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Modeling site suitability and production potential of carinata-based sustainable jet fuel in the southeastern United States

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A R T I C L E I N F O

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A B S T R A C T

The aviation sector is currently responsible for 2.6% of global carbon emissions. Carbon emissions of the aviation sector are expected to increase by 3–4% each year due to the rising demand for air travel. The use of bio-jet fuel derived from carinata (*Brassica carinata*) is a potential solution for mitigating carbon emissions from the aviation sector. This study determines suitable sites for growing carinata across three southeastern states of Georgia, Alabama, and Florida. Suitable edaphic (average soil storage, soil organic carbon, root zone depth) and climatic variables (temperature) along with historical land use trajectories were used for determining the land suitability for carinata production. The weights of the edaphic variables were decided by surveying experts using the Analytical Hierarchy Process. This study also determined the susceptibility of frost events in growing season of carinata from 2010 to 2017. Finally, the composite risk was calculated by multiplying the probability of potential damage risk and probability of land risk. Considering minimum risk level of 5%, about 45.56% (0.77 million ha) of land in Georgia, 0.81% (0.01 million ha) land in Alabama and about 3.04% (0.05 million ha) of land in Florida is suitable for growing carinata. Depending upon the composite risk level and expected carinata yields, the total production potential of carinata was between 1.87 and 3.91 million metric tons which was sufficient for producing between 980 and 2045 million liters of bio-jet fuel sufficient enough to replace 1.4%–2.33% of the current jet fuel consumption in the United States. Our study will feed into current policy debate about reducing carbon footprint of the aviation sector in the United States and promote development of bio-economy for rural America.

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 flew 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 mitigation initiatives (IATA, 2018).

In order to reduce the carbon footprint of the aviation sector, 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 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

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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 component 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 suggest that the use of biomass-based jet fuel will 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 can be potentially utilized for the production of biomass-based jet fuel worldwide, in general and the United States, in particular which 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).

Ethiopian Mustard (*Brassica carinata*) was introduced in the southeastern United States in 2010 through a joint research collaboration between University of Florida and Agrisoma Biosciences Incorporated (https://agrisoma.com/). 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. It may improve 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 rural economies and, thus, could jump-start the bio-economy in the southeastern United States. In this regard, the study first undertakes a spatially explicit suitability analysis for determining the total potential of carinata production in three southeastern states (Georgia, Alabama, and Florida) of the United States in the presence of risks related to climate and land availability, and then evaluates the total replacement potential of petroleum-based jet fuel consumed at the national level with the jet fuel derived from carinata produced in southeastern United States.

2. Literature review

Numerous studies have analyzed the suitability of various crops and their byproducts and dedicated bioenergy crops in different regions worldwide (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 ha) for the production of 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 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 for producing 56.6 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 and \$55 and \$36 and \$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 for the production of 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 ha 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 (Sharma et al., 2017; Sahoo et al., 2016; Zhang et al., 2011; Haddad and Anderson, 2008; Ma et al., 2005; Noon et al., 2002). 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 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

Table 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	Relative Savings in carbon dioxide emissions (%)	Reference
Canola	US	50%	Ukaew et al. (2016)
Algae	US	76%	Fortier et al. (2014)
Camelina	US	74%	Agusdinata et al. (2011)
Residual Wood	US	78%	Ganguly et al. (2018)
Sugarcane	US	71%–75%	Jong et al. (2017)
Corn stover	US	60%–75%	Jong et al. (2017)

initiatives led by different corporate and non-corporate entities 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. This understanding is critical for ascertaining 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 provide guidance to future studies focusing on suitability modeling of bioenergy feedstocks in the United States and beyond.

3. Study area

The southeastern states of Georgia, Florida, and Alabama (Fig. 1) cover a total land area of 43.2 million hectares (Georgia 15.2 million ha, Florida 14.7 million ha, Alabama 13.4 million ha) out of which 6.5% (2.8 million hectares) was under agriculture in 2017 (Fig. 2). Out of the total area under agriculture in 2017, about 1.7 million hectares were under cropland. In 2017, farmers grew winter cover crops on about 7% of the total area under cropland (Duzy et al., 2016). This indicates that a large portion of area under cropland in selected states could be potentially utilized for producing carinata first and then carinata-based jet fuel, feed, and other valuable industrial products. Furthermore, the average winter temperatures in Georgia, Florida, and Alabama are 9.3 °C, 12.7 °C, and 10.3 °C, respectively and the majority of 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.

4. Materials and methods

4.1. Survey for ascertaining critical and screening variables

First, we surveyed scientists from the University of Florida, the University of Georgia, Aubulrn University, Mississippi State University, and the United States Department of Agriculture 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 the carinata productivity. Participating scientists also mention 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 crops, double crops, and winter crops 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 to include the probability of frost events based on historical climate data and risk of land availability based on past land use as a part of the suitability analysis for estimating the total production potential of carinata and corresponding bio-jet fuel in the selected states.

4.2. 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). Then, we resampled the input raster datasets to 500×500 m (25 ha) resolution using the nearest neighbor resampling technique. We selected this resolution for two reasons. First, the

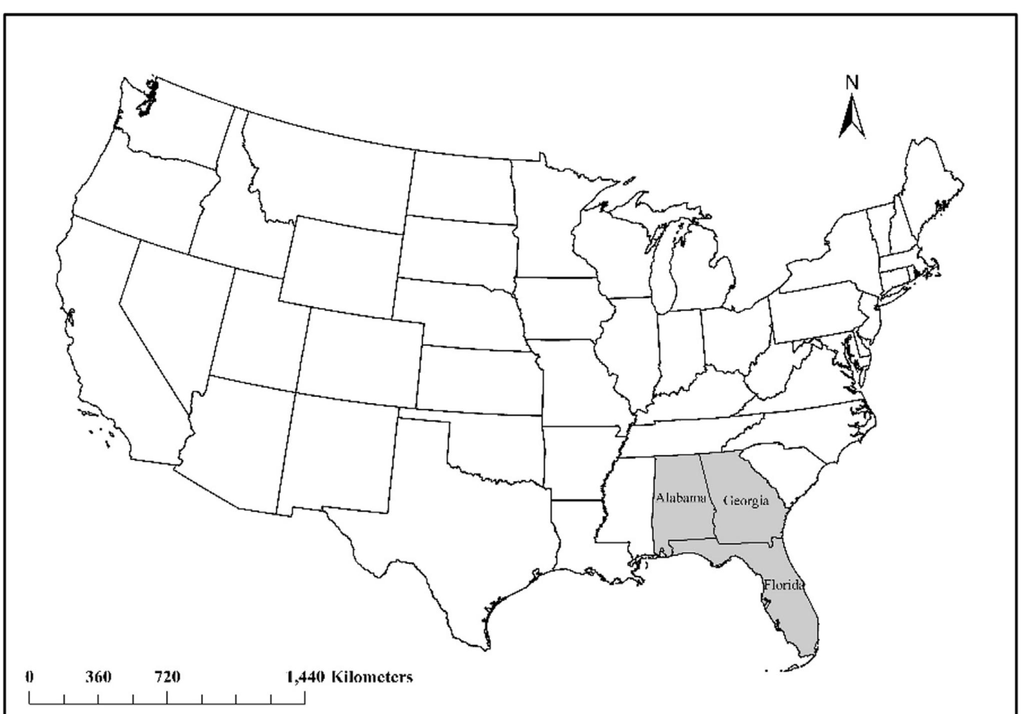

Fig. 1. Location of selected states for the suitability analysis.

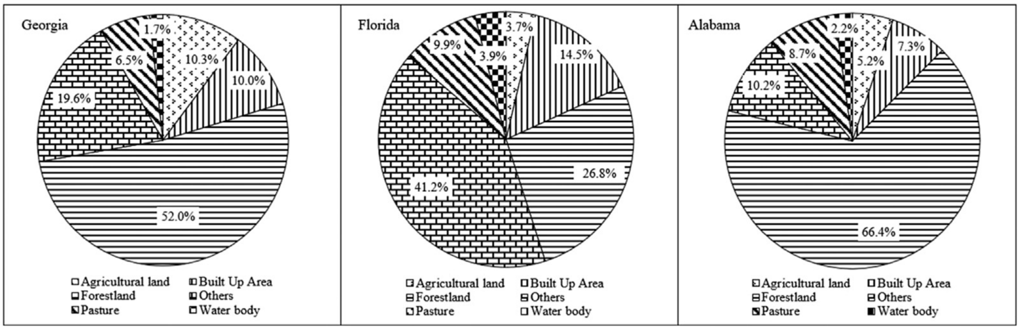

Fig. 2. Major land uses in Georgia, Florida, and Alabama in 2017 (Source: NRCS, 2017).

Table 2
Details of the input spatial data used in the analysis.

Data label	Data Type	Resolution	Data Source
Cropscape Data Layer	Raster	30 × 30 m	National Agricultural Statistics Service (NASS), USDA
Soil	Raster	10 × 10 m	National Resource Conservation Service (NRCS), USDA
Rainfall	Raster	4 × 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
Land Ownership	Vector		Florida- Institute of Food and Agricultural Service (IFAS), University of Florida
			Alabama- National Oceanic and Atmospheric Administration (NOAA), United States Dept. of Commerce
			National Resource Conservation Service (NRCS), USDA

selected resolution was reasonable enough to capture variations across farms for selected variables as it represented about 20% of average farm size across Georgia (92.2 ha), Florida (80.9 ha), and Alabama (83.3 ha) (NASS, 2017). Second, the selected resolution facilitated data analysis considering computing constraints. For example, at an original resolution of 30 × 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 within the limits of available resources. After resampling, we re-projected datasets used 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) 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, respectively with each row presenting a pixel of 500 × 500m resolution on the ground. Each dataset had 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 (2017) and historical (2010–2017) land use, and ownership. We used ArcGIS 10.4 for the spatial analysis.

4.3. Data preparation for suitability analysis

We screened the datasets for rows where land use in 2017 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 the further analysis. Then, we created three new columns for 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 other two new columns, the normalized value for other two critical variables namely soil organic matter and root zone depth were calculated. We followed Equation (1) for obtaining normalized values.

4.4. 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 decision-making settings (Dwivedi et al., 2015; Kukrety et al., 2013; Kurttila et al., 2000; Ramirez et al., 2012). Several bioenergy related studies have also integrated spatial modeling with AHP (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” (Fig. 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 Saaty and Vargas (2012) and then used a standard AHP methodology for

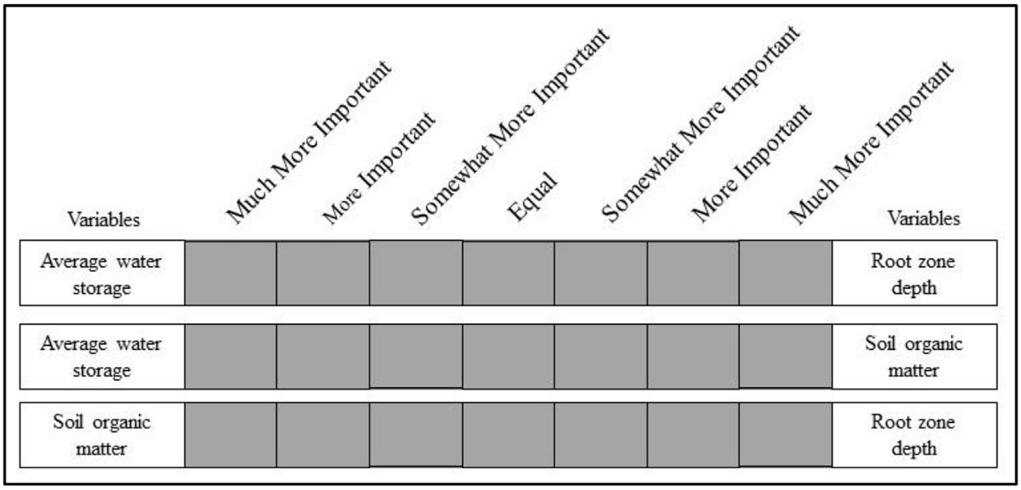

Fig. 3. Scale used for pairwise comparisons for obtaining relative weights of critical variables using Analytical Hierarchy Process.

calculating relative weights of each critical variable. We also estimated the consistency of the subjective judgment using consistency ratio by following Dwivedi and Alavalapati (2009). If the consistency ratio value is less than or equal to 10% the consistency is considered to be acceptable. Otherwise, the subjective judgment needs to be revised (Saaty and Vargas, 2012).

4.5. 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. Fig. 4 shows the brief process flow diagram of locating suitable sites for growing carinata including the risk analysis in the southeastern United States.

4.6. 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 2017. Then, we created a buffer of 80 km 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 for further analysis. We followed three rules to select these weather stations: First, these weather stations minimized overlapping of 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 the historical weather data for selected weather stations from different sources (Table 2). The frequency of weather data for Georgia and Florida was 15 min whereas, for Alabama, the frequency was 60 min subject to the data availability. We defined a frost event which would potentially damage carinata as when the temperature is less than $-6.67\,^{\circ}C$ for 20 or more hours between October to March (personal communication, Dr. R. Seepaul at the North Florida Research and Education Center, University of Florida). We used weather data from 2010 to 2017 to estimate the probability of potential damage risk at each weather station

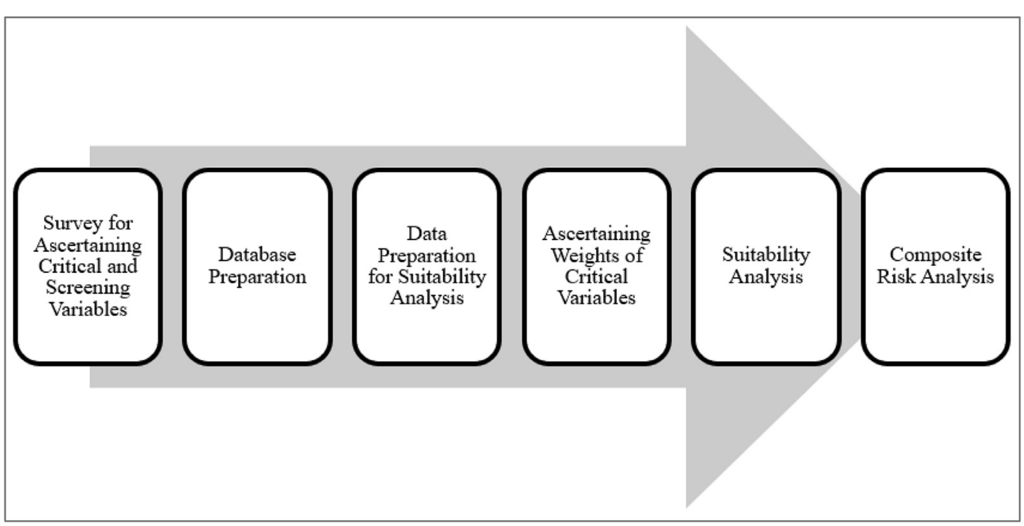

Fig. 4. Process flow diagram for determining suitable locations with risk in the southeastern United States.

Table 3
Amount of suitable land (million hectares) across three states under selected suitability index class.

	Suitable land area	Low	Medium	High
Georgia	0.91	0.03 (3.05%)	0.69 (76.47%)	0.19 (20.48%)
Florida	0.10	0.06 (67.67%)	0.03 (31.68%)	0.01 (0.68%)
Alabama	0.33	0.01 (1.38%)	0.02 (5.96%)	0.31 (92.66%)
Total	1.34	0.10 (7.10%)	0.74 (55.91%)	0.49 (37.01%)

assuming a total number of growing days as 180 (October—March). Then, we adopted the ordinary kriging approach in ArcGIS 10.4 to create a surface map (500×500 m resolution) of potential damage risk at the state level. We calculated the probability of land availability for growing carinata (500×500m resolution) based on the historical land use using Equation (4). Then, we calculated the risk of land availability using Equation (5). Finally, we multiplied the probability of potential damange risk and risk of land availability at each pixel and calculated the composite risk for each pixel.

5. Results

In our case, consistency ratio for all the pairwise comparisons was less than one percent which was much lower than the limit of 10% suggesting that strong consistency across responses obtained from participating scientists in the survey. 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 68% of all land suitable for growing carinata across selected states (Table 3). The majority of land suitable for growing carinata across selected states was in the medium category covering 0.74 million hectares, i.e., about 56% of total land suitable for growing carinata across selected states. Fig. 5 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 rising urban population, relatively warmer winter temperatures, high water table affecting root zone depth, and lack of machinery needed for growing carinata. Our results suggested that medium and high suitable sites for carinata production in Georgia were located in the southern and northern part of the state, respectively. The majority of sites present in Alabama were highly suitable to grow carinata and were located in the southern and northern part of the state. We also found that low suitable sites were spread across part of Florida analyzed in this study.

Fig. 6 shows the spatial distribution of potential damange risk based on a number of historical frost events for selected states. The probability of potential damage risk decreased from North to South in Georgia following the temperature gradient. The same trend was also noticed for Alabama where the probability of potential damage risk decreased from North to South. For Florida, the probability of potential damage risk decreased from West to East to a large extent as noticed in the historical weather records used for the analysis. Fig. 7 shows the land availability risk for potentially growing carinata across three states. We have only considered only those lands which were used for row cropping, double cropping, and winter cropping and excluded land under orchards, grasslands, and other agricluture- and forestry-based land uses to avoid issues related to indirect land use changes. We found that land availability risk was lower on pixels which were located in the agricultural region of selected states. For example, land availability risk was lower in the southwestern part of Georgia which produces 20.3% of total farm value in Georgia (NASS, 2017). Fig. 8 shows the distribution of composite risk, a equal combination of potential damage and land use risks. As noticed, southwestern region of Georgia, south and southeastern region of Alabama, and the northern Florida were suitable for growing carinata up to 5% risk level. Table 4 shows the availability of land across selected states under different risk levels. The suitable land for carinata production at five percent composite risk level was 0.83 million hectares across selected states whereas it increased to 1.16 million hectares at 20% composite risk level. We also found that Georgia had the highest amount of suitable land across selected states.

We used input parameters reported in Table 5 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 2.34 million metric tons of carinata could be produced across selected states at 5% composite risk level

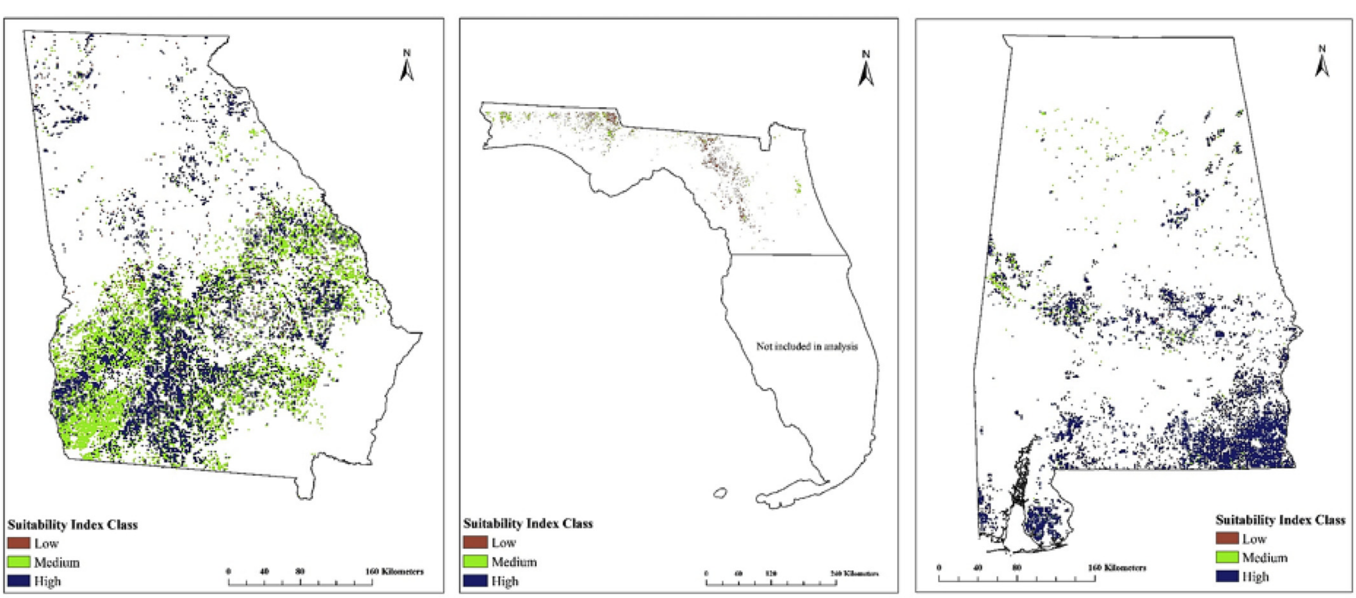

Fig. 5. Spatial distribution of land suitability categories for carinata production in Georgia, Florida, and Alabama. The reported suitability maps are based on edaphic conditions only without accounting for weather and land use history.

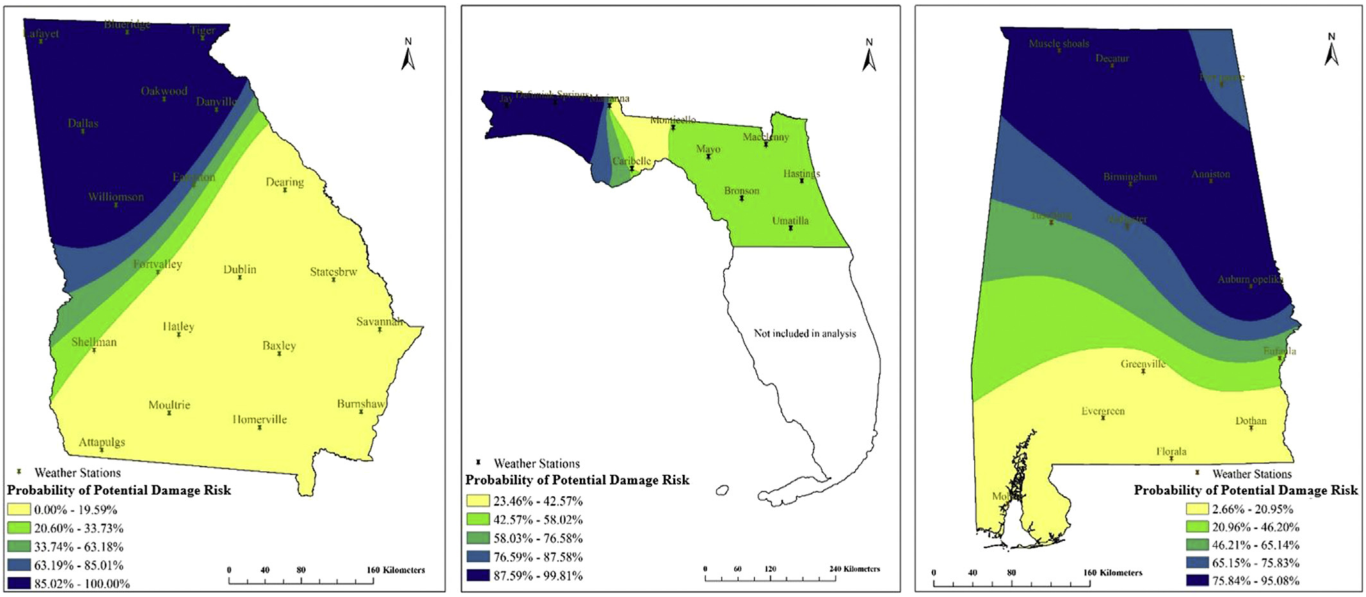

Fig. 6. Spatial distribution of potential damage risk for carinata production in selected states.

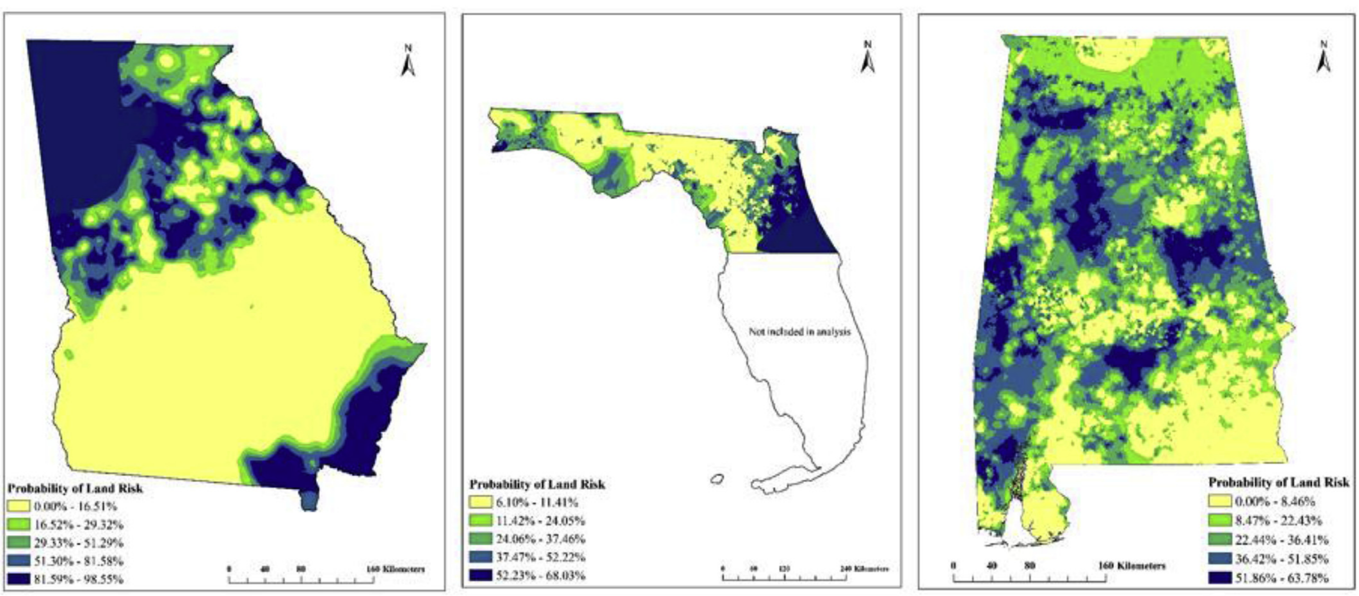

Fig. 7. Spatial distribution of land availability risk for carinata production in selected states. These maps are based on a total number of times land was classified as under some agriculture crop over 2010 to 2017.

out of which 92% could be potentially sourced from Georgia alone (Table 6). The range varied from 1.87 to 2.81 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 7 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 1224.33 million liters of carinata-based jet fuel could be produced (Table 7) using average carinata yield and land availability at the 5% composite risk level across selected states which will be sufficient enough to replace 1.75% of total jet fuel consumed at the national level (64.35 billion liters) in 2017. We also found that this range could vary from 1.40% to 2.33% depending upon the selected yield and composite risk levels (Table 8).

6. Discussion

We found that 1.33 million hectares of land is suitable for carinata production without accounting for risks related to climate and land availability. After accounting for selected risks related to climate and land availability, we found that only 0.83, 1.08, and 1.16 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 further suggests that suitability studies should

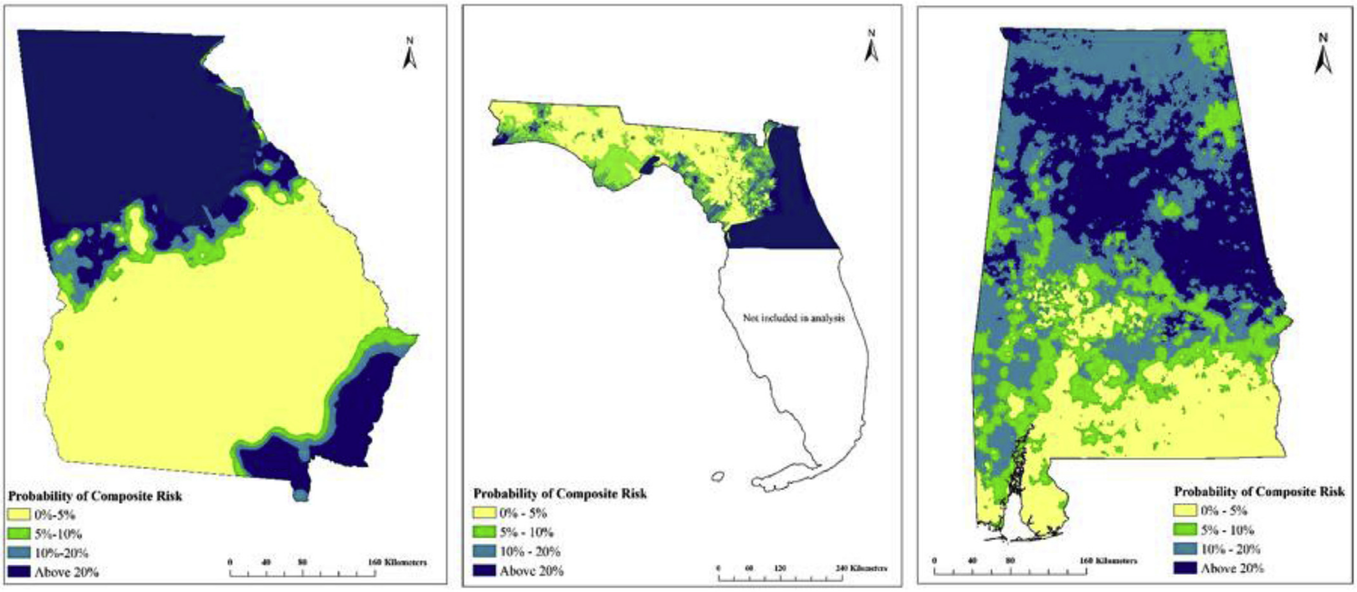

Fig. 8. Spatial distribution of composite risk for carinata production in selected states.

Table 4
Availability of suitable lands (million hectares) for carinata production at selected composite risk levels.

	5% Risk Level	10% Risk Level	20% Risk Level
Georgia	0.77	0.81	0.85
Florida	0.05	0.09	0.09
Alabama	0.01	0.17	0.22
	0.83	**1.08**	**1.16**

incorporate risks to avoid over projection 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 1.40% and 2.33% of total petroleum-based jet fuel nationwide depending upon expected carinata yields and composite risk levels. This range suggests that we should explore the

Table 5
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 Conversion	**0.63**	kg/kg	ANL 2018 (GREET Model)
Density of Jet Fuel	**0.878**	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 6
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	1.73, 2.16, 2.59	1.82, 2.27, 2.73	1.91, 2.38, 2.86
Florida	0.12, 0.14, 0.17	0.21, 0.26, 0.31	0.21, 0.26, 0.31
Alabama	0.03, 0.04, 0.05	0.39, 0.49, 0.59	0.49, 0.61, 0.74
Total	**1.87, 2.34, 2.81**	**2.42, 3.02, 3.63**	**2.61, 3.26, 3.91**

Table 7
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	903.27, 1129.09, 1354.91	952.47, 1190.59, 1428.71	998.5, 1248.13, 1497.75
Florida	60.19, 75.24, 90.29	107.51, 134.39, 161.27	107.51, 134.39, 161.27
Alabama	15.98, 19.98, 23.98	204.91, 256.14, 307.37	257.4, 321.75, 386.10
Total	**979.46, 1224.33, 1469.19**	**1264.91, 1581.14, 1897.36**	**1363.42, 1704.28, 2045.13**

Table 8
Replacement of annual jet fuel consumption at low, average and high yields of carinata at the national level.

Yield	5% Risk Level	10% Risk Level	20% Risk Level
Low Yield	1.40%	1.48%	1.55%
Average Yield	1.75%	1.85%	1.94%
High Yield	2.11%	2.22%	2.33%

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 in the region (Sieverding et al., 2016; Gesch et al., 2015). Additionally, there exists a need to explore other bioenergy feedstocks which could be potentially used for bio-jet fuel production for displacing the majority of the 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/).

7. Conclusion

In this study, we developed a spatially explicit suitability model for ascertaining the production potential of carinata in three southeastern states of Georgia, Alabama, and Florida. First, we integrated advanced spatial modeling with the multi-criteria decision-making approach for determining the spatial distribution of sites suitable for carinata production in selected states without accounting for risks related to climate and availability of land. Then, we integrated both risks in the analysis for ascertaining a realistic range of possible carinata production in selected states. Our results suggest that we can produce about 2.34 million metric tons of carinata in selected states using average carinata yields at five percent composite risk level which would be sufficient enough to displace about two percent of total petroleum-based jet fuel currently consumed in the United States.

In this study, we have only focused on the site suitability of the carinata production in three southeastern states (Georgia, Alabama, and Florida) of the United States. Future studies should cover othr southern states for exploring the feasibiity of carinata production at the regional level. The future research should also evaluate additional income to farmers related to the production of carinata. This will help us in understanding the adoption behavior of farmers in the context of carinata, a key component in determining the total feasible production of carinata in the selected states. Additionally, we have to keep in mind that research on carinata as a potential feedstock for bio-jet fuel production is still ongoing where new varieties are continously being tested. It is quite likely that a new variety is developed soon which better suits climate and edaphic conditions in the southeastern region. As a result, this study should be considered as a snapshot of the relaity at best, and should be revisited in some years for projecting potential of carinata production in the southeastern states. We hope that our study will positively contribute to future studies looking into social, economic, environmental, and supply chain aspects of sustainable carinata production in the southeastern region of the United States for reducing the carbon footprint of the aviation sector in the United States and beyond.

Authors contribution

AL collected and analyzed the data, developed the model, and wrote the first draft of the manuscript. PD conceptualized the research, undertook the surveys, wrote the manuscript, and supervised the overall research.

Conflicts of interest

Authors declare no conflict of interest.

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Equations

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

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

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

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

$$\text{Probability of Land Availability Risk} = 1\text{- Probability of Land Availability for Growing Carinata} \quad (5)$$

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.117817.

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