ASSESSING ENVIRONMENTAL AND ECONOMIC IMPACTS OF CARINATA-BASED SUSTAINABLE AVIATION FUEL PRODUCTION IN THE SE UNITED STATES

by

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(Under the Direction of Puneet Dwivedi)

ABSTRACT

The aviation sector in the United States emitted 255 million metric tons of carbon dioxide (CO_2) emissions in 2019, i.e., about five percent of the total domestic CO_2 emissions from the energy sector. Sustainable aviation fuel (SAF) from carinata (*Brassica carinata*) could reduce the CO_2 emissions of the aviation sector nationwide. The southeastern (SE) region of the United States could play a crucial role in carinata production with their year-round growing season, suitable soils, and sufficient rainfall. In this context, it is essential to assess the environmental-economic impacts of carinata-based SAF both at the farm and supply chain levels. We assessed a total of 292 crop rotations with/without carinata in South Georgia. We also set up a supply chain model for carinata-based SAF in Georgia. Farm-level results show that carinata has the highest profit in corn-corn-soybean rotation. It has the lowest risk in cotton-cotton-peanut rotation. We found that carinata is the most eco-efficient in cotton-cotton-peanut rotation. Carinata improves NPV and risk by $260.59/ha and 8.08%. It also decreases environmental impacts by about 1,039 kg of CO_2/ha. The supply chain model showed that carinata-based SAF is not economically feasible since the SAF unit price can be as low as $1.23/liter, which is still higher than the conventional fuel of

$0.49/liter. Overall, carinata make farms more profitable, less risky, and more eco-efficient; however, economic incentives from the government are needed to make carinata-based SAF supply chain feasible in the SE United States.

INDEX WORDS: Crop Rotation, Eco-Efficiency, Farm-Level Risk, Supply Chain

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DEDICATION

I didcate my dissertation work to my family, especially my mom, who I love the most. I also dedicate this dissertation to all Iranian people who suffered under sanctions.

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CHAPTER 1

INTRODUCTION

The aviation industry was responsible for 785 million metric tons of CO_2 emissions in 2019, i.e., around 2% of all human-induced CO_2 emissions (Graver, 2020). The aviation sector in the United States alone emitted 255 million metric tons, which was about 23% of the total aviation-related carbon emissions in the world (Graver, 2020). In 2019, the CO_2 emissions from the United States' aviation sector corresponded to about 5% of total energy-related CO_2 emissions nationwide (U.S. Energy Information Administration, 2019).

Regardless of the COVID-19 impact, there will be an annual growth of 3.7% in global air passengers by 2039 (IATA, 2020). As a result, the number of passengers in 2039 will be 2.1 times more than the 2019 level (IATA, 2020). If the trend continues, this surge in aviation demand is projected to result in around 2.27 billion tonnes of CO_2 emissions by 2039, which is 2.32 times greater than the 2021 baseline of almost one billion tonnes (Arnaldo Valdés & Gómez Comendador, 2021).

For the United States, the available seat-miles flights increased by 30.2% and 100% for domestic and international flights between 2003 and 2019, respectively (U.S. Department of Transportation, 2019). In the same period, jet fuel consumption in the United States increased from 63.86 billion liters to 69.16 billion liters (U.S. Department of Transportation, 2019). This clearly shows a high positive correlation between the demand for air travel and total CO_2 emission.

In 2008, the aviation industry implemented a set of ambitious targets to decrease the overall CO_2 emissions, including a) an average improvement in fuel efficiency of 1.5%/year between 2009 and 2020; b) a cap on net aviation carbon emissions from 2020 (carbon-neutral growth); and c) a reduction in net aviation carbon emissions of 50% by 2050, relative to 2005 levels (European Aviation Safety Agency et al., 2016). Due to COVID-19, the International Air Transport Association adjusted the goals to be compared with the 2019 emissions only (Graver, 2020). The industry has implemented a four-pillar policy to accomplish CO_2 reduction goals, including but not limited to technology development, operational efficiencies, infrastructure improvements, and market-based economic measures.

Several methods have been explored for reducing CO_2 emissions in the aviation sector. For instance, Fukui & Miyoshi (2017) explored the option of aviation fuel tax and found that a 4.3 cents/gal increase in aviation fuel tax would reduce CO_2 emissions in the United States by 0.14–0.18% in the short run. Similarly, Faber & Huigen (2018) explored the option of ticket tax and reported that the tax rate should be between €2 to €26 depending upon the distance of the flight in Europe. Furthermore, China has included the aviation industry in the newly established national carbon trading market (Liao et al., 2021). In addition to these policy-based options, the use of Sustainable Aviation Fuel (SAF) is becoming popular (Kousoulidou & Lonza, 2016; Larson et al., 2001) as one of the most promising ways to mitigate CO_2 emissions from the aviation sector (IBAC, 2019).

Some studies indicate that SAF has a lower carbon footprint than conventional jet fuel; however, CO_2 savings vary across different biomass feedstocks. Bailis & Baka (2010) investigated the environmental impacts of jatropha (*Jatropha Curcas*) based SAF. The SAF could reduce 55% of CO_2 emission relative to conventional jet fuel in Brazil. Budsberg et al. (2016) found out that the SAF produced from poplar biomass decreases global warming potential up to 56% compared with conventional jet fuel. Pamula et al. (2021) showed that SAF from switchgrass has 44% lower environmental impacts than conventional jet fuel.

Although there are many environmental benefits for SAF, there are several issues of farm-level profitability, farm-level financial risk, and optimal supply chain of SAF that need to be considered regarding the SAF production process. First, it is not always economically feasible to produce SAF (Michailos, 2018; Yang et al., 2018; Tao et al., 2017). It is crucial to consider both environmental and economic information into a single framework for SAF production. Eco-efficiency is a tool that jointly measures economic and environmental performances (Arabi et al., 2014).

Secondly, there are a lot of risky factors in the context of SAF production. Existing studies typically assume that it is easy for farmers to adopt a bioenergy crop in their production plan. However, many factors impact the adoption rate, including economic benefits and financial risk at the farm level. Not many studies included risk in bioenergy crops farm-level economics. Bocquého & Jacquet (2010) concluded that switchgrass and miscanthus make French farms less profitable and risky in rape/wheat/barley rotation. Clancy et al. (2012) found that miscanthus is a less risky option than willow at Irish farms. Alexander & Moran (2013) found that miscanthus was the best option for risk-averse farmers in the United Kingdom. Skevas et al. (2016) reported that perennial bioenergy crops have a higher potential to compete with corn under marginal crop production conditions in Florida. Spiegel et al. (2018) reported that a guaranteed short rotation coppice biomass price could decrease risks at farms in Germany.

In addition to numerous farm-level issues, there are several issues beyond the farm-level for SAF production because of the low density and distributed nature of biomass resources (Espinoza Pérez et al., 2017). Due to the low energy density of biomass, a supply chain system of biofuel requires a large sourcing area to meet a level of demand (Castillo-Villar, 2014). Additionally, the biomass supply sites and demand centers are not adjacent (Lin et al., 2016). Therefore, the cost of bioenergy production is typically higher than a comparable conventional energy source. Reimer & Zheng (2017) suggested a 17% subsidy on the alternative fuel, a 20% tax on the conventional fuel, or a combination 9% subsidy on the alternative and 9% tax on the conventional fuel, to make camelina-based SAF feasible in the Pacific Northwest in the United States. Perkis & Tyner (2018) found that it is not economically feasible for firms to set up a supply chain with current economic incentives in Indiana. Huang et al. (2019) showed that the most cost-effective solution for SAF was $1.23/liter, and the most environmental-friendly solution was 0.03 kg CO_2/liter, in the Midwestern United States.

Carinata (*Brassica carinata A. Braun*), also called Ethiopian mustard, is a viable source for SAF production due to the high concentration of erucic acid in the seed (Seepaul et al., 2019). Carinata is a native African crop; it has been sowed and studied in America (Rakow & Getinet, 1998; Christ et al., 2020), Australia (Uloth et al., 2015), Europe (Cardone et al., 2002; Gasol et al., 2007; Basili & Rossi, 2018), Africa (Abdelazim Mohdaly & Ramadan, 2020), and Asia (Malik, 1990; Lal et al., 2019) for many years ago. Alam & Dwivedi (2019) found that 1.4 million hectares are suitable for growing carinata in the Southeastern United States. Farmers can include carinata in crop rotations as a winter crop to increase income and provide soil health benefits (SPARC, 2019). Carinata can be in rotation with late corn, cotton, peanut, soybean, and grain sorghum. Crop rotation can help decrease disease risk since Fusarium and Sclerotinia remain on the residues (SPARC, 2019).

A closer look at the existing literature suggests that no study has analyzed the economic and environmental impacts of SAF derived from winter crops, in general, and carinata in particular, at the farm level. Additionally, the literature is practically silent about the economic risks that winter bioenergy crops like carinata pose to farmers relative to risks related to current crop rotations. Finally, the information on the economics of carinata-based SAF production is practically missing at the supply chain level for ascertaining a realistic overall cost.

In this context, this study aims to decrease CO_2 emissions in the aviation sector by analyzing the economic and environmental feasibility of carinata-based SAF production in the United States, in general, and the SE United States, in particular. We address the goal of our study in three different chapters with the following objectives: a) to determine changes in the profitability and financial risks of farmers with/without carinata in their crop rotations; b) to determine changes in the farm-level eco-efficiency with/without carinata in crop rotations; and c) to determine the unit cost of carinata-based SAF production at the supply chain level relative to scaling in the state of Georgia. This study does not consider any state-specific policies, like California LCFS (Low Carbon Fuel Standard). This study does not consider any existing incentives/mandates because these policies are not guaranteed to continue, and therefore carinata economics must be favorable even without any policy support.

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Chapter 2

Economics of Crop Rotations with and without Carinata for Sustainable Aviation Fuel Production in the SE United States[1]

[1] Karami, Omid; Dwivedi, Puneet; Lamb, Marshall, To be Submitted to Frontiers in Energy

Abstract

The aviation sector in the United States emitted 255 million metric tons of carbon dioxide (CO_2) emissions in 2019, i.e., about five percent of the total domestic CO_2 emissions from the energy sector. The sustainable aviation fuel (SAF) derived from carinata (*Brassica carinata*) could reduce CO_2 emissions of the aviation sector in the United States. The southeastern (SE) region of the United States could play a crucial role in carinata production with their year-round growing season, suitable soils, and sufficient rainfall. Therefore, it is essential to assess the suitability of carinata as a winter crop in the current crop rotations in this region. Additionally, it is vital to assess the financial implications of growing carinata for farmers. Both these factors would help in estimating the likelihood of carinata production in the SE United States. In this context, we first identified a combination of 12 popular rotations of corn, cotton, peanut, and soybean with winter crops of winter wheat and carinata in South Georgia over four years. Then, we developed a risk model for ascertaining the probability distributions of net present values (NPVs) subject to uncertainties related to prices and yields of selected summer and winter crops. A total of 292 rotations are possible with winter cover crops of carinata and winter wheat. Carinata in the corn-corn-soybean rotation has the highest NPV ($2996/ha). The least risky rotation is cotton-cotton-peanut, with a 60% probability of a positive NPV. Analyses of both risk-averse and risk neural choices show that farmers could have higher profit and lower risk on average by $260.59/ha and 8.08%, respectively, by including carinata in their crop rotations. Overall, our study indicates that carinata would increase farmers' profitability in the SE United States and should be promoted for reducing the overall carbon footprint of the aviation sector nationwide and beyond.

2.1. Introduction

The global aviation industry emitted 785 million metric tons of carbon dioxide (CO_2) in 2019, i.e., around 2% of all human-induced CO_2 emissions (Graver et al., 2020). In the United States, CO_2 emitted by the aviation sector (international and domestic flights) in 2019 was 255 million metric tons, i.e., almost 5% of total energy-related CO_2 emissions nationwide (U.S. Energy Information Administration, 2019). A comparison of CO_2 emissions across national and international levels suggests that the United States emits almost 23% of the global aviation-related CO_2 emissions (Graver et al., 2020). This high contribution could be ascribed to the total jet fuel consumed across domestic and international flights nationwide. For example, jet fuel consumption in the United States rose from 63.86 billion liters to 69.16 billion liters between 2003 and 2019. This increase in jet fuel consumption could be easily related to a surge in demand for air travel in the United States, as available seat-miles for domestic and international flights increased by 30.2% and 100.0% for domestic and international flights between 2003 and 2019, respectively (U.S. Department of Transportation, 2019).

The aviation industry adopted a set of ambitious targets in 2008 to reduce their carbon footprint, including a) an average improvement in fuel efficiency of 1.5%/year between 2009 and 2020; b) a cap on net aviation carbon emissions from 2020 (carbon-neutral growth); and c) a reduction in net aviation carbon emissions of 50% by 2050, relative to 2005 levels (European Aviation Safety Agency et al., 2016). In addition, the aviation industry has implemented a four-pillar policy to accomplish CO_2 reduction goals, including but not limited to technology development, operational efficiencies, infrastructure improvements, and market-based economic measures.

Sustainable Aviation Fuel (SAF) development is vital for meeting the aviation sector's carbon reduction goal. Existing studies suggest that the use of SAF can mitigate up to 80% of CO_2 emissions (IATA, 2020). Cox et al. (2014) concluded that using microalgae, *Pongamia pinnata*, and sugarcane molasses as feedstocks for SAF production could save between 43% and 50% GHG emissions. Tanzil et al. (2021) found that the SAF derived from corn ethanol can mitigate GHG emissions ranging from 13 to 93% across different scenarios. Many other studies, such as Hayward et al. (2015), McGrath et al. (2017), Michailos (2018), and Capaz et al. (2021), also report that there are significant carbon benefits related to the production of SAF from biomass-based feedstocks. On the other hand, several studies exploring the production cost of biomass-based SAF throughout the supply chain have found that the production cost of SAF is higher than conventional jet fuel. Perkis & Tyner (2018) concluded that SAF supply chain production cost varies between $0.84/liter to $0.97/liter. Huang et al. (2019) found that the SAF production cost can be as low as $0.74/liter, which was 47% higher than conventional jet fuel. Reimer & Zheng (2017) suggested that a 17% subsidy on SAF, a 20% tax on the conventional fuel, or a combination 9% subsidy on SAF and 9% tax on the conventional fuel are needed for SAF production.

The majority of the existing studies assume that SAF production would start once economic incentives are in place. This assumption is not valid as risk plays a crucial role in determining the overall economic feasibility of SAF production. Only a handful of studies have incorporated risks into their economic analysis for SAF production. Richardson et al. (2014) addressed price- and technology-related risks for bio-crude oil production from two projected algae farms. They found that neither cultivation system offers a reasonable probability of economic success with current prices and technology. Chu et al. (2017) assessed the financial risk analysis of SAF production from camelina, carinata, and used cooking oil. They found that probabilities of having a positive net present value (NPV) are 29%, 18%, and 8% for the SAF produced using camelina, carinata, and used cooking oil, respectively. Hansen et al. (2019) analyzed cost and risk in herbaceous feedstock supply chains in Virginia and Iowa. They found that the logistics cost for switchgrass and corn stover could range between $50/t and $74/t, respectively, after accounting for risks. Mamun et al. (2020) found that a distributed depots approach may reduce the operational and market risks by 17.5% and 5%, respectively, for a cellulosic biorefinery located in the Great Plains of the United States.

Existing studies typically assume that farmers will adopt a bioenergy crop immediately. However, the adoption decision is complicated and is affected by several factors. Bocquého & Jacquet (2010) analyzed the effect of farmers' liquidity constraints and risk preferences in central France. They found that switchgrass and miscanthus make farms less profitable in terms of an annualized net margin than the usual rape/wheat/barley rotation. They also found that switchgrass and miscanthus can be highly competitive as diversification crops when appropriate contracts are offered to farmers, despite the additional liquidity they require. Clancy et al. (2012) used a stochastic budgeting model and reported that miscanthus is a less risky option than willow at Irish farms. Alexander & Moran (2013) developed a farm-level mathematical programing model and found that miscanthus was the best option for risk-averse farmers in the United Kingdom. They also found that the inclusion of risk reduced the energy crop prices required to adopt these crops. Skevas et al. (2016) developed an economic model with stochastic prices and yields. They found that perennial bioenergy crops have a higher potential to successfully compete with corn under marginal crop production conditions in Florida. Hauk et al. (2017) reported that the inclusion of Short Rotation Woody Crops (SRWCs) at the farm level had the lowest economic risk of all crops compared and gross margins, which were competitive with most alternative crops. Spiegel et al.

(2018) found that a guaranteed short rotation coppice biomass price exhibits poor overall performance because it eliminates both positive and negative risks in Germany.

Another factor affecting farmers' adoption decisions is the suitability of a bioenergy crop in existing crop rotation systems. Styles et al. (2008) compared the economic performances of conventional agricultural systems with the cases having willow or miscanthus in the crop rotation in Ireland. Faasch & Patenaude (2012) examined the profitability of existing crop rotations with and without short rotation coppice in Germany. They found that without any subsidies, the short rotation coppice made less profit than the conventional crops. Moore et al. (2020) suggested that bioenergy crops can diversify corn-soybean rotation in the Midwest United States and has the potential to clean water and protect the soil. They concluded that growing bioenergy crops on marginal lands could have minimal impacts on food and feed production.

A review of current studies shows that the use of SAF could save significant carbon emissions, suitable economic incentives are needed for encouraging the production of biomass-based SAF, there are inherent risks involved in the production of biomass-based SAF, and most importantly, the production of bioenergy crops could alter the farm economics. For studies focusing on farm-level economics with and without bioenergy crops, we noticed that most of them focus on perennial cellulosic bioenergy feedstocks. There is a gap in the literature on understanding the farm-level economics of those potential bioenergy crops that could be grown in the winter months. Our study addresses this gap by developing a farm-level risk analysis model by incorporating carinata into existing crop rotations in South Georgia, a state located in the SE United States. Accordingly, the objective of the study is to determine the change in profitability of farmers with/without carinata in their rotations and to determine the related farm-level risk changes. We hope that our study will better situate the use of carinata-based SAF production in the SE United

States for achieving policy goals of mitigating climate changes, developing rural economies, and supporting bio-economy development.

2.2. Modeling Approach and Data

2.2.1. Carinata

The oil obtained from the seeds of *Brassica carinat*a, also known as Ethiopian mustard, could be refined to produce drop-in SAF. The use of carinata for producing SAF provides several advantages relative to other potential crops. First, it is not fit for human consumption due to the high content of erucic acid, and therefore, it avoids any fuel versus food issues (Seepaul et al., 2019). Second, it is an off-season crop and does not interfere with the main crops such as corn, thereby providing additional income to farmers. Third, it reduces soil erosion, builds soil carbon, and reduces instances of nematodes (Seepaul et al., 2019). Moreover, carinata has high protein content and low fiber content. It makes it possible for carinata meal which is leftover after extracting oil from the seed, to be a good source for animal feed (Iboyi et al., 2021). Alam & Dwivedi (2019) found that up to 1.2 million hectares of land are available for growing carinata across Georgia, Florida, and Alabama, which could potentially produce up to 2,045.1 million liters of SAF, sufficient enough to replace 2.3% of the total conventional jet fuel consumed in the United States.

2.2.2. Study Area

We selected Georgia as a case study, as agriculture is a prime sector of Georgia's economy. In 2019, the agricultural sector cash receipt was $8.4 billion in Georgia, making it the 16th state in overall agricultural cash receipts (U.S. Department of Agriculture, 2020). Additionally, Alam & Dwivedi (2019) found that up to 0.85 million hectares of the land in Georgia are suitable for carinata production, the highest out of all the states in the SE United States. Figure 2.1 illustrates the amount of agricultural land present in each county of the state (NASS, 2020). As our study area, we selected 50 counties across South Georgia. In 2019, about 755 thousand hectares of the land across selected counties were devoted to corn, cotton, and peanuts, which amounted to 98.5% of the total croplands in South Georgia and 56.4% of total cropland in the state (NASS, 2020).

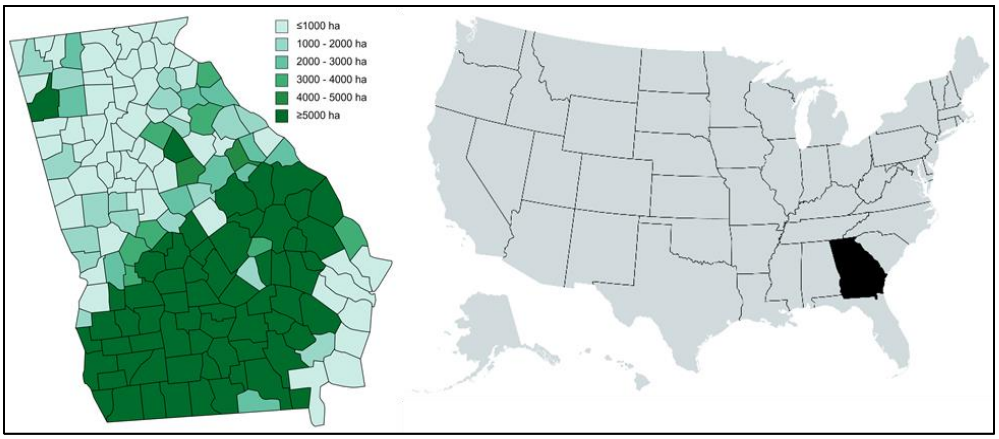
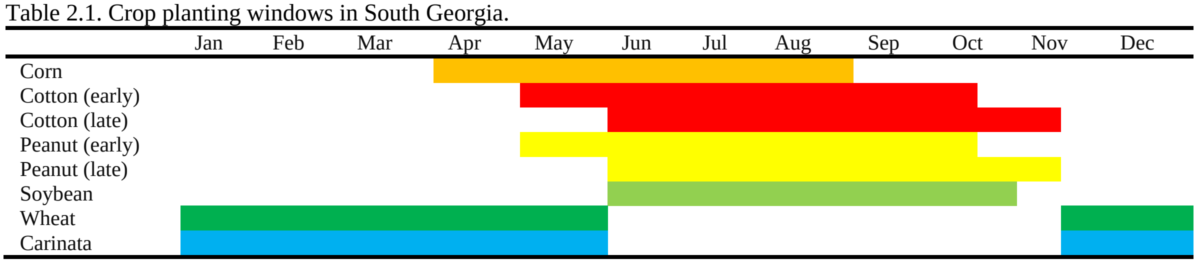


Figure 2.1. Total agricultural land in each county of Georgia (NASS, 2020)

2.2.3. Possible Crop Rotations (with/without Carinata)

Since it is an annual plant, the carinata production process should be rotated with the other crops. We considered rotations of cotton-cotton-peanut, cotton-cotton-corn-peanut, corn-corn-peanut, cotton-cotton-cotton-peanut, corn-corn-corn-peanut, and cotton-corn-peanut — the most popular crops in South Georgia. A four-year timeline can have 972 rotations by choosing either fallow or winter crops of either wheat or carinata. However, there are three primary constraints when it comes to carinata production. First, growing carinata after peanut is currently not recommended due to residual herbicide effects (Seepaul et al., 2019). Second, there should be at least a gap of two years between two successive carinata crops (Seepaul et al., 2019). Finally, carinata and wheat are harvested in late May/early June, resulting in a situation where one cannot grow corn after carinata or wheat. Taking all the constraints together, the number of possible crop rotations drops to 292, out of which 180 crop rotations involve carinata and the remaining 112 do not. There are 245 rotations with the other winter crop of wheat. Regarding the constraints related to the other crops, there is the main concern related to summer crops: continuous corn and continuous cotton make yield penalties of 10% and 15%, respectively (Salassi et al., 2013). Therefore, we considered a yield penalty for continuous corn and cotton. Table 2.1 presents the timeline of each crop to ascertain crop planting and harvesting schedules.

Table 2.1. Crop planting windows in South Georgia.



2.2.4. Carinata Yield Simulation

The DayCent model (Parton et al., 1998) was adapted to make spatially explicit estimates of carinata seed yield across the frost-safe region of northern Florida, South Alabama, and South Georgia (Alam & Dwivedi, 2019). DayCent was previously calibrated to represent carinata grown in the SE United States based on the data provided by Agrisoma Biosciences, Inc (now NuSeed Inc.). The model was calibrated using data on aboveground biomass, root biomass, and tissue carbon:nitrogen ratios for carinata grown at the University of Florida North Florida Research & Education Center in Quincy, Florida for one season (winter 2015–2016) at four different nitrogen (N) fertilizer application rates and validated against five commercial-scale production plots from Georgia collected between 2016 and 2018. Data inputs and methods for high-resolution DayCent simulation were modified from those described previously in the context of simulations of other dedicated bioenergy crops (Field et al., 2018). Those prior methods were updated such that carinata production was simulated on all cultivated annual cropland per the 2016 National Land Cover Database (Homer et al., 2020), and to use historical weather data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), which results in low-bias DayCent yield simulations (Zhang et al., 2019). The DayCent simulations assumed that carinata is grown as a winter cover crop between the two cotton cash crops of a three-year cotton–cotton–peanut rotation, with moderate-intensity field preparation and planting in mid-November, fertilizer application at an annual rate of 90 kg N/ha, plant physiological maturity in early May, and seed harvest in late May. DayCent simulation output was then post-processed for area-weighted aggregation of simulated yields and environmental impacts to the county scale.

2.2.5. Farm-Level Economics

We obtained production cost data for all summer crops and winter wheat from the University of Georgia Cooperative Extension (2019). In addition, we obtained all the production cost data related to carinata from the Whole Farm report by (National Peanut Research Laboratory, 2020). For all crops, we considered the variable costs because farmers cannot change fixed costs in the short term. Since carinata is a new crop in the region, there are no historical data of yields and prices. Therefore, we used the fixed carinata price in this study ($440.9/t based on the contracted price by NuSeed Inc.). For carinata yield, we implemented the distribution DayCent to simulate yield across different counties in Georgia. For all other crops except carinata, we used the National Agricultural Statistics Services database (NASS, 2020) for price and yield historical data. All production costs and incomes for a hectare of farmland for carinata, corn, cotton, peanut, soybean, and wheat are provided in the Appendix (Table S1 to Table S6).

We considered a four-year timeline examining winter crops of winter wheat and carinata for all 12 rotations of cotton-cotton-peanut, cotton-cotton-corn-peanut, corn-corn-peanut, cotton-cotton-cotton-peanut, corn-corn-corn-peanut, cotton-corn-peanut, cotton-cotton-soybean, cotton-cotton-corn-soybean, corn-corn-soybean, cotton-cotton-cotton-soybean, corn-corn-corn-soybean, and cotton-corn-soybean. NPV is a standard criterion to assess economic decisions. It can be calculated by the current value of Annual Cash Flow in different years (ACFt), which means adjusting ACFt by discount rate rd over the timeline of T (Zore et al., 2018):

$$\text{NPV} = \sum_{t=0}^{T} \frac{ACF_t}{(1+r_d)^t} \quad (1)$$

In the case of crop rotation, both cash flow of summer and winter crops should be in NPV calculation:

$$\text{NPV} = \sum_{t=0}^{T} \frac{SCF_t+WCF_t}{(1+r_d)^t} \quad (2)$$

In which SCFt and WCFt are summer and winter crops cash flows, respectively. We implement an inflation rate of 2% and an interest rate of 6%, which both are the average of the past 30 years (U.S. Department of Labor, 2019).

2.2.6. Financial Risk and Sensitivity Analyses

The study of risk analysis in financial investment projects is possible by using the stochastic Monte Carlo method (Simões et al., 2016). We used @Risk 8.1 (Copyright © 2020 Palisade Corporation, Ithaca, USA) for risk analysis. The input variables of the stochastic simulation model are the crop incomes which in turn are dependent upon stochastic crop prices ($/kg) and yields (kg/ha). The former represents the market risks, and the latter represents the stochasticity related to technology and the weather. Instead of using random numbers to fit the distribution functions, we used the historical data between 1988 and 2019 for both price and yield data of corn, cotton, peanut, soybean, and winter wheat. As mentioned before, we used high-resolution DayCent simulation to estimate carinata yield across counties in Georgia. We used the distribution for the yield across counties as a proxy for carinata yield distribution. We assumed carinata price as a fixed parameter. NPV was used as the output when the variables change according to the historical data distributions. Finally, we should see how our results change if we have different interest rate levels.

2.3. Results

2.3.1. Profitability of Carinata and Other Crops

Figure 2.2 presents the annual profitability of selected crops in South Georgia on a per-unit area basis. Corn has the highest profit of $706.2/ha, whereas wheat with $134.7/ha has the lowest profit. We found that soybean produces lower income than the other crops, but costs were much lower. Therefore, the lower production cost made a higher profit in soybean farms. Carinata, with $369.3/ha, make a higher profit than winter wheat in South Georgia.

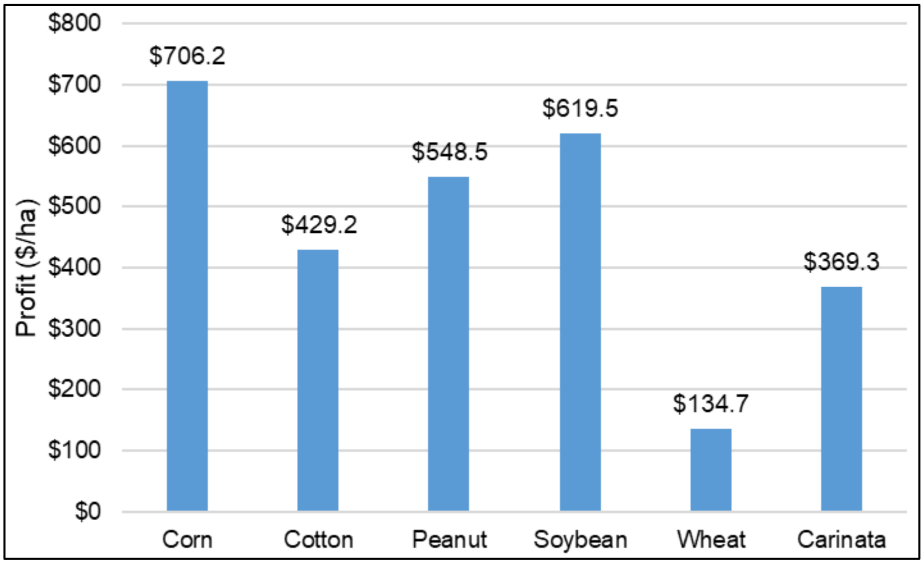


Figure 2.2. Profitability of crops in South Georgia in 2019.

However, soybean and corn have the highest profit, they are not major crops in Georgia (Lee, 2019; Bryant, 2021). Georgia soybean acreage decreased from 325,000 in 2015 to a low of 100,000 acres planted in the last two years (Bryant, 2021). The main reason for this decline is soybean prices, as many Georgia peanut growers are unwilling to sow soybean when prices declined below $0.37/kg (Bryant, 2021). In the same period, cotton and peanut prices have not changed dramatically (NASS, 2020). They hovered around $1.44/kg and $46/kg for cotton and peanut, respectively (NASS, 2020). There is an economic risk for corn production associated with unpredictable weather patterns (Lee, 2019). 27% and 37%, respectively (University of Georgia Cooperative Extension, 2021). These show that farmers' do not prefer to have soybean and corn due to production and market risks.

2.3.2. Profitability in Rotations with/without Carinata

Table 2.2 presents the top 20 rotations with the highest NPVs. The majority of the top 20 rotations (17 out of 20) are with carinata. Corn-fallow-corn-carinata-soybean-fallow-corn-wheat with an

NPV of $2996/ha is the most profitable. Few rotations with either cotton or peanut are among rotations with the highest NPV because of the higher profit of corn and soybean. It means carinata does better in rotation with corn and soybean in making a higher profit. Considering all 292 rotations and comparing the rotations with and without carinata, the energy crop could increase four-year rotation NPV by $260.6/ha on average.

2.3.3. Risk Assessment

The risk sources are crop price and yield variations. Figure 2.3 and Figure 2.4 illustrates price and yield variations for different crops, respectively. The yield and price data for corn, cotton, peanut, soybean, and wheat are from 1988 to 2019. However, as mentioned before, we used yield data across different counties in Georgia as a proxy for carinata yield variation. Since most farms are in South Georgia, we used the yield variations from counties in the same region. It is because we do not have historical yield data for carinata. Carinata price is fixed, as NuSeed Inc. offers the fixed price of $440.9/t to farmers in the tri-state region of the SE United States. According to Figure 2.3, cotton has the highest price variations. Figure 2.4 indicates that corn has the highest yield variations. Following Anderson (2008), we fitted suitable distribution forms to the price and yield data for undertaking the risk analysis (Table 2.3). We used Akaike Information Criterion (AIC) for selecting appropriate distribution forms across all the possible distribution forms for each series of price and yield for each crop. Using the Monte Carlo simulation method with 1000 iteration, we simulated NPVs of all 292 rotations. Figure 2.5 shows the relative distribution and cumulative frequency of simulated NPV for the top six rotations, which have the highest probability for a positive NPV. Cotton-carinata-cotton-fallow-peanut-fallow-cotton-carinata is the best-case scenario, and there is a possibility of 58.9% to have a positive NPV.

Table 2.2. Top 20 crop rotations with the highest NPV.

Year 1		Year 2		Year 3		Year 4		NPV ($/ha)
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	
corn	fallow	corn	carinata	soybean	Fallow	corn	wheat	2996.0
corn	fallow	corn	wheat	soybean	Fallow	corn	carinata	2979.3
corn	fallow	corn	carinata	peanut	fallow	corn	wheat	2930.3
corn	fallow	corn	wheat	peanut	fallow	corn	carinata	2913.5
corn	fallow	corn	carinata	soybean	fallow	corn	fallow	2876.0
corn	fallow	corn	fallow	corn	carinata	soybean	wheat	2854.9
corn	fallow	corn	fallow	soybean	fallow	corn	carinata	2849.7
corn	fallow	corn	fallow	corn	wheat	soybean	carinata	2846.7
corn	fallow	corn	carinata	peanut	fallow	corn	fallow	2810.3
cotton	carinata	cotton	fallow	corn	wheat	soybean	carinata	2809.2
corn	fallow	corn	fallow	corn	carinata	peanut	wheat	2791.6
corn	fallow	corn	fallow	peanut	fallow	corn	carinata	2783.9
corn	fallow	corn	wheat	soybean	fallow	corn	wheat	2770.3
corn	fallow	corn	fallow	corn	carinata	soybean	fallow	2734.8
corn	fallow	corn	fallow	corn	fallow	soybean	carinata	2721.9
corn	fallow	corn	wheat	peanut	fallow	corn	wheat	2704.5
cotton	carinata	cotton	wheat	soybean	wheat	cotton	carinata	2689.0
cotton	carinata	cotton	fallow	corn	fallow	soybean	carinata	2684.5
corn	fallow	corn	fallow	corn	carinata	peanut	fallow	2671.6
corn	fallow	corn	wheat	soybean	fallow	corn	fallow	2650.3

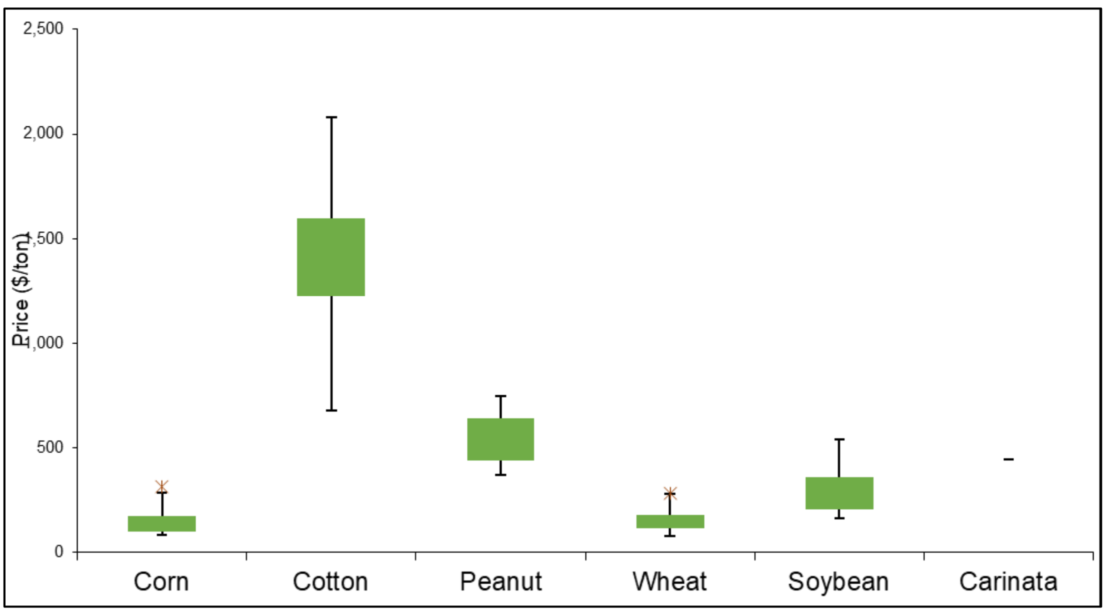


Figure 2.3. Price variability for different crops in South Georgia.

Table 2.3. Fitted distribution forms for the price and yield of different crops.

	Corn	Cotton	Peanut	Soybean	Wheat	Carinata
Price (AIC)	Exponential (-109.4)	Normal (19.0)	Uniform (-54.4)	Triangle (-325.9)	Triangle (-101.6)	Fixed
Yield (AIC)	Uniform (578.7)	Triangle (410.9)	Triangle (523.6)	Triangle (410.1)	Normal (488.0)	Pert (1,150.2)

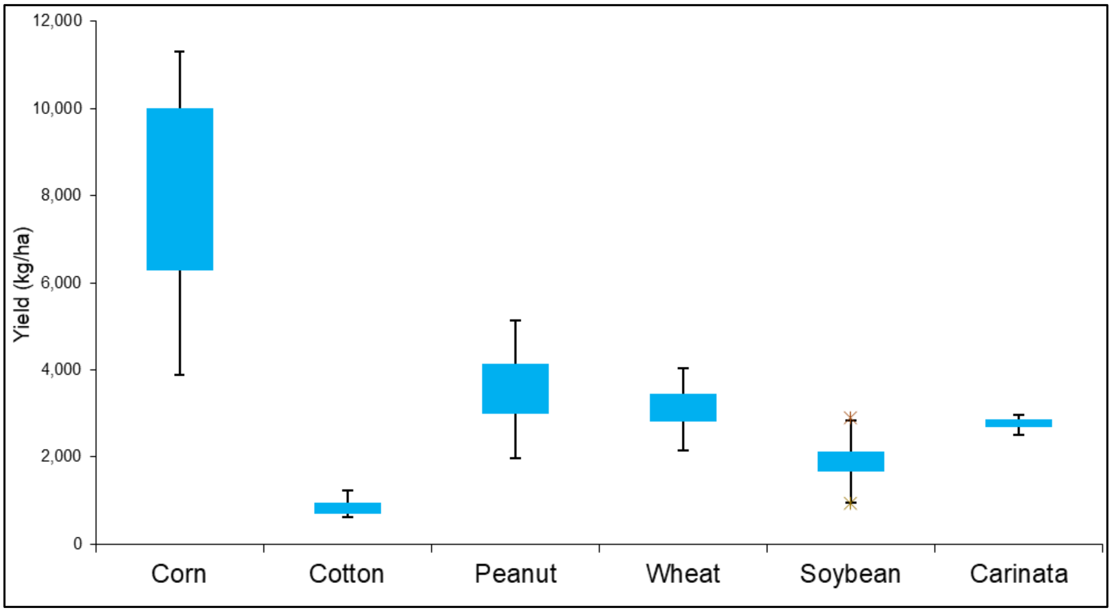


Figure 2.4. Yield variability for different crops in South Georgia.

Table 4 shows the corresponding NPV and the possibility of having a positive NPV for the rotations with the lowest risk. Compared to Table 2.2, carinata in rotation with corn-corn-soybean generates the highest NPV; however, the least risky option is cotton-cotton-peanut with carinata as a cover crop. It seems that the difference between the two top rotations mainly comes from the summer crops. It is peanut that lowers the risk; however, soybean makes the most profitable choices. Like the last section, if we want to compare the effect of carinata on risk, we should compare two groups of rotations with and without carinata. Possibilities of having positive NPV between two groups of 180 rotations with carinata and 112 rotations without it show the average difference of 8.1% higher risk. Therefore, carinata could better the risk level by around 8%; it also improves the NPV by $260.6/ha.

If a farmer has a risk-averse point of view, the least risky option is the most likely choice. Carinata makes the lowest risk in the rotation of cotton-cotton-peanut. If we compare the least risky rotation with the same rotation of cotton-cotton-peanut and leave the land fallow in winters (not in the top 20 rotation in Table 2.4), there is a 23.5% higher risk for cotton-fallow-cotton-fallow-peanut-fallow-cotton-fallow. It means that carinata can decrease the risk by 23.5% compared to no cover crop rotation. The rotation with carinata also has a higher NPV of $698.3/ha. If the farmers choose wheat instead of carinata, the rotation of cotton-cotton-peanut with winter wheat in the first and last years will have a $433.6/ha lower profit and 25.7% higher risk.

On the other hand, if a farmer prefers having a risk-neutral perspective, corn-fallow-corn-carinata-soybean-fallow-corn-wheat is the best rotation with an NPV of $2996.0/ha. If a farmer chooses fallow instead of carinata in the second year of the rotation, there will be a $355.32/ha profit loss and no risk level change. Similarly, wheat instead of carinata in the second year will cause a loss of $255.7/ha in profit with the same risk level. Therefore, carinata can be a winter option for both groups of risk-neutral and risk-averse farmers.

Soybean is an alternative to peanut because of a higher profit of $71.0/ha. Rotations with peanut and carinata make a lower profit than rotations with soybean and carinata (max NPV $2930.3/ha versus $2996.0/ha). However, carinata can lower risky rotations with peanuts than soybean (max possibility of positive NPV 58.9% versus 27.0%). To have peanut and carinata in the rotation, carinata should come before the peanut, not after it. Therefore, carinata-soybean and carinata-peanut should be acceptable for risk-neutral and risk-averse farmers, respectively.

Table 2.4. Top 20 Rotations with the highest probability of positive NPV.

Year 1		Year 2		Year 3		Year 4		NPV($/ha)	Prob (NPV>0)
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter		
cotton	carinata	cotton	fallow	peanut	fallow	cotton	carinata	2368.9	58.9%
cotton	carinata	cotton	wheat	peanut	fallow	cotton	carinata	2498.5	57.5%
cotton	carinata	cotton	fallow	peanut	wheat	cotton	carinata	2493.6	57.4%
cotton	carinata	cotton	wheat	peanut	wheat	cotton	carinata	2623.2	54.6%
cotton	carinata	cotton	fallow	cotton	fallow	peanut	fallow	1916.5	50.1%
cotton	fallow	cotton	carinata	cotton	fallow	peanut	fallow	1902.6	49.8%
cotton	fallow	cotton	fallow	cotton	carinata	peanut	fallow	1889.1	48.9%
cotton	carinata	cotton	fallow	peanut	fallow	cotton	fallow	2039.9	48.0%
cotton	fallow	cotton	carinata	peanut	fallow	cotton	fallow	2026.0	47.4%
cotton	carinata	cotton	fallow	cotton	fallow	peanut	wheat	2036.5	47.0%
cotton	carinata	cotton	wheat	cotton	fallow	peanut	fallow	2046.1	46.8%
cotton	carinata	cotton	fallow	cotton	wheat	peanut	fallow	2041.2	46.8%
cotton	fallow	cotton	carinata	cotton	fallow	peanut	wheat	2022.6	46.4%
cotton	fallow	cotton	fallow	peanut	fallow	cotton	carinata	1999.6	46.3%
cotton	fallow	cotton	carinata	cotton	wheat	peanut	fallow	2027.3	46.3%
cotton	wheat	cotton	carinata	cotton	fallow	peanut	fallow	2037.2	45.9%
cotton	fallow	cotton	fallow	cotton	carinata	peanut	wheat	2009.2	45.7%
cotton	carinata	cotton	wheat	cotton	fallow	peanut	wheat	2166.1	45.6%
cotton	carinata	cotton	wheat	peanut	fallow	cotton	fallow	2169.5	45.5%
cotton	carinata	cotton	fallow	peanut	wheat	cotton	fallow	2164.6	45.5%

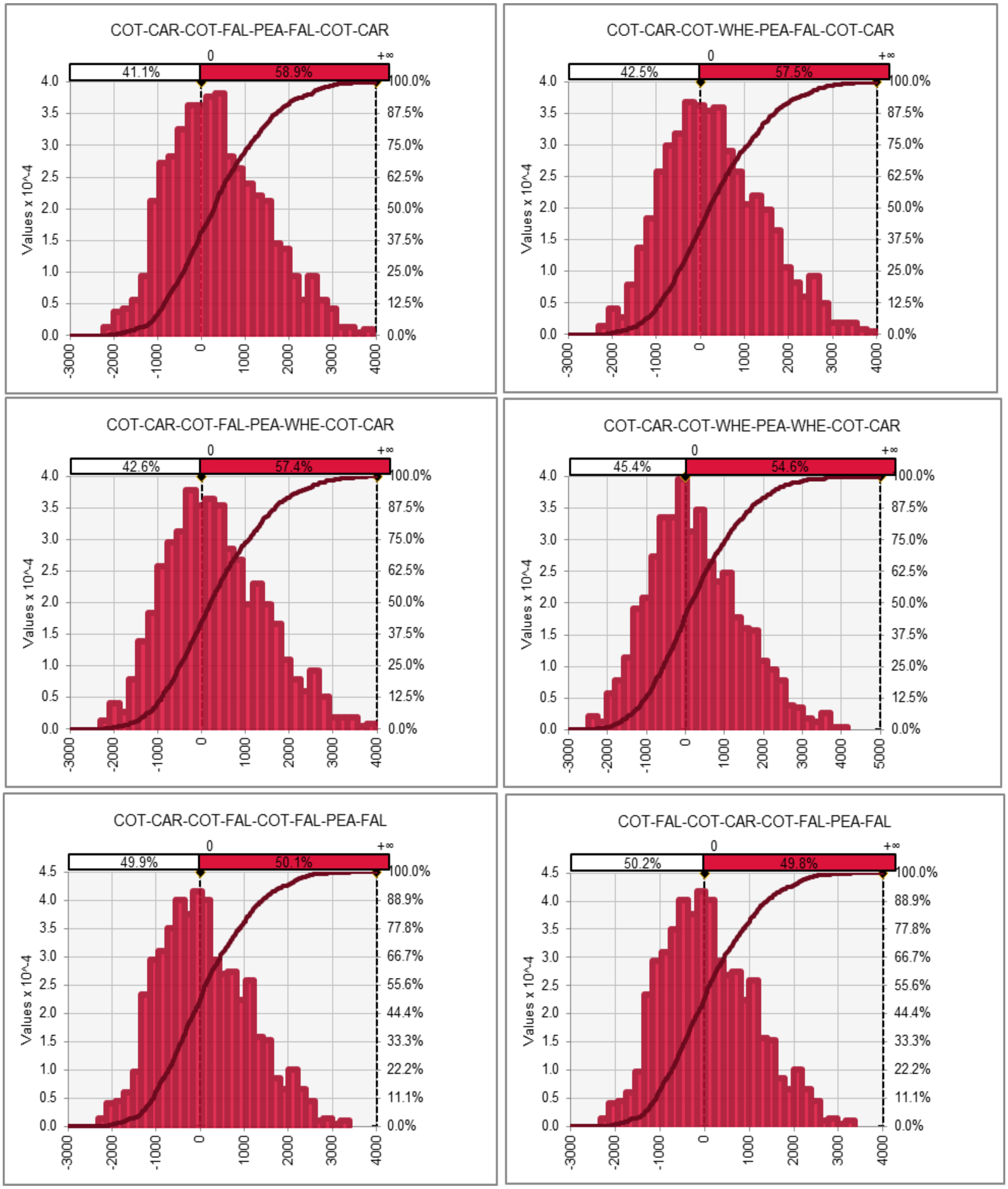


Figure 2.4. Relative distribution and cumulative frequency of top-six rotations with the highest chance of positive NPVs.

To see how changes in interest rate can make an impact on our results, we did a sensitivity analysis. We chose two scenarios of a lower interest rate and a higher interest rate. One scenario is to set the interest rate as low as an inflation rate of 2%, and in the second scenario, we tried an interest rate of 12%, which is two times more than the current interest rate. The results showed that the ranking of the rotations according to their NPV does not change since the interest rate changes NPV across all crop rotations with the same ratio. Therefore, the ranking is the same. However, it may change the difference between NPVs and the possibility of positive NPV (or risk) across crop rotations. The results are provided in Figure 2.6 and Figure 2.7. Accordingly, NPV declines as the interest rate increases. However, the changes are less than $20 when we changed the interest rate from 2% to 6%, then 12%. The sensitivity analysis shows that the possibility of positive NPV between the rotations with and without carinata does not change very much. For the 2% interest rate scenario, the risk difference between the rotations with and without carinata is 8.1%, and it is 8.22% for the 12% interest rate scenario. The difference between possibility of positive NPVs is not sensitive very much to the changes in interest rate relative to base scenario.

Figure 2.6. The effect of an interest rate change on NPV difference of crop rotations with and without carinata.

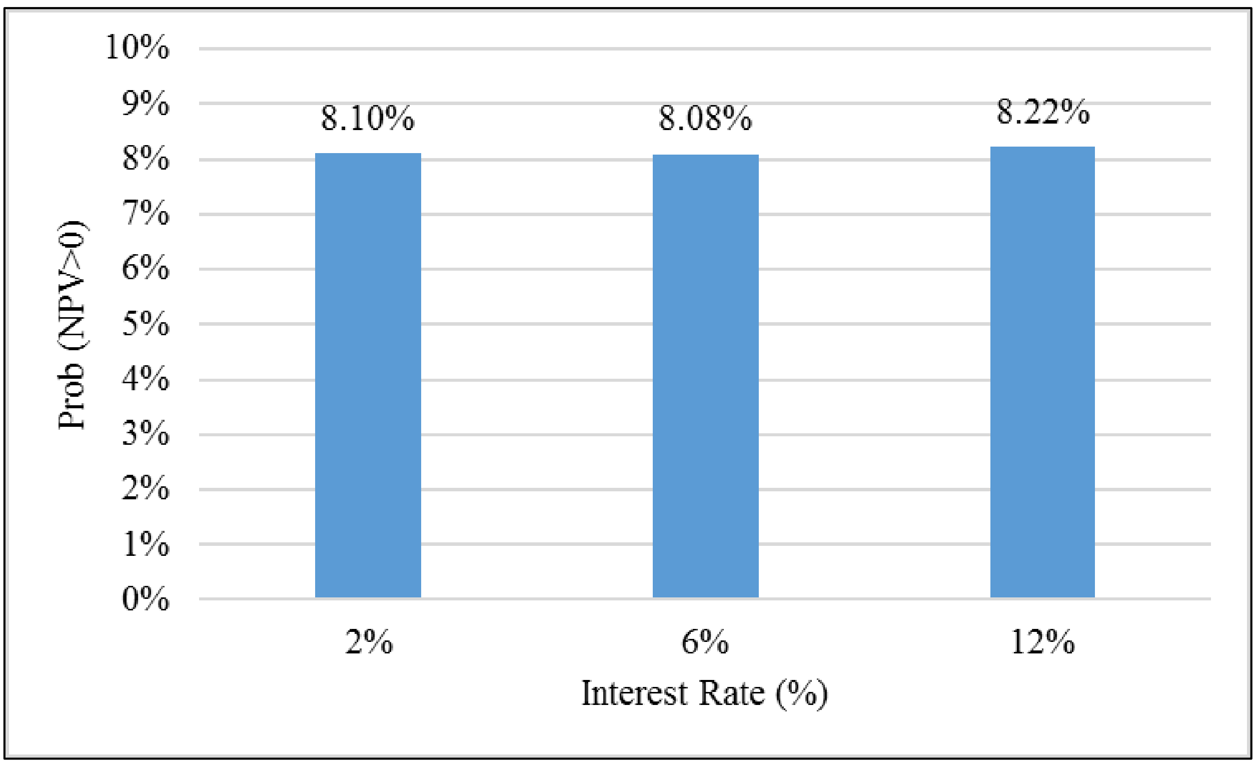


Figure 2.7. The effect of an interest rate change on the possibility of positive NPV difference of crop rotations with and without carinata

2.4. Discussions and Conclusion

The challenge of meeting increasing energy demands in the aviation sector and related policies to climate change have made governmental support possible for renewable energy sources. These development policies may motivate farmers to sow energy crops, which are risky due to unpredictable yields and prices. Therefore, it is essential to know the effects of a new bioenergy crop on farmers' risk and profit.

In this study, we implemented a Monte Carlo simulation and historical data distribution of both yields and prices of corn, cotton, peanut, soybean, and winter wheat to assess the effects of market and production risks on farmers' profitability in a four-year timeline. Considering the most popular rotations in South Georgia, we examined whether the carinata fits in the rotations or not. According to the current study, if we include the energy crop in the second year and wheat in the fourth year of corn-corn-soybean, we would observe the highest NPV across all possible rotations. The rotation is suitable for a risk-neutral farmer. On the other hand, the risk-averse rotation is cotton-cotton-peanut. The risk-neural choice makes the NPV $2996/ha; however, the corresponding amount for risk-averse choice is $2368.9/ha. Farmers should accept a loss of $627.1/ha to have a 58.9% lower risk rotation. Including carinata causes a lower risk of 8.1% and higher NPV, around $260.6/ha on average. In conclusion, regardless of farmers' risk preferences, carinata helps to have a greater NPV and lowers the risk level.

Energy crops were the case studies in similar research; however, few have resolved that they are profitable at the farm level without any subsidy. Faasch & Patenaude (2012) concluded that short rotation energy crops are less profitable than conventional crops, and it is not economically feasible to have them in the rotation without any subsidy. In a comparable study, Spiegel et al. (2018) suggested a floor price policy to make it possible to have a short rotation coppice as an energy crop. To make the highest profit from energy crops, not only support from the government is needed, but also the farmers should choose efficient farming systems. Acuña et al. (2018), in a related study, proved that short rotation energy crops are not profitable when productivities are less than 351 m^3/ha of green biomass. However, Styles et al. (2008) have comparable results to our investigation. They found that energy crops like miscanthus and willow make more profitable rotations compared to conventional agricultural systems. From the perspective of risk analysis, not many studies exist in the context of energy crops. Zafeiriou & Karelakis (2016), as an example, focused on the energy crop of rapeseed and could not obtain any clear picture related to the income volatility of the crop. However, in a similar study to ours, Chu et al. (2017) estimated the financial risk of SAF production from camelina, carinata, and cooking oil as the possibility of having positive NPVs of 29%, 18%, and 8%, sequentially. Our study estimates the average possibility of positive NPV for carinata farms is 22.8% which is different than Chu et al. (2017) because we only considered farm-level risks, not risks related to setting up biorefinery and other facilities.

Since carinata is a crop that makes the farms in South Georgia more profitable and less risky, the main implication of our research should be increased support from the government for the extension of the crop all over the area. Farmers should know about the benefits of the crop to make better-informed decisions about their crop rotation. They should know that carinata in rotation with corn-corn-soybean has the highest profit; however, it makes the lowest risk in cotton-cotton-cotton-peanut rotation. It is also recommended to consider the interactions of the energy crops with conventional crops. Peanut impacts carinata yield; however, it decreases risk on average if we sow carinata before peanut in the rotation. Deciding about the profitability of an energy crop cannot be only according to the NPV of the crop itself. The crop rotation in several years should be assessed, and then we will have a better picture of energy crops' impacts on the overall farm profitability.

We had the price and yield of carinata in 2019, which were enough for estimating NPV, but did not provide enough data for the simulation. Therefore, we used the distributions of carinata across counties in Georgia instead of one county for different years. Moreover, since there is no historical data for carinata price, and farmers were in contracts with NuSeed, Inc. In previous years, we assumed the carinata price to be fixed. NuSeed, Inc. is not offering contracts with fixed prices anymore, but there is no other option for carinata price distribution. The assumptions made the study possible; however, the main limitation of the research is the lack of historical yield and price data for carinata as an energy crop. Moreover, erratic changes in inflation or interest rate create limitations, making the prediction of NPV for the next four years biased.

In this study, we analyzed the farm-level risk of carinata. Since the crop is used as an input for SAF production, the financial risk of the whole supply chain can be a subject for future investigations. Our results suggest that carinata-based SAF production could increase farmers' profitability in the SE United States, and therefore should be promoted as an alternate winter crop. However, the adoption will still be challenging in the absence of demand for SAF production (e.g., the establishment of an actual SAF production facility) at the regional level. Therefore, a need exists for a region-wide partnership involving multiple stakeholder groups for establishing the supply chain of carinata-based SAF production in the region and realizing bio-economy development in the region while reducing carbon emissions of the aviation sector and improving the flow of ecosystem services.

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Chapter 3

Does Carinata, a Potential Oil-Seed Crop for the Production of Sustainable Aviation Fuel, Improve Eco-Efficiency of Crop Rotations in South Georgia, United States? [2]

[2] Karami, Omid; Dwivedi, Puneet. To be Submitted to Frontiers in Energy.

Abstract

In 2019, the aviation sector emitted about five percent of the total energy-related carbon dioxide (CO_2) emissions in the United States. The replacement of conventional jet fuel by the drop-in sustainable aviation fuel (SAF) derived from various biomass-based feedstocks is vital to reduce the overall CO_2 emissions of the aviation sector. In this context, the SAF derived from carinata (*Brassica carinata*), an oil seed-producing winter crop, could help the aviation sector mitigate CO_2 emissions. Therefore, it is vital to develop a framework for assessing the eco-effectiveness of carinata in crop rotations by combining economic and environmental benefits. This analysis would enhance the role of carinata as a potential bioenergy crop relative to other competitive crops. We identified 292 rotations (with and without carinata) in South Georgia. We conducted a comprehensive life cycle assessment to determine the carbon emissions of selected rotations. Similarly, we conducted a detailed economic analysis to ascertain the profitability of selected crop rotations. We combined both information using data envelopment analysis (DEA) to estimate the eco-efficiency score of each rotation. The results showed that crop rotations with carinata emit 1,038.88 kg of CO_2/ha less than rotations without it. Also, carinata makes the highest profit in the rotation of corn-corn-soybean. Finally, our results indicate that cotton-carinata-cotton-fallow-soybean-fallow-cotton-carinata is the most eco-efficient rotation. Since carinata increases eco-efficiency at the farm level, it should be promoted as a potential winter crop in South Georgia for promoting bio-economy in the region and beyond.

3.1. Introduction

The aviation sector contributes 2% of global carbon emissions (ATAG, 2020). The United States alone contributes about 23% of the total aviation-related carbon emissions globally (Graver et al., 2020). To reduce the carbon emissions of the aviation sector, the International Civil Aviation Organization has adopted a goal of carbon-neutral growth of international aviation from 2020. Also, the International Air Transport Association has set a goal of a 50% reduction in carbon emissions by 2050. The use of sustainable aviation fuel (SAF) derived from various biomass feedstocks is critical for reducing the overall carbon emissions of the aviation sector.

Several studies have analyzed the carbon benefits related to the use of SAF relative to conventional jet fuel. Bailis & Baka (2010) investigated the environmental impacts of jatropha (Jatropha Curcas) based SAF in Brazil. The SAF emissions were 40 kg CO_2e/GJ of fuel produced, a 55% reduction relative to conventional jet fuel. Budsberg et al. (2016) found out that SAF produced from poplar biomass decrease the global warming potential up to 56% compared with conventional jet fuel. In one of the latest studies, Pamula et al. (2021) showed that SAF from switchgrass has 44% lower environmental impacts than conventional jet fuel. These studies indicate that SAF has a lower carbon footprint than conventional jet fuel; however, the amount of CO_2 savings vary across different biomass feedstocks.

At the same time, many studies show that it is not economically feasible to produce SAF. Michailos (2018) analyzed the environmental and economic impacts of SAF production from sugar cane residues. They mentioned economic feasibility as the main barrier of SAF production since sugar cane-based SAF cost was $2.87/L - higher than the price of conventional jet fuel. In a similar study, Yang et al. (2018) estimated a cheaper production cost of $1/L for lignocellulosic SAF, which was still higher than conventional jet fuel. Tao et al. (2017) showed that SAF production costs for five oilseed crops of camelina, pennycress, jatropha, castor bean, and yellow grease range between $1/L and $2.91/L.

It is important to reconcile environmental and economic information into a single framework for developing an informed pathway for SAF production in the United States. Eco-efficiency is a tool that jointly measures economic and environmental performances (Arabi et al., 2014). The use of eco-efficiency could inform policymakers and other relevant stakeholder groups about the trade-offs between economics and environmental components of SAF production, thereby facilitating science-based decision-making.

Eco-efficiency is based on the concept of creating more goods or services, and at the same time, using a lower amount of resources and creating less waste and pollution (Cabeza et al., 2015). Ren et al. (2014) evaluated the eco-efficiency of biofuel production from wheat, corn, cassava, and sweet potato under different scenarios, and they concluded that sweet potato is the most efficient feedstock for ethanol production in China. Salazar-Ordóñez et al. (2013) found that only 4% of sugar beet farms for ethanol production are eco-efficient in Spain. Their results showed that it is possible to decrease inputs by up to 40% to improve the eco-efficiency of ethanol production further. Ren et al. (2014) concluded that cassava-based ethanol is the most eco-efficient biofuel in China. Some studies have also focused beyond farm-level bioenergy production. Sesmero et al. (2012) evaluated the eco-efficiency of seven recently constructed ethanol plants in the United States. Their results showed that it is possible to decrease emissions by 6% by eliminating allocative inefficiencies. Wang et al. (2019) concluded that direct-combustion power generation from agriculture residues has the best environmental benefits.

Carinata (*Brassica carinata A. Braun*), also called Ethiopian mustard, is a good source for SAF production due to the high concentration of erucic acid in the seed. Since at least 3000 BC, it has been grown in northeastern Africa. The crop has a higher tolerance to warmer weather than canola and oilseed rape, making it a better option as a winter crop to produce SAF in subtropical areas, like the Southern United States (Mulvaney et al., 2019). Alam & Dwivedi (2019) found that 1.4 million hectares are suitable for growing carinata in the Southeastern United States. The farmers can grow carinata in crop rotations as a winter crop to make more income and provide soil health benefits (SPARC, 2019). Carinata can be in rotation with late corn, cotton, peanut, soybean, and grain sorghum. Crop rotation can help decrease disease risk since Fusarium and Sclerotinia remain on carinata residues left in the field and could increase with consecutive plantings (SPARC, 2019).

Carinata is a native African crop; it has been sowed and studied in America (Rakow & Getinet, 1998), Australia (Uloth et al., 2015), Europe (Cardone et al., 2002), and Asia (Malik, 1990) for many years. Most of the studies related to carinata focused on agronomy (Katiyar et al., 1986; Taylor et al., 2010; Husen et al., 2014; Mulvaney et al., 2019; Campanella et al., 2020; Kumar et al., 2020); as well as SAF and the co-product technologies (Vicente et al., 2005; Bouaid et al., 2005; Bouaid et al., 2009; Newson et al., 2013; Drenth et al., 2014; Kasiga et al., 2020). Only a few studies have focused on the economics of carinata production. Diniz et al. (2018) concluded that a high risk exists for a negative NPV in a carinata-based SAF facility. They suggested a $0.39/L subsidy to decrease the risk to about 30%. Elliott et al. (2018) considered the farm-level profitability and risk in South Dakota's carinata farms. Carinata could decrease risk and increase profitability in western South Dakota; however, it only could decrease risk by diversification benefits in the eastern area. They did not study carinata in a rotation with other conventional crops; therefore, they did not include rotational benefits. On the contrary, Basili & Rossi (2018) analyzed the environmental and economic effects of carinata in wheat rotation. Their results showed that carinata-based SAF production is economically feasible and environmentally sustainable in Italy. The main obstacle for the second-generation production was importing cheap feedstocks, mainly palm oil. They suggested an import tax policy to compete with the dumping trade policy from Indonesia.

Not many studies focus on the economics of carinata, and even if they do, they typically do not consider the economics of carinata in relation to popular crop rotations. More so, no study has characterized the eco-efficiency of winter bioenergy crops as a part of the overall production system in a given region worldwide. As a result, our study fills a critical knowledge gap by analyzing the eco-efficiency of carinata in South Georgia, a state located in the Southern United States. The overall goal of the study is to identify the environmental and economic trade-offs of carinata production in current rotations and evaluating any gains in eco-efficiency over time relative to traditional rotations with no carinata production. In this context, the objectives of the study are, a) to determine changes in farm profitability with and without carinata in crop rotations; b) to determine changes in carbon impacts with and without carinata in crop rotations; and c) to determine changes in farm-level eco-efficiency scores with and without carinata in crop rotation. This study will feed into current initiatives which are promoting SAF production worldwide, in general, and in the United States, in particular for achieving policy objectives of mitigating climate change, enhancing the provision of ecosystem services, and supporting rural economies.

3.2. Modeling Approach and Data

3.2.1. Study Area

We selected Georgia as a case study for this study. In 2019, the state agricultural sector cash receipt was $8.4 billion, making it the 16th state in overall cash receipts nationwide (U.S. Department of Agriculture, 2020). Specifically, we selected 50 counties in South Georgia for our study. These counties cover 56.4% of the total cropland in the state (NASS, 2020). Corn, cotton, and peanuts amounted to 755 thousand hectares of the land across the study area, covering 98.5% of the total croplands in South Georgia. Additionally, Alam & Dwivedi (2019) reported that about 0.85 million hectares of agricultural land in South Georgia is suitable for carinata production, as the major crops of corn, cotton, and peanut, can make complementary crop rotations with carinata (Kumar et al., 2020).

3.2.2. Farm-Level Economics

The crop rotations of cotton-cotton-peanut, cotton-cotton-corn-peanut, corn-corn-peanut, cotton-cotton-cotton-peanut, corn-corn-corn-peanut, and cotton-corn-peanut are the most popular rotations in South Georgia. We can also replace peanut with soybean to have 12 rotations with peanut or soybean. If we have a four-year timeline for the crop rotation, we will have 972 rotations by choosing winter options of fallow, wheat, and carinata. Although the winter crops are profitable; they can decrease the crop rotation profit by the following limitations: 1) we cannot sow carinata after peanut because of the sharp decrease in yield due to residual herbicide effects, 2) we should have at least two years among carinata crops (Seepaul et al., 2019), 3) we cannot grow corn after winter wheat or carinata because winter crops harvest times are in June. Thus, we can only sow peanuts, soybeans, and cotton after winter wheat and carinata. Table 3.1 provides more information about the planting and harvesting dates in South Georgia. Cotton planting duration is considered two weeks of defoliation, and peanut planting time also includes one week for digging. We should also consider the interactions between summer crops: continuous corn and continuous cotton yield penalties of 10% and 15%, respectively (Salassi et al., 2013). Considering all the constraints, the number of crop rotations will be 292, of which 180 rotations are with carinata and 112 without it.

Table 3.1. Planting and harvesting time of crops in South Georgia

Crop	Planting date	Harvesting	From plant to harvest (months)
Corn	April 2	August 23	5
Cotton	June1	October 23	5.5
Peanut	June 6	November 1	5
Soybean	June1	October 19	5
Winter Wheat	November 16	June 1	6.5
Carinata	November 15	May 20	6.5

To analyze the financial effects of choosing carinata in the rotations, we should examine both NPV scenarios with and without carinata:

$$NPV = \sum_{t=0}^{T} \frac{(ACF_t)}{(1+r_d)^t} \tag{1}$$

ACF_t and r_d are annual cash flows in year t and interest rate, respectively. The farm-level costs, incomes, and yields of corn, cotton, peanut, soybean, winter wheat, and carinata are provided in Appendix (Table S1 to S6). After finding all 292 possible crop rotations, we will be able to calculate the NPV of each rotation using data provided in the Appendix and Eq.1.

3.2.3. LCA Method

Life Cycle Assessment (LCA) is a method to analyze the possible environmental impacts of different products and services during their total life cycle, from raw material acquisition through manufacturing, use, end-of-life treatment, recycling, and final disposal (Jonker & Harmsen, 2012). The International Organization for Standardization (ISO) has standardized this method in ISO 14040:2006 and ISO 14044:2006. Figure 3.1 illustrates the overall system boundary for carinata-based SAF production for estimating total carbon emissions. In this study, we focused on the farm-level carbon emissions only. The functional unit is the amount of CO_2 emission per hectare for each crop rotation. Table 3.2 reports the inputs needed with the production of crops for one hectare of land. We suitably combined the farm-level input data (Table 3.2) with GREET® Model 2019 to estimate total CO_2 emissions for each hectare of selected crops.

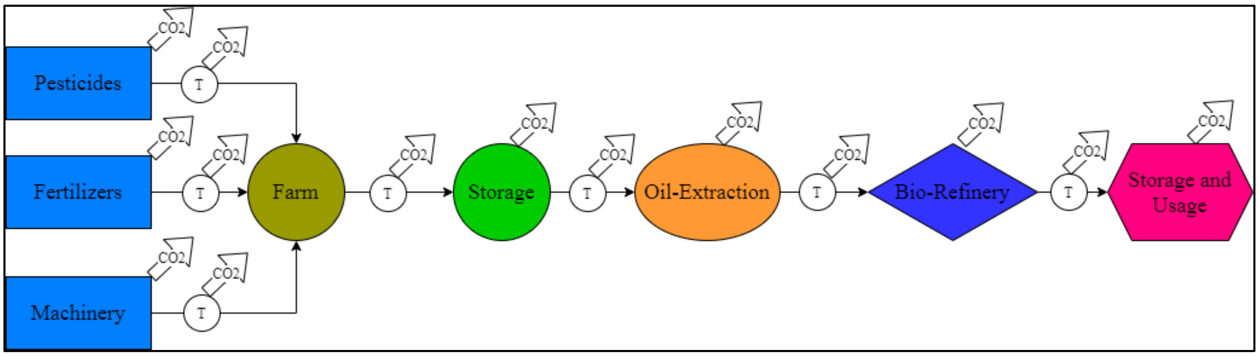

Figure 3.1. System boundary of carinata-based SAF

Table 3.2. Farm-level inputs for different crops in South Georgia

	Inputs	Corn*	Cotton*	Peanut*	Soybean*	Carinata**	Wheat*
Fertilizers (kg/ha)	N	269	100.9	0	0	89.7	89.7
	P	112.1	78.5	0	44.8	0	44.8
	K	224.2	78.5	0	89.7	0	44.8
	Lime	1,100	740	1,120	740	0	560
	Inoculant	0	0	5.6	3.9	0	0
	Boron	0	0	0.6	0.6	0	0
	Phosphoric Pentoxide	0	0	0	0	44.8	0
	Potassium Oxide	0	0	0	0	89.7	0
	Sulphur	0	0	0	0	28	0
Chemicals (liter/ha)	Insecticide	0.9	1.1	23.5	0.2	0.08	0.1
	Herbicide	7.0	3.1	6.1	17.6	4.41	5.7
	Fungicide	0.8	2.6	12.4	0.9	0.3	0.3
Fuels	Diesel (liter/ha)	69.6	121.2	160	63.6	219.6	62.8
	Electricity (MJ)	90.6	90.6	67.9	56.6	11.3	11.3

Source: (University of Georgia Cooperative Extension, 2019) and (National Peanut Research Laboratory, 2020)

3.2.4. DEA Method

Efficiency is the production level in which the lowest inputs produce the highest output (Ueasin et al., 2015). There are two different approaches of parametric and non-parametric to measure efficiency. Stochastic Frontier Approach (SFA) is the most common parametric approach, which has three main issues: 1) it needs a specific functional form for the efficient frontier, 2) it needs a specific probability distribution for the efficiency level, and 3) any misspecification will cause errors in efficiency measurement. However, the non-parametric approach of Data Envelopment

Analysis (DEA) does not suffer from specification errors since it does not require any functional form (Dong et al., 2014).

There is significant literature on implementing DEA to assess technical efficiency (Lilienfeld & Asmild, 2007; Gerdessen & Pascucci, 2013; Atici & Podinovski, 2015; Li et al., 2018; Mosbah et al., 2020; Pan et al., 2021). Researchers included pollution variables in different ways; however, DEA has been limited by its inability to interpret an economic criterion. Simultaneously, many papers used the DEA to analyze economic and environmental impacts (Thanh Nguyen et al., 2012; Wang et al., 2018; Mardani et al., 2018; Wang et al., 2019; Xian et al., 2019). Given DEA, there are two approaches to modeling emissions. In the first approach, emissions are either a joint output or a byproduct in an explicit emission function. The emission is emitted as a byproduct or joint when another main desired output is produced. Emission is an input (quasi-input) to produce the desired output in the second approach (Ebert & Welsch, 2007). Here we employ the DEA method, and we consider the amount of CO_2 emissions as an input. The method is a version of a single-input single-output technical efficiency index used by Farrell (1957). A Decision-Making Unit (DMU) is an efficient choice if no other DMU can give more output with the same or lesser input. It is known as the main advantage of DEA that the method does not need any functional relationship between inputs and outputs (Imran et al., 2018). Crop rotations represent DMUs in this study, and we need to find out the most efficient rotation/DMU by implementing DEA.

Assuming $S\acute{S}$ is the unique isoquant of a fully efficient firm that consumes inputs of x_2 and x_1 to produce y (Figure 3.2). The input price ratio is also known as $A\acute{A}$. Therefore, the Technical Efficiency (TE), Allocative Efficiency (AE), and the total Economic Efficiency (EE) for a DMU in point P are as follow (Coelli, 2016):

$$TE = OQ/OP \quad (1)$$

$$AE = OR/OQ \quad (2)$$

$$EE = OR/OP \quad (3)$$

Here in this study, we estimate the amount of CO_2 of environmental impacts of each crop rotation by the LCA method and GREET 2019 software. Then, the efficiency of the rotations was estimated by the DEA method using DEAP software. The input and the output for DEA analysis are CO_2 emissions and Net Present Value.

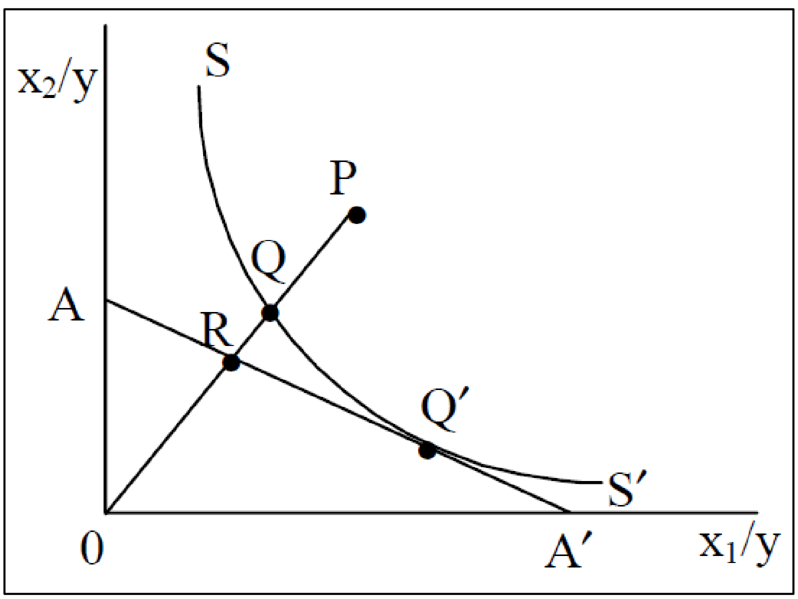

Figure 3.2. Technical, allocative, and economic efficiencies (Coelli, 2016)

3.3. Results

3.3.1. NPV of Crop Rotations

Figure 3.3 compares the profitability of crops in South Georgia. Corn is the most profitable with \$706.2/ha, although wheat makes the lowest profit at \$134.7/ha. Soybean and corn are not major crops in Georgia, although they have the highest profit (Lee, 2019; Bryant, 2021). Soybean acreage dipped from 325,000 in 2015 to 100,000 acres in the last two years in Georgia (Bryant, 2021). The major reason is low soybean prices, as many Georgia peanut growers are not willing to sow soybean when prices declined below $0.37/kg (Bryant, 2021). Cotton and peanut prices have not changed dramatically in the past few years (NASS, 2020). The prices hovered around $1.44/kg and $46/kg for cotton and peanut, respectively (NASS, 2020). For corn, there is a production risk associated with unpredictable weather patterns (Lee, 2019). The average yield difference between irrigated and non-irrigated corn is 48% which is now greater in recent years because of the La Nina effects (Lee, 2019). In contrast, the highest yield differences between non-irrigated and irrigated cotton and peanut are between 27% and 37% (University of Georgia Cooperative Extension, 2021). All in all, farmers' do not prefer to have soybean and corn due to production and market risks.

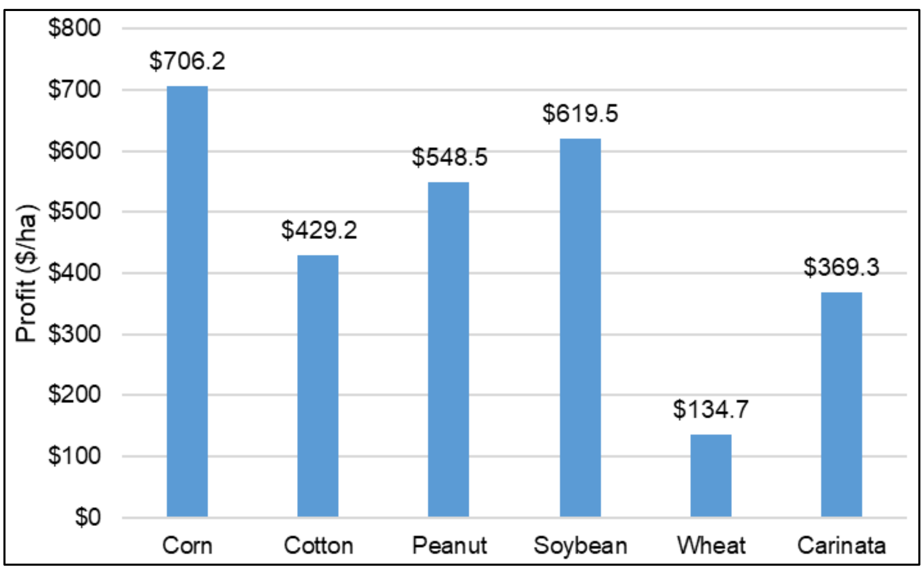

Figure 3.3. Profitability of crops in South Georgia in 2019

Table 3.3 reports the top 20 crop rotations with the highest NPVs. Corn-fallow-corn-carinata-soybean-fallow-corn-wheat has the highest NPV with $2,996.01/ha. The top 20 rotations mostly have the summer crops of corn and soybean. It is because of the higher profit of corn and soybean. Between the top 20 rotations, 18 rotations are with carinata. Across all 292 possible crop rotations, carinata could increase NPV by $260.59/ha on average. It is around 13% better off in NPV.

Table 3.3. Top 20 rotations with the highest NPV.

Year 1		Year 2		Year 3		Year 4		NPV ($/ha)
Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	
corn	fallow	corn	carinata	soybean	fallow	corn	wheat	2,996.01
corn	fallow	corn	wheat	soybean	fallow	corn	carinata	2,979.29
corn	fallow	corn	carinata	peanut	fallow	corn	wheat	2,930.25
corn	fallow	corn	wheat	peanut	fallow	corn	carinata	2,913.54
corn	fallow	corn	carinata	soybean	fallow	corn	fallow	2,876.00
corn	fallow	corn	fallow	corn	carinata	soybean	wheat	2,854.85
corn	fallow	corn	fallow	soybean	fallow	corn	carinata	2,849.69
corn	fallow	corn	fallow	corn	wheat	soybean	carinata	2,846.65
corn	fallow	corn	carinata	peanut	fallow	corn	fallow	2,810.25
cotton	carinata	cotton	fallow	corn	wheat	soybean	carinata	2,809.18
corn	fallow	corn	fallow	corn	carinata	peanut	wheat	2,791.57
corn	fallow	corn	fallow	peanut	fallow	corn	carinata	2,783.94
corn	fallow	corn	wheat	soybean	fallow	corn	wheat	2,770.29
corn	fallow	corn	fallow	corn	carinata	soybean	fallow	2,734.84
corn	fallow	corn	fallow	corn	fallow	soybean	carinata	2,721.94
corn	fallow	corn	wheat	peanut	fallow	corn	wheat	2,704.53
cotton	carinata	cotton	wheat	soybean	wheat	cotton	carinata	2,688.96
cotton	carinata	cotton	fallow	corn	fallow	soybean	carinata	2,684.47
corn	fallow	corn	fallow	corn	carinata	peanut	fallow	2,671.57
corn	fallow	corn	wheat	soybean	fallow	corn	fallow	2,650.29

3.3.2. LCA of Crop Rotations

Using farm-level inputs data (Table 3.2), GaBi ts, and GREET® Model 2019 versions, we estimated CO_2 emissions for both per kg and per hectare of crops. GaBi ts is used for estimating the environmental impacts of cotton, peanut, and wheat. However, GREET® Model 2019 version is used for farm-level LCA of corn, soybean, and carinata. Figure 3.4 provides the results of LCA. Accordingly, the CO_2 amount for one hectare of corn is the highest by 3,389.3 kg of CO_2/ha. Cotton emits the least amount of CO_2 of 294.0 kg/ha. Carinata is the second least pollutant crop on a per unit area basis.

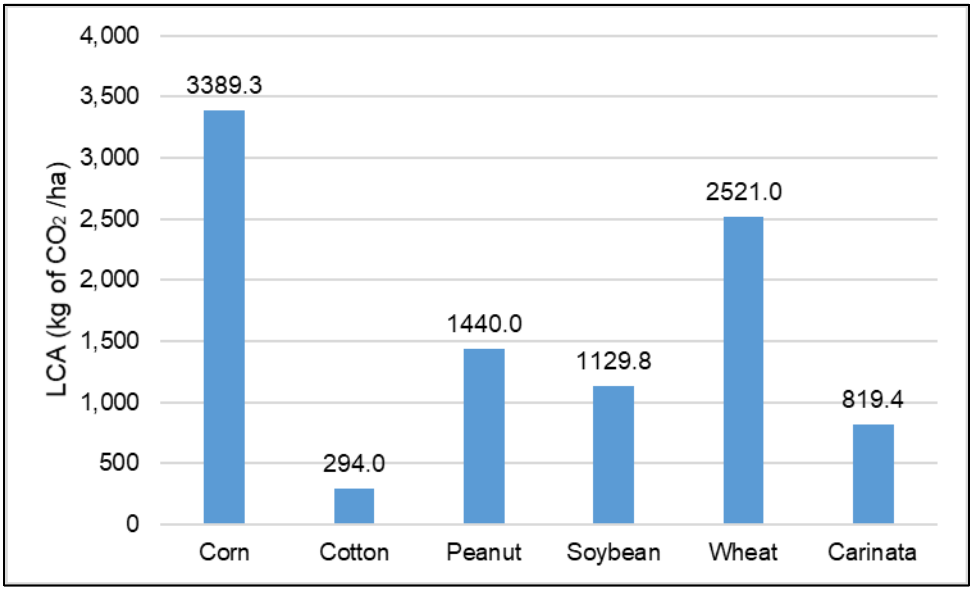

Figure 3.4. CO_2 emissions at the farm level for different crops in South Georgia

Figure 3.5 provided the share of inputs in CO_2 emissions. For all crops except peanut, the share of fertilizers is higher than both pesticides and fossil fuels. Pesticides are the dominant pollutant for peanuts. The portion of fertilizers is the highest for corn by 99%. This is because corn requires 3,354.5 kg/ha of fertilizers. It is carinata which has the most significant share of fossil fuel by 55.6%.

Table 3.4 provides LCA results for the best crop rotations (the rotations with the least amount of CO_2 emissions). Cotton-cotton-soybean with CO_2 emissions of 2,011.84 kg of CO_2/ha is the best due to the lowest emission. The rotation does not include carinata; however, 16 out of the top 20 rotations include the energy crop. If we want to have carinata in the rotation, Cotton-carinata-cotton-fallow-soybean-fallow-cotton-fallow (ranked fifth) with CO_2 emission 2,831.25 kg of CO_2/ha is the best choice. Wheat is not in any of the top 20 rotations. Therefore, either carinata or fallow can be winter choices to have the least CO_2 emissions.

Figure 3.6 gives a better idea about the effect of carinata across all 292 rotations. Accordingly, carinata could decrease the emission in the rotation by around 1,038.88 kg of CO_2/ha.

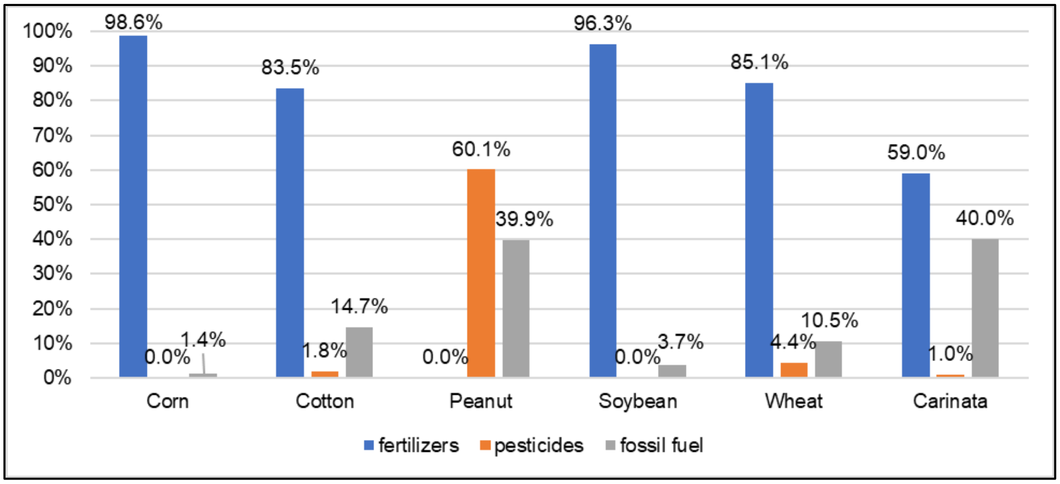

Figure 3.5. Share of inputs in farm-level CO_2 emissions.

Table 3.4. Top 20 crop rotations with the lowest CO_2 emissions

Year 1 Summer	Winter	Year 2 Summer	Winter	Year 3 Summer	Winter	Year 4 Summer	Winter	kg of CO_2/ha
cotton	fallow	cotton	fallow	soybean	fallow	cotton	fallow	2011.84
cotton	fallow	cotton	fallow	cotton	fallow	soybean	fallow	2011.84
cotton	fallow	cotton	fallow	peanut	fallow	cotton	fallow	2322.00
cotton	fallow	cotton	fallow	cotton	fallow	peanut	fallow	2322.00
cotton	carinata	cotton	fallow	soybean	fallow	cotton	fallow	2831.25
cotton	fallow	cotton	carinata	soybean	fallow	cotton	fallow	2831.25
cotton	fallow	cotton	fallow	soybean	carinata	cotton	fallow	2831.25
cotton	fallow	cotton	fallow	soybean	fallow	cotton	carinata	2831.25
cotton	carinata	cotton	fallow	cotton	fallow	soybean	fallow	2831.25
cotton	fallow	cotton	carinata	cotton	fallow	soybean	fallow	2831.25
cotton	fallow	cotton	fallow	cotton	carinata	soybean	fallow	2831.25
cotton	fallow	cotton	fallow	cotton	fallow	soybean	carinata	2831.25
cotton	carinata	cotton	fallow	peanut	fallow	cotton	fallow	3141.41
cotton	fallow	cotton	carinata	peanut	fallow	cotton	fallow	3141.41
cotton	fallow	cotton	fallow	peanut	fallow	cotton	carinata	3141.41
cotton	carinata	cotton	fallow	cotton	fallow	peanut	fallow	3141.41
cotton	fallow	cotton	carinata	cotton	fallow	peanut	fallow	3141.41
cotton	fallow	cotton	fallow	cotton	carinata	peanut	fallow	3141.41
cotton	carinata	cotton	fallow	soybean	fallow	cotton	carinata	3650.65
cotton	carinata	cotton	fallow	cotton	fallow	soybean	carinata	3650.65

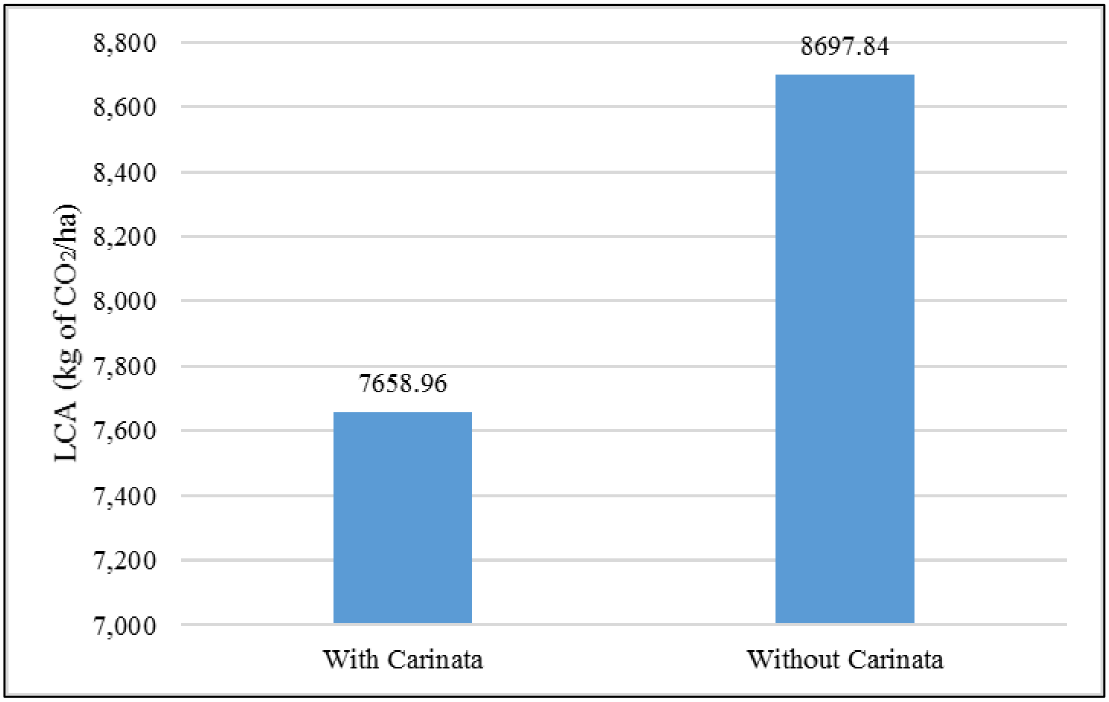

Figure 3.6. CO_2 emissions of rotations with and without carinata.

3.3.3. DEA of Crop Rotations

By considering the CO_2 emission as an independent variable and NPV as a dependent variable, we plotted data in Figure 7. We can understand from Figure 3.7 that the rotations with carinata (blue dots) are above the rotations without carinata (yellow dots). It is to say that at the same level of emissions, it is possible for rotations with carinata to have higher NPV.

We calculated the eco-efficiency of each rotation by implementing DEAP Version 2.1 (Coelli, 2016). The most eco-efficient rotations are in Table 3.5. Knowing from the last section, the rotation that emits the least amount of CO_2 (top 4 rotations) does not include carinata; however, Table 3.5 proves the cotton-carinata-cotton-fallow-soybean-fallow-cotton-carinata is the only eco-efficient rotation. Therefore, carinata does not make the best rotation when considering LCA; however, it makes the most eco-efficient rotation. There is only one rotation that has efficiency equal to one. It is to say that the rotation emits the least CO_2 compared to the NPV level.

Interestingly, 18 out of 20 most eco-efficient rotations include carinata. It means that the energy crop can help to have better eco-efficient rotations.

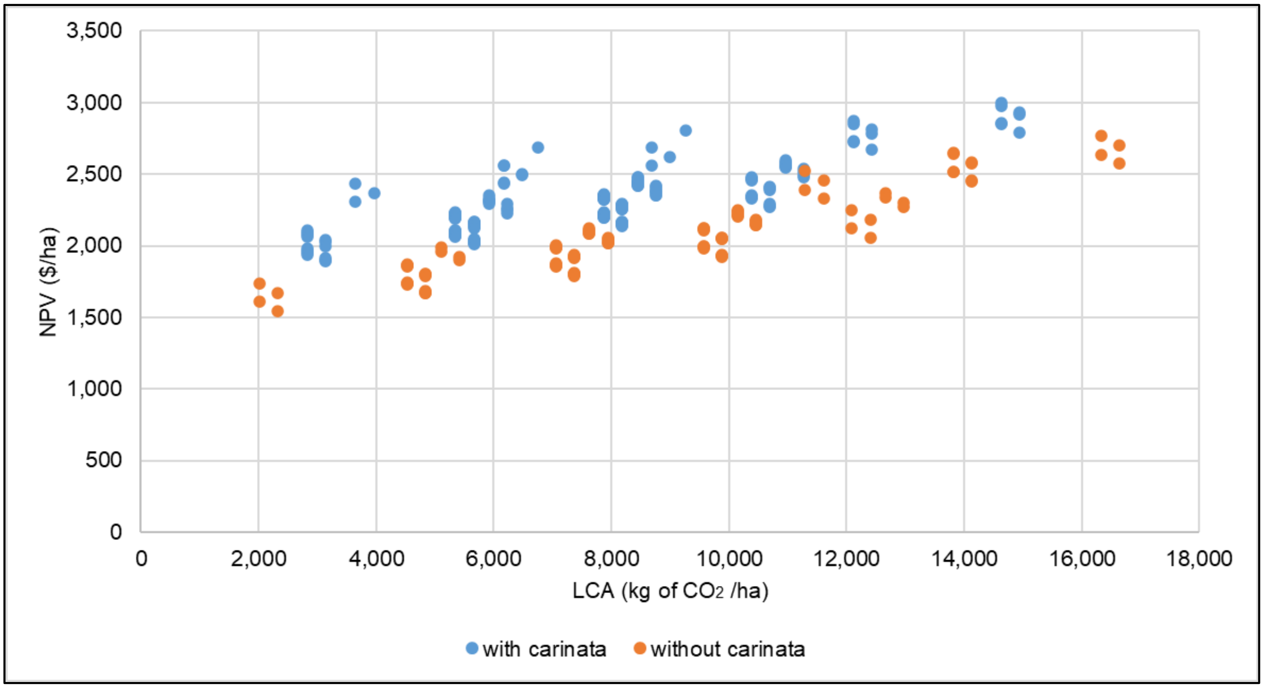

Figure 3.7. CO_2 emissions versus NPV across rotations with and without carinata

Table 3.5. Eco-efficiency levels of top 20 rotations by data envelopment analysis

Year 1		Year 2		Year 3		Year 4		Eco-Efficiency
Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	
cotton	carinata	cotton	fallow	soybean	fallow	cotton	carinata	1.000
cotton	carinata	cotton	fallow	soybean	fallow	cotton	fallow	0.962
cotton	Fallow	cotton	carinata	soybean	fallow	cotton	fallow	0.957
cotton	Fallow	cotton	fallow	soybean	carinata	cotton	fallow	0.951
cotton	Fallow	cotton	fallow	soybean	fallow	cotton	carinata	0.946
cotton	carinata	cotton	fallow	cotton	fallow	soybean	carinata	0.944
cotton	carinata	cotton	fallow	cotton	fallow	soybean	fallow	0.901
cotton	Fallow	cotton	fallow	soybean	fallow	cotton	fallow	0.898
cotton	Fallow	cotton	carinata	cotton	fallow	soybean	fallow	0.895
cotton	Fallow	cotton	fallow	cotton	carinata	soybean	fallow	0.89
cotton	Fallow	cotton	fallow	cotton	fallow	soybean	carinata	0.885
cotton	carinata	cotton	wheat	soybean	fallow	cotton	carinata	0.872
cotton	carinata	cotton	fallow	soybean	wheat	cotton	carinata	0.871
cotton	carinata	cotton	fallow	corn	fallow	soybean	carinata	0.841
cotton	carinata	cotton	fallow	peanut	fallow	cotton	carinata	0.834
cotton	carinata	cotton	wheat	soybean	fallow	cotton	fallow	0.831
cotton	Fallow	cotton	fallow	cotton	fallow	soybean	fallow	0.83
cotton	carinata	cotton	fallow	soybean	wheat	cotton	fallow	0.829
cotton	carinata	cotton	fallow	soybean	fallow	cotton	wheat	0.828
cotton	wheat	cotton	carinata	soybean	fallow	cotton	fallow	0.827

To better understand the carinata effects on the eco-efficiency level of crop rotations, we compare eco-efficiency levels across rotations with and without carinata. Figure 3.8 shows that rotations with carinata have a higher eco-efficiency level than others. The difference between eco-efficiency levels between rotations with carinata and rotations without carinata is around 0.055.

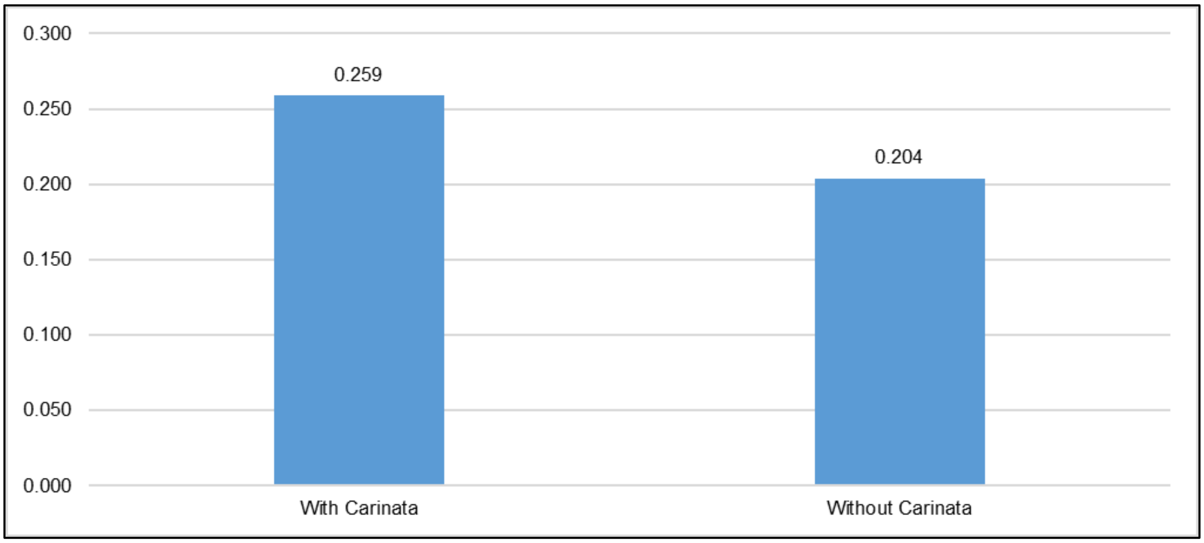

Figure 3.8. Carinata effect on eco-efficiency level of rotations

3.4. Discussions and Conclusion

There is no doubt that bioenergy crops can save CO_2 emissions by sequestration; however, there are concerns about their production process. Since bioenergy crop production relies on fertilizers and fossil fuels, we need to analyze their life cycles to save CO_2 emissions. Besides, it is important to know how their production is eco-efficient. Here in this study, we used the farm-level data of crops in South Georgia to find the most eco-efficient crop rotation in having carinata as an option in the rotation. The results showed that the energy crop is the second least pollutant crop in the region. Borzecka-Walker et al. (2011) also concluded that willow for biofuel production emits the least greenhouse gas compared to most conventional crops in Poland. In a similar study, Fazio & Monti (2011) obtained comparable results for the second-generation biofuels from switchgrass.

According to LCA results, carinata rotations have the lowest environmental impacts. Several reasons make carinata rotations better from an environmental perspective. First, carinata requires limited chemicals due to the aggressiveness of the crop, which makes it possible to outcompete many winter weeds (Seepaul et al., 2019). This results in the CO_2 emissions of carinata production being one of the lowest (Figure 3.4). Second, as mentioned above, it is not possible to sow corn after winter wheat or carinata because winter crops are harvested in June. This means that peanuts, soybeans, and cotton are summer crop choices after winter wheat and carinata. Moreover, Figure 3.4 shows that corn has the highest impact of 3,389.3 kg of CO_2/ha. Therefore, the harvest and planting schedules of winter/summer crops made it less possible for carinata rotations to include corn (only 14 crop rotations out of 292 rotations have corn and carinata), a crop with the highest CO_2 emission. Third, most of the carinata rotations do not include peanut also, because as mentioned above, carinata cannot come after peanut (Seepaul et al., 2019). Only 40 rotations out of 292 have both carinata and peanut. We also know that peanut is the second pollutant summer crop after corn (Figure 3.4). Peanut needs the highest amounts of insecticides, fungicides, inoculants, and boron between all crops (Table 3.2). Carinata decreases the environmental impacts of the rotation because of excluding peanut from the rotation. 4) Carinata has more possible rotations with soybean (52 rotations) and cotton (166 rotations). Soybean and cotton have the lowest emissions per hectare than other summer crops (Figure 3.4). Thus, carinata comes in rotation with the crops that emit lower CO_2 at the farm level.

DEA results show that carinata makes the most eco-efficient crop rotations for the region. Carinata makes the most eco-efficient rotation in cotton-cotton-soybean rotation. There are some studies such as Nabavi-Pelesaraei et al. (2014), Masuda (2016), and Vásquez-Ibarra et al. (2020), which combined LCA and DEA to investigate the eco-efficiency; however, there is no study that implemented the methodology to analyze eco-efficiency for energy crops rotation or even food crop rotations. Therefore, this makes the comparison of the results impossible. Several reasons can explain the higher eco-efficiency for carinata rotations. First, carinata has a lower CO_2 emission per hectare compared to winter wheat (Figure 3.4). Second, it also has a higher profit per hectare ($369.25 versus $134.68). Third, as mentioned above, it is possible for carinata to be in rotation with cotton and soybean rather than corn and peanut. Cotton and soybean emit lower CO_2 than corn and peanut (Figure 3.4). In summary, carinata has a higher profit and lower CO_2 emissions than wheat, and the energy crop is included in rotations with summer crops that have lower CO_2 emissions. Consequently, it is sensible that carinata rotations are eco-efficient.

Here we only discussed farm-level LCA and the related eco-efficiency. Nevertheless, it is important to know how the eco-efficiency levels are in the non-farm production process of bio-aviation. We also did not consider the eco-efficiency across different farmers. It may differ across farms due to farmers' knowledge and perspectives. We suggest that future studies may focus on the whole life cycle of the crops in the rotations and analyze efficiency across various farms.

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Chapter 4

Estimating the Production Cost of Carinata-Based Sustainable Aviation Fuel at the Supply Chain Level: A Case Study from Georgia, United States[3]

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Abstract

The aviation sector currently contributes about 2.5% of global greenhouse gas (GHG) emissions. Due to the rising demand for air travel, GHG emissions from the aviation sector by 2039 will grow by 2.1 times relative to the 2019 level. Sustainable Aviation Fuel (SAF) could help in reducing the GHG emissions of the aviation sector. However, the exact production cost of SAF is not known as the majority of the existing studies determine the production cost on a per unit area basis without accounting for supply chain-related costs. In this study, we have developed a case study using Mixed Integer Linear Programing Model (MILP) for ascertaining the production cost of SAF derived from carinata (an oilseed crop) in Georgia, United States, after accounting for costs related to every component of the supply chain starting from seed production to the transportation of SAF from a biorefinery to the Atlanta Airport, the busiest airport on the Earth. Our results show that carinata-based SAF could displace a maximum of approximately 13% of Atlanta's total jet fuel consumed each year over four years. Also, we chose four different scenarios of 2.6%, 5.2%, 7.8%, and 10.4% to examine the impacts of scale on the SAF production cost. We found that 998 seed storage facilities, four crushing mills, and two biorefineries are needed to meet 13% of the annual SAF demand at Atlanta Airport. A total area of 1.30 million hectares across 72 counties is needed to replace 13% of conventional jet fuel by the carinata-based SAF. SAF production cost was $1.24/liter, much higher than the price of conventional jet fuel ($0.49/liter). The scale analysis showed that the unit cost of carinata-based SAF is the lowest ($1.23/liter) while meeting 7.8% of Atlanta's SAF demand. Under all scenarios, financial support is needed to encourage the production of carinata-based SAF in Georgia, United States.

4.1. Introduction

Globally, aviation contributes to $2.7 trillion and 65.5 million jobs (Gittens et al., 2019). In 2019, CO_2 emitted by the aviation sector of the United States was 255 million metric tons, i.e., almost 5% of total energy-related CO_2 emissions nationwide (U.S. Energy Information Administration, 2019). According to International Air Transport Association (IATA), there will be an annual growth of 3.7% in global air passenger traffic by 2039 regardless of the COVID-19 impact (IATA, 2020). It will make the number of passengers in 2039 around 2.1 times more than the 2019 level (IATA, 2020). If the trend continues, this surge in aviation demand is projected to result in around 2.27 billion tonnes of GHG emissions by 2039, which is 2.32 times greater than the 2021 baseline of almost one billion tonnes (Valdés and Comendador, 2021).

Several methods have been explored for reducing CO_2 emissions in the aviation sector. For instance, Fukui & Miyoshi (2017) explored the option of aviation fuel tax and found that a 4.3 cents/gal increase in aviation fuel tax would reduce CO_2 emissions in the United States by 0.14–0.18% in the short run. Similarly, Faber & Huigen (2018) explored the option of ticket tax and reported that the tax rate should be around $2.39 to $31.01, depending upon the distance of the flight in Europe. Furthermore, China has now included the aviation industry in the newly established national carbon trading market (Liao et al., 2021). In addition to these policy-based options, the use of Sustainable Aviation Fuel (SAF) is becoming popular (Kousoulidou & Lonza, 2016; Larsson et al., 2019) as one of the most promising ways to mitigate CO_2 emissions from the aviation sector (IBAC, 2019).

Sustainable aviation fuel (SAF), derived from renewable feedstocks, is one the most promising ways to mitigate aviation CO_2 emissions (IBAC, 2019). SAF, essentially Jet-A with a non-fossil fuel element, blended with up to a currently certified 50% mix; has benefits of a cleaner burn and commensurate reduction of overall CO_2 emissions over the life cycle of the fuels' manufacturing process, together with the environmental benefits in sourcing such fuels from renewable resources (IBAC, 2019).

SAF or any biofuel production needs system analysis because of distributed biomass resources as well as the low energy density of biomass (Espinoza Pérez et al., 2017). One of the main issues is that biomass supply sites and demand centers are not adjacent (Lin et al., 2016). Due to the low energy density of biomass, a biofuel supply chain requires a large sourcing area to meet the level of demand (Castillo-Villar, 2014). For this, transportation cost and optimal transportation mode were the main issues in many studies. Bambara et al. (2017) optimized the Jatropha biofuel supply chain in Burkina Faso and Mali. The results showed that after the first year of harvesting, the transportation cost would be more than 60% of the seed cost. Zhang et al. (2016) designed a model to minimize the cost of supplying biofuel facilities while meeting necessary delivery requirements in Michigan. Truck and rail were two different transportation modes in the model. They concluded that the optimum transportation mode for short distances and long distances were trucks and rails, consecutively.

Many factors, such as feedstock availability, conversion technology, and facility locations, should be considered in finding an optimal supply chain for SAF production (Nugroho and Zhu, 2019). To solve these issues, we should find the optimal supply chain which minimizes costs and gives the numbers, locations, and capacities of facilities at different levels of the supply chain. The big challenge for most studies is that the price of fossil fuels is less than biofuel production costs. That is the reason that they suggest economic incentives for biofuel production. de Jong et al. (2017) addressed the issue in Sweden. According to them, it is not economically feasible to use biofuels instead of fossil fuels. They concluded that other policy support and further technological learning are needed, and cost reduction strategies cannot be effective.

There are not many studies that focus on the SAF supply chain. Reimer & Zheng (2017) analyzed the aviation bioenergy supply chain in the Pacific Northwest region of the United States using Social Accounting Matrix (SAM). The results showed that if policy-makers want to use camelina-based fuel instead of conventional fuels, they should implement one of these policies: a 17% subsidy on the alternative fuel, a 20% tax on the conventional fuel, or a combination 9% subsidy on the alternative and 9% tax on the conventional fuel. Perkis & Tyner (2018) set up a supply chain to optimize cellulosic biomass into SAF in Indiana. They concluded that it is not economically feasible for firms to set up a supply chain with current economic incentives. Huang et al. (2019) optimized a multi-objective supply chain for the Midwestern United States. They showed that the most cost-effective solution was $1.23/liter, however, the most environmental-friendly solution was 0.03 kg CO_2/liter.

Carinata, known as Ethiopian mustard, has 42% to 52% oil content (Kumar et al., 2020), and its varieties can be grown either as a winter crop or a spring crop in humid subtropical and humid continental climates, respectively (Kumar et al., 1984). The crop is heat tolerant, resistant to diseases and seed shattering, and has lower water-use requirements than other oilseed brassicas (Kumar et al., 1984). Carinata has been developed as a carbon-saving, non-food oilseed biomolecular platform to produce advanced drop-in jet fuel (Seepaul et al., 2021). Like other SAF, there are many issues in the carinata-based SAF supply chain that need to be considered to make its production feasible.

A closer look into existing studies suggests that no study has analyzed the economics of carinata-based SAF at the supply chain. We also noticed that only a few studies have analyzed the impact of scale on the economics of biofuels, in general, or SAF, in particular. Hayward et al. (2015) analyzed the economics of producing sustainable aviation fuel in Australia. They concluded that there was a $0.12/liter difference between the small- and large-scale unit costs, with the larger unit costs being lower. In a similar study, Farooq et al. (2020) concluded that increasing the scale of SAF production in the United Kingdom by a 50% increase in capital costs results in a 4.4% increase in the unit price. Tanzil et al. (2021a) found out that if they scale up SAF production capacity from 130 million tons/day of lignocellulosic feedstock to 2,500 million tons/day, the unit cost of SAF will drop almost 2.3 times. In contrast, few studies like Tanzil et al. (2021b) concluded that there would be a 3-67% decrease in SAF unit cost from corn in the case of decreasing the production scale. It is expected that production cost decreases with scale, however; it is not always the case because larger scales require larger feedstock collection areas, as well as greater average transport distances and delivered feedstock costs (Brinsmead et al., 2015). In this context, it is critical to understand the economies of scale in light of carinata-based SAF production in Georgia for developing suitable incentives.

This paper addresses the literature gap by developing a supply chain model in Georgia to meet different percentages of jet fuel demand at Atlanta airport. Accordingly, the objective of the paper is to set up a carinata-based SAF supply chain model to minimize total cost. We will find the optimal counties for feedstock production and facilities locations. Finally, the optimal scale of the supply chain will be determined.

4.2. Methodology

4.2.1. Study Area

The agriculture sector in Georgia, with a cash receipt of $8.4 billion, is the largest sector of Georgia's economy (U.S. Department of Agriculture, 2020). Corn, cotton, and peanuts occupy

56.4% of the total cropland in the state (NASS, 2020). The major crops of corn, cotton, and peanut, can come in rotation with carinata (Kumar et al., 2020). This made Georgia a state with a high potential for carinata production. According to Alam & Dwivedi (2019), up to 0.85 million hectares of the land in Georgia is suitable for carinata production, which is the highest of all in the southeastern United States.

The Hartsfield-Jackson International Airport (ATL) in Atlanta is the busiest in the world due to its strategic location as a major "gateway" to entry into North America and is reported to be two hours away from 80% of the population of the United States (Henriques and Feiteira, 2018). In 2019, the airport had around 62 million available seat miles which 63.9% were for domestic flights, and 36.1% were for internationals (U.S. Department of Transportation, 2019). Around 3.3% of the available seat miles in the country were from Atlanta airport, which consumed 4.4 billion liters of jet fuel in 2019 (U.S. Department of Transportation, 2019).

4.2.2. Data

We developed a supply chain model which combines geographical information and optimization tools to find decision variable levels in the supply chain. The primary input data for a supply chain model should be the biomass availability and farm-level prices, transportation distances, annual capacity of various facilities, capital costs of facilities, and annual operating costs of facilities (Lin et al., 2016). Figure 4.1 explains the supply chain for carinata-based SAF selected in this study. Each county sends carinata seeds to storage; then, the seeds go to oil extraction facilities from storage. The carinata oil from oil extraction facilities will be delivered to biorefineries, and finally, the manufactured SAF will be delivered to Atlanta airport. There are co-products that are produced both at oil extraction facilities and biorefineries. Carinata meal is produced at oil extraction facilities, and naphtha and propane are produced in biorefinery. Carinata is a seasonal crop and is typically harvested in late May/early June; therefore, storage facilities are needed for the yearlong production of SAF.

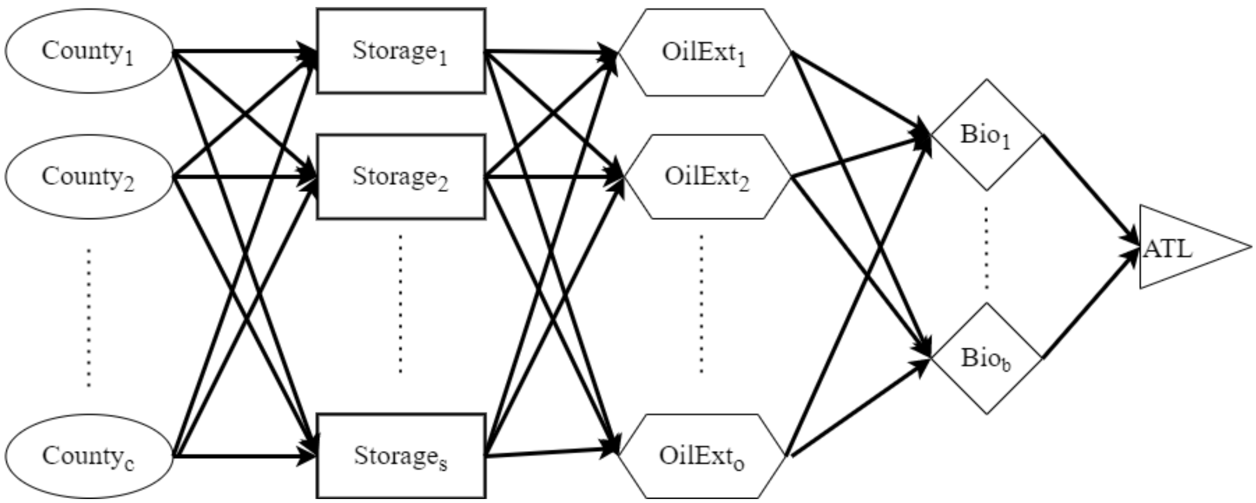

Figure 4.1. Simplified schematic of the supply chain process with carinata feedstock.

To assemble a distance matrix between facilities, ArcGIS10.8 was used to calculate the shortest transportation distances between counties using the existing road network. For annual facility capital and operational costs, we used data from Chu et al. (2017b) and changed all costs in 2019 prices by an inflation rate of 1.9% (U.S. Department of Labor, 2019).

We used a DayCent simulation model to estimate the yield and maximum area available in each county in Georgia for biomass availability. The DayCent model (Parton et al., 1998) was adapted to make spatially-explicit estimates of carinata seed yield and associated changes in soil organic carbon (SOC) levels and nitrous oxide (N_2O) emissions when carinata is grown across the frost-safe region of northern Florida, southern Alabama, and southern Georgia (Alam and Dwivedi, 2019). DayCent was previously calibrated to represent carinata grown in the SE United States based on data from Agrisoma Biosciences, Inc. The model was calibrated using data on aboveground biomass, root biomass, and tissue carbon:nitrogen ratios for carinata grown at the

University of Florida North Florida Research & Education Center in Quincy, Florida for one season (winter 2015–2016) at four different nitrogen (N) fertilizer application rates and validated against five commercial-scale production plots from Georgia collected between 2016 and 2018. Data inputs and methods for high-resolution DayCent simulation were modified from those described previously in the context of simulations of other dedicated bioenergy crops (Field et al., 2018).

Those prior methods were updated such that carinata production was simulated on all cultivated annual cropland as per the 2016 National Land Cover Database (Homer et al., 2020), and to use historical weather data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), which results in low-bias DayCent yield simulations (Zhang and Paustian, 2019). The DayCent simulations assumed that carinata is grown as a winter cover crop between the two cotton cash crops of a three-year cotton–cotton–peanut rotation, with moderate-intensity field preparation and planting in mid-November, fertilizer application at a rate of 90 kg N ha^{-1} y^{-1}, plant physiological maturity in early May, and seed harvest in late May. DayCent simulation output was then post-processed for area-weighted aggregation of simulated yields and environmental impacts to the county scale. Changes in SOC levels and N_2O rates under carinata were evaluated relative to business-as-usual management cotton–cotton–peanut rotations, with those crops calibrated as per the DayCent simulations used in the annual EPA Inventory of U.S. greenhouse gas emissions and sinks (US EPA, 2020).

The parameters for the supply chain model are provided in Table 4.1. Table 4.2 presenting the yield and available area for 95 counties in Georgia with the potential to produce carinata. We assume that from 159 counties in Georgia, 105 rural counties can set up biorefinery and oil extraction facilities. However, it is possible to set up storage facilities in all counties. Rural counties are those that have a population of less than 50,000 (Ratcliffe et al., 2016).

Table 4.1. Parameters of carinata-based SAF supply chain in Georgia

Item	**Unit**	**Value**	**Reference**
Price of carinata	$/kg	0.44	NuSeed Inc.
Adoption (scenarios)	%	100	Assumption
Transportation cost of carinata seed	$/t per km	1.21	(University of Georgia Cooperative Extension, 2019)
Holding cost of carinata seeds at storage	$/(t*month)	2.20	Personal correspondence with Dr. Frayne Olson, Associate Professor and Crop Economist, at North Dakota State University
Capacity of a grain elevator	Kg	1,133,980	
Storage capital cost	$	125,000	
Storage age	Year	15	
Storage facility salvage value	% of capital cost	10	
Transportation cost of carinata oil/jet fuel	$/t per km	0.051	(University of Georgia Cooperative Extension, 2019)
Oil extraction facility operational cost	$/kg of oil	0.02	(Chu et al., 2017b)
Oil extraction age	Year	20	(Chu et al., 2017b)
Biorefinery age	Year	20	(Chu et al., 2017b)
Oil extraction salvage value	% of capital cost	20	(Chu et al., 2017b)
Biorefinery salvage value	% of capital cost	20	(Chu et al., 2017b)
Oil extraction facility capital cost	million $	16.13	(Chu et al., 2017b)
Oil extraction facility capacity	million kg	1,796.7	(Chu et al., 2017b)
Carinata meal price	$/t	375	(Diniz et al., 2018)
Biorefinery capital cost	million $	409.22	(Chu et al., 2017b)
Biorefinery Annual Capacity	million kg	317.83	(Chu et al., 2017b)
Operational cost of biorefinery	$/kg of jet fuel	0.94	(Chu et al., 2017b)
Conversion factor of drying carinata	%	97	NuSeed Inc.
Conversion factor of carinata seed to oil	%	43.29	(GREET, 2020)
Conversion factor of carinata oil to SAF	%	71.94	(GREET, 2020)
Conversion factor of carinata oil to Naphtha	%	6.2	(Diniz et al., 2018)
Conversion factor of carinata oil to Propane	%	8.82	(Diniz et al., 2018)
Conversion factor of carinata oil to water	%	13.4	(Stratton et al., 2010)
Naphtha price	$/1000 liter	935	(Diniz et al., 2018)
Propane	$/1000 liter	608	(Diniz et al., 2018)
Technologies in biorefinery	-	HEFA	Assumption
Jet fuel demand that should be met by SAF	%	1.5 and 10	Assumption
Total jet fuel demand of ATL airport	billion liters per year	4.4	(U.S. Department of Transportation, 2019)
Inflation (average from 2000 to 2019)	%	1.9	(U.S. Department of Labor, 2019)
Interest rate	%	6	(U.S. Department of Labor, 2019)

Table 4.2. Yield and available area for carinata in each county

County	Yield (t/ha)	Area (1000*ha)	County	Yield (t/ha)	Area (1000*ha)
Appling	2.74	24.75	Jones	2.63	0.07
Atkinson	2.89	20.55	Lanier	2.91	8.67
Bacon	2.74	11.54	Laurens	2.79	29.82
Baker	2.91	34.55	Lee	2.91	35.12
Baldwin	2.65	0.45	Liberty	2.77	0.14
Ben Hill	2.77	12.70	Long	2.75	0.98
Berrien	2.91	43.47	Lowndes	2.87	23.27
Bibb	2.85	2.16	Macon	2.83	38.14
Bleckley	2.80	17.15	Marion	2.77	9.06
Brantley	2.61	1.04	McDuffie	2.62	0.96
Brooks	2.80	37.60	Miller	2.92	39.58
Bryan	2.67	1.50	Mitchell	2.90	62.59
Bulloch	2.72	56.95	Montgomery	2.72	7.47
Burke	2.67	49.54	Oglethorpe	2.68	0.60
Calhoun	2.91	26.96	Peach	2.81	14.18
Candler	2.63	14.22	Pierce	2.66	13.42
Charlton	2.52	0.06	Pulaski	2.79	23.46
Chatham	2.65	0.01	Putnam	2.88	0.20
Chattahoochee	2.80	0.30	Quitman	2.86	2.45
Clay	2.89	11.85	Randolph	2.90	25.59
Clinch	2.79	0.76	Richmond	2.73	3.71
Coffee	2.87	48.71	Schley	2.80	7.99
Colquitt	2.95	51.76	Screven	2.66	46.16
Columbia	2.68	0.18	Seminole	2.89	31.39
Cook	2.92	21.47	Stewart	2.83	8.95
Crawford	2.84	6.07	Sumter	2.96	44.52
Crisp	2.88	29.57	Taliaferro	2.73	0.01
Decatur	2.88	47.96	Tattnall	2.73	24.06
Dodge	2.75	23.60	Taylor	2.71	9.83
Dooly	2.89	46.87	Telfair	2.77	12.57
Dougherty	2.88	18.17	Terrell	2.87	32.55
Early	2.89	47.92	Thomas	2.86	31.99
Echols	2.82	3.97	Tift	2.85	24.62
Effingham	2.64	6.85	Toombs	2.72	13.70
Elbert	2.49	0.71	Treutlen	2.72	4.99
Emanuel	2.68	21.62	Turner	2.82	27.17
Evans	2.65	8.69	Twiggs	2.76	4.75
Glascock	2.54	2.80	Ware	2.73	5.52
Glynn	2.63	0.01	Warren	2.66	2.01
Grady	2.90	34.85	Washington	2.66	13.72
Greene	2.76	0.21	Wayne	2.71	12.03
Hancock	2.62	0.09	Webster	2.84	11.93
Houston	2.84	17.75	Wheeler	2.70	7.15
Irwin	2.80	32.51	Wilcox	2.75	26.05
Jeff Davis	2.72	16.81	Wilkes	2.69	0.05
Jefferson	2.67	31.78	Wilkinson	2.71	1.86
Jenkins	2.63	18.71	Worth	2.88	50.25
Johnson	2.70	9.91			

4.2.3. Supply Chain Model

MIP (Mixed Integer Programming) is widely used to manage the SAF supply chain. Both mixed-integer linear programming (MILP) (Zhang et al., 2013; Lee et al., 2017; Tesfamichael et al., 2020) and mixed-integer non-linear programming (MINLP) (Babazadeh et al., 2017; Shu et al., 2017) were implemented for the SAF supply chain to optimize profit (Yu et al., 2016; Haji Esmaeili et al., 2020), cost (Albashabsheh & Heier Stamm, 2019), risk (Osmani & Zhang, 2013; Geraili et al., 2016), environmental indexes (Osmani & Zhang, 2014) or multi-objectives (Ghaderi et al., 2018).

Many studies implemented a single objective optimization approach for bioenergy supply chain models, and they primarily addressed cost minimization problems. In this study, we also implement a single objective MIP model to find the optimum supply chain for carinata-based SAF in Georgia. The economic objective of the optimization model to find an optimal supply chain is total supply chain cost for a 4-year timeline. The following is the objective function of the optimization model.

$$\text{Min Cost} = \sum_q \sum_c \sum_s [p_{car} * (SPLY_{c,s,q} + SPLY_{c,o,q}) + SPLY_{c,s,q} * dis_{c,s} * st_q + SPLY_{c,o,q} * dis_{c,o} * st_q + SPLY_{s,o,q} * dis_{s,o} * st_q + SPLY_{o,b,q} * dis_{o,b} * ot_q + SPLY_{b,d,q} * dis_{b,d} * jt_q + STOCK_{s,q} * stor_q + SPLY_{o,b,q} * ExOpx_q + SPLY_{b,d,q} * BiOpx_q]/((1 + apr)^{year_q}) + \sum_s STORAGE_s * StoCapx * \left(\frac{Dep_s}{StoAge}\right) * y + \sum_o OIEx_o * OiCapx * \left(\frac{Dep_o}{OiAge}\right) * y + \sum_b BIO_b * BiCapx * \left(\frac{Dep_b}{BiAge}\right) * y - p_{meal} * MEAL_{o,q} - p_{naphtha} * NAPHTHA_{b,q} - p_{propane} * PROPANE_{b,q}] \quad (1)$$

where Cost = total cost of the supply chain, p_{car}= price of carinata seed at farm level, $SPLY_{c,s,q}$ = supply of carinata seed from county c to storage s in time q, $SPLY_{c,o,q}$ = supply of carinata seed from county c to oil extraction o in time q, $dis_{c,s}$ = distance between county c and storage s, st_q= seed transportation cost in time q, $dis_{c,o}$ = distance between county c and oil extraction o, $dis_{s,o}$= distance between storage s and oil extraction o, $dis_{o,b}$= distance between oil extraction o and biorefinery b, ot_q= oil transportation cost in time q, $dis_{b,d}$= distance between biorefinery b and demand center d, jt_q= jet fuel transportation cost in time q, $STOCK_{s,q}$= amount of seed stored in storage s in time q, $stor_q$= storage cost in time q, the amount of seed which is stored in each storage will lose its mass according to Eq.5 due to drying, loading/unloading, and aeration, $ExOpx_q$= operational cost of oil extraction in time q, $BiOpx_q$= operational cost of biorefinery in time q, apr = interest rate, $year_q$= corresponding year of quarter q, $OiEx_o$= dummy variable to put oil extraction o or not, $OiCapx$ = capital cost of oil extraction, Dep_o= depreciated value of an oil extraction facility, $OiAge$= age of an oil extraction facility, y= total year of the study, $STORAGE_s$= variable for the number of storage facilities in county s, $StoCapx$ = storage capital cost, Dep_s= depreciated value of storage, $StoAge$ = storage age, BIO_b = dummy variable to put biorefinery b or not, $BiCapx$ = biorefinery capital cost, Dep_b= depreciated value of a biorefinery, $BiAge$ = biorefinery age,p_{meal}= price of carinata meal, $MEAL_{o,q}$= amount of carinata meal produced in oil extraction facility o in time q, $p_{naphtha}$= price of naphtha, $NAPHTHA_{b,q}$= amount of naphtha produced in biorefinery, $p_{propane}$= price of propane, $PROPANE_{b,q}$= amount of propane produced at the biorefinery.

The constraints are as follow:

$$\sum_{s,o}(SPLY_{c,s,q} + SPLY_{c,o,q}) \leq area_{c,q}/3 * yield_{c,q} * adoption \qquad (2)$$

where: $area_{c,q}$= total available area in county c in time q, $yield_{c,q}$ = yield in county c in time q, $adoption$ = adoption rate of growing carinata by farmers. Eq. 2 means that the total amount of carinata that can be delivered from county c should be less than one-third of the total suitable area for carinata in county c by the yield of county c. The reason for putting one-third of the total area is that carinata cannot be sowed every year in the same field. There should be at least two years gap between carinata growing in the rotation. We also adjusted the right-hand side by an adoption rate. Here we assume a 100% adoption rate at the farm level.

$$\sum_{c,q} SPLY_{c,s,q} * \mathrm{DRY} = \sum_{o,q} SPLY_{s,o,q} \quad (3)$$

where: DRY = conversion factor for storage. Since some of the seeds are lost in storage due to losing weight, loading/unloading issues, etc., we used the DRY parameter. According to the constraint in Eq. 3, there is a relationship between the amount of carinata seed that goes into storage and the amount that goes out.

$$\sum_{c} SPLY_{c,s,q} \;\; and \; STOCK_{s,q} \leq Storage_{s} * \mathrm{CAP_{STO}} \quad (4)$$

where: $\mathrm{CAP_{STO}}$ = storage capacity of each storage facility. According to constraint in Eq. 4, the amount of the seed stored in storage s in time q should be less than or equal to its capacity. Also, the amount of the seed that enters each storage should be less than the storage capacity.

Eq. 5 shows that the amount of the seed that is stored in each storage in time q is equal to the amount of the seed that remained from time q-1 and decayed by a specific rate until time q, plus the balance of the seed, which comes from county c and goes to oil extraction o.

$$STOCK_{s,q} = (STOCK_{s,q-1} / \mathrm{decay}) + \sum_{c} SPLY_{c,s,q} - \sum_{o} SPLY_{s,o,q} \quad (5)$$

Where: decay = the rate that seed lose its mass by storing one quarter in a storage.

According to Eq. 6, the seed amount, which comes either from storage or county to oil extraction, is converted to oil by factor SeedOil.

$$\sum_b SPLY_{o,b,q} = \sum_{c,s}(SPLY_{s,o,q} + SPLY_{c,o,q}) * \text{SeedOil} \quad (6)$$

where, SeedOil = conversion factor for seed to oil.

The amount of oil that is processed in each oil extraction should be less than the oil extraction capacity (Eq. 7). Oil extraction facilities can only be located in 105 rural counties in Georgia.

$$\sum_b SPLY_{o,b,q} \leq OiEx_o * \text{CAP}_{\text{OEF}} \quad (7)$$

where, CAP_{OEF} = oil extraction capacity

The amount of SAF that goes out from each biorefinery is a portion of the oil that is entered into the biorefinery (Eq. 8).

$$\sum_d SPLY_{b,d,q} = \text{OilFuel} * \sum_o SPLY_{o,b,q} \quad (8)$$

where, OilFuel = the conversion factor for converting oil to SAF.

The model should produce at least a portion of the demand center d (Eq. 9). Therefore, we consider the demand share of 13%. It is the maximum SAF produced from the available area and the yield in all counties.

$$\sum_b SPLY_{b,d,q} \geq \text{DemandShare} * demand_{d,q} \qquad (9)$$

where, DemandShare = the percentage of the demand that should be met, $demand_{d,q}$ = the jet fuel demand of center d in time q.

The SAF produced from each biorefinery is less than the biorefinery capacity (Eq.10). Biorefinery facilities also can only be located in 105 rural counties in Georgia.

$$\sum_d SPLY_{b,d,q} \leq Bio_b * \text{CAP}_{\text{BIO}} \qquad (10)$$

where, CAP_{BIO} = biorefinery capacity.

The decision variables include the optimal carinata area harvested from each county and the location of storages, oil extractions, biorefineries, and the optimal biomass and SAF flow patterns between each stage. The optimization model is a mixed-integer linear programming model with the optimality gap set at 0.2%. The model is developed on GAMS Studio 1.4.5.

4.3. Results

Our model aimed to meet 13% of Atlanta airport jet fuel demand with carinata-based SAF. We did supply chain optimization to produce 573,217,893 liters/year of SAF. For biomass production, the counties provided in Figure 4.2 are the best places to produce carinata seed. To replace 13% of

Atlanta airport conventional fuel by SAF, we need 72 counties to produce carinata. Figure 4.2 also shows that the south center and southwest of the state have more area to provide carinata. However, the counties in the southeast are not suitable to grow carinata. This is because that the south center and southwest are closer to the demand center. Figure 4.3 illustrates where the counties for feedstock production and facilities are located compared to the demand center. For storage, 998 facilities in 25 counties are needed. The number of storage facilities in each county is provided in the graph.

There are four counties of Baker, Berrien, Crisp, and Montgomery that are the best places to set up oil extraction facilities. In the model, each county has one oil extraction facility. For biorefinery locations, there are two counties of Dooly and Wilcox that are suitable for minimizing the overall cost of carinata-based SAF production in Georgia, United States. Each county needs one biorefinery.

Figure 4.4 gives a better view of the mass flow in the supply chain. It illustrates carinata seed, carinata oil, carinata meal, storage waste, SAF, and biorefinery co-products flows between counties. For example, 30.5 thousand tons of seed produced in Laurens county are delivered to Treutlen County’s storage facilities and oil extraction facilities. Carinata seed produced at farms can either be delivered to oil extraction facilities or storage facilities. Then, the extracted oil will go to biorefineries. Finally, the produced SAF goes to Atlanta airport. There are co-products of carinata meal, naphtha, and propane, which are produced in different levels.

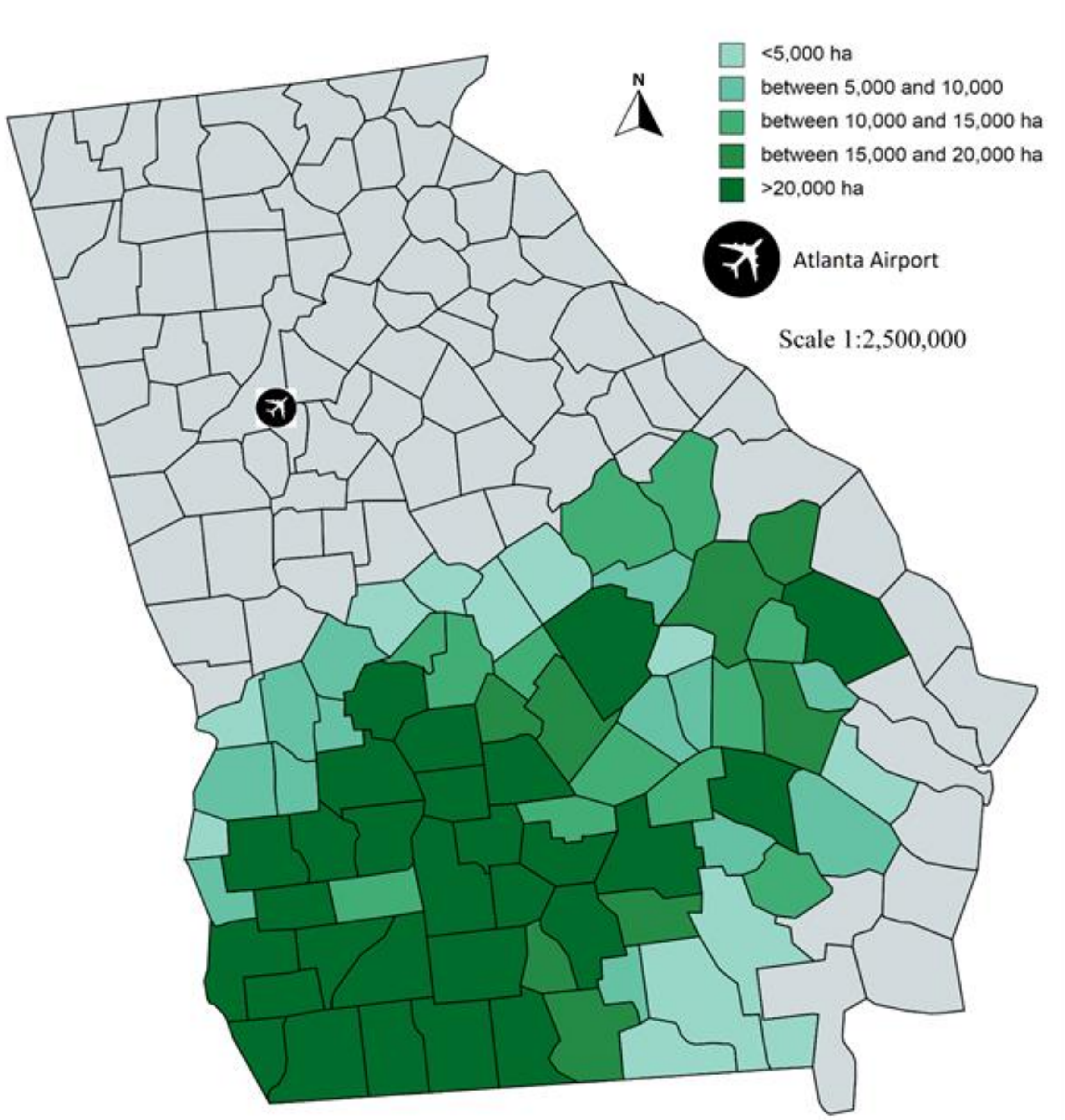

Figure 4.2. Area planted under carinata across counties located in Georgia, United States.

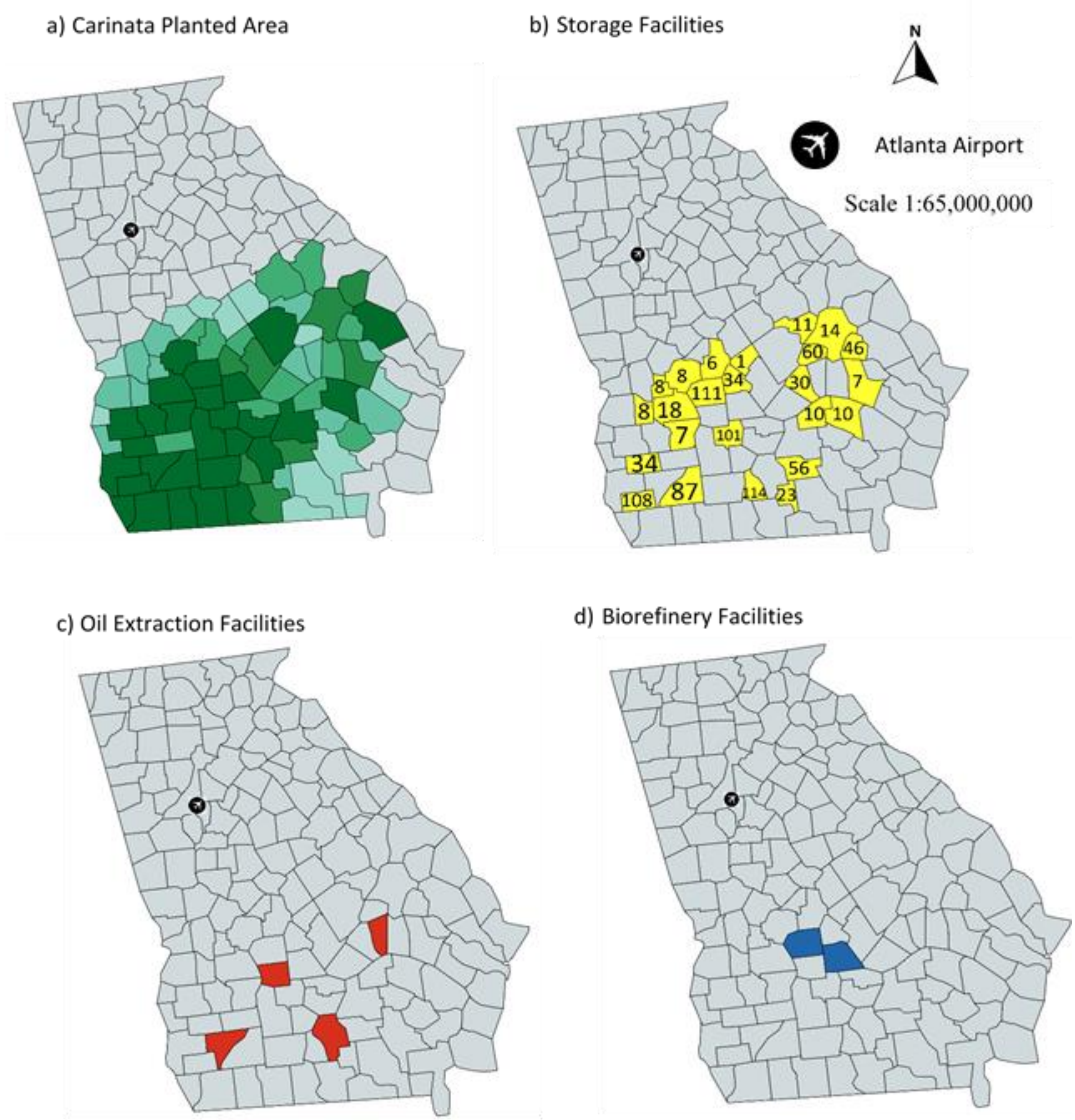

Figure 4.3. Carinata-based SAF supply chain feedstock and facilities locations.

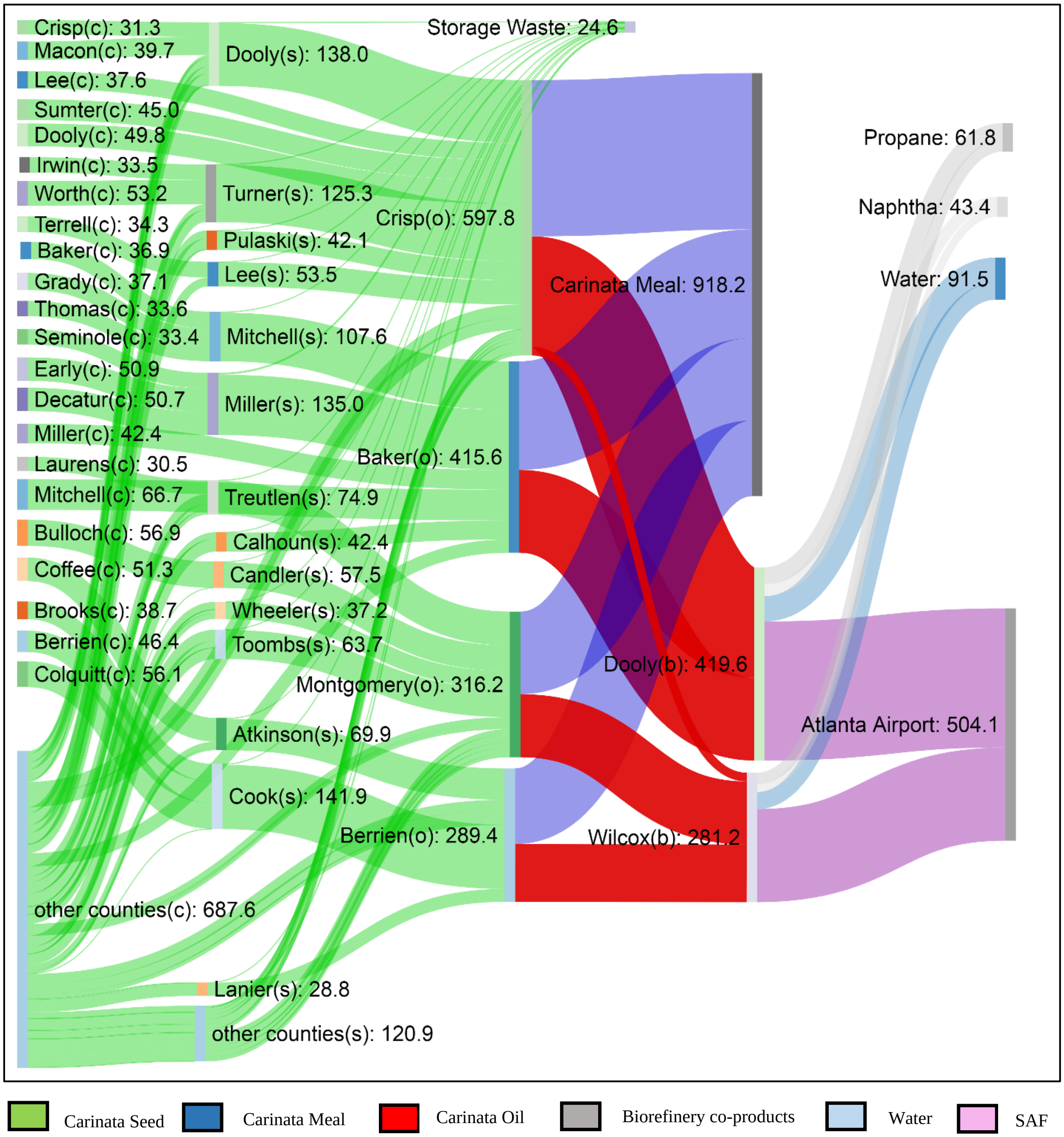

Figure 4.4. Carinata seed, carinata oil, and SAF mass flow across counties (all in thousand tons).

The results show that the total supply chain cost over four years is $2.85 billion, which gives a SAF unit cost of $1.24/liter. Figure 4.5 shows the share of the cost in the unit cost of SAF. From the $1.24/liter production cost of carinata-based SAF, $1.08 is the share of carinata seed cost, $0.99 is for biorefinery cost, $0.07 oil extraction cost, $0.05 storage cost, and $0.03 is transportation cost. Co-products of carinata-meal, propane, and naphtha decrease the unit cost by $0.51, $0.11, and $0.09/liter, respectively.

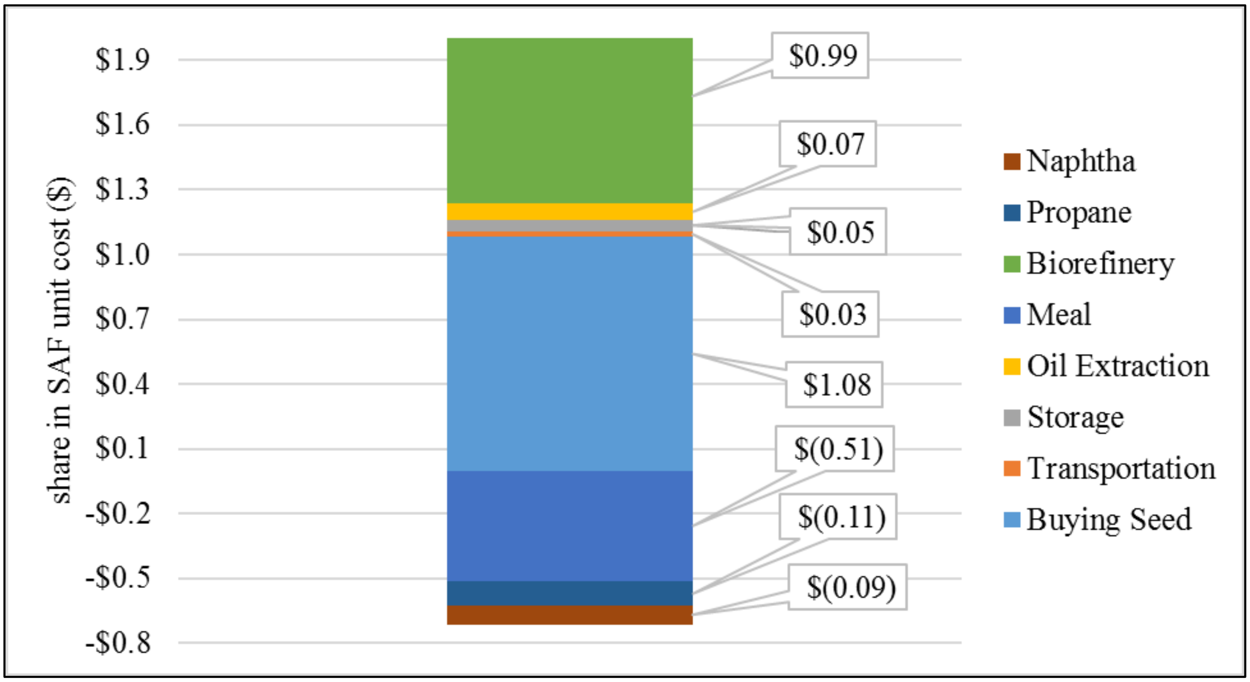

Figure 4.5. Cost of different stages in the unit price of carinata-based SAF

To address the issue of the supply chain scale, we ran the model for five different scenarios. We tried to see what will be the total and unit cost changes if we produce different amounts of SAF. The same supply chain model was estimated to replace 2.6%, 5.2%, 7.8%, 10.4%, and 13% of ATL conventional fuel demand with SAF. We wanted to analyze the impacts of scale on the unit cost of carinata-based SAF. Figure 4.7 illustrates the impacts of the supply chain scale on SAF unit cost per liter. The general trend shows that the relationship between the scale and cost is not linear. It decreases from $1.32 to $1.23 per liter when we produce 7.6% instead of 2.6% of conventional fuel. Afterwards, it increases and ends at $1.24 for the last scenario. Accordingly, the SAF unit cost of $1.24/ liter is the highest for the last scenario when we want to replace 13% of conventional fuel with SAF. In contrast, the lowest cost of $1.23/ liter is for the third scenario. Therefore, it is the best scale due to the lowest unit cost.

Figure 4.5 illustrates the share of different stages in total carinata SAF supply chain cost. The feedstock cost with 87.0% has the highest share, and transportation cost has the lowest share with 1.6%. The co-products of carinata meal, propane, and naphtha decrease the unit cost by 41.4%, 8.9%, and 7.1%, respectively.

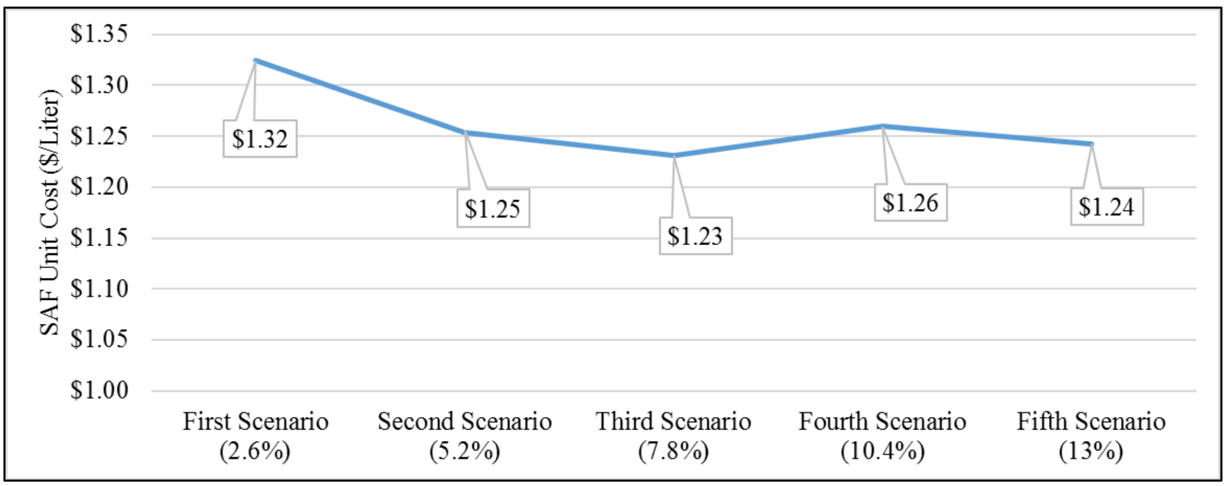

Figure 4.6. Effects of supply chain scale on SAF production cost

To better understand why the SAF unit cost is different across scenarios, we need to see what is the share of different stages in SAF unit cost across scenarios. Figure 4.7 illustrates the share of various stages in total carinata SAF supply chain cost for different scenarios. For example, in 13% scenario, the feedstock cost with 55.3% has the highest share, and transportation cost has the lowest share with 1.0%. The co-products of carinata meal, propane, and naphtha decrease the unit cost by 26.3%, 5.7%, and 4.5%, respectively.

Oil extraction and storage costs are rather the same across the first three scenarios. The reason that the SAF unit cost is the least in the third scenario is that the model is using the biorefinery facilities in a more efficient way. The share of biorefinery cost in the third scenario is \$0.76/liter, which is the lowest across all scenarios. For the first three scenarios, there is one biorefinery to be used (not showed in the graph). However, a lower amount of SAF is produced in the first and the second scenario. It is possible to produce more SAF (at least 2.6% more) in the third scenario with one biorefinery. It lowers the unit cost at biorefinery (38.9% for the third scenario versus 39.7% and 41.8% for the second and third scenarios, respectively). As a result, SAF production unit cost also goes down (\$1.23/liter for the third scenario versus \$1.32/liter and \$1.25/liter for the first and second scenarios, consecutively). Finally, in the fifth scenario, which is using two biorefinery facilities (not shown in the graph), it is possible to produce 5.2% more SAF compared to the third scenario. The difference between SAF unit costs decreases to \$0.1/liter (\$1.23/liter versus \$1.24/liter).

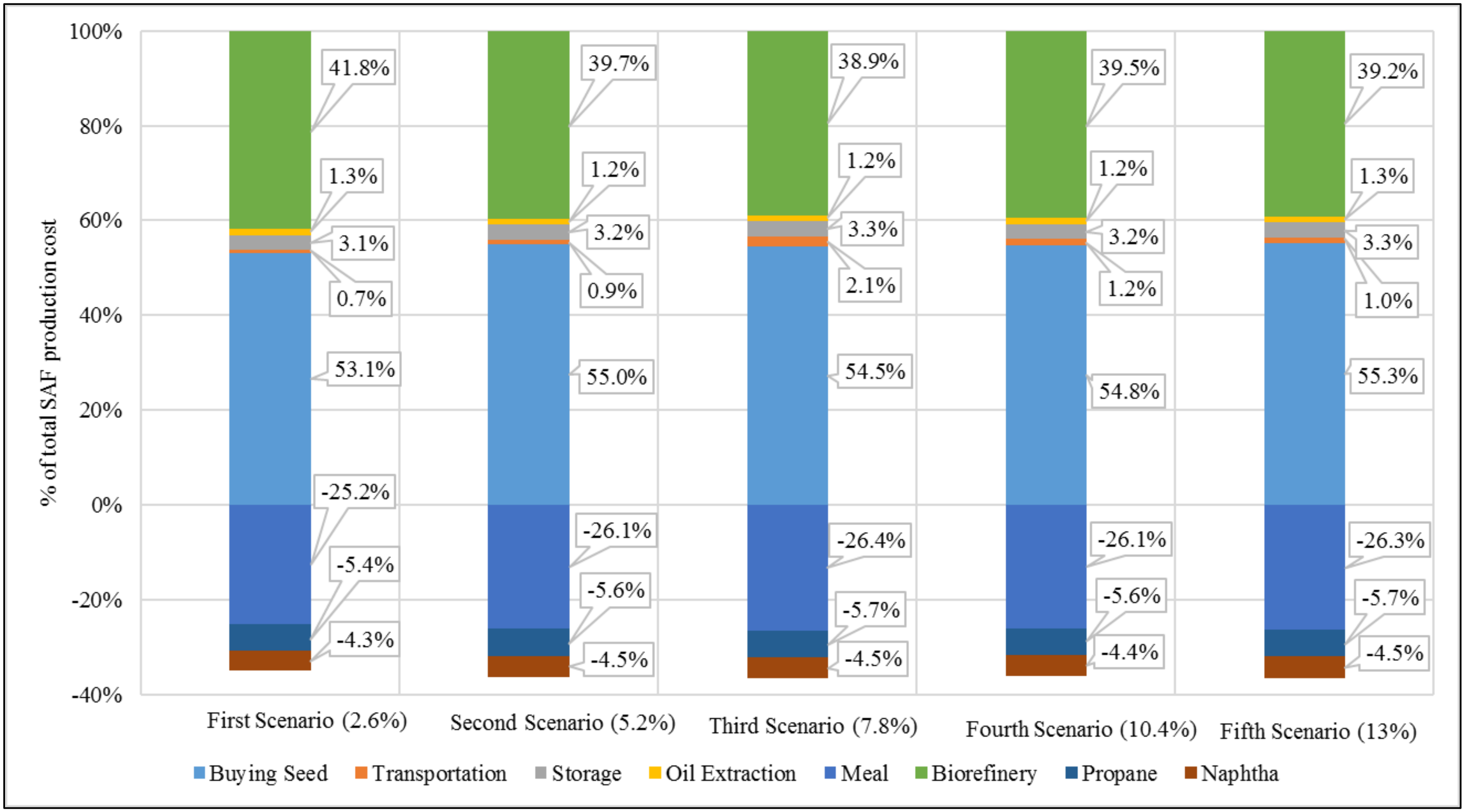

Figure 4.7. Share of different. stages in total supply chain cost across different scenarios

4.4. Discussions and Conclusion

The aviation industry emitted 785 million metric tons of CO_2 emissions in 2019, which accounted for around 2% of all human-induced CO_2 emissions (Graver, 2020). The development of SAF can help to reduce GHG emissions from aviation, reduce fossil fuel imports, and improve energy security. The advantage of carinata-based SAF is that it uses renewable biomass as the primary feedstock, which does not compete with the food supply. However, due to low energy intensity and the spread of biomass, managing the supply chain is very challenging. In this study, we set up the supply chain for SAF from carinata in Georgia to replace 13% of fossil fuel for Atlanta airport. The production cost for carinata-based SAF is much higher than the jet fuel price of $0.49 per liter in 2019 (EIA, 2021). This means that without support from the government (tax credits etc.), it is not economically feasible to produce SAF from carinata in Georgia. Similar results were obtained by Huang et al. (2019), Perkis & Tyner (2018), and Reimer & Zheng (2017). However, the amount of the difference between conventional jet fuel and SAF is different. For instance, Huang et al. (2019) found that the production cost of SAF is around $1.23/liter. This is very similar result to our study. Similar results were obtained by Perkis & Tyner (2018) and Reimer & Zheng (2017). In one the most similar studies to the current study, Eswaran et al. (2021) estimated the SAF production cost from carinata oil which was $1.32/liter. However, the feedstock for SAF was carinata oil, and they did not consider oil extraction process. To decrease the gap between the conventional jet fuel and SAF, Reimer & Zheng (2017) suggested a 17% subsidy on the alternative fuel, a 20% tax on the conventional fuel, or a combination 9% subsidy on the alternative and 9% tax on the conventional fuel.

We also tried to see what is the impact of economy of scale on the supply chain results. Across five different scenarios, the scenario where we are displacing 7.8% of the total conventional jet fuel consumed at Atlanta airport was the cheapest, with a unit cost of $1.23/liter of carinata-based jet fuel produced. We found that the production cost usually decreases with scale, however; larger scales require larger feedstock collection areas, as well as greater average transport distances and delivered feedstock costs (Brinsmead et al., 2015). There will always be a trade-off between diseconomies for transport/facilities cost and economies of scale for plant processing (Brinsmead et al., 2015). However, we found that even replacing 13.3% of the annual conventional jet fuel consumed at Atlanta, would only increase the unit cost of carinata-based SAF by $.0.1/liter.

The main limitation of the study is the 4-year timeline. We choose the timeline of 4-years because we wanted to consider the two-year gap between carinata planting at the farm. This is the minimum timeline that we can consider for a supply chain model. Because the ages of facilities are more than four years, we used depreciated values of facilities for a four-year plan. Future studies can consider longer timelines.

Carinata is not the only biomass that can be used for SAF production in Georgia. Other feedstocks, such as corn stover, etc., are available as well. The current study is limited to SAF production from carinata only. For future studies, we suggest looking into other feedstocks for SAF production in Georgia.

The other objective functions in the supply chain can be minimizing GHG emission and/or risk function. Future studies can optimize the supply chain with other objectives or can use a multi-objective optimization approach.

We hope that our study will guide ongoing initiatives across the United States for promoting SAF production from numerous feedstocks for achieving policy objectives of mitigating carbon emissions, supporting rural economies, and promoting bio-economy development for achieving goals of sustainable development at regional and national levels.

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Chapter 5

Conclusion

The emission from the aviation sector was 785 million metric tons of CO_2 in 2019, which was around 2% of all human-induced CO_2 emissions (Graver et al., 2020). The share of United States aviation was around 255 million metric tons, around 23% of the global aviation-related carbon emissions (Graver et al., 2020).

Drop-in sustainable aviation fuel (SAF) derived from carinata (*Brassica carinata*) could reduce CO_2 emissions of the aviation sector in the United States. The SE United States could play a crucial role in carinata production with their year-round growing season, suitable soils, and sufficient rainfall. However, a need exists to understand better the tradeoffs between economic and environmental impacts of carinata production at the farm level relative to current crop rotations practiced by farmers in the SE United States.

In the second and third chapters of this dissertation, I considered 292 possible crop rotations in South Georgia to see the impact of carinata on farm-level environmental impacts and profitability over time. My results show that carinata makes the highest profit in corn-corn-soybean; however, cotton-cotton-peanut is the best rotation for carinata to have the minimum risk. Including both the environmental and economic (NPV) criteria showed that carinata is the most eco-efficient in cotton-cotton-soybean rotation. In general, carinata rotations had higher NPV, and they also had lower financial risk and environmental impacts. Since carinata has a higher profit and lower CO_2 emissions than wheat, and the energy crop comes in rotation with summer crops that have lower CO_2 emissions. Also, cotton and soybean emit lower CO_2 than corn and peanut. Consequently, it is sensible that carinata rotations with cotton and soybean are eco-efficient. Therefore, farmers should sow carinata in rotation with cotton and soybean to make more profit and emit lower emissions.

Due to low energy intensity and the spread supply of biomass, managing the supply chain of SAF is challenging. In the fourth chapter, I optimized a supply chain for carinata-based SAF production in Georgia to replace 13% of jet fuel consumed at Atlanta airport. The production cost for carinata-based SAF is much higher than the jet fuel price of $0.49 /liter in 2019 (EIA, 2021). It means that without support from the government (tax credits etc.), it is not economically feasible to SAF from carinata in Georgia. We suggest either a tax on conventional jet fuel or a subsidy on produced SAF to make it feasible for the companies to invest in the industry. The economy scale results showed that the optimal scale of the supply chain is when we meet 7.8% of conventional fuel by carinata-based SAF.

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Appendix

Table S1: Farm-level production cost and income of carinata in Georgia in 2019

Costs	Unit	Amount	$/Unit	$/ha
Seed	kg	5.6	$11.0	$61.8
Nitrogen	kg	89.7	$1.1	$98.8
phosphoric pentoxide	kg	44.8	$0.9	$41.5
Potassium oxide	kg	89.7	$0.8	$69.2
Sulphur	kg	28.0	$2.7	$74.1
Crop Insurance	ha	1.0	$49.4	$49.4
Prevathon (Chlorantraniliprole)	liter	1.5	$30.4	$44.4
Glyphosate	kg	1.7	$6.4	$11.1
Ethalfluralin	kg	2.62	30.9	$81.0
Saflufenacil	kg	5%	507.0	$25.0
Priaxor Xemium	liter	1	139.0	$81.1
Delivery	ha	1	12.4	12.4
Land Preparation	ha	1	43.2	43.2
Fuel	liter	178.2	0.7	124.8
Irrigation	application	1	17.3	17.3
Interest on Operating Cost	%	6	-	50.1
Total Costs	$/ha	$707.2		
Price	$/t	$440.9		
Yield	kg/ha	2522.0		

Source: (National Peanut Research Laboratory 2020) and (R Seepaul et al. 2019)

Table S2: Farm-level production cost and income of corn in Georgia in 2019

Costs	Unit	Amount	$/Unit	Cost/ha
Treated Seed	thousand	79.1	3.5	276.8
Lime	t	1.1	49.6	55.6
Nitrogen	kg	269.0	1.1	296.5
Phosphate	kg	112.1	0.97	108.7
Potash	kg	224.2	0.7	158.1
Weed Control	ha	1.0	28.3	28.3
Insect Control	ha	1.0	20.6	20.6
Disease Control	ha	1.0	46.4	46.4
Fuel	liter	69.6	0.7	46.0
Repairs and Maintenance	ha	1.0	50.6	50.6
Labor	hours	2.6	13.3	34.2
Irrigation*	applications	8	22.7	181.9
Crop Insurance	ha	1	34.6	34.6
Interest on Operating Cost	%	6	-	41.8
Drying - 8 Points	kg	13776.9	0.01	151.9
Total Costs	$/ha			1,532.0
Price	$/t			178.3
Yield	kg/ha			12552.9

Source: (University of Georgia Cooperative Extension 2019)

Table S3: Farm-level production cost and income of cotton in Georgia in 2019

Costs	**Unit**	**Amount**	**$/Unit**	**Cost/ha**
Crop Insurance (Excluding STAX)	ha	1.00	19.8	19.8
Seed (Including Tech Fees and Seed Treatments)	1,000 seed	89.7	2.6	236.8
Lime- Custom Spread	t	0.7	49.6	36.7
Nitrogen	kg	100.9	1.1	111.2
Phosphate (P2O5)	kg	78.5	0.97	76.1
Potash (K2O)	kg	78.5	0.7	55.4
Boron, Sulfer, and Others	ha	1.0	14.8	14.8
At Planting or PRE	ha	1.0	23.6	23.6
POST	ha	1.0	100.9	100.9
Layby	ha	1.0	35.9	35.9
Hand Weeding	ha	1.0	24.7	24.7
Scouting	ha	1.0	24.7	24.7
Spray- Stink Bugs, Other Pests	applications	2.0	16.9	33.7
PGR	liter	2.6	1.7	4.6
Defoliant and Boll Opener	ha	1.0	35.3	35.3
Irrigation	applications	8.0	22.7	181.9
Fuel and Lube	liter	121.2	0.66	80.0
Repairs and Maintenance	ha	1.0	70.6	70.6
Labor	hours	4.9	13.3	65.1
Interest on Operating Cost	%	6	-	38.5
Ginning	kg	1345.0	0.2	237.2
Storage and Warehousing	kg	1355.9	0.05	62.8
Promotions, Boards, Classing	kg	1355.9	0.03	36.1
Cottonseed Credit	t	1.7	132.3	-222.4
BWEP	kg	1.4	3.3	4.5
Total Cost	$/ha			1388.5
Price	$/t			1,351.4
Yield	kg/ha			1,345.0

Source: (University of Georgia Cooperative Extension 2019)

Table S4: Farm-level production cost and income of peanut in Georgia in 2019

Costs	Unit	Amount	$/Unit	Cost/ha
Seed	kg	156.9	1.9	294.1
Inoculant	kg	5.6	4.2	22.9
Lime/Gypsum	t	1.1	115.7	129.7
Boron	kg	0.6	13.2	7.4
Weed Control	ha	1	95.0	95.0
Hand weeding	ha	1	37.1	37.1
Insect Control	ha	1	151.3	151.3
Scouting	ha	1	24.7	24.7
Disease Control	ha	1	229.0	229.0
Fuel	liter	160	0.66	105.8
Repairs and Maintenance	ha	1	116.9	116.9
Labor	hours	6.2	13.3	82.3
Irrigation	applications	6	22.7	136.4
Crop Insurance	ha	1	44.5	44.5
Interest on Operating Cost	%	6	-	46.2
Cleaning	t	1.7	22.1	38.3
Drying	t	3.5	33.1	116.7
Marketing	t	5.3	3.3	17.4
NPB Checkoff	$	0.01	2061.5	20.6
Total Cost	$/ha			1,716.2
Price	$/t			429.9
Yield	kg/ha			5268.0

Source: (University of Georgia Cooperative Extension 2019)

Table S5: Farm-level production cost and income of soybean in Georgia in 2019

Costs	Unit (SI)	Amount	$/Unit (SI)	Cost/ha
Seed	bag	2.5	53.0	131.0
Inoculant	ha	1.0	16.1	16.1
Lime	t	0.7	49.6	36.7
Phosphate	kg	44.8	0.97	43.5
Potash	kg	89.7	0.7	63.3
Boron	kg	0.6	13.2	7.4
Weed Control	ha	1.0	67.2	67.2
Insect Control	ha	1.0	9.9	9.9
Disease Control	ha	1.0	59.0	59.0
Fuel	liter	63.1	0.66	41.7
Repairs and Maintenance	ha	1.0	45.0	45.0
Labor	hours	2.3	13.3	30.4
Irrigation	application	5.0	22.7	113.7
Crop Insurance	ha	1.0	22.2	22.2
Interest on Operating Cost	%	6	-	20.6
Total Costs	$/ha			707.5
Price	$/t			328.9
Yield	kg/ha			4035.1

Source: (University of Georgia Cooperative Extension 2019)

Table S6: Farm-level production cost and income of winter wheat in Georgia in 2019

Variable Costs	Unit	Amount	$/Unit	Cost/ha
Treated Seed	kg	100.9	0.6	60.1
Lime	t	560	0.5	28.4
Nitrogen	kg	89.7	1.0	92.9
Phosphate	kg	44.8	0.9	41.5
Potash	kg	44.8	0.7	31.6
Weed Control	ha	1.0	94.9	94.9
Insect Control	ha	1.0	7.4	7.4
Disease Control	ha	1.0	11.9	11.9
Fuel	liter	62.8	0.7	44.0
Repairs and Maintenance	ha	1.0	35.2	35.2
Labor	hours	1.8	13.0	24.0
Crop Insurance	ha	1.0	30.9	30.9
Interest on Operating Cost	%	6	-	15.1
Drying - 2 Points	kg	4.1	3.3	13.4
Total Costs	$/ha			531.3
Price	$/t			180.0
Yield	kg/ha			3698.9

Source: (University of Georgia Cooperative Extension 2019)