance	Acre	1	$	10.30	$	10.30
Other Fixed Costs	Acre	1	$	-	$	-
				Total Fixed Expenses	**$**	**33.96**
				Return Above All Specified Expenses	**$**	**(1.43)**

Table 3.17: Summary of enterprise budget for Carinata in Tennessee with documented yield representing harvest quantity

Field Carinata Brassica: Documented Yield

	Unit	Quantity		Price		Total
Revenue				**Gross Revenue ($/Acre)**		
Carinata [1]	lbs.	1933	$	0.095	$	183.64
				Total Revenue	**$**	**183.64**
Variable Expenses						
Seed [1]	lbs.	5	$	4.00	$	20.00
Fertilizer [2]	Acre	1	$	40.30	$	40.30
Chemical [2]	Acre	1	$	27.50	$	27.50
Repair & Maint. [3]	Acre	1	$	14.33	$	14.33
Fuel, Oil, & Filter [3]	Acre	1	$	11.46	$	11.46
Operator Labor [3]	Acre	1	$	5.14	$	5.14
Machinery cost- Seed Drill #3	Acre	1	$	0.12	$	0.12
Crop Insurance [5]	Acre	1	$	-	$	-
Operating Interest [6]	Acre	1	$	0.77	$	0.77
Other Variable Cost	Acre	1	$	-	$	-
				Total Variable Expenses	**$**	**119.62**
				Return Above Variable Expenses	**$**	**64.02**
Fixed Expenses						
Machinery [3]						
Capital Recovery	Acre	1	$	23.66	$	23.66
Other Fixed Machinery Cost	Acre	1	$	-	$	-
Taxes, Housing, & Insurance	Acre	1	$	10.30	$	10.30
Other Fixed Costs	Acre	1	$	-	$	-
				Total Fixed Expenses	**$**	**33.96**
				Return Above All Specified Expenses	**$**	**30.06**

Figures

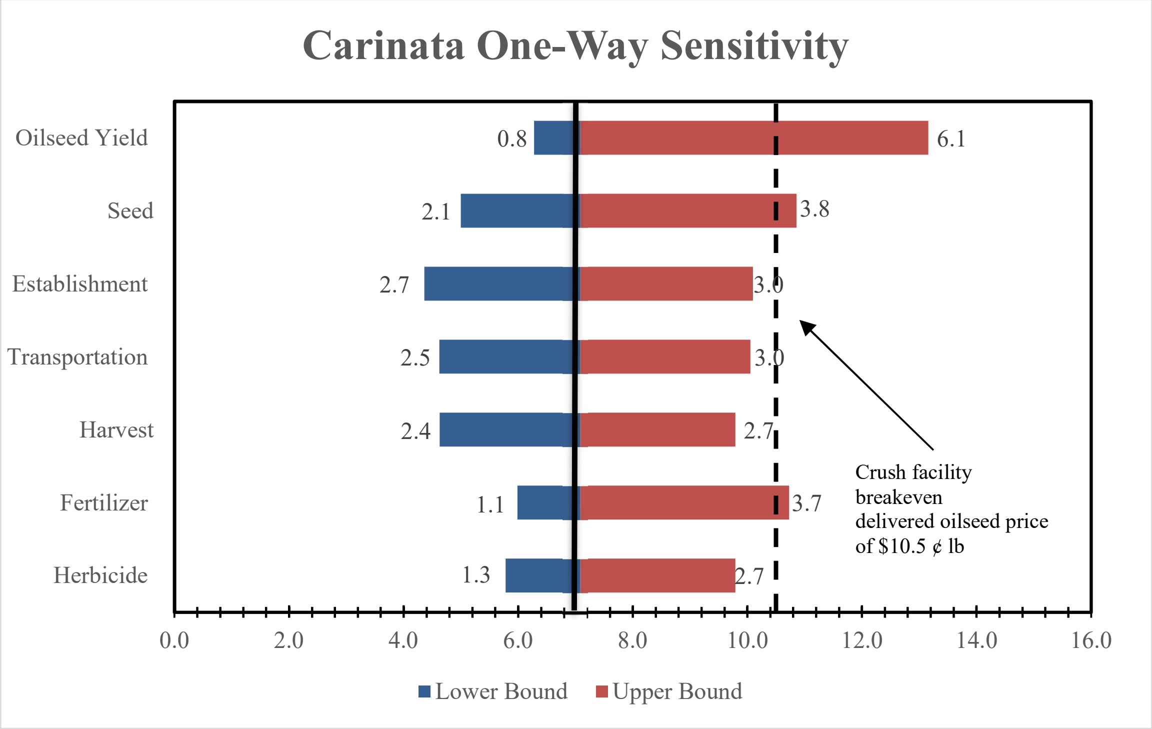

Figure 3.11: Tornado diagram showing the breakeven analysis results for Carinata

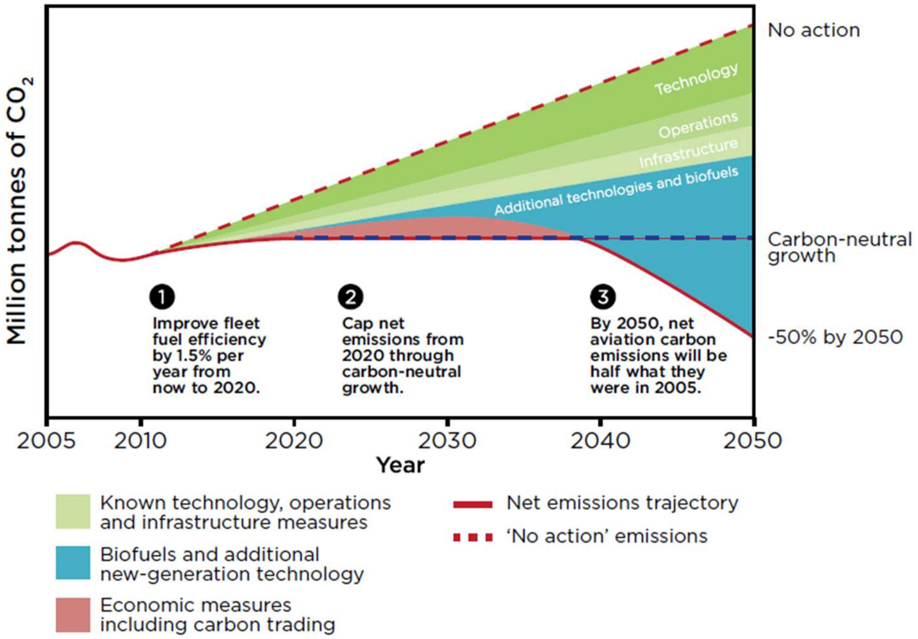

Figure 3.12: Visual representation of aviation emissions in the absence of conservative actions and with emission-reduction goals from industry.

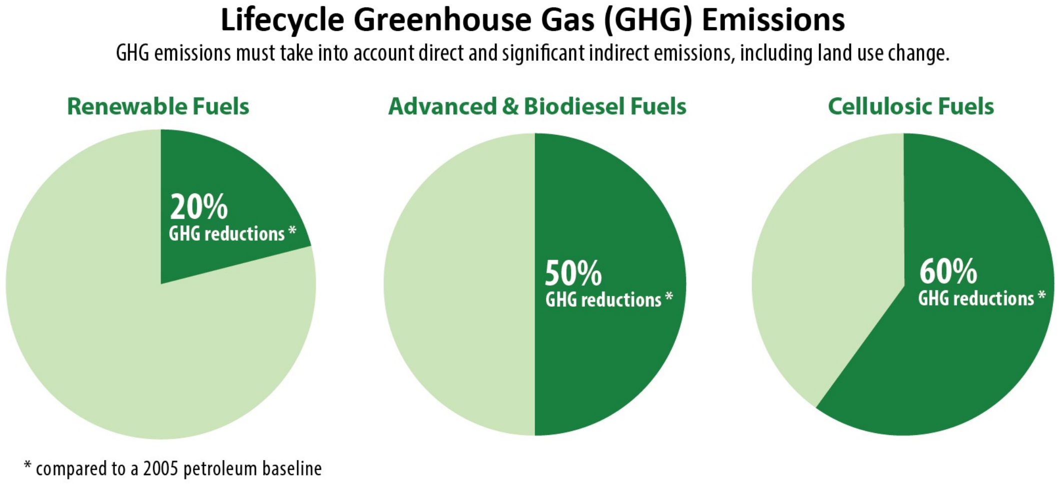

Figure 3.13: Breakdown of Greenhouse Gas (GHG) Emission reduction when utilizing renewable, advanced and biodiesel, and cellulosic fuels.

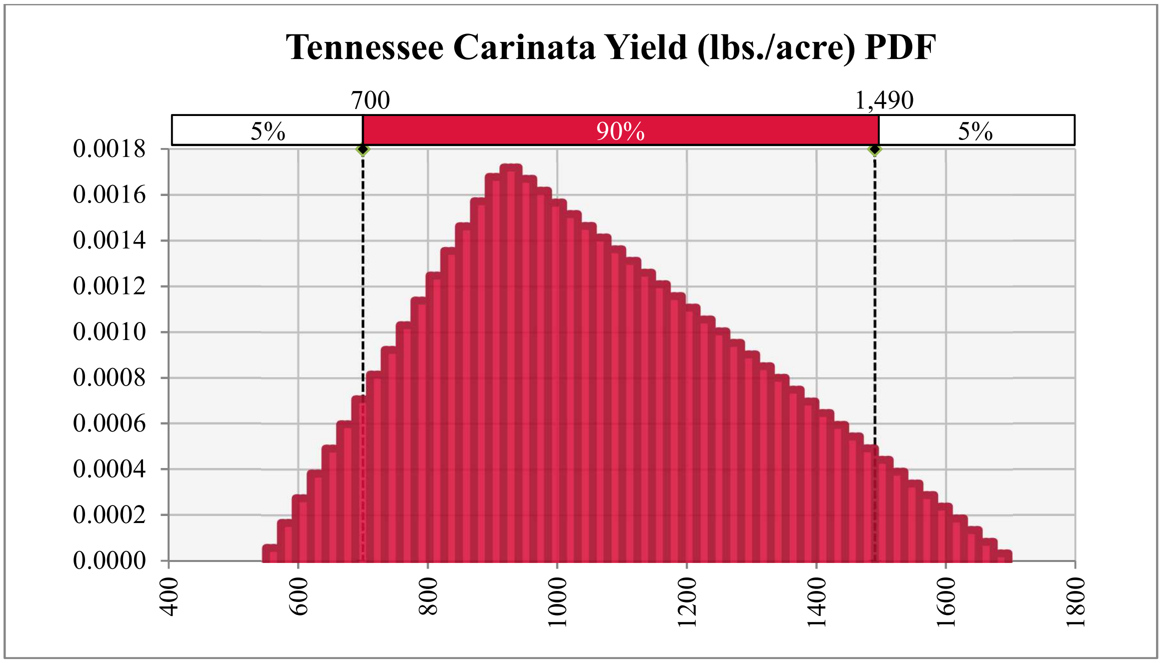

Figure 3.14: Carinata probability density chart for estimated Tennessee yield (lb./acre)

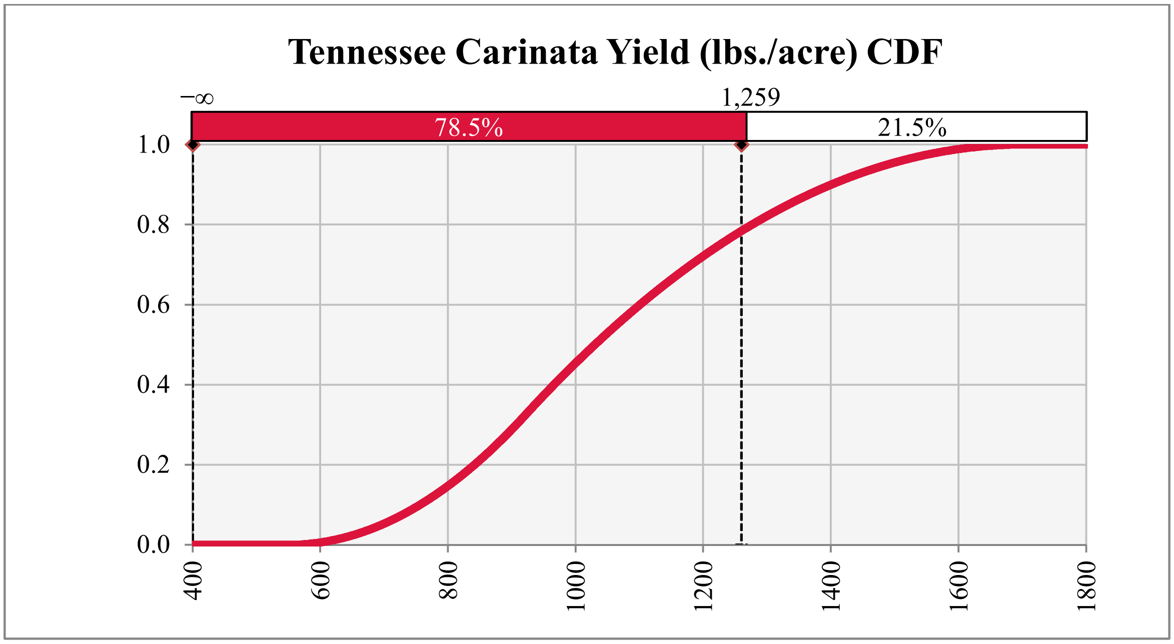

Figure 3.15: Carinata cumulative distribution for estimated Tennessee yield (lb./acre)

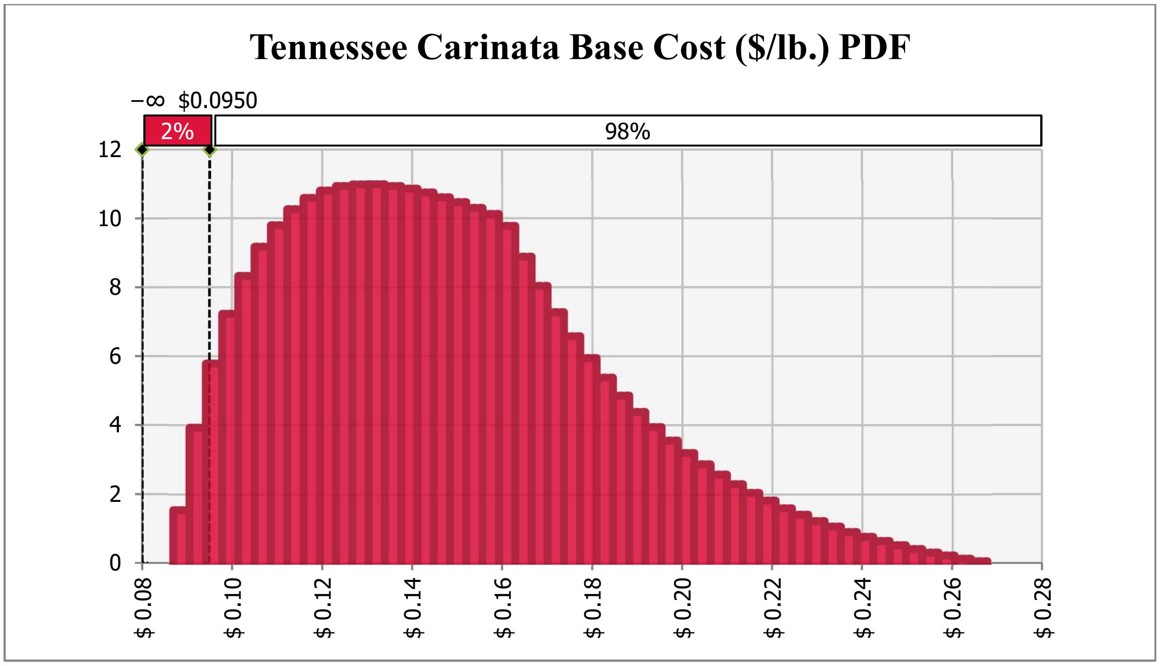

Figure 3.16: Carinata probability density chart for cost based on estimated Tennessee yield ($/lb.)

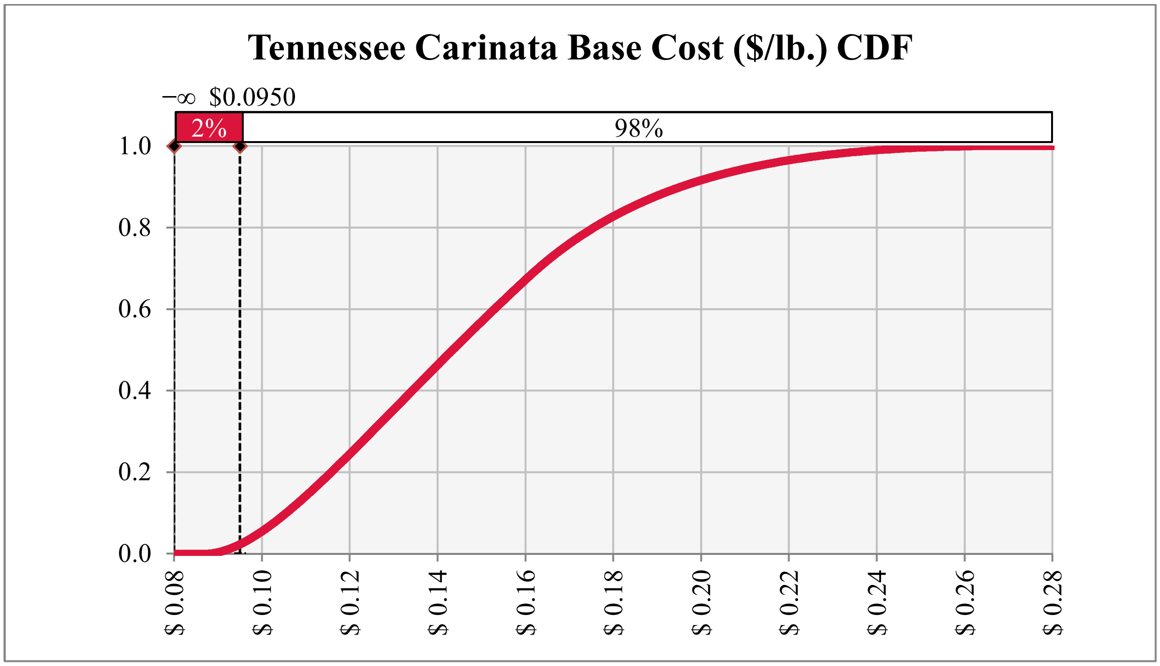

Figure 17: Carinata cumulative distribution for base cost based on estimated Tennessee yield ($/lb.)

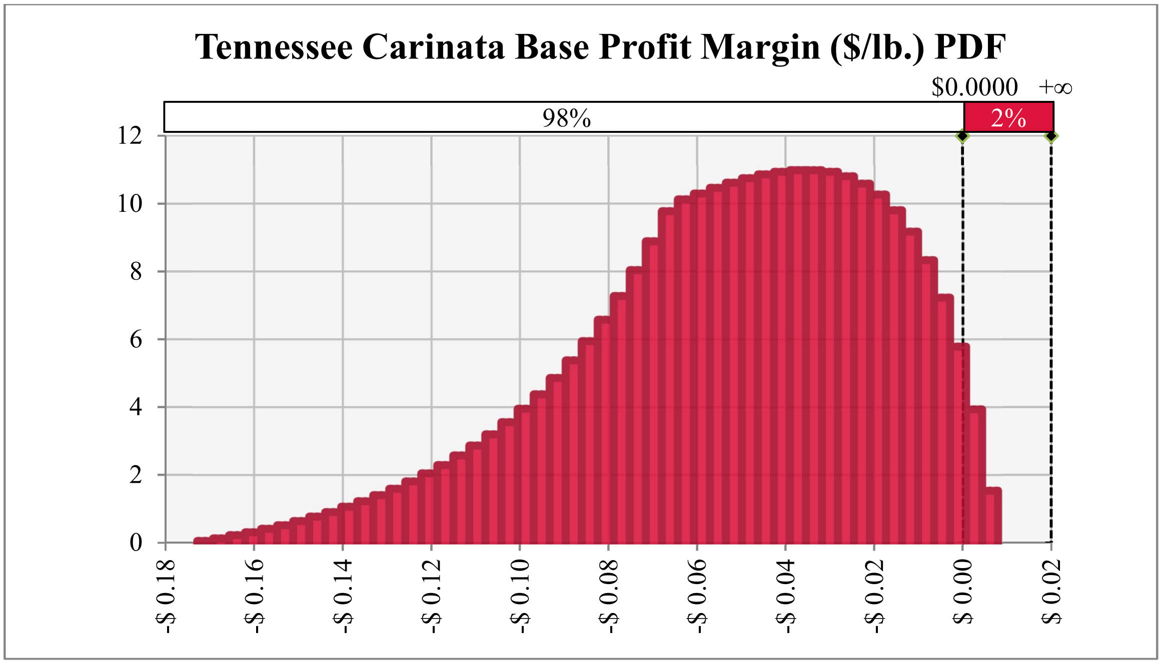

Figure 18: Carinata probability density chart for profit margin based on estimated Tennessee yield ($/lb.)

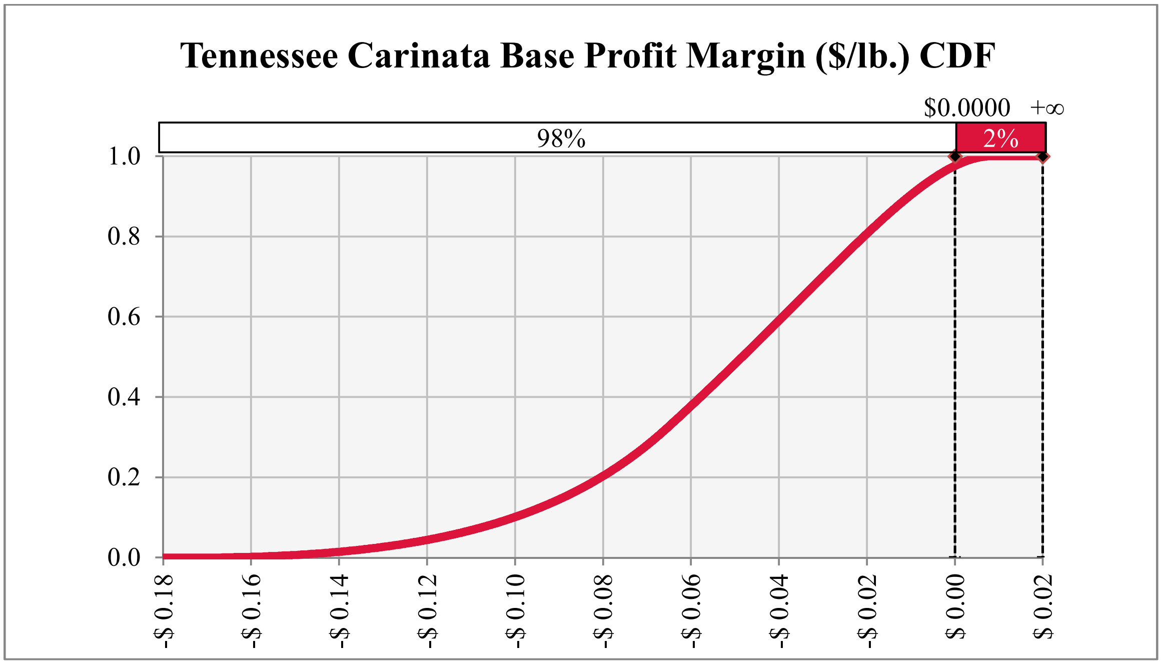

Figure 19: Carinata cumulative distribution for profit margin based on estimated Tennessee yield ($/lb.)

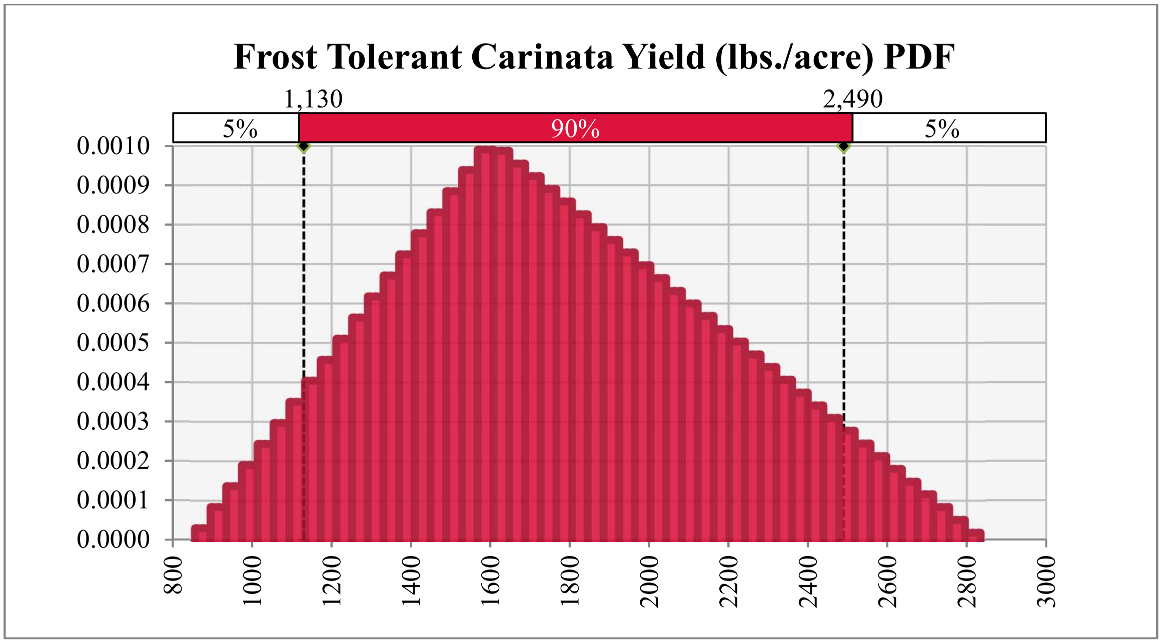

Figure 3.20: Carinata probability density chart for estimated frost tolerant yield (lb./acre)

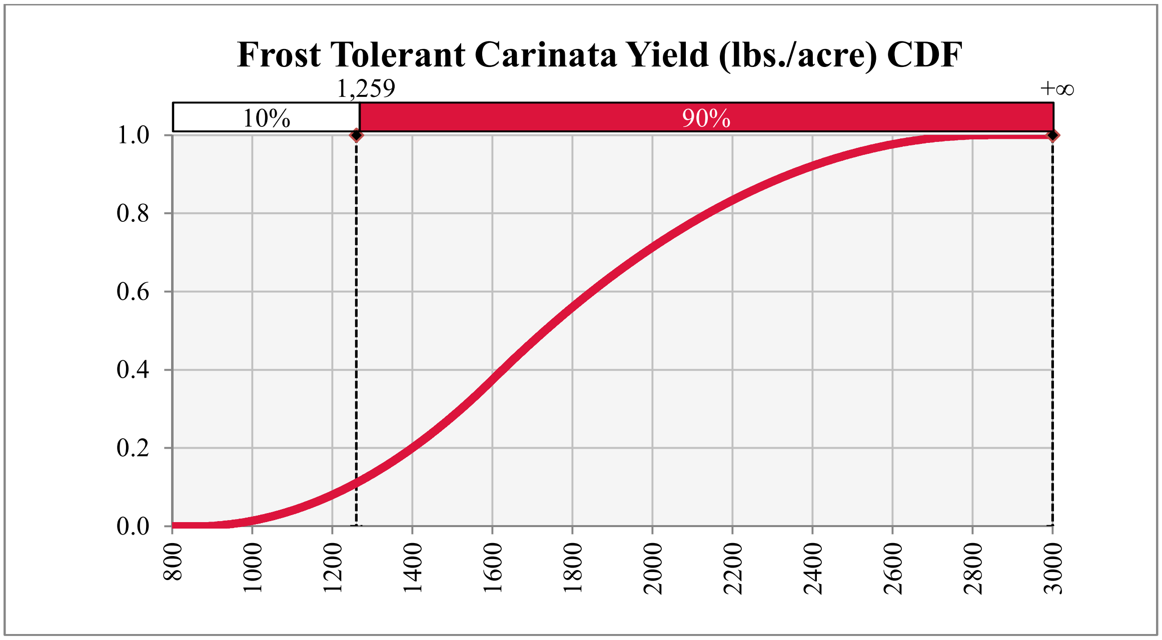

Figure 3.21: Carinata cumulative distribution chart for estimated frost tolerant yield (lb./acre)

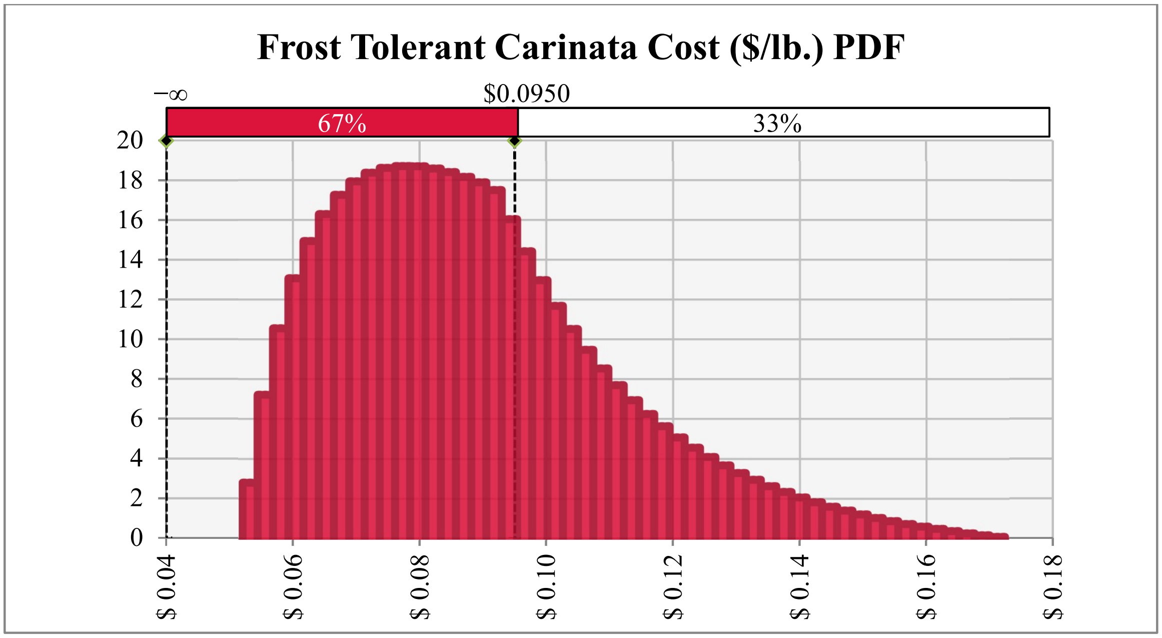

Figure 3.22: Carinata probability density chart for cost based on estimated frost tolerant yield ($/lb.)

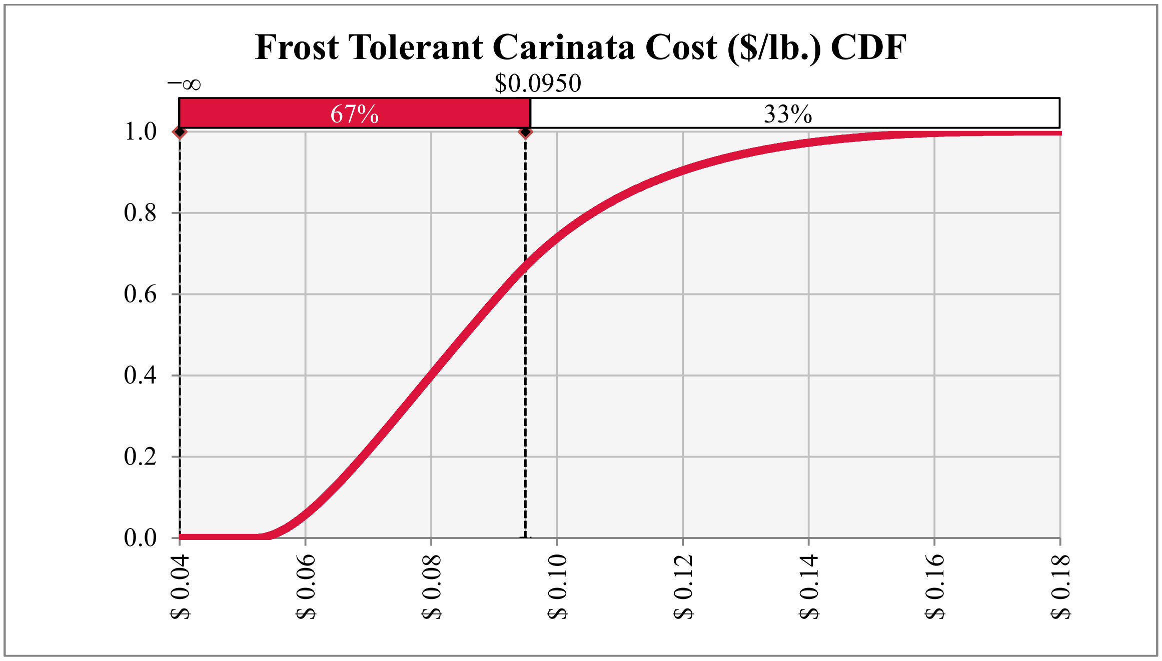

Figure 3.23: Carinata cumulative distribution chart for cost based on estimated frost tolerant yield ($/lb.)

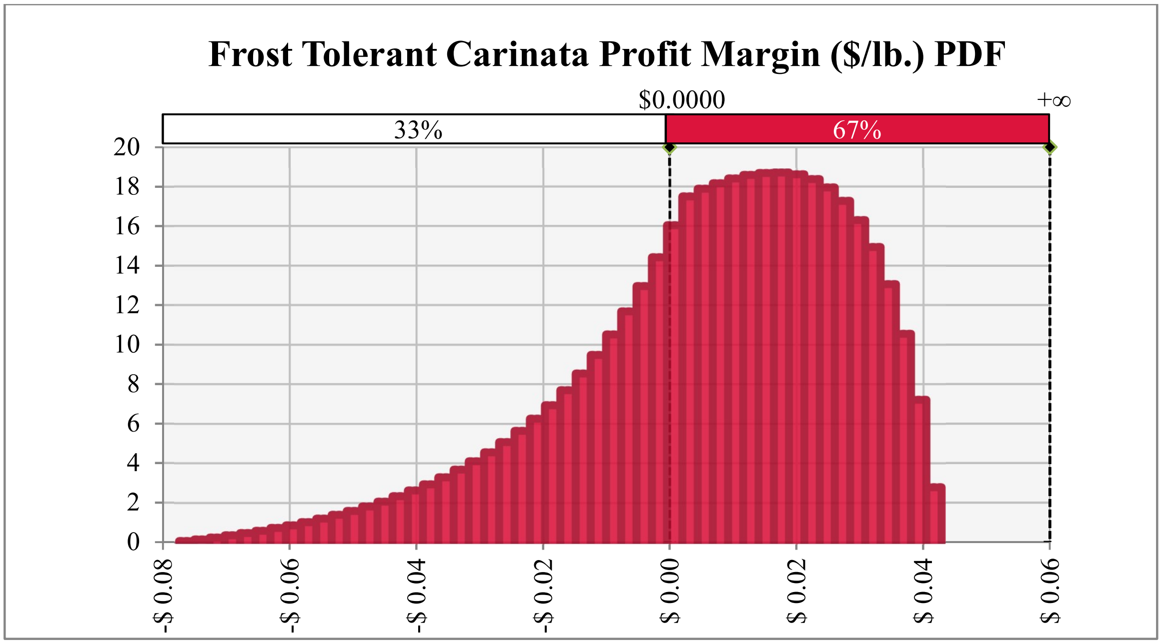

Figure 3.24: Carinata probability density chart for profit margin based on estimated frost tolerant yield ($/lb.)

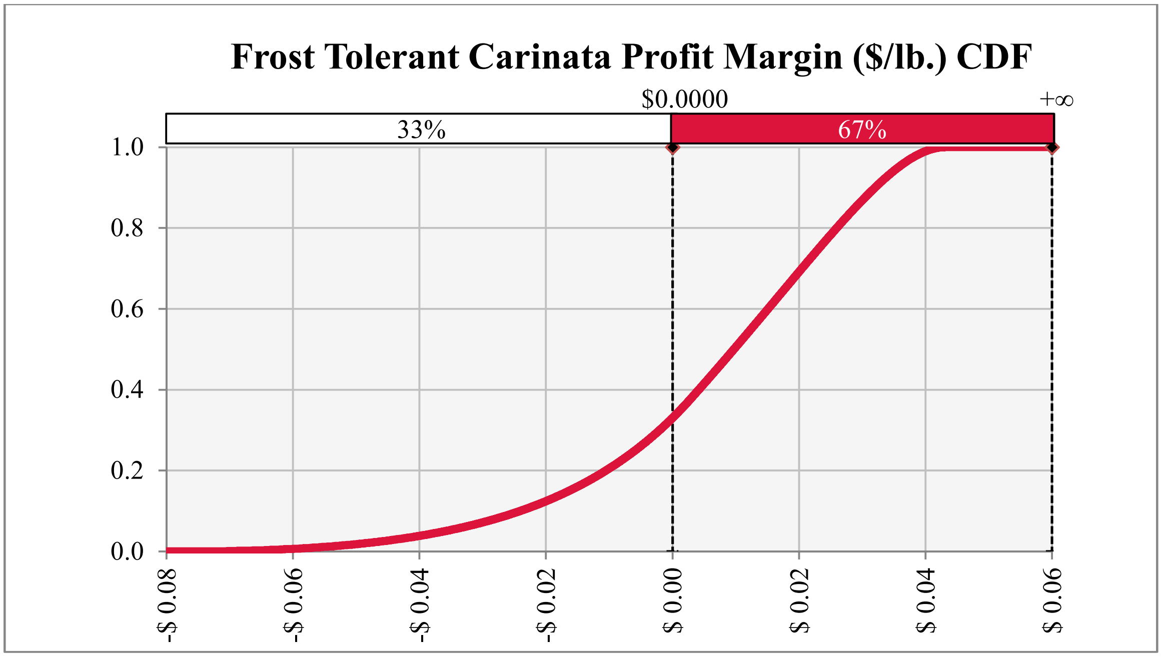

Figure 3.25: Carinata cumulative distribution for profit margin based on estimated frost tolerant yield ($/lb.)

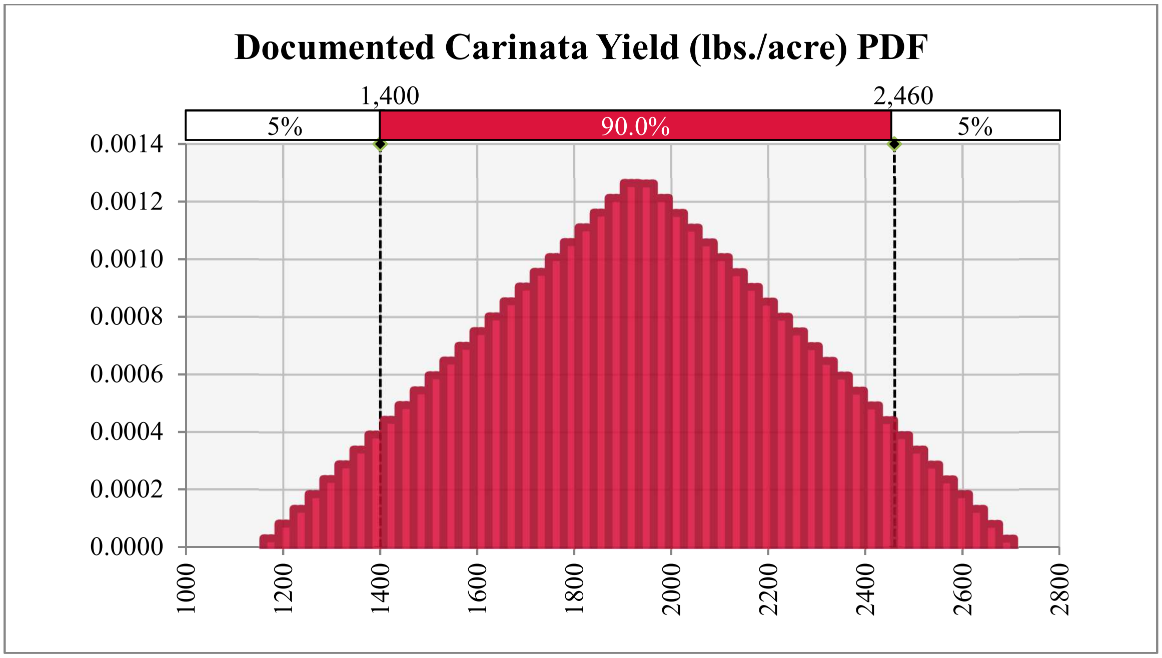

Figure 3.26: Carinata probability density chart for documented Florida yield (lb./acre)

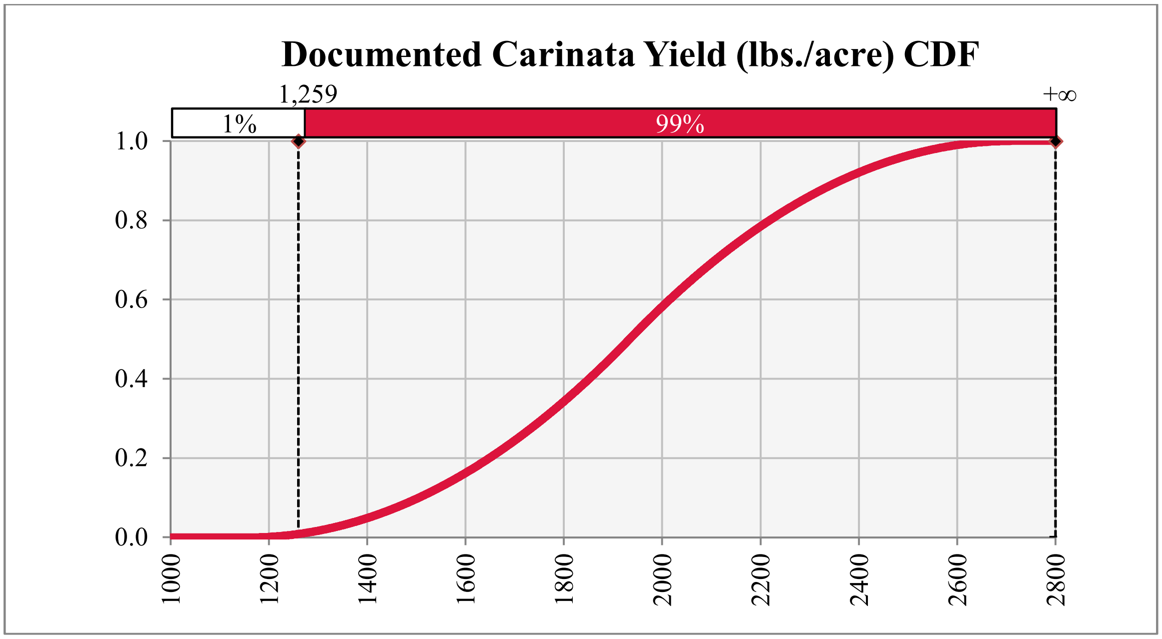

Figure 3.27: Carinata cumulative distribution chart for documented Florida yield (lb./acre)

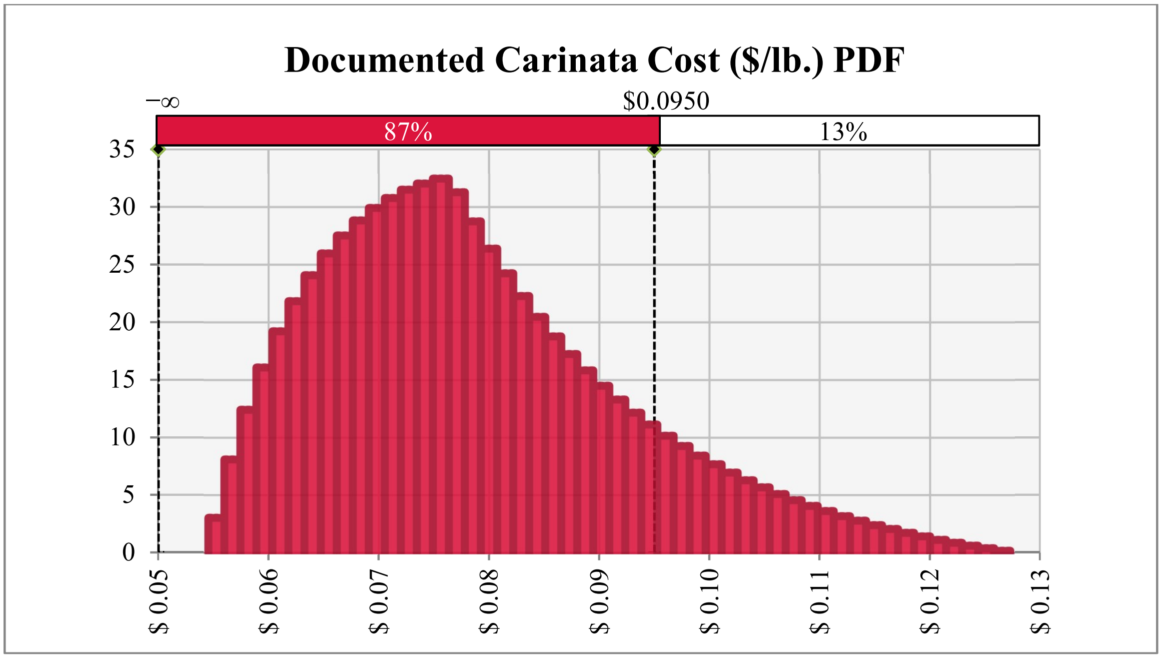

Figure 3.28: Carinata probability density chart for cost based on documented Florida yield ($/lb.)

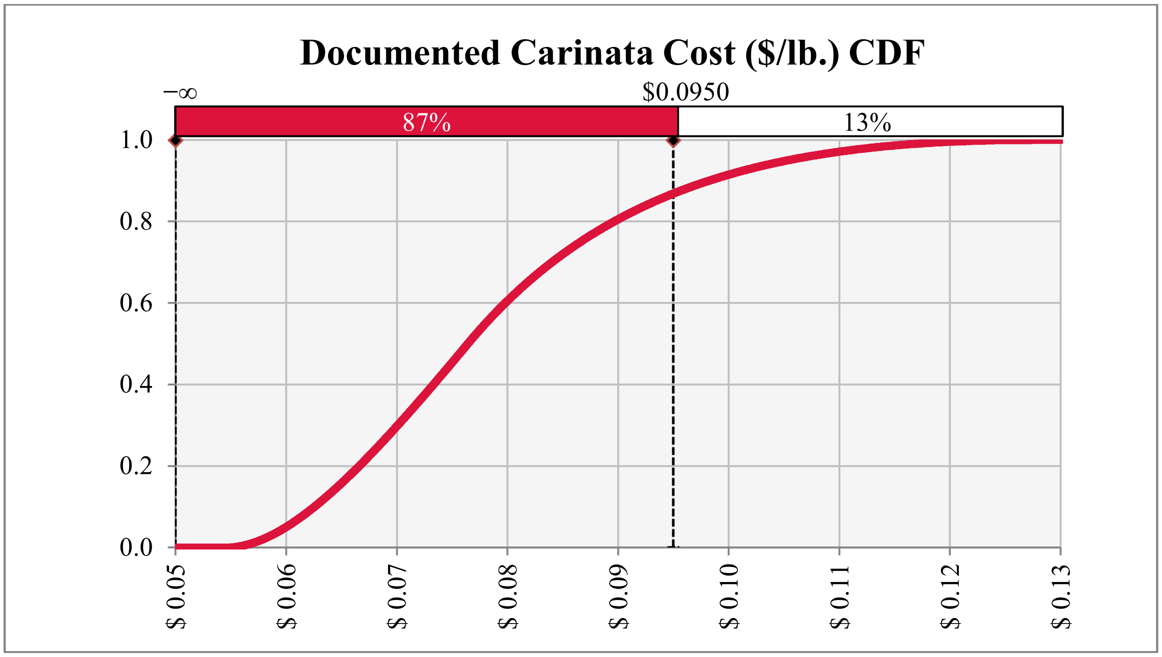

Figure 3.29: Carinata cumulative distribution chart for cost based on documented Florida yield ($/lb.)

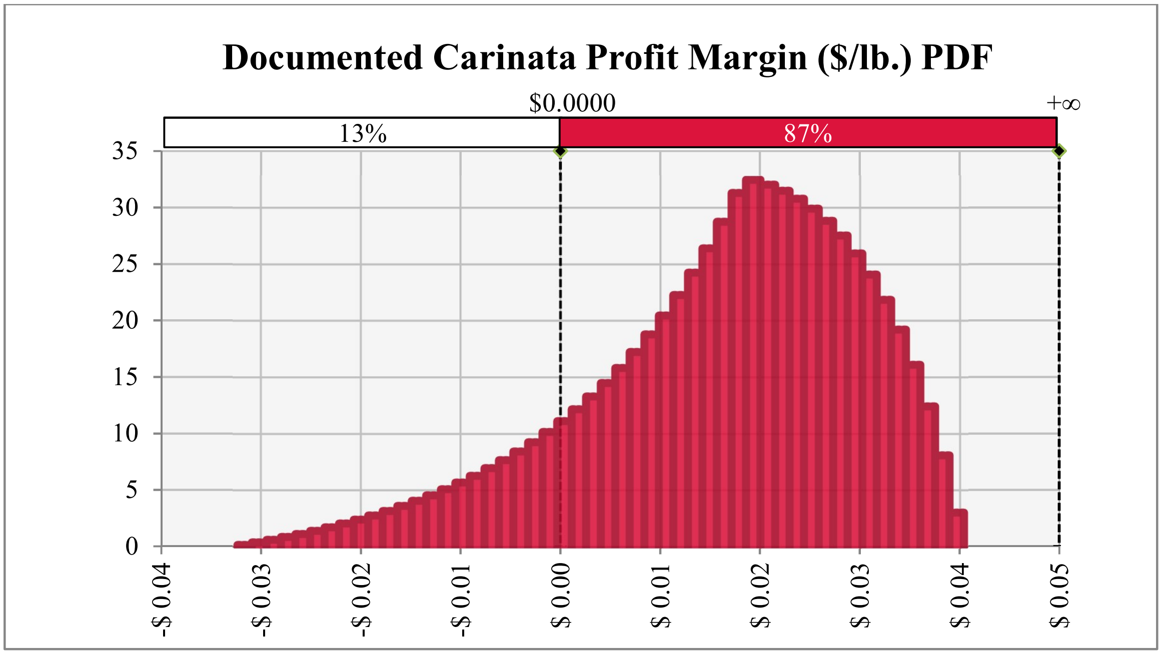

Figure 3.30: Carinata probability density chart for profit margin based on documented Florida yield ($/lb.)

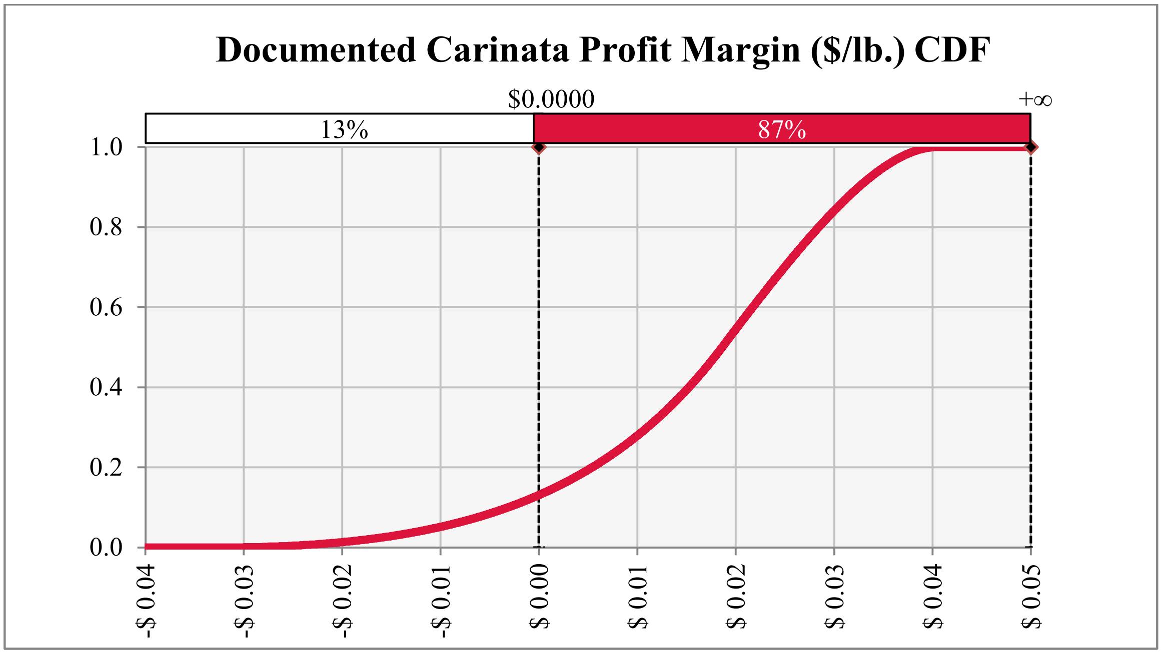

Figure 3.31: Carinata cumulative distribution chart for profit margin based on documented Florida yield ($/lb.)

CHAPTER 4: CONCLUSION

4.1 Conclusion

The implications of growing switchgrass in Tennessee shows promising results when analyzing the profitability at both the farm and refinery levels. Nitrogen fertilizer (N) plays an important role in production because it decreases crop yield beyond 124 pounds per acre, which is valuable to the farmer. However, the limiting effects of ash content on thermochemical biofuel conversion are decreased as the N application approaches 139 pounds per acre. Through econometric and microeconomic methods, the link between N fertilizer and profit is analyzed at the farm as well as the biorefinery. Results show that the optimal N rate at the farm is 47 pounds per acre which yields an estimated 6.77 dry tons per acre of switchgrass with an ash content of 2.28% of total biomass. Applying this optimal N rate maximizes net returns at $472.87 per acre at the farm gate. At the biorefinery the optimal N application during switchgrass production is 114 pounds per acre yielding an estimated 7.46 dry tons per acre with an ash content of 2.09% of total biomass. At this optimal N rate, biorefinery net returns total $3,729.39 per ton of feedstock input. Therefore, the discussion is opened for potential incentive programs or the creation of an integrated industry to control for profit decreasing externalities and unknowns.

The third chapter analyzes the enterprise viability at the farm level of Carinata to be grown as sustainable aviation fuel in Tennessee. Because the only documented research on this crop have been done in Florida, EPIC yield estimations had to be used for Tennessee. The model showed decreasing yields as the crop moves north. This result is backed by literature which shows frost damage as being a severely limiting factor in production. Therefore, the frost tolerant yield was calculated using an intermediate weather pattern in Alabama while holding the rest of the assumptions constant. The results of the budget analysis show little potential for the current crop variety to be profitable in Tennessee. The resulting average yield was 919 far below the breakeven point of 1,259. The results of the frost tolerant and documented Florida yields surpassed the breakeven benchmark. A stochastic simulation of a triangular distribution of each yield scenario was conducted generating a PDF and CDF of yield, cost, and profit for each. As expected, the Tennessee yields showed an extremely low probability of 2% for a farmer to break even off of his/her investment to grow Carinata. The frost tolerant scenario had more promising potential of 67% probability of breaking even. Finally, the documented yields performed very well with an 87% probability of breaking even. The problem with these results is that the Tennessee yield scenario is reality. The possibility for a frost tolerant variety being made available is waiting on technological advancements and the documented yield scenario is an even farther stretch.

This study completes an important step in the agricultural production research sector by providing an in-depth analysis of potential energy crops to be grown in Tennessee. As demand increases, technology advances, and markets for these crops are secured, bioenergy will trend toward the future. The limitations of the switchgrass profitability analysis include a lack of a complete enterprise budget from which to draw a multi-faceted cost scenario. Further research could include this dynamic budgeting scenario which may provide a different optimal N fertilizer application for both the farm as well as biorefinery. The biorefinery did not have a complex budget tied to production costs, either. Therefore, it is difficult to assume the optimal N application estimated at the refinery is totally accurate. An extension of this research would be to include both of these budgets and determine the optimal N application throughout the supply chain. Implementing interaction variables between moisture and carbon content could also add to the value of the research. The Carinata enterprise viability analysis also has limitations in the research. One of which being a lack of observed Tennessee yields. Also, the yield loss of soybeans after a winter season cover crop was not assumed in this analysis. Further research could include the observed Tennessee Carinata yields given the same budget analysis. Also, using the yield decrease in soybeans to determine the profitability of the complete two-year cropping cycle. Another extension of this research could include a cotton-Carinata-soybean cropping analysis could prove more profitable as well.

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VITA

Alan Robertson grew up in Mt. Juliet, Tennessee and is the only child of Kevin and Dana Robertson. He is an accomplished musician, golfer, public speaker, and outdoorsman. Having been surrounded by agriculture for much of his life, it was an easy step to become involved in FFA during high school. After being state and national champion in multiple Career Development Events such as Extemporaneous Public Speaking and Soil Evaluation, he was elected as the 2014-15 TN State FFA President. During this term he also began his college career at the beautiful campus of UT Martin where he studied agricultural business. Socially, he was involved in many on-campus clubs and charitable organizations such as the Sigma Chi International Fraternity where he served as Chapter President and was a Balfour Outstanding Brother for North America. Upon graduation, he relocated to the mountains of East Tennessee for his master's degree in agricultural economics where he was elected Graduate Student President and conducted research on the economics behind biofuels and alternative energy under the supervision of his major professor Dr. Burt English. Alan is pursuing a career in the agriculture industry in hopes of paying forward the opportunities that were afforded to him.