ASSESSING POTENTIAL, CARBON INTENSITY, AND UNIT COST OF JET FUEL DERIVED FROM CARINATA IN THE SOUTHEASTERN UNITED STATES

by

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(Under the Direction of Puneet Dwivedi)

ABSTRACT

The use of oil obtained from crushing carinata (Brassica carinata) seeds for producing drop-in jet fuel could help in reducing the carbon footprint of the aviation sector. Our suitability model suggests that about 7.12 million metric tons of carinata can be produced in southeastern states using average carinata yield of 2802.70 kg per hectare at 5% composite risk level. We found that 821.84 kg of CO_2 equivalent GHGs (greenhouse gases) are released while producing 1,000 liters of carinata-based jet fuel. Total savings in GHG emissions will be 85.9%, 69.8%, and 76.4% relative to 1,000 liters of conventional jet fuel based on the mass, market, and energy allocations, respectively. The estimated production price at bio-refinery gate ($0.85/l) was about 30% higher than the current price of conventional jet fuel ($0.55/l) indicating that an incentive of $0.30/l is needed for promoting the production of carinata-based jet fuel in the southeastern United States.

Keywords: Greenhouse Gases, Suitability Model, Life Cycle Analysis, Hydroprocessed Esters and Fatty Acids, Co-products, Bio-jet Fuel, Economic Incentives

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CHAPTER 1

INTRODUCTION

The total number of air travelers will reach up to 7.8 billion by the end of 2036, a near doubling of the four billion air travelers in 2017 (IATA 2017a). Currently, the global aviation sector consumes about 341 billion liters of jet fuel every year (IATA 2017b), and it is expected that the demand for jet fuel will increase by 50% by the end of 2050 (IATA 2017c). Rising demand for jet fuel is raising concern about the carbon footprint of the aviation sector. In 2017, commercial aviation emitted about 859 million metric tons of carbon dioxide which was about two percent of all man-made carbon dioxide emissions (IATA 2018). It is projected that the carbon dioxide emissions from the aviation sector could soar up to 20.2% of total man-made global carbon dioxide emissions by 2050 in the absence of any immediate initiatives focusing on reducing the carbon footprint of the sector (IATA 2018).

The International Civil Aviation Organization (ICAO), a specialized agency of the United Nations established in 1944 with currently 192 member states, adopted an ambitious goal in 2010 emphasizing on the carbon-neutral growth of the aviation sector by 2020 (ICAO 2017). Correspondingly, the International Air Transport Association (IATA), a global trade association of airlines currently with 280 members over 120 countries adopted the following three goals for reducing the carbon footprint of the aviation sector. The first goal focuses on an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020. The second goal focuses on capping net aviation carbon dioxide emissions from 2020 emphasizing on carbon-neutral growth of the aviation sector reflecting on ICAO’s resolution. The third goal aims to achieve a reduction in net aviation carbon dioxide emissions of 50% by 2050, relative to 2005 levels (IATA 2018). For realizing carbon reduction goals, the ICAO in conjunction with IATA launched Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2018 laying the foundation for states and airlines to adopt and use market-based mechanisms for offsetting carbon emissions related to the global aviation sector (IATA 2018).

The use of biomass-based jet fuel is a critical part for achieving the overall goal of carbon-neutral growth of the global aviation sector by 2020 (EIA 2017a). Several studies have analyzed carbon savings resulting from the use of various biomass-based jet fuels relative to petroleum-based jet fuel (Table 1). These studies overwhelmingly suggest that the use of biomass-based jet fuel will significantly save carbon emissions ranging from 50% to 78% relative to petroleum-based jet fuel. However, a closer look on existing studies suggest that the majority of these studies rely upon traditional bioenergy feedstocks (e.g., switchgrass (*Panicum virgatum*), jatropha (*Jatropha curcas*), algae, etc.) and overlook new feedstocks which could be potentially utilized for the production of bio-jet fuel.

Table 1.1: Summary of studies reflecting on carbon savings related to the use of bio-jet fuel relative to petroleum-based jet fuel.

Feedstock	Study Area	Savings in Greenhouse Gas Emissions	Reference
Canola	United States	50%	Ukaew et al. 2016
Algae	United States	76%	Fortier et al. 2014
Camelina	United States	74%	Agusdinata et al. 2011
Residual Wood	United States	78%	Ganguly et al. 2018
Sugarcane	United States	71%-75%	Jong et al. 2017
Corn Stover	United States	60%-75%	Jong et al. 2017

Ethiopian Mustard (*Brassica carinata*) was introduced in the southeastern United States in 2010 through a joint research collaboration between the University of Florida and Agrisoma Biosciences, Inc. Carinata could provide a climate-friendly, sustainable option for replacing jet fuel consumed in the United States without getting into the debate of food versus fuel as it is not fit for direct human consumption. This is especially true as the United States alone consumed 64.3 billion liters of jet fuel in 2017, i.e., 18.7% of the global jet fuel consumption in 2017 (EIA 2017b). Moreover, carinata is well integrated into the current cropping systems in the southeastern region, as it grows well in winter months and, therefore, provides much-needed cover to otherwise exposed soils. It improves soil quality by recycling deeper soil nutrients, reducing erosion, and controlling weeds and diseases when added to the current crop rotation. Additionally, carinata is agronomically superior and frost tolerant than any other oilseed crops grown in the southeastern United States with higher oil content (more than 40%), larger seed size, and lower lodging and shattering rates (Seepaul et al. 2016). Finally, the use of carinata for jet fuels, feed, and chemicals could provide increased income to farmers, create local jobs, and boost local economies and, thus, could jumpstart the bio-economy in the southeastern United States.

The overall aim of the research is to determine the overall availability and environmental and economic sustainability of carinata-based jet-fuel across three southeastern states of Georgia, Florida, and Alabama using a mixture of advanced geospatial technologies and a combination of life-cycle and techno-economic analyses. This study is further divided into two objectives. The first objective models the site suitability of carinata production and then determines the production potential of carinata-based jet fuel in the southeastern United States. The second objective calculates the unit aboveground GHG emission and unit cost related to the production of carinata-based jet fuel by following a farm-to-gate system boundary. We are hopeful that this study will bring forward the role of carinata-based jet fuel in reducing the overall emission of GHGs from the aviation sector, thereby establishing a sustainable supply chain of carinata-based jet fuel in the southeastern states.

CHAPTER 2

MODELING SITE SUITABILITY AND PRODUCTION POTENTIAL OF CARINATA-BASED JET FUEL IN THE SOUTHEASTERN UNITED STATES

Literature Review

Several studies have analyzed the suitability of various crops and their byproducts and dedicated bioenergy crops in different regions of the world (Lewis and Kelly 2014). Miyake et al. (2015) developed a site suitability model and integrated the same with a land cover change model for two different crops Pongamia (*Millettia pinnata*) and two eucalypt species (spotted gum (*Corymbia citriodora* subsp. *Variegata*) and Chinchilla white gum [*Eucalptus argophloia*]) for Burnett River catchment in subtropical Queensland, Australia. Pulighe et al. (2016) assessed the agronomic feasibility of biomass crops (several lignocellulosic crops, starch-based crops, sugar-based crops, and oilseed crops including rapeseed and carinata) using advanced geospatial modeling tools for ascertaining the most profitable renewable feedstock for a marginal and heavy-metal polluted area located in the Sulcis District, Sardinia, Italy. It was found that giant reed (*Arundo donax* L.), native perennial grasses, and milk thistle (*Silybum marianum*) were the most suitable energy crops in the study area. Abolina et al. (2015) used advanced geospatial techniques for ascertaining the availability of land (261,710 hectares) to produce the short rotation woody crop in Latvia for meeting the European Union renewable energy targets by 2020. Lu et al. (2012) determined the spatial distribution, quality and the total amount of marginal land resources suitable for cultivating *Pistacia chinensis* using multiple datasets (natural habitat, remote sensing-derived land use, meteorological and soil data) and geoinformatic techniques and found that 19.9 million hectares of marginal land can be used for planting *Pistacia chinensis* in China sufficient enough for producing 56.85 million tons of biodiesel annually.

In the United States, Graham et al. (2000) developed a spatial explicit model for determining the economic suitability of supplying switchgrass (*Panicum virgatum*) for eleven states and found that the delivered feedstock costs ranged from $33-$55 and $36-$58 per dry metric ton for a facility requiring 100,000 and 630,000 dry metric tons of biomass annually, respectively. Nepal et al. (2014) developed a spatially explicit model for determining suitable sites to produce sweet gum (*Liquidambar styraciflua* L.) for bioenergy development in northern Kentucky by integrating existing road networks and economics related to biomass production and transportation. It was found that 10,088 hectares of land could be potentially used for sweet gum considering site suitability and economic feasibility. Recently, Shrestha and Dwivedi (2017) developed a suitability model for analyzing the feasibility of growing loblolly pine (*Pinus taeda*) in the southeastern United States in the context of growing transatlantic wood pellet trade and then integrated the same for ascertaining projected land use changes over time at the watershed level. Similarly, several other studies have integrated site suitability with economic modeling or land use change modeling for ascertaining the production feasibility of a potential bioenergy feedstock or location of a potential bioenergy conversion facility in the United States (Noon et al. 2002; Ma et al. 2005; Haddad and Anderson 2008; Zhang et al. 2011; Sahoo et al. 2016; Sharma et al. 2017). A few studies have also considered the suitability of growing bioenergy crops at national and regional scales using advanced suitability modeling approaches (Barney and DiTomaso 2010; EVANS et al. 2010).

A perusal of current literature suggests that no study has analyzed the site suitability of growing carinata in the United States, in general, and the southeastern United States, in particular to the best of our knowledge. An understanding about the total production potential of carinata followed by the total production potential of carinata-based jet fuel is critical for streamlining current initiatives led by different corporations and non-corporations for reducing the carbon footprint of the aviation sector at national and global levels. Second, no study has accounted for climate-related and land availability related risks simultaneously while determining the total production feasibility of bioenergy feedstocks at any scale. As a result, our study is extending the current frontiers of suitability modeling for bioenergy feedstocks. We hope that our study will guide future studies focusing on suitability modeling of bioenergy feedstocks in the United States and beyond.

Study Area

The southeastern states of Georgia, Florida, and Alabama (Figure 2.1) cover a total land area of 43.2 million hectares out of which 17.5% (7.6 million hectares) is under agriculture (Figure 2). Out of the total area under agriculture, farmers grow winter cover crops only in 0.11 million hectares suggesting that about 98.56% (7.4 million hectares) of agriculture land in selected states is fallow in winter months. This land can be potentially utilized for producing carinata. Furthermore, the average winter temperatures in Georgia, Florida, and Alabama are 9.3°C, 12.7°C, and 10.3°C, respectively and most of the rainfall happens in winter and spring months in these states. Since carinata prefers cooler temperatures and requires lower water inputs; therefore, carinata is well placed as a winter crop in the selected southeastern states.

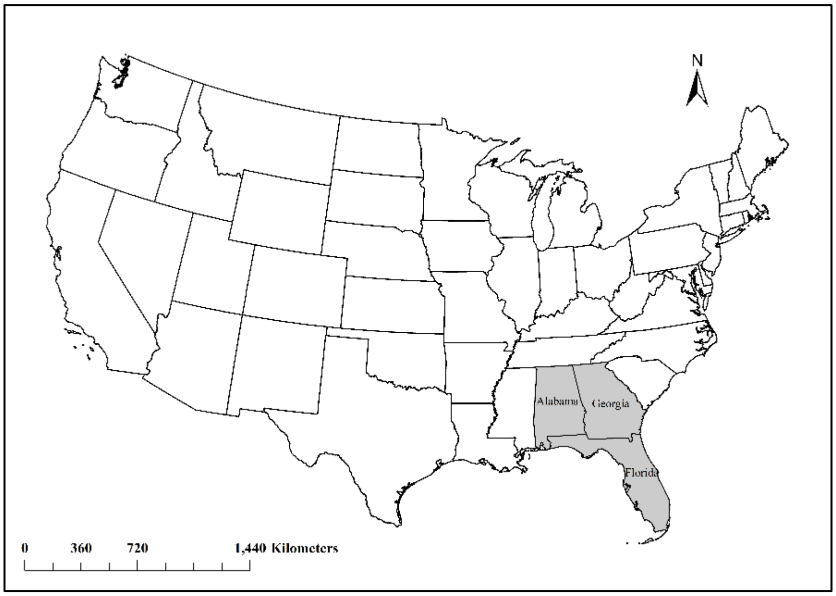

Figure 2.1: Location of selected states (Georgia, Florida & Alabama) for the suitability analysis

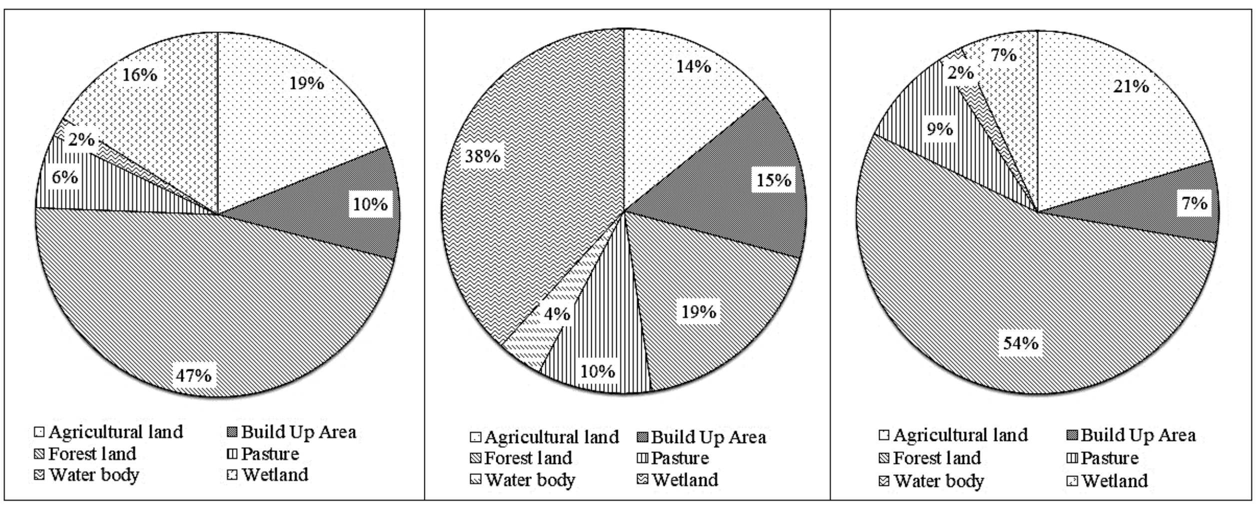

Figure 2.2: Major land uses in Georgia, Florida, and Alabama in 2015 (USDA 2017)

Methods

Survey for Ascertaining Critical and Screening Variables

First, we surveyed scientists from the University of Florida, the University of Georgia, Auburn University, Mississippi State University, and the United States Agricultural Research Service working together under the recently funded Coordinated Agricultural Project Southeast

Partnership for Advanced Renewables from Carinata (SPARC, https://sparc-cap.org/) for identifying factors which would potentially affect carinata productivity and acreage in selected states. Based on the received inputs, three variables namely average water storage (quantity of water that the soil is capable of storing for use by plants), soil organic matter (component of soil, consisting of plant and animal residues at various stages of decomposition), and root zone depth (the depth within the soil profile that roots can effectively extract water and nutrients for growth) were identified as critical in determining carinata productivity. Participating scientists also mentioned that current land use should be used as a screening variable and the suitability analysis should only include those lands which are currently under agriculture (row crop, double crop, and winter crop excluding land under orchards) in selected states. It was also suggested that soil texture, soil pH, and public lands should be used as other screening variables in the suitability analysis. Finally, participating scientists suggested including the probability of frost events based on historical climate data and risk of land availability based on historical land use as a part of the suitability analysis for estimating the total potential of carinata production and corresponding bio-jet fuel supply in the selected states.

Database Preparation

We collected and organized various public raster datasets to prepare a combined database containing information on the spatial distribution of average water storage, soil organic matter, root zone depth, soil texture, soil pH, current and historical land use (Table 2.1). Then, we resampled the input raster datasets to 500 x 500 meters (25 hectares) resolution using the nearest neighbor resampling technique. We selected this resolution for two reasons. First, the selected resolution was reasonable enough to capture any within farm variations for selected variables as it represented about 23% of average farm size across Georgia (92.2 hectares), Florida (80.9 hectares), and Alabama (83.3 hectares) (USDA 2017). Second, the selected resolution facilitated data analysis considering computing constraints. For example, at an original resolution of 30 x 30 m for land use input data, the total number of rows in the database would have been 169.4 million for Georgia alone making analysis time-consuming and perhaps, not possible. After resampling, we re-projected datasets used in the analysis using Universal Transverse Mercator (UTM) 17N for Georgia and Florida and UTM 16N for Alabama. We also included public ownership dataset in a vector format (Table 2.1) for selected states in the combined database. Finally, we created three separate datasets, one for each selected state, containing information on all the variables for each pixel present in the state. The dataset for Georgia, Florida, and Alabama had 14.23, 14.56, and 14.06 million rows of data with each row presenting a pixel of 500 x 500-meter resolution, respectively on the ground. Each dataset has 20 columns where the first column contained unique ID of every pixel, the second column contained latitude, the third column contained longitude, and remaining columns contained information about average water storage, soil organic matter, root zone depth, soil texture, soil pH, current (2015) and historical (2010-2015) land use, and ownership. We used ArcGIS 10.4 for the spatial analysis.

Table 2.1: Details of the input spatial data used in the analysis

Data label	Data Type	Resolution	Data Source
Cropscape Data Layer	Raster	30 x 30 m	National Agricultural Statistics Service (NASS), USDA
Soil	Raster	10 x 10 m	National Resource Conservation Service (NRCS), USDA
Rainfall	Raster	4 x 4 km	PRISM Climate Group, Oregon State University
Temperature	Tabular		Georgia- Georgia GIS Clearing House Florida- Institute of Food and Agricultural Service (IFAS), University of Florida Alabama- National Oceanic and Atmospheric Administration (NOAA), United States Dept. of Commerce
Historical Weather Data	Tabular		Georgia- Georgia GIS Clearing House Florida- Institute of Food and Agricultural Service (IFAS), University of Florida Alabama- National Oceanic and Atmospheric Administration (NOAA), United States Dept. of Commerce
Land Ownership	Vector		National Resource Conservation Service (NRCS), USDA

Data Preparation for Suitability Analysis

We screened the datasets for rows where land use in 2015 was not agriculture, pH was equal or less than 5, ownership was public, or soil texture was hard clay soil. These selected rows were deleted from further analysis. Then, we created three new columns for the remaining rows in each dataset. In the first column, normalized value for the critical variable average water storage was calculated for each row to ensure that the range of values across all rows is between 0 and 1. Similarly, for the other two new columns, the normalized value for the other two critical variables namely soil organic matter and root zone depth were calculated. We followed Equation 1 for obtaining normalized values.

$$\text{Normalized Value} = \frac{\text{Current Value of the Variable at a Given Pixel} - \text{Lowest Value of the Variable Across all Pixels}}{\text{Highest Value of the Variable Across all Across all Pixels} - \text{Lowest Value of the Variable Across all Across all Pixels}} \quad (1)$$

Ascertaining Weights of Critical Variables

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making technique that measures the relative priority of one variable over other variables through pairwise comparisons. The data obtained through pairwise comparisons are analyzed by following the EigenValue technique for determining relative weights of variables themselves. The use of AHP and its variants has become popular in the sustainable management of natural resources due to its operational simplicity in complex settings. Several bioenergy related studies have also integrated spatial modeling with AHP for successful completion of research objectives (Ma et al. 2005; Wu et al. 2011; Kurka 2013; Sharma et al. 2017).

We used the AHP for determining the relative weights of critical variables (average water storage, soil organic matter, and root zone depth) towards suitability analysis. First, we developed a questionnaire for surveying participating scientists. This questionnaire included detailed instructions for completing the questionnaire and short explanations of critical variables. For example, the questionnaire asked participants to compare the critical variable "average water storage" and "soil organic matter" (Figure 2.3). The questionnaire asked respondents to indicate their preference of one variable over the other for each pairwise comparison using the scale of Equal, Somewhat More Important, More Important, or Much More Important. We collected a total of 11 responses through an online survey. We assigned weighted numerical values (Equal = 1, Somewhat More Important = 3, More Important = 5, and Much More Important = 7) to the responses for analysis based on Dwivedi and Alavalapati (2009). We aggregated individual responses from the survey using the geometric mean method by following Dwivedi and Alavalapati (2009) and then used a standard AHP methodology for calculating relative weights of each critical variable. We also estimated the consistency of the subjective judgment using consistency ratio (CR) by following Dwivedi and Alavalapati (2009). If the CR value is less than or equal to 10% the consistency is considered to be acceptable. Otherwise, subjective judgment needs to be revised. In our case, CR was 0.35% which is much lower than the limit of 10% suggesting strong consistency across responses.

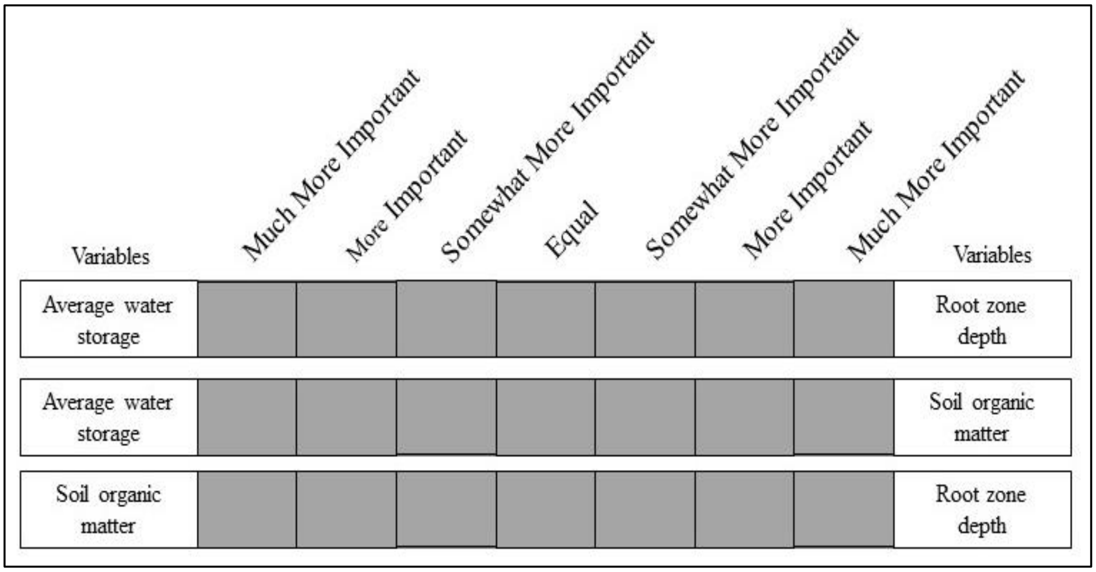

Figure 2.3: Scale used for pairwise comparisons for obtaining relative weights of critical variables using Analytical Hierarchy Process.

Suitability Analysis

We used Equation 2 to determine the overall site suitability score of each remaining row in the dataset. In Equation 2, W_1, W_2, and W_3 represent relative weights of critical variables namely average water storage, soil organic carbon, and root zone depth, respectively. For each state, we divided pixels into three categories of high, medium, and low suitability based on natural breaks present in the overall site suitability score.

$$\text{Overall Site Suitability Score} = W_1 \text{ x Normalized Value of Average Water Storage} + W_2 \text{ x Normalized Value of Soil Organic Carbon} + W_3 \text{ x Normalized Value of Root Zone Depth} \quad (2)$$

Composite Risk

We plotted weather stations located in each state and then deleted those weather stations for which data was unavailable in the public domain between 2010 and 2015. Then, we created a buffer of 80km around weather stations assuming that weather will be the same within the buffer distance at a given point in time (personal communication, Dr. Ian Flitcroft at the University of Georgia). Then, we selected 20, 17, and 14 weather stations in Georgia, Florida, and Alabama, respectively, for further analysis. We followed three rules to select these weather stations: First, these weather stations minimized overlapping buffer areas. Second, buffer around selected weather stations covered the entire state. Finally, selected weather stations were located along a gradient from North to South, similar to the temperature gradient observed in selected states. We obtained historical weather data for selected weather stations from different sources (Table 2.1). The frequency of weather data for Georgia and Florida was 15 minutes whereas, for Alabama, the frequency was 60 minutes due to restrictive data availability. We defined a catastrophic frost event as one when the temperature is less than -6.67 °C for 15 or more hours between December to February (personal communication, Dr. Ramdeo Seepaul at the University of Florida based on carinata field trials). We used weather data from 2010 to 2015 to estimate the probability of catastrophic risk at each weather station assuming a total number of growing days as 180. Then, we adopted the ordinary kriging approach in ArcGIS 10.4 to create a surface map (500 x 500-meter resolution) of catastrophic risk at the state level.

$$\text{Pr (Catastrophic Risk)} = \frac{\text{Number of frost events}}{\text{Number of days in growing season}} \quad (3)$$

We calculated the probability of land availability for growing carinata (500 x 500-meter resolution) based on historical land use using Equation 4. Then, we calculated the risk of land availability using Equation 5. Finally, we multiplied the probability of catastrophic risk and risk of land availability at each pixel and calculated the composite risk at each pixel.

$$\text{Pr (Land Availability for Growing Carinata)} = \frac{\text{Number of Agricultural/ Double/Winter Cropping Events}}{\text{Number of Growing Seasons}} \tag{4}$$

$$\text{Pr (Land Availability Risk)} = 1 - \text{Pr (Land Availability for Growing Carinata)} \tag{5}$$

Results

The relative weights for critical variables average water storage, soil organic carbon, and root zone depth were 0.249, 0.443, and 0.308, respectively. We found that Georgia had 42.12% of all land suitable for growing carinata across selected states (Table 2.2). We also noticed that most of the land suitable for growing carinata was in the medium category covering 2.32 million hectares, i.e., about 50% of total land suitable for growing carinata across selected states. Figure 2.4 details the spatial distribution of land suitability classes across each state. We did not include the southern part of Florida (starting from the City of Ocala in Florida) in our analysis due to the rising urban population, relatively warmer winter temperatures, high water table affecting root zone depth, and current lack of infrastructure to support carinata production and post-production logistics. Our results suggested that medium and high suitable sites for carinata production in Georgia are in the southern and northern part of the state, respectively. Most sites present in Alabama are highly suitable to grow carinata and are in the southern and northern part of the state. We also found that medium suitable sites are spread across parts of Florida analyzed in this study.

Table 2.2: Amount of suitable land (million hectares) across three states under selected suitability index class

	Suitable land area	Low	Medium	High
Georgia	1.95	0.33 (16.8%)	1.16 (59.4%)	0.46 (23.7%)
Florida	0.77	0.12 (16.2%)	0.62 (80.7%)	0.02 (3.0%)
Alabama	1.91	0.19 (10.2%)	0.54 (28.1%)	1.18 (61.6%)
Total	4.63	0.78 (16.9%)	2.32 (50.1%)	1.53 (33.0%)

Figure 2.5 shows the spatial distribution of catastrophic risk based on a few historical frost events for selected states. As expected, the probability of catastrophic risk decreases from North to South in Georgia following the temperature gradient which decreases from North to South as well. The same trend was also noticed for Alabama where the probability of catastrophic risk decreases from North to South. For Florida, the catastrophic risk decreases from West to East to a large extent as noticed in the historical weather records used for the analysis. Figure 2.6 shows the land availability risk for potentially growing carinata across three states. We have only considered those lands which were used for row cropping, double cropping, and winter cropping excluding land under orchards. We found that low land availability risks are related to those pixels which are in the agricultural region of selected states. For example, land availability risk was lower in the south-western part of Georgia which produces 20.3% of total farm value in Georgia (USDA 2017). A similar situation was observed for the other selected states. Figure 2.7 shows the distribution of composite risk. As noticed, south-western region of Georgia, south and south-eastern region of Alabama, and the Northern portion of Florida are suitable for growing carinata up to 5% risk level. Table 2.3 shows the availability of land across selected states under different risk levels. The suitable land for carinata production at five percent composite risk level is 2.54 million hectares across selected states whereas it increases to 4.42 million hectares at 20% composite risk level.

We also found that Alabama had the highest amount of suitable land whereas Florida had the lowest amount of suitable land for composite risk level up to 20%.

Table 2.3: Availability of suitable lands (million hectares) for carinata production at selected composite risk levels

	5% Risk Level	10% Risk Level	20% Risk Level
Georgia	0.88	1.39	1.84
Florida	0.45	0.63	0.72
Alabama	1.21	1.46	1.86
	2.54	**3.48**	**4.42**

We used input parameters reported in Table 2.4 for determining the total carinata production across selected states at different composite risk levels for three potential yield levels. Using average yield of carinata, we found that 7.12 million metric tons of carinata could be produced across selected states at 5% composite risk level out of which 47.12% could be potentially sourced from Alabama alone (Table 2.4). The range varied from 5.70 to 8.54 million metric tons using low and high carinata yield scenarios, respectively at the 5% composite risk level. We also found that as the composite risk level rises, the potential production of carinata goes up due to an increase in land availability. Table 2.5 reports the total production feasibility of bio-jet fuel production in selected states using Hydroprocessed Esters and Fatty Acids (HEFA) conversion technology as reported in GREET (Elgowainy et al. 2012). We found that 3,894.31 million liters of carinata-based jet fuel could be produced (Table 2.6) using average carinata yield and land availability at the 5% composite risk level across selected states which will be enough to replace 6.05% of total petroleum-based jet fuel consumed at the national level (64.35 billion liters) in 2017. We also found that this range could vary from 4.84% and 12.64% depending upon the selected yield and composite risk levels (Table 2.7).

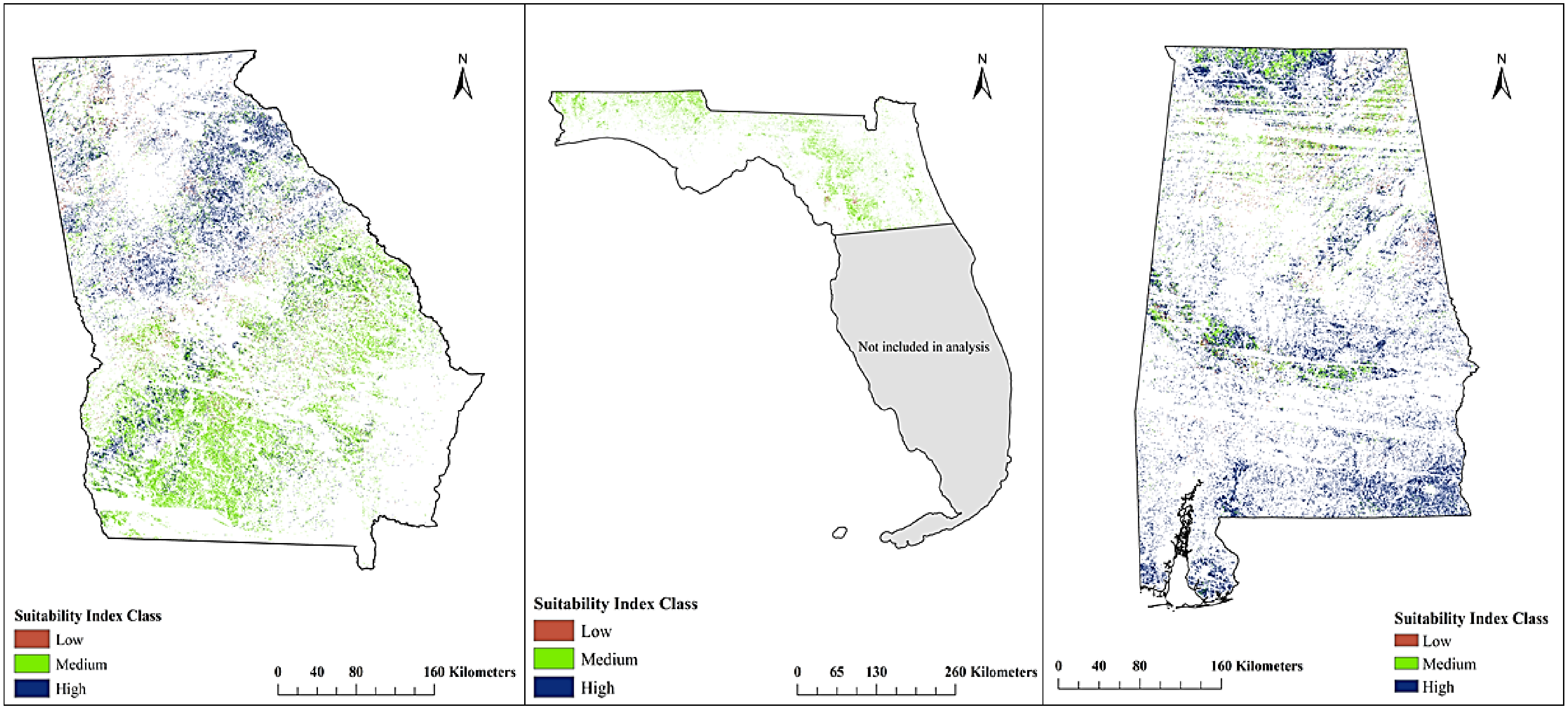

Figure 2.4: Spatial distribution of land suitability categories for carinata production in Georgia, Florida, and Alabama. The reported suitability maps are based on edaphic conditions only without accounting for weather and land use history.

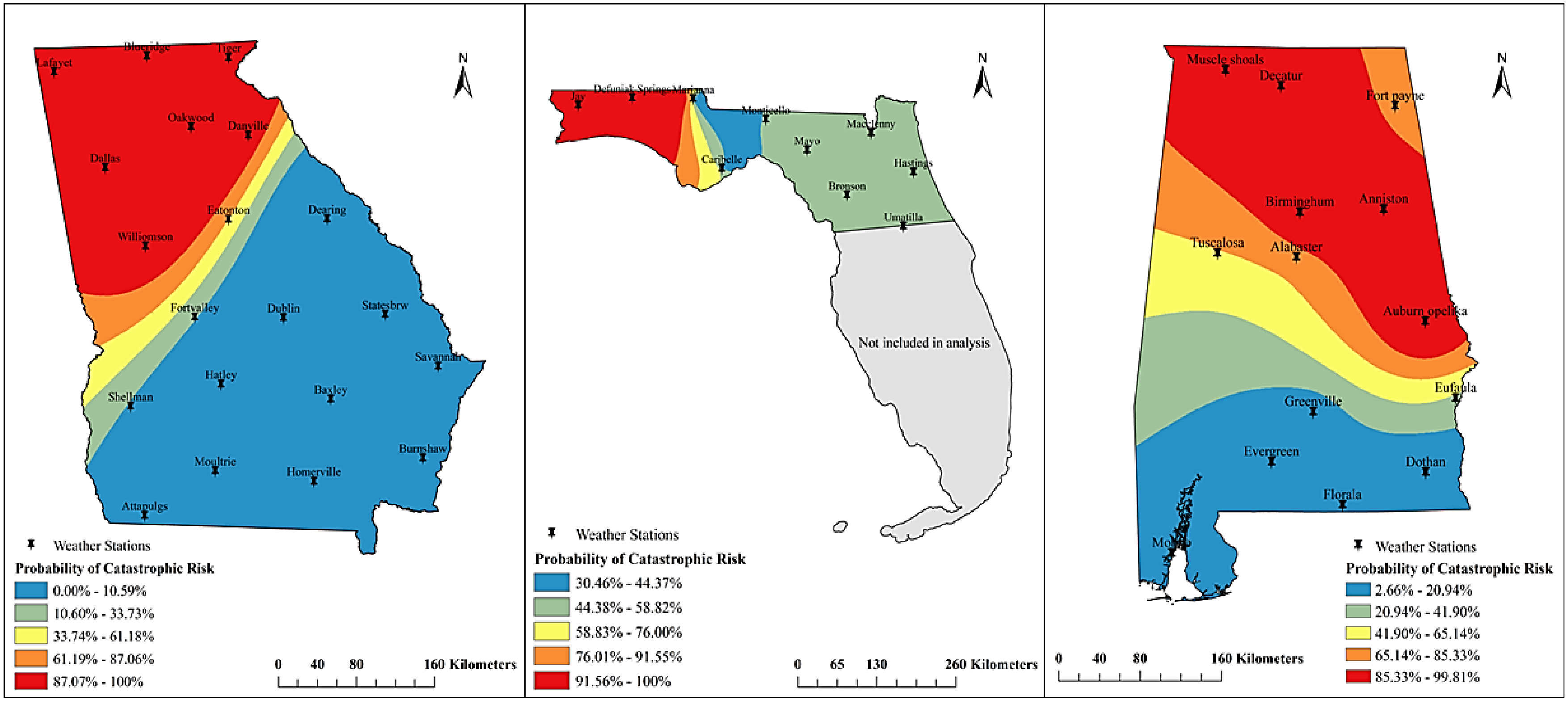

Figure 2.5: Spatial distribution of catastrophic risk for carinata production in selected states. These maps are based on a total number of catastrophic frost events over 2010 to 2015

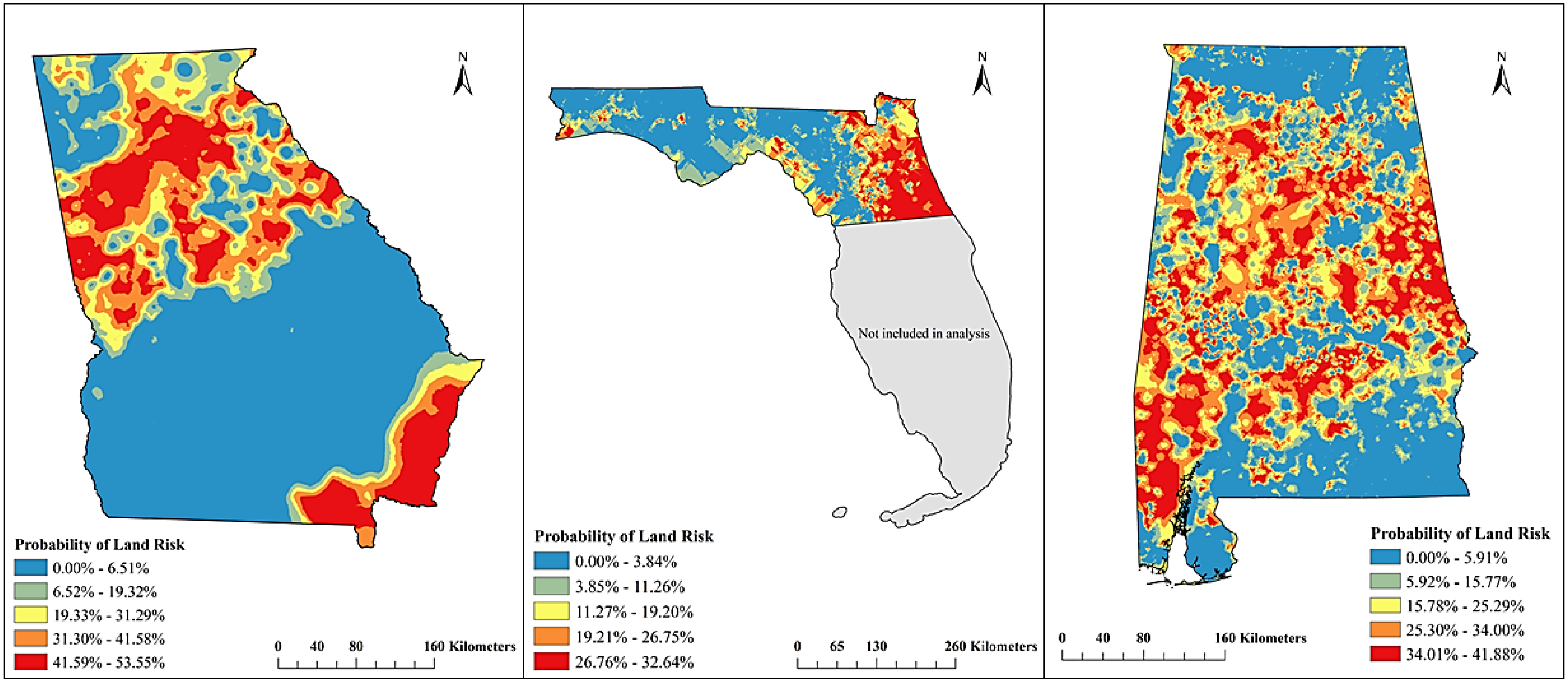

Figure 2.6: Spatial distribution of land availability risk for carinata production in selected states. These maps are based on a total number of times land was classified as under some agriculture crop over 2010 to 2015

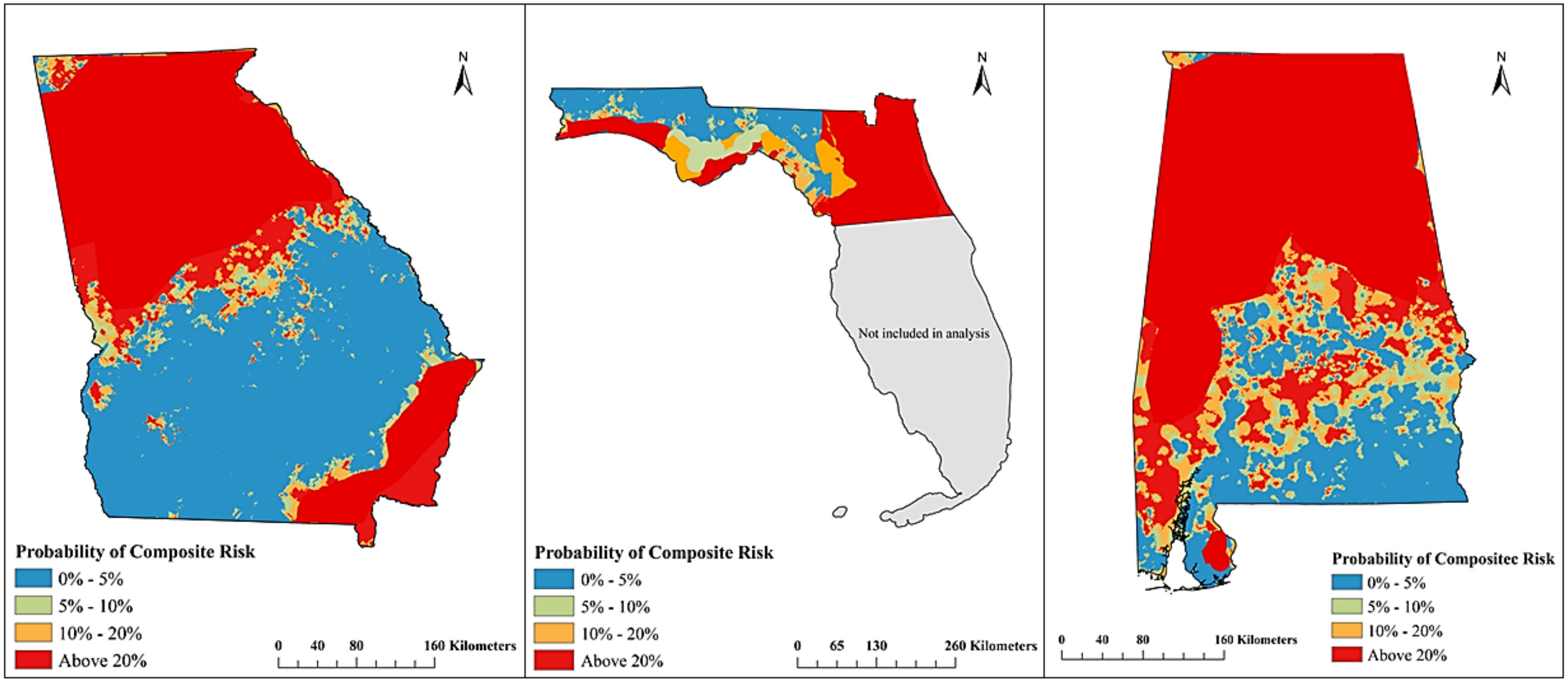

Figure 2.7: Spatial distribution of composite risk for carinata production in selected states

Table 2.4: Parameters used for ascertaining total production of carinata-based jet fuel production at the national level. High, average, and lowest yields of carinata are based on experimental plots under SPARC

	Value	Unit	Source
High Yield	**3363.30**	kg/ha	IFAS, UFL
Average Yield	**2802.70**	kg/ha	IFAS, UFL
Lowest yield	**2242.20**	kg/ha	IFAS, UFL
Seed to Carinata oil	**0.73**	kg/kg	ANL 2018 (GREET Model)
Carinata oil to Bio-jet Fuel	**0.63**	kg/kg	ANL 2018 (GREET Model)
Density of Jet Fuel	**0.84**	kg/L	ANL 2018 (GREET Model)
Annual Jet fuel consumption	**64.35**	billion liters	EIA 2017b

** ANL- Argonne National Laboratory ** GREET- The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model*

Table 2.5: Potential carinata production (million metric tons) for selected states at different composite risk levels

	5% Composite Risk Level	10% Composite Risk Level	20% Composite Risk Level
Georgia	1.97, 2.47, 2.96	3.12, 3.90, 4.68	4.13, 5.16, 6.19
Florida	1.01, 1.26, 1.51	1.41, 1.77, 2.12	1.61, 2.02, 2.42
Alabama	2.71, 3.39, 4.07	3.17, 4.09, 4.91	4.17, 5.21, 6.26
Total	**5.70, 7.12, 8.54**	**7.80, 9.75, 11.70**	**9.91, 12.39, 14.87**

Table 2.6: Bio-jet fuel availability (million liters) at selected composite risk levels and carinata yields (low, average, and high)

	5% Risk Level	10% Risk Level	20% Risk Level
Georgia	1079.37, 1349.21, 1619.05	1704.91, 2131.14, 2557.37	2256.86, 2821.08, 3385.29
Florida	551.95, 689.94, 827.93	772.73, 965.91, 1159.10	883.12, 1103.90, 1324.68
Alabama	1484.15, 1855.17, 2226.20	1790.77, 2238.46, 2686.16	2281.39, 2851.74, 3422.09
Total	**3115.45, 3894.31, 4673.18**	**4268.41, 5335.52, 6402.62**	**5421.38, 6776.72, 8132.06**

Table 2.7: Replacement of annual jet fuel consumption at low, average and high yields of carinata

Yield	5% Risk Level	10% Risk Level	20% Risk Level
Low Yield	4.84%	6.63%	8.42%
Average Yield	6.05%	8.29%	10.53%
High Yield	7.26%	9.95%	12.64%

Discussion

Out of 7.6 million hectares of land under agriculture in selected states including pasture lands, we found that 4.63 million hectares of land is suitable for carinata production without accounting for risks related to climate and land availability. After accounting for risks related to climate and land availability, we found that 2.54, 3.48, and 4.42 million hectares of land is available for carinata production at composite risk levels of 5%, 10%, and 20% levels, respectively. This analysis suggests that incorporation of risk reduces the total availability of land suitable for carinata production in selected states. This suggests that suitability studies should incorporate risks to avoid over-projecting the potential of bioenergy feedstock production. We also find that the total land suitable for carinata production overlapped with major existing agricultural regions located within every state.

We found that the jet fuel derived from carinata could displace between five to thirteen percent of total petroleum-based jet fuel nationwide depending upon selected carinata yields and composite risk levels. This range suggests that we should explore the feasibility of carinata production not only in other southern states but also in other regions of the United States. For example, some existing studies from the mid-western region of the United States indicate that carinata could be viable bioenergy crop especially in the spring season (Gesch et al. 2015; Sieverding et al. 2016). Additionally, there exists a need to explore other bioenergy feedstocks which could be potentially used for bio-jet fuel production for displacing petroleum-jet fuel consumption in the United States. For example, jet fuel derived from logging residues in northwestern states of the United States could help in displacing a certain portion of total petroleum-based jet fuel consumed nationwide based on research conducted by Northwest Advanced Renewable Alliance (https://nararenewables.org/).

CHAPTER 3

ESTIMATING ABOVEGROUND GHG EMISSIONS AND UNIT PRODUCTION COST OF CARINATA-BASED JET FUEL IN THE SOUTHEASTERN UNITED STATES

Literature Review

In the United States, various feedstocks are being developed to produce biofuels, industrial chemicals, non-edible products for humans, and edible products for animals (Sieverding et al. 2016). Currently, the focus of the bioenergy industry is shifting from cellulosic ethanol production to the production of jet fuels from biomass-based feedstocks.

In this context, several studies have analyzed GHG savings related to the use of bio-jet fuel relative to petroleum-based jet fuel. Fortier et al. (2014) estimated that about 76% GHG emissions could be reduced compared to conventional jet fuel by using algal bio-jet fuel through hydrothermal liquefaction (HTL) process. Agusdinata et al. (2011) used Latin-Hypercube sampling method to demonstrate the uncertainty analysis for Camelina (*Camelina sativa*) based bio-jet fuel. Results from this study illustrated about 74% of GHG emissions can be reduced compared to conventional jet fuel emission in 2005. Lokesh et al. (2015) estimated 70% savings in GHG emissions compared to conventional jet (A1 type) by using camelina-based jet fuel for various ranges of calorific values. Canola (*Brassica napus*), currently considered as another potential feedstock for bio-jet fuel since it provides more oil per hectare than other comparable oilseed crops. Ukaew et al. (2016) suggested the use of anhydrous ammonia in nitrogen fertilizer for canola cultivation could save 50% GHG emissions in Hydroprocessed Ester and Fatty Acids (HEFA) refining process. Ganguly et al. (2018) conducted a comparative analysis of residual woody biomass-based jet fuel and conventional jet fuel and revealed about 78% GHG emissions reduction of global warming potential can be achieved by substituting fossil fuel with residual woody biomass-based jet fuel. De Jong et al. (2017) compared different conversion pathways of cellulosic bio-jet fuel and found about 71-75% GHG emission reduction for sugarcane and corn stover-based Alcohol-to-Jet fuel. Attaining higher seed yield would lower environmental impacts associated with seed, oil, and fuel production (Li and Mupondwa 2014).

Geographical context is crucial to maintaining the environmental and energy-related impact of the crop management zone. Moeller et al. (2017) investigated the comparative benefit of carinata and camelina production over canola and soybean in the Northern part of the United States, and regional results of climate change found in this study for freshwater and marine eutrophication potential are considered to be significant for accounting benefits. Elgowainy et al. (2012) compared life cycle GHG emissions of soybean, palm, rapeseed, jatropha, camelina and Wang et al. (2018) suggested carinata as a new potential feedstock for jet fuel production facilitating the RFS requirements.

Table 3.1: Comparing the unit cost of bio-jet and GHG emission comparison in different feedstocks

Feedstock	**Cost ($/liter)**	**GHG emission (gCO_2/MJ)**	**Source**
Algae	0.9	95	Fortier et al. 2014
Bagasse	2.8	40	Michailos 2017
Camelina	0.8	75	Li et al. 2018
Corn stover	1.05	27	Agusdinata et al. 2011
Forest residues	0.98	14	Tzanetis et al. 2017
Short rotation woody crops	1.03	40	Agusdinata et al. 2011
Sugarcane	1.6	30	Santos et al. 2018
Switchgrass	4.4	78	Li et al. 2017

The economics of bio-jet fuel production pathways is critical because of uncertainties associated with the investment in large scale. The unit cost of production is considered as a key parameter for the commercial viability of bio-jet fuel (Wang and Tao 2016). Literature found on different cost of production depending upon GHG emissions from different feedstocks is illustrated in Table 3.1. Bio-jet fuel produced from cellulosic biomass (i.e., sugarcane, switchgrass, etc.) costs significantly higher than the oilseed crops and algae. However, the reduction of GHG emission increases notably for the cellulosic feedstocks. Price sensitivities in using cellulosic biomass for bio-jet fuel production still requires intensive economic analysis to make it profitable for the producers. The potential to increase renewable jet fuel production is still restricted by the lack of low production cost and sustainable feedstocks (Mawhood et al. 2016). The production cost of feedstocks is the largest amount on investment and conversion of bio-jet is the second largest investment (Stelle and Pearce 2011). Major challenges impeding investments in the bio-jet fuel industry are crude oil price, feedstock availability and cost, conversion technology yields and costs, environmental impacts and government policies (Bittner et al. 2015).

The global average price of aviation jet fuel in January 2019 is \$0.49/L, and this price is 18% higher than that of 2017 December (IATA 2019). For economic viability, bio-jet fuel must be cost competitive with petroleum jet fuel and policies need to be taken to develop the bio-based jet fuel industry. Due to the environmental concerns, bio-jet fuel industries are incentivized by the government in many countries (Brown 2013), and these bio-jet fuel industries are mainly owned by the private owners (Bittner et al. 2015). Substantial financing in bio-jet fuel industries from the private sector is considered to be unlikely without robust cost predictions (Zhao et al. 2015). Winchester et al. (2013) estimated an implicit subsidy of \$0.58/L from airlines to renewable jet fuel producers with the development of oilseed rotation crops to meet the FAA’s aviation biofuel goal of consuming 3.78 billion liters of renewable jet fuel each year. Chu et al. (2017) assessed two different hypothetical biofuel economics incentives; carbon trading and tradable credits to the Renewable Identification Number (RIN). This study also assumed an incentive of \$0.20/L of renewable jet fuel could help to achieve positive net present value (NPV) for camelina, carinata and used cooking oil. Diniz et al. (2018a) estimated an incentive of \$0.31/l, \$0.39/l, and \$0.61/l should target the production facilities of camelina, carinata and jatropha-based bio-jet fuel respectively to operate under the acceptable risk limit of 30%. To maximize the production of bio-jet fuel, camelina project requires incentives to operate under the 30% risk limits while carinata and jatropha require subsidies for the deployment of bio-jet and bio-diesel profiles.

Carinata (*Brassica carinata*), also known as Ethiopian Mustard and Abyssinian Mustard, was introduced in the southeastern United States in 2010 through a joint research collaboration between the University of Florida and Agrisoma Biosciences, Inc. Carinata could provide a climate-friendly, sustainable option for replacing jet fuel in the United States without getting into the debate of food versus fuel as it is not fit for direct human consumption. Carinata is well integrated into the current cropping systems in the southeastern region, as it grows well in winter months and, therefore, provides much-needed cover to otherwise exposed soils (Agrisoma 2017). It may improve soil quality by recycling deeper soil nutrients, reducing erosion, and controlling weeds and diseases when added to the current crop rotation. Carinata is agronomically superior and frost tolerant than any other oilseed crops grown in the southeastern United States with higher oil content (more than 40%), larger seed size, and lower lodging and shattering rates (Seepaul et al. 2016). Also, carinata could displace the use of edible oils in biofuel production while providing another source of high-quality protein (~43%) for animal feed markets (Agrisoma 2016; Agrisoma 2017). Finally, the use of carinata for jet fuels, feed, and chemicals could provide increased income to farmers, create local jobs, and boost local economies and, thus, could jump-start the bio-economy in the southeastern United States. In this context, this study aims to estimate the life cycle GHG emissions from producing carinata based bio-jet fuel and the cost of production at the biorefinery gate, using carinata as a new potential feedstock. A comprehensive study on economic analysis along with life cycle GHG emissions of bio-jet fuel production may help policymakers to reduce the carbon footprint of the aviation sector in the United States.

Methods

Carinata *(Brassica carinata)* is considered as a potential feedstock under the Renewable Fuel Standard (RFS) program by the United States Environmental Protection Agency (USEPA) for producing renewable jet fuel, biodiesel, naphtha, and liquefied petroleum gas (LPG) (US EPA 2015). We applied data from Lal (2004) for determining carbon dioxide emissions from farm operations and The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) 2018 model to examine farm to gate GHG emissions of carinata based jet fuel production. We used updated emission factors for GHG inventories (US EPA 2018a) to estimate emissions from transport in delivering carinata oil storage and distribution and emissions from mechanical use in bio-refineries. Farm operation from the field to bio-refinery gate storage point follows Hydro-processed Esters and Fatty Acids (HEFA) jet fuel pathways. Our system boundary and jet fuel pathway were comparable to guidelines provided by the Energy Systems Division, Argonne National Laboratory (Wang et al. 2018; Sieverding et al. 2016). System boundary of carinata based bio-jet fuel includes jet fuel storage from the bio-refinery plant; however, we did not include combustion from aircraft operation in this analysis due to lack of proper validation with HEFA combustion in aircraft operations. The boundary of the life cycle assessment also excludes crop rotations, direct and indirect land use change, and soil carbon dynamics. Current GREET model has a limitation with the nonfood feedstock carbon sequestration process; therefore, the land use change model is not included in our system boundary. Many nonfood oilseeds (i.e., camelina, jatropha, etc.) can be grown as an alternative to fallow land in single winter wheat-fallow rotation and production of these oilseeds are assumed not to displace any other crops in the agricultural land (Sieverding et al. 2016). Farm-to-gate HEFA jet fuel production system boundary is illustrated in Figure 3.1, and key parameters for feedstock production are illustrated in the supplementary Table S1. Co-products handling methods are discussed in the fuel refining stage. Since this study focuses on HEFA fuel production stages, a production functional unit (1000L fuel production at the bio-refinery gate) is selected to make a comparison with the conventional jet fuel production emission and energy consumption at the factory gate.

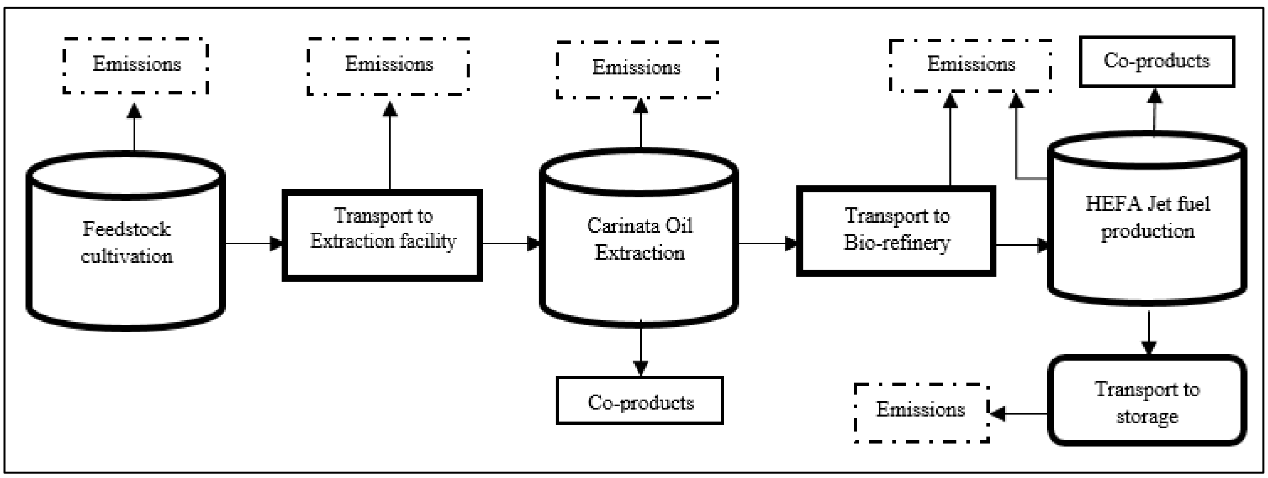

Figure 3.1: Farm to gate system boundary of producing carinata based HEFA jet fuel

Table 3.2: Parametric assumptions for Hydro processed Ester & Fatty Acid (HEFA) jet fuel production

Major Stages of LCA	Unit	Value	Source
Farming: per dry Mg of oilseed			
Farming energy use	MJ	7931.2	GREET 2018
N fertilizer use	kg/ha	88.92	IFAS, UFL
P fertilizer use	kg/ha	44.46	IFAS, UFL
K fertilizer use	kg/ha	88.92	IFAS, UFL
S fertilizer use	kg/ha	22.23	IFAS, UFL
Herbicide use	kg/ha	6.37	IFAS, UFL
Fungicide use	kg/ha	0.93	IFAS, UFL
Insecticide use	kg/ha	0.69	IFAS, UFL
Desiccant use	kg/ha	0.14	IFAS, UFL
Oil Extraction: Per Mg of HEFA			
Carinata Oil yield	Mg oil/dry Mg oilseed	0.44	(Sieverding et al. 2016)
Carinata Meal yield	dry Mg	0.56	(Sieverding et al. 2016)
Extraction energy use	MJ	6822.43	GREET 2018
HEFA fuel production: per Mg of HEFA			
HEFA yield	Mg HEFA/Mg oil	0.71	GREET 2018
H_2 use	MJ	4050.25	GREET 2018
Natural Gas use	MJ	6231.70	GREET 2018
Electricity use	Kwh	60	(Han et al. 2013)
Propane mix yield	MJ	4548.10	(Wang et al. 2018)
Naphtha yield	MJ	3223.65	(Wang et al. 2018)

Hydro-processed Esters and Fatty Acids (HEFA) jet fuel pathways

Parametric assumptions for seed farming, oil extraction, and fuel production are listed in Table 3.2. During feedstock production, nitrogen fertilizer and fossil fuel are the main sources for GHG emissions. Nitrification and denitrification from nitrogen fertilizer, which requires a large amount of natural gas to produce, is a major source of GHG during feedstock production (Han et al. 2013). Carinata oil extraction co-produces carinata meal which is a valuable animal feed and this animal feed benefits with significant GHG emissions credits (Agrisoma 2017). Natural gas and coal are potential sources of GHG emissions in the oil extraction and hydroprocessing stage. GREET model accounts GHG emissions associated with natural gas and coal production and distribution stage. Triglyceride in vegetable oil is hydrogenated to saturate the double bonds and release the fatty acids by breaking its glycerin backbone, which co-produces propane during HEFA production. Removal of oxygen from free fatty acids is done by either hydrodeoxygenation (producing H_2O) or decarboxylation (producing CO_2) which generate straight chain alkanes (Han et al. 2013). These straight-chain alkanes are hydrocracked and isomerized according to the standard of American Society for Testing and Materials (ASTM) for increasing fuel yields. HEFA fuel production and bio-oil refine process consume a large amount of hydrogen which is a major source of GHG emissions during production from natural gas. Literature found on process assumptions for HEFA jet fuel production from carinata is limited. For the account of oil feedstock (carinata) dependency, this study follows the assumptions from Wang et al. (2018), Sieverding et al. (2016), Pearlson et al. (2013), and Diniz et al. (2018) to adjust the hydrogen demands and co-product yields for carinata depending on fatty acid profile. Carinata (C22:1) has a higher probability of optimal cracking due to longer carbon chain length (Johnson et al. 2014). Carinata is high in erucic and linoleic acid and contains less than 7% saturated fatty acids which make it a desirable oil that can be processed into drop-in bio-jet fuel (Agrisoma 2016).

A few transportation scenarios were collected from Elgowainy et al. (2012), and Wang et al. (2018) as literature on carinata transportation is limited. These transportation modes are matched with the standard feedstock and oil transportation carriers used by the Department of Transport, Florida. All transportation modes are considered with empty backhaul in one way for product transport purpose. Co-products transportation was not included in this study. The feedstock was assumed to be transported from the field by a medium heavy-duty truck to local storage and then again transported to an oil extraction plant by a heavy-duty truck. This study assumed the oil extraction plant is located 100 kilometers away from the feedstock source. From the oil extraction plant carinata, oil was transported by heavy-heavy duty truck to a bio-refinery plant. Average sourcing radius from the oil extraction plant to bio-refinery and from bio-refinery to HEFA oil storage are assumed as 130 kilometers and 150 kilometers respectively. These oil transportation and HEFA fuel transportation are done by heavy-heavy duty trucks. The payload of the medium and heavy-duty trucks was varied based on estimated holding volume and density of carinata oil and HEFA jet fuel (Table 3.3). Detailed transportation parameters are illustrated in Table S2.

Table 3.3: Feedstock and resource parameters used in GREET 2018 modeling. Agronomic characteristics used in the GREET model are based on data from the northern United States (Sieverding et al. 2016)

	Density (kg/m^3)	LHV* (MJ/kg)	HHV** (MJ/kg)	Moisture Content (%)	Sulfur ratio (%)	Carbon ratio (%)
Carinata seed	703	17.73	27.39	4.92	0.60	59.4
Carinata meal	600	17.70	22.09	N/A	0.52	50.3
Carinata oil	878	37.39	40.38	0.06	0.18	77.0

* *LHV – Low Heating Value*
** *HHV- High Heating Value*

Handling of co-products is critical in terms of the field to flight analysis of the alternative fuels. Though allocation and displacement are common methods for co-products handling in alternative fuel, carinata oilseed is assumed not to displace any other crops in the agricultural land (Moeller et al. 2017; Sieverding et al. 2016). This study does not consider the displacement method for co-product handling. Three allocation methods; mass, energy, and market value used in GREET modeling were applied in this study to calculate the energy and emission of each co-product. Allocation methods are appropriate to use when the bases are well defined in the system boundary. In allocation methods, the value of each product (per allocation unit) is assumed to be equal to that of other co-products; thus energy and mass allocation methods may not be applicable when the characteristics (i.e., LHV, density, etc.) of the co-products are different (Han et al. 2013). Allocation boundary (Table S3) for the co-products handling methods is divided into two stages: oil extraction and HEFA jet fuel production in the GREET model. Carinata meal (animal feed) is produced in the oil extraction stage, and propane mix and naphtha are produced in the HEFA jet fuel production stage. All energy and chemical inputs to oil extraction and HEFA jet fuel production are combined and allocated among the main product (HEFA jet fuel) and the co-products (meal, propane mix, and naphtha). This study follows the system level approach used in Han et al. (2013) and Huo, H., M. Wang (2008) for handling co-products. In system level approach extracted carinata oil is assumed to be an intermediate product, and thus the uncertainty of oil properties; LHV, HHV does not affect field to flight results (Han et al. 2013).

Assumptions listed in Table 3.4 were adopted from Diniz et al. (2018a), Chu et al. (2017), Pearlson et al. (2013) and Wang et al. (2011) to determine gate prices of HEFA fuel from the bio-refinery. These studies used Aspen simulation for bio-refinery size, production profiles, and project finance structure. Installation and capital cost were adopted from petroleum cost curves (Gary JH, Handwerk GE 2007). For economic analysis two different bio-refinery size according to annual capacity; 116 million liters/year and 398 million liters/year are assumed in this study. Total direct cost is the sum of the total equipment installation cost and the costs associated with the site development (Diniz et al. 2018b). Cost of operating the bio-refinery plant is divided into a fixed and variable cost. Fixed operating costs are constant and independent of production levels. To estimate the variable cost of operation in extracting and refining facilities this study used unpublished field data from the University of Florida's Quincy trial plot of carinata. The working capital is assumed to be 10% of the total cost investment. Total cost investment combined with total capital investment and working capital. Chu et al. (2017) estimated the total project investment for hydro-processed renewable jet (HRJ) plant are $287 million for the lower annual capacity plant and $534 million for the higher annual capacity plant. Both plants are designed for 20 years. Fixed operating cost also includes labor, overhead, maintenance, insurance, taxes, and contingency. Finally, the HEFA jet fuel price determines with the comparison of conventional jet fuel in 2017.

Results

Field data collected from the Institute of Food and Agricultural Science (IFAS), University of Florida were used to determine the GHG emissions from carinata feedstock production. The rate of fertilizers (N, P, K, S), pesticides, herbicides fungicides are standardized for north-eastern part of Florida and management practices adopted in Florida. It is assumed that carinata production varies in different seasons and highly dependent upon climate and location. Figure 3.2 shows the distribution of CO_2, CH_4, and N_2O gas emissions to produce 1000 liters bio-jet fuel at the bio-refinery gate and figure 3.3 shows the total GHG emissions from life cycle stages for producing 1000 liters of bio-jet fuel at the bio-refinery gate. During seed production stage CO_2 (~70%) and CH_4 (~25%) emission is higher than N_2O because of using intensive transportation equipment for land preparation, plantation, irrigation, fertilizer application, and harvesting. Equipment's run by fossil fuel acts as a major driving force for GHG emissions in the farming stage. This proportion of emission can be changed significantly based on management practices. Oil extraction stage consumes mostly fossil fuel-based energy, among them, mostly used electricity for seed crushing causes intensive GHG emissions. Intensive electricity use in the bio-refinery plant significantly increases CO_2 emission. Resource parameters in GREET modified for electricity and water sources (Table S4). This study only uses data from the Floridian perspective for electricity resource mix and water sources. Natural gas (66.5%) and coal (16.6%) are the main sources for producing electricity in Florida (US EPA 2018b). These resource mixes cause more than 95% CO_2 emission in the oil extraction stage and 90% in the bio-jet fuel production stage. CH_4 and N_2O are less significant in these two stages; however, in transportation stages, a small percentage of N_2O emits due to the resource mix of natural gas and fossil fuel.

Total GHG emissions from producing 1000 liters of bio-jet fuel at the bio-refinery gate were estimated 821.84 kg CO_2e using the updated 100-year global warming potential. Seed farming, oil extraction, and bio-jet fuel production stages consume a bulk amount of fossil energy (Figure 3.4) and identically responsible for the major amount of GHG emissions. Fossil fuel derived from natural gas, electricity generated from coal, crude oil, natural gas, and petroleum product consumption such as conventional diesel was grouped as fossil fuel and hydroelectric, solar and wind are considered as renewable sources in GREET 2018 model. Energy calculation in GREET model estimates about 30376.82 MJ of fossil energy is used to produce per 1000 liters of bio-jet fuel. Figure 3.4 shows farm-to-gate fossil fuel energy consumption for producing 1000 liters bio-jet fuel at bio-refinery gate. Though transportation and distribution stages used fossil fuel, energy consumption and emitted GHG emission is negligible compared to farming, extraction and bio-jet production stage. Assumed farming location, oil extraction location and bio-refinery location used in this study may vary with the emission rate since data used for Florida alone. Larger states, i.e., California, Texas, Georgia, etc. in the southeastern United States may use their in-state oil processing for producing a bulk amount of jet fuel through pipeline and Berge which is assumed to minimize transportation-related emissions in comparison with the production unit. Farm-to-gate model run in GREET 2018 for Canola, rapeseed, camelina shows differences in terms of GHG emissions changes in the feedstock production stage. High yield of carinata seed during production stage incentivizes GHG emissions from fertilizer, insecticide, herbicide and fungicide applications (Wang et al. 2018). With relatively less use of fertilizers and other agricultural equipment than other oilseed feedstocks (canola, camelina, sunflower, etc.), carinata emits less GHG emissions at the farming stage (Moeller et al. 2017; Sieverding et al. 2016).

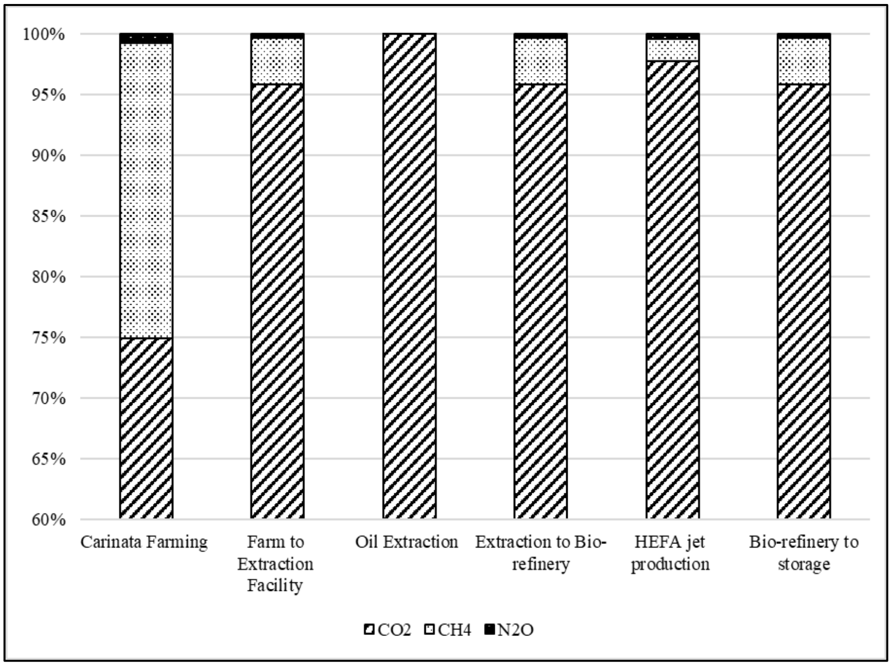

Figure 3.2: Emission distribution of GHG gases for producing a thousand liters bio-jet fuel at bio-refinery gate

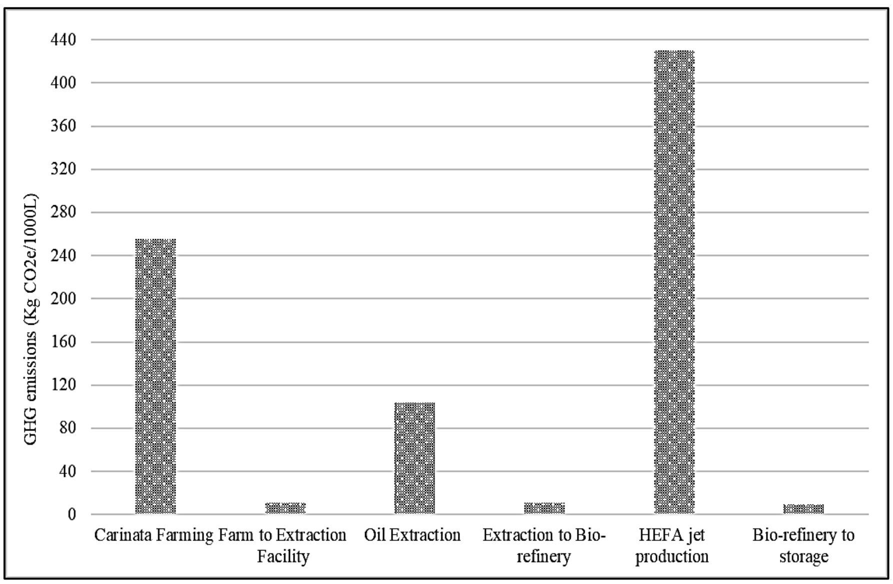

Figure 3.3: Total GHG emissions for producing a thousand liters of bio-jet fuel at bio-refinery gate

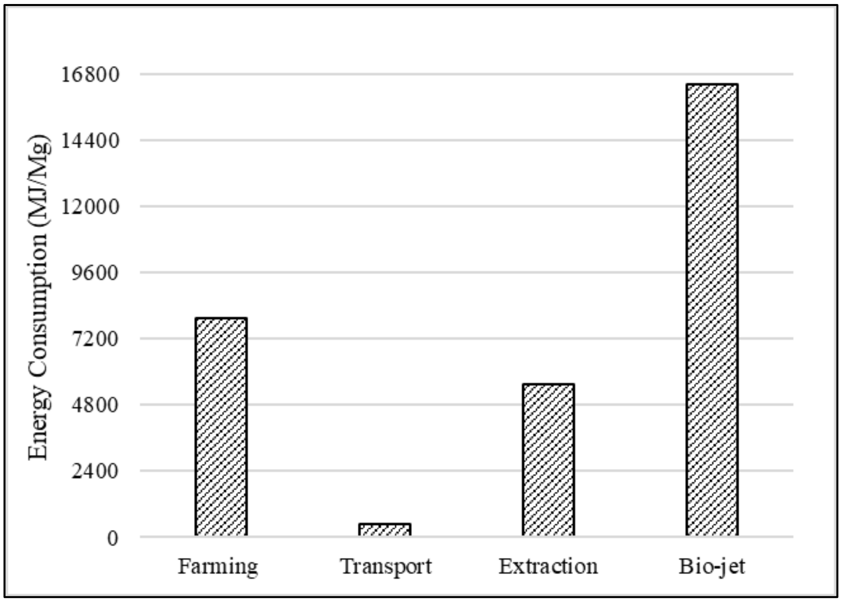

Figure 3.4: Fossil fuel energy consumption for producing a thousand liters of bio-jet fuel at bio-refinery gate

Figure 3.5 shows the impact on GHG emissions of different allocation methods (mass, market, energy) for handling co-products. Farm-to-gate GHG emission is dominated by fuel production activities because of the large consumption of natural gas and H_2 gas. Figure 3.6 shows the allocation of fossil energy consumption in oil extraction and bio-jet production stage to handle main products (carinata oil, bio-jet) and co-products (carinata meal, propane mix, and naphtha). Allocation factors for oil extraction and bio-jet production stage are illustrated using equation-6 (Supplementary Table S3). Intensive use of natural gas and H_2 gas in bio-jet production stage allocated energy is high and estimated calorific value of bio-jet is 33.38 MJ per liter at the storage point. It is assumed that transport bio-jet from the refinery to storage point does not contain moisture and no energy loss is observed. Hence, the calorific value of bio-jet remains the same. Still feedstock production and bio-jet fuel production are significantly dependent on fossil fuels, renewable sources (carinata oil, bio-jet) offset the energy consumption of fossil fuels. Considering the energy content of main products and co-products GREET model estimates around 23% energy savings in producing 1000 liters of carinata based bio-jet (30376.82 MJ) than producing 1000 liters of conventional jet fuel (39326 MJ).

$$\text{Allocation factor} = \frac{\text{Energy (product)}}{\text{Energy (Product)} + \text{Energy (Coproduct)}} \quad (6)$$

As mentioned earlier, the system-level approach is adapted to handle the co-product emissions through mass, energy and market value allocations. This system level approach used in this study is adapted from (Han et al. 2013) that assembles the system boundary along with oil extraction and bio-jet fuel production. Mass allocation method determines less amount of GHG emissions from feedstock and oil extraction stages because of the large mass proportion of carinata meal (animal feed). Depending upon the market value allocation of co-products and energy allocation of co-products GHG emission distribution is higher than mass allocation in the system level approach. Han et al. (2013) And Elgowainy et al. (2012) suggested a process level approach to distribute separately chemical and energy inputs and co-products for each stage. Inputs of oil extraction are allocated between oil and meal while the inputs of bio-jet fuel production are allocated among the bio-jet fuel, propane mix, and naphtha. The GHG emissions for the main product (i.e., bio-jet) in mass, market, and energy allocation boundary are 33%, 62%, and 52% respectively. Our results suggest that total savings in GHG emissions will be 85.9%, 69.8%, and 76.4% relative to 1000 liters of conventional jet fuel based on mass, market, and energy allocations, respectively and overall GHG savings are estimated about 63% than conventional jet fuel (2206 kg CO_2e) (US EPA 2018a).

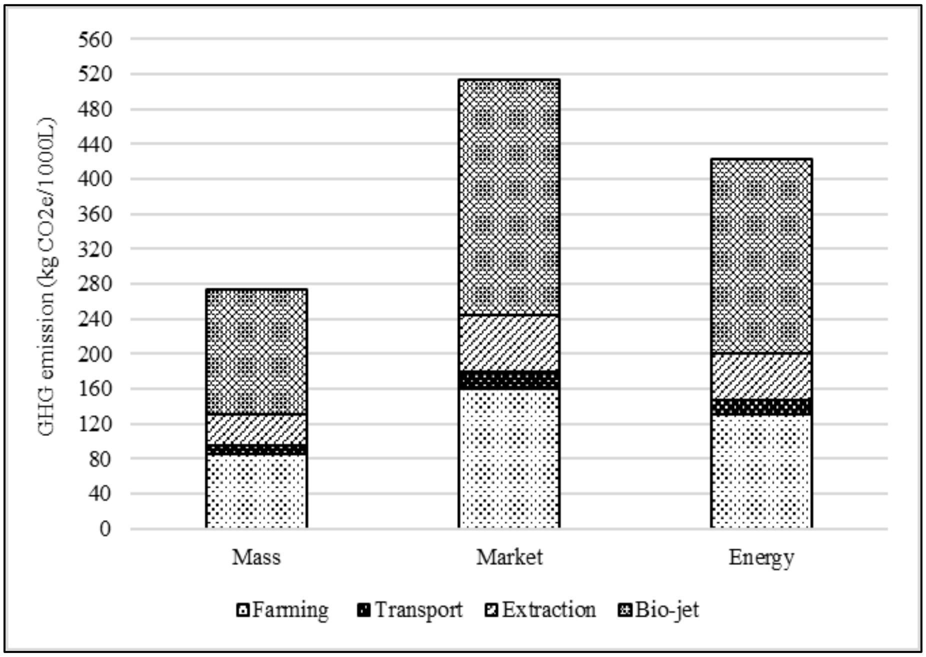

Figure 3.5: Impact of allocation boundary with different co-product handling methods

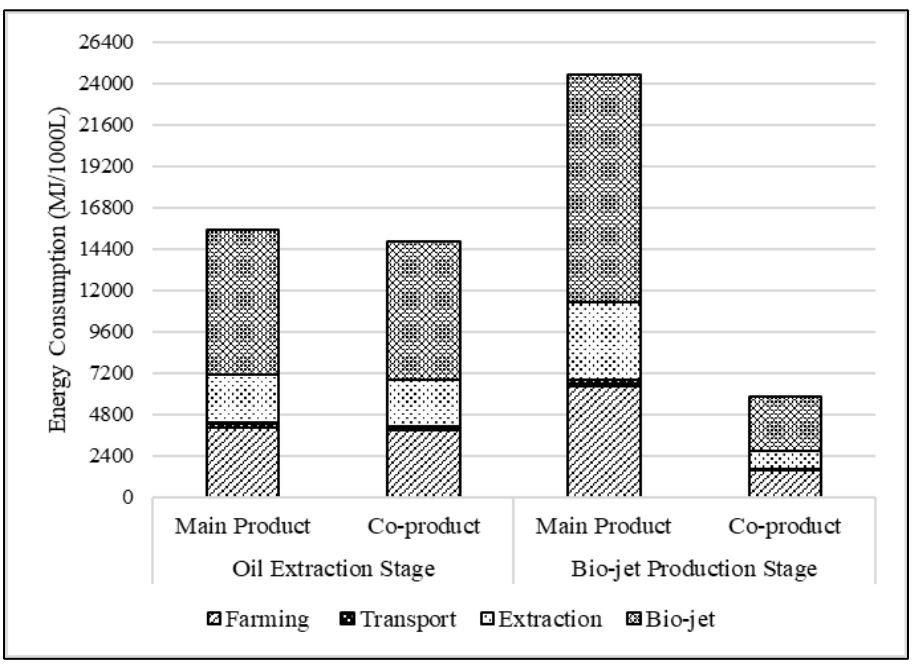

Figure 3.6: Allocation of energy consumption for main products and co-products in oil extraction and bio-jet production stage

Table 3.4 shows the breakdown of capital cost and sources of income of bio-refinery from co-products. HEFA plant converts carinata oil and hydrogen gas into a variety of products and co-products. Current study considers salable products and co-products in the US market. Carinata based bio-jet fuel accounted as the main product and carinata meal (animal feed), naphtha and propane mix as co-products for this analysis. Farm-to-gate unit price range of agronomic activities, transportation, intermediate products, and co-products are illustrated in Table S5. Results of economic analysis of carinata based HEFA bio-jet fuel production at farm gate are subdivided into four scenarios- Low plant capacity-Lower price range, Low plant capacity-Upper price range, High Plant capacity-lower price range and High plant capacity-higher price range. Figure 3.7 shows per liter price variation of HEFA jet fuel in different plant capacity and price scenarios. This study deals with the price and economic model data from literature; therefore, the results reported in this study are not affected by the sensitivity and uncertainty analysis

Table 3.4: Breakdown of the capital expenses for the HEFA jet fuel facilities for Carinata

Itemized Detail	**Rate**	**Lower Range**	**Upper Range**	**Unit**	**Source**
Labor Cost	12	$0.86*	$0.96*	$/year	(Diniz et al. 2018a)
Capital Cost for a bio-refinery (TPI)**		$287.00*	$534.00*	MM$	(Chu et al. 2017)
Overhead cost	0.20%	$0.57*	$1.07*	% of TPI	(Diniz et al. 2018a)
Maintenance Cost	5.50%	$15.79*	$29.37*	% of TPI	(Diniz et al. 2018a)
Insurance Cost	0.50%	$1.44*	$2.67*	% of TPI	(Diniz et al. 2018a)
Tax	1.00%	$2.87*	$5.34*	% of TPI	(Diniz et al. 2018a)
Contingency	10.00%	$30.85*	$57.34*	% of above Subtotal	(Pearlson et al. 2013; Diniz et al. 2018a)
Total Fixed Cost		$339.38*	$630.75*	$/Mg	
Total Variable Cost (Expenditure per Mg)		$643.95	$957.18	$/Mg	
Total Variable Cost (Expenditure per 1000L)		$699.95	$1,040.42	$/1000L	
Total Cost (Fixed+Variable)		$339.38	$630.74	$/1000L	
Total Income		$556.41	$1,091.95	$/1000L	
Total Revenue (per Mg)***		-$87.54	$134.77	$/Mg	
Total Revenue (per 1000L)***		-$95.15	$146.49	$/1000L	

**** Million US Dollars***

***** TPI- Total Project Investment***

****** Considering variable cost only***

Discussion

Emissions from carinata feedstock production and bio-jet fuel production at farm gate are lower than reported in default GREET emissions of canola, rapeseed, soybean (Han et al. 2013; Elgowainy et al. 2012). Other oilseeds; canola, rapeseed, soybean, etc. need more intensive fertilization (Moeller et al. 2017; Sieverding et al. 2016) than carinata which accounts for major GHG emissions. Since carinata has a higher production level and lower fertilizer application than other oilseeds, it offsets GHG emissions in oil extraction and HEFA bio-jet fuel production. Yields can be variated with soil characteristics, management practices and purpose of use of carinata. Current study deals with the plot level data from the University of Florida, and the soil carbon sequestration model is yet to be developed with a small amount of plot-level data. Carbon calculator for land use change from carinata production was not available in GREET 2018. GREET 2018 has few modules (canola, soybean, etc.) for soil carbon sequestration; therefore, currently, it is not possible to compare the soil carbon benefits among other oilseeds. Further studies can be initiated to estimate the soil carbon sequestration and expected changes in land use due to carinata production. The CO_2, CH_4, and N_2O emissions were determined by using standardized emission factors (US EPA 2018a) and these emissions occur due to the natural process of fertilizer application and agricultural equipment use and transportation purpose. The GHG emissions were dominated by CO_2 emissions, mainly occurs by fossil fuel combustion in oil extraction and bio-jet production contributing more than 80% of the total GHG emissions.

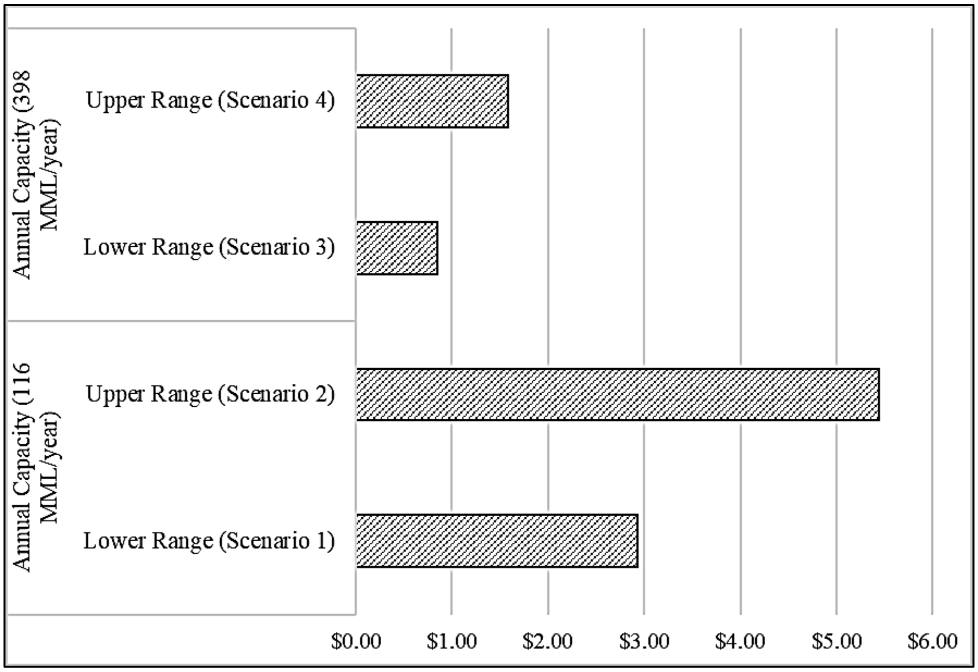

Figure 3.7: Distribution of per liter bio-jet fuel price in different price and bio-refinery annual capacity scenarios

Fossil fuel combustion is closely related to feedstock and bio-jet production stages (Lokesh et al. 2015). Fossil fuel mostly combusts in the electricity generation process, transportation or in agronomic practices. The best option to reduce related nitrogen emissions is to decrease fossil fuel use during feedstock production (Sieverding et al. 2016). Changing management practices or using efficient transport and agricultural feedstock moods can help reducing nitrous related emissions. Density and oil content influences Nitrous and Sulphur related emissions. Small seed density and size help carinata minimize transport and handling cost. (Daylan and Ciliz 2016) Reported emission variations for different transport modes carrying capacity, seed density and size are highly correlated with the carrying capacity and long-haul transportation. Impacts of GHG emissions from the oil extraction stage influences seed density and oil content ratio. Moisture content also influences fossil fuel consumption during transportation. It is assumed that moisture in the feedstock (Table 3.2) needs to be controlled during storage to prevent spoilage and more fossil fuels are consumed to transport feedstock with additional moisture.

Feedstock production, carinata oil extraction, and bio-jet fuel production consume a high amount of energy, and GHG emissions occur mostly in these three life cycle stages. Since this study uses production function unit 1000 liters at bio-refinery gate, results are expressed in kg CO_2e to keep similarities in all the stages of the life cycle. Emissions from carinata production, oil extraction and bio-jet fuel production accounts for 31% (255.64 kg CO_2e), 12% (103.95 kg CO_2e) and 52% (430.33 kg CO_2e) respectively. These three major stages of jet fuel production use electricity which constitutes a minor portion of energy consumption compared to fossil fuel consumption. Changing electricity and natural gas source profile does not make much impact since fossil fuel still be the major energy source of electricity production in Florida. GREET 2018 (Wang et al. 2018) did not populate with the standardized data; it used the data from the northern plain (Moeller et al. 2017; Sieverding et al. 2016). Therefore, this needs to be understood when interpreting results with different soil regions, climate, and management practices. Product sustainability largely depends on the proportion of renewable to fossil fuel energy. Estimated energy consumption at the farm gate to produce 1000 liters bio-jet fuel is 30376.82 MJ which is around 24% less than that fossil energy consumed for producing 1000 liters conventional jet fuel (39807.5 MJ). However, accounting co-products (i.e., carinata meal, naphtha, propane mix) in the life cycle analysis provide a net energy benefit to HEFA jet fuel production.

According to the Renewable Fuel Standard of the United States Environmental Protection Agency (USEPA), carbon trading is proposed as an economic incentive for HEFA bio-jet fuel. This study estimated the fuel price by summing the production cost with the co-products credit considering the annual capacity of the bio-refinery plant. Table 3.5 shows the gate price and incentives required for producing per liter of HEFA bio-jet fuel according to bio-refinery annual production capacity and price scenarios.

Table 3.5: Bio-refinery gate price and incentives for producing per liter bio-jet according to different annual capacity and price scenarios

	Annual Capacity (116 MML/year)		**Annual Capacity (398 MML/year)**	
	Lower Range (Scenario 1)	**Upper Range (Scenario 2)**	**Lower Range (Scenario 3)**	**Upper Range (Scenario 4)**
Bio-jet fuel Price ($/L)	$2.93	$5.44	$0.85	$1.58
Incentives required ($/L)	$2.38	$4.89	$0.30	$1.03

The estimated production price at bio-refinery gate ($0.85/l) was about 29% higher than the current price of conventional jet fuel ($0.55/l) (IATA 2019). Difference between the conventional jet fuel price and estimated bio-jet fuel prices represents the incentives necessary for the carinata-based jet fuel. Considering the high annual capacity-lower price range determines the best case for per liter HEFA jet oil price ($0.85/L) and incentive ($0.30/L) for the bio-refineries. Results from the economic analysis estimate that greater annual capacity of bio-refineries incentivizes the price of carinata based jet fuel considering their co-products sale in the eligible market. Other incentives can be implemented through supporting bio-refineries by allocating RIN (Renewable Identification Number). Recent updates from the US EPA shows that advanced renewable jet fuel (D5) priced $0.35/L at the end of October 2018 (US EPA 2018c). Estimates of this study ($0.30/L) are still under the recent RIN price available in the market, and this project is substantially more attractive. Additional $0.05/L would cover the price gap of conventional jet fuel and carinata based HEFA bio-jet fuel. Observed RIN prices are still less than $1.00/L since the carbon market operates, and the current study assumes RIN prices would not variate more than 20%. However, analysis of price uncertainty and sensitivity could be a great scope to study for fuel price stability and environmental sustainability. In addition, further study on life cycle GHG emissions impact; acidification, nitrification, eutrophication, etc. could get future interest.

SUPPLEMENTARY TABLES

Table S1: Agronomic parameters used for producing carinata in trial plots at Quincey, Florida

Activity	Material	Material Type	Data Unit	Amount
Pre-plant burndown	Glyphosate	Herbicide	kg/ha	4.64
	Diesel	Tractor	L/ha	1.41
Tillage	Diesel	Tractor	L/ha	9.15
Premergent herbicide application	Pendimenthalin	Herbicide	kg/ha	1.73
	Diesel	Tractor	L/ha	1.41
Planting	Seed/Plant	Seed	kg/ha	5.58
	Diesel	Tractor	L/ha	1.41
Fertilizer Application (First Phase)	Nitrogen	Fertilizer	kg/ha	22.23
	Sulphur	Fertilizer	kg/ha	11.12
	Phosphorous	Fertilizer	kg/ha	44.46
	Potassium	Fertilizer	kg/ha	44.46
	Diesel	Tractor	L/ha	1.41
Fertilizer Application (Second Phase)	Nitrogen	Fertilizer	kg/ha	44.46
	Sulphur	Fertilizer	kg/ha	11.12
	Potassium	Fertilizer	kg/ha	44.46
	Diesel	Tractor	L/ha	1.41
Fertilizer Application (Third Phase)	Nitrogen	Fertilizer	kg/ha	22.23
	Diesel	Tractor	L/ha	1.41
Fungicide application	Picoxystrobin (Galileo, haapela)	Fungicide	L/ha	0.95
	Diesel	Tractor	L/ha	1.41
Insecticide application	Methoxyfenozide (Intrepid)	Insecticide	L/ha	0.69
	Diesel	Tractor	L/ha	1.41
Desiccant application	Sharpen	Desiccant	kg/ha	0.14
	Diesel	Tractor	L/ha	1.41
Harvesting	Diesel	Tractor	L/ha	16.89
Irrigation	Diesel	Tractor	L/ha	1.41
	Electricity		KWh/ha in	382.85

Table S2: Transportation parameters used to calculate fossil fuel based GHG emissions.

Transportation parameters	Value	Unit	Source
Average distance from field to the extraction facility	100	km	Assumption
Average distance from extraction facility to bio-refinery	130	km	Assumption
Average distance from bio-refinery to storage	150	km	Assumption
Heavy-Duty truck payload	20	ton	(BTS 2018)
Heavy-Heavy Duty Truck payload	25	ton	(BTS 2018)
Oil tanker payload	30	ton	(BTS 2018)
Heavy-Duty truck mileage	5.29	km/L	(BTS 2018)
Heavy-Heavy-Duty truck mileage	3.96	km/L	(BTS 2018)
Oil tanker mileage	3.17	km/L	(BTS 2018)
Diesel price (min)	0.75	$/L	(EIA 2019a)
Diesel price (max)	0.84	$/L	(EIA 2019a)

Table S3: Allocation factors for energy consumption used in GREET calculations

Oil Extraction	**Allocation**
Carinata oil	51.10%
Carinata Meal	48.90%
Bio-fuel processing	**Allocation**
Bio-jet	80.80%
Propane mix	7.70%
Naphtha	11.50%

Table S4: Electricity resources mix used in Florida (US EPA 2016)

Resources	% of each resource	Net Generation (MWh)
Coal	16.6	39,429,468
Oil	1.2	2,820,303
Gas	66.5	158,459,723
Nuclear	12.3	29,320,022
Hydro-generation	0.1	174,551
Biomass Generation	2.6	6,098,942
Wind	0.0	0
Solar	0.1	223,983
Geothermal	0.0	0
Fossil	0.0	23,790
Other	0.7	1,675,646

Table S5: Farm-to-gate unit price range of agronomic activities, transportation, intermediate products and co-products

Life cycle stages	Items	Unit	Lower price range	Upper price range	Source
Carinata farming	Land preparation	$/ha	36	48	Personal communication with Sheeja George in IFAS, UFL
	Seed	$/ha	48	72	
	Fertilizer application	$/ha	240	336	
	Irrigation	$/ha	0	72	
	Crop protection	$/ha	12	84	
	Non-road diesel fuel	$/ha	9.6	16.8	
	Harvesting	$/ha	96	120	
	Delivery	$/ha	0	24	
	Crop Insurance	$/ha	36	60	
Farm to extraction facility	per Mg of Carinata seed	$/Mg	1.8	2.016	(EIA 2019a)
Oil Extraction	Carinata Oil	$/l	0.744	1.488	(Diniz et al. 2018b)
	Carinata Meal	$/kg	0.768	1.032	(Diniz et al. 2018b)
	Natural Gas	$/MJ	0.00624	0.01128	(EIA 2018)
	Hexane	$/MJ	2.4	7.2	(Chu et al. 2017)
	Water	$/l	0.00432	0.00504	(DOE 2017)
	Electricity	$/kWh	0.27288	0.28848	(EIA 2019b)
Extraction to Bio-refinery	per Mg of Carinata Oil	$/Mg	1.8	2.016	(EIA 2019a)
HEFA Jet Production	Bio-jet*	$/l	0.744	1.488	(Diniz et al. 2018b)
	H_2	$/kg	2.64	4.8	(Saur and Ainscough 2011)
	Natural Gas	$/MJ	0.00624	0.01128	(EIA 2018)
	Water	$/l	0.00432	0.00504	(DOE 2017)
	Electricity	$/kWh	0.27288	0.28848	(EIA 2019b)
	Naphtha	$/l	0.912	3.576	(Chu et al. 2017)
	Propane	$/l	0.36	1.416	(Chu et al. 2017)
Bio-refinery to storage	per Mg of HEFA Jet fuel	$/Mg	1.8	2.016	(EIA 2019a)

** Intermediate price of bio-jet, the final price of bio-jet is determined with the annual capacity of the bio-refinery plant, total production investment, tax, labor cost, maintenance cost, insurance, and contingency.*

CHAPTER 4

CONCLUSION

Commercial aviation emitted about 859 million metric tons of greenhouse gases in 2017 which was 2.6% of all human-made greenhouse gas emissions (IATA 2017). It is projected that carbon dioxide, one of the major greenhouse gases emissions from the aviation sector could rise to 20.2% by 2050 (IATA 2018). Member states of the International Civil Aviation Organization (ICAO) agreed to facilitate carbon-neutral growth by 2021 through a market-based mechanism to address aviation emissions. Also, the International Air Transport Association (IATA) has set a goal of 50% reduction in carbon dioxide emissions by 2050. To achieve these goals, the displacement of petroleum-based jet fuel is essential with the jet fuel obtained from biomass-based feedstocks. In this regard, the carinata-based jet fuel becomes important as carinata can be grown in the southeastern United States during the winter months on existing farms without getting into the debate of indirect land use changes.

Our results suggested about 7.12 million metric tons of carinata can be produced in Georgia, Florida, and Alabama using average carinata yields at five percent composite risk level which would be enough to displace about 4.96% of total petroleum-based jet fuel currently consumed in the United States. Total GHG emissions from producing a thousand liters of bio-jet fuel at the bio-refinery gate were estimated about 821.84 kg CO_2e and life cycle greenhouse gas emissions from carinata jet fuel save around 63% than conventional jet fuel. Our study also estimated about 24% less energy consumption for producing a similar amount of bio-jet fuel than conventional jet fuel production. The unit price of bio-jet at bio-refinery gate is estimated to be $0.85/l, representing a 30% higher price than the current price of conventional jet fuel. An incentive of $0.30/l will help in promoting the production of carinata-based jet fuel production in the southeastern United States.

Further studies are needed to determine the total carbon benefits related to the use of carinata-based jet fuel production in the southeastern United States. For example, we have not included soil carbon dynamics related to carinata production in our analysis. Similarly, we have not estimated the carbon emissions related to the supply chain of carinata-based jet fuel operating at the landscape level. In the economic analysis, we have not considered risks related to prices of carinata and other competitive winter crops grown in the southeastern United States. We have also not estimated the role of current government policies and incentives on the production cost of carinata-based jet fuel. We hope that our study will be able to guide future research suitably.

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