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Does carinata, an oilseed crop for sustainable aviation fuel, improve the eco-efficiency of crop rotations in South Georgia, United States?

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ABSTRACT

In 2019, the aviation sector emitted about five percent of the total energy-related carbon dioxide equivalent (CO_2e) emissions in the United States. The replacement of conventional aviation fuel with drop-in sustainable aviation fuel (SAF) derived from various biomass-based feedstocks is vital to reduce the overall CO_2e emissions of the aviation sector. The SAF derived from *Brassica carinata* (carinata), an oilseed winter crop, could help the aviation sector mitigate CO_2e emissions. Therefore, it is vital to develop a framework for assessing the eco-effectiveness of carinata in crop rotations by combining economic and environmental benefits. We identified 292 crop rotations (over a four-year rotation period with and without carinata) in South Georgia, a major agricultural region of the United States. We conducted a comprehensive life cycle assessment to determine the total carbon emissions of selected crop rotations. We combined the carbon emissions and profitability information using data envelopment analysis (DEA) to estimate the eco-efficiency score of each crop rotation. The results indicate that crop rotations with carinata emit less CO_2e than crop rotations without it, especially when carinata replaces winter wheat. Carinata's profitability (net present value of \$2996/acre) is highest in a "corn-corn-soybean" rotation at a contract price of \$441 per metric ton. Finally, "cotton-carinata-cotton-fallow-soybean-fallow-cotton-carinata" is the most eco-efficient rotation at the same contract price. Overall, carinata increases eco-efficiency at the farm level and, thereby, has the potential to promote the bioeconomy in South Georgia and beyond.

1. Introduction

The aviation sector contributes around \$2.7 trillion to the world economy (Zhao et al., 2021); however, the industry emits two percent of global carbon emissions (ATAG, 2020). The United States alone contributes about 23% of aviation-related carbon emissions globally (Graver et al., 2020). Although the industry implemented several policies to increase fuel efficiency (70% improvement relative to 1960) and to mitigate carbon dioxide equivalent (CO_2e) emissions (50% decrease per seat kilometer relative to 1990), the industry remains a significant contributor to the global greenhouse gas emissions (Zhao et al., 2021). If no policies are implemented until 2050, the carbon impacts will rise between four and six times higher than the 2010 levels (Liao et al., 2022).

The International Air Transport Association has set several goals to mitigate carbon emissions by 2050 (European Aviation Safety Agency et al., 2016). As of March 2022, 109 countries have announced their voluntary participation in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to mitigate CO_2 emissions by 50% through 2050 (ICAO, 2022). They are striving to decrease the environmental impacts of aviation while encouraging the continued growth of a globally critical industry.

There are several alternative technologies for sustainable aviation that can be classified into four main categories: 1) biofuels, 2) electrofuels, 3) electric (battery-based), and 4) hydrogen aviation (Su-ungkavatin et al., 2023). Sustainable aviation fuel (SAF) is the most promising opportunity for long-term aviation emissions mitigation (IATA, 2021). It can potentially reduce greenhouse gas emissions in the aviation sector by 80% (IATA, 2021). Several studies have analyzed the carbon benefits of SAF relative to conventional aviation fuel (Chao et al., 2019; Ahmad et al., 2021; Pamula et al., 2021; Barke et al., 2022). The majority indicated that SAF has a lower carbon footprint than conventional

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aviation fuel; however, the amount of greenhouse gas emission savings varies across different biomass feedstocks. The type of feedstock and technology determines the CO_2 savings of SAF. In most of the studies, the emissions savings were up to 80% less for SAF than for conventional aviation fuel (IATA, 2022).

Although there are environmental benefits of SAF production, there are also several barriers, mainly the higher production cost and, to a lesser degree, fuel logistics and quality control of the transport, storage, and blending (Smith et al., 2017). Multiple studies have addressed the high production cost of SAF and concluded that it is not economically feasible to produce them relative to conventional aviation fuel (Michailos, 2018; Yang et al., 2018; Barke et al., 2022; Bhatt et al., 2023). Most studies suggested a co-product credit or other subsidies, such as renewable identification number (RIN) credit, to attain economic viability (Alam et al., 2021; Zhao et al., 2021; Barke et al., 2022). Other studies such as Cui and Chen (2024) suggested a carbon price on conventional fuels. They concluded that SAFs are profitable when the government implements a carbon price policy of more than 0.273 times the SAFs-kerosene price gap in South America. In a similar study, Cui et al. (2024) concluded that carbon price should be increased by 12.84 times to make it feasible for African airlines to promote and adopt SAFs.

It is crucial to integrate environmental and economic factors into a cohesive framework to develop an informed pathway for SAF production in the United States. Eco-efficiency is a measurement that jointly measures economic and environmental performances (Arabi et al., 2014). Eco-efficiency is based on creating more goods or services while consuming fewer resources and imposing fewer negative externalities (Cabeza et al., 2015). The application of eco-efficiency could inform policymakers and other relevant stakeholder groups about the trade-offs between economic and environmental components of SAF production, thereby facilitating science-based decision-making.

Silalertruksa et al. (2015) proposed a sugarcane-based biorefinery system that can improve overall eco-efficiency by 20–70% in Thailand. Álvarez del Castillo-Romo et al. (2018) presented a mixed integer non-linear programming problem to find the most eco-efficient approach to produce biofuels and bioproducts from lignocellulosic biomass in Mexico. Gabisa and Gheewala (2020) assessed, using locally produced molasses, ethanol instead of imported gasoline through an eco-efficiency approach in Ethiopia. They concluded that the utilization of byproducts and cane trash has the potential to improve the eco-efficiency by 40%. In a more recent study, Barbero and Zofío (2023) concluded that the supply chain eco-efficiency of castor oil in Greece is 0.14 (EUR/kg CO_2e). Some other studies addressed the eco-efficiency of bioenergy crops at the farm level. Salazar-Ordóñez et al. (2013) found that only 4% of sugar beet farms for ethanol production are eco-efficient in Spain. It was suggested that farmers should reduce inputs by up to 40% to improve the eco-efficiency of ethanol production. Ren et al. (2014) evaluated the eco-efficiency of biofuel production from wheat, corn, cassava, and sweet potato under different scenarios. The sweet potato was the most eco-efficient feedstock for ethanol production in China. In a similar study but for other crops, Ren et al. (2014) concluded that cassava-based ethanol is the most eco-efficient biofuel in China. In an Italian case, Forleo et al. (2018) proved that rapeseed farms have a higher eco-efficiency ratio than sunflower farms for biofuel production. Yang et al. (2022) found that sugarcane as a bioenergy crop can improve eco-efficiency in a crop rotation by 28% in China.

Brassica carinata A. Braun (carinata), also called Ethiopian mustard, is a non-edible oilseed brassica and a suitable feedstock for SAF production due to the low environmental impact and minimal indirect land-use change (George et al., 2021). Since at least 3000 BC, it has been grown in northeastern Africa (Mulvaney et al., 2019). The crop has a higher tolerance for warmer weather than canola and oilseed rape, making it a better option as a winter crop to produce SAF in subtropical areas like the Southern United States (Mulvaney et al., 2019). American Society for Testing and Materials approved catalytic hydrothermolysis to convert carinata oil to drop-in SAF (George et al., 2021). Alam and Dwivedi (2019) found that 1.4 million hectares are suitable for growing carinata in the Southeastern United States. The farmers can grow carinata in crop rotations as a winter crop to make more income and provide soil health benefits (George et al., 2021). Carinata can be in rotation with late corn, cotton, peanuts, soybean, and grain sorghum (SPARC, 2019). Crop rotation can help decrease disease risk because *Fusarium* and *Sclerotinia* remain on carinata residues (SPARC, 2019).

Carinata is a native African crop; it has been sown and studied in North America (Rakow and Getinet, 1998), Australia (Uloth et al., 2015), Europe (Cardone et al., 2002), and Asia (Malik, 1990) for many years. Most studies related to carinata focused on agronomy (Husen et al., 2014; Mulvaney et al., 2019; Campanella et al., 2020; Kumar et al., 2020; Bashyal et al., 2021; Seepaul et al., 2021) as well as SAF and the co-product technologies (Newson et al., 2013; Drenth et al., 2014; Kasiga et al., 2020). Only a few studies have focused on the economics of carinata production. Diniz et al. (2018) suggested a \$0.39/L subsidy to decrease carinata-based SAF production risk from 99% to about 30%. Elliott et al. (2018) found that carinata could decrease risk and increase profitability in western South Dakota farms; however, it could only reduce risk by diversification benefits in the eastern area. They did not study carinata in a rotation with other conventional crops; therefore, they did not include rotational benefits. On the contrary, Basili and Rossi (2018) analyzed the environmental and economic effects of carinata in wheat rotation. Their results showed that carinata-based SAF production is economically feasible and environmentally sustainable in Italy. The main obstacle for the second-generation production was importing cheap feedstocks, mainly palm oil. They suggested an import tax policy to compete with the trade policy from Indonesia. Alam et al. (2021) concluded that carinata-based SAF is costlier than conventional fuel (\$0.85/L to \$1.28/L versus \$0.5/L), but the co-product and RIN credits drop the SAF cost between -\$0.66/L and -\$0.12/L. Similar results were obtained by Masum et al. (2023) after analyzing the trade-offs between the economic and environmental performance of carinata-based SAF production over the supply chain. Finally, Ullah et al. (2023) concluded that carinata-based SAF has the potential to decrease carbon intensity by 66% compared to the conventional fuels in the United States; however, it comes at a higher cost of \$0.44/L.

Not many studies focus on the economics of carinata, and even if they do, they typically do not consider the economics of carinata in relation to popular crop rotations. Moreover, no study has characterized the eco-efficiency of winter bioenergy crops as a part of the overall production system in a given region. As a result, our study fills a critical knowledge gap by analyzing the eco-efficiency of carinata in South Georgia, a major agricultural region of the United States. The overall goal of the study is to identify the environmental and economic trade-offs of carinata production in current rotations and to evaluate any gains in eco-efficiency relative to traditional rotations with no carinata production. In this context, the study's objectives are to determine changes in carbon savings with and without carinata in crop rotations and to determine changes in farm-level eco-efficiency scores with and without carinata in crop rotations. This study will feed into current initiatives promoting SAF production worldwide, in general, and in the United States, in particular, to achieve policy objectives of mitigating climate change, enhancing the provision of ecosystem services, and supporting rural economies. The results of the study become even more relevant in light of the recently announced SAF Grand Challenge by the Biden-Harris administration, which targets to completely replace conventional aviation fuel by 2050 (The White House, 2021).

2. Materials and methods

2.1. Study area and crop rotations

For this study, we selected 50 counties in South Georgia, which collectively account for 56.4% of the total cropland in the state (NASS, 2020). The predominant crop rotations in South Georgia are cotton-cotton-peanut; cotton-cotton-corn-peanut; corn-corn-peanut; cotton-cotton-cotton-peanut; corn-corn-corn-peanut; and cotton-corn-peanut (Bullock, 1992). After factoring in various constraints,[1] we identified a total of 292 four-year crop rotations for our study, with 180 of them involving carinata and 112 without it. A comprehensive list of the selected 292 four-year rotations is in Appendix 1.

2.2. Farm-level economics

To account for variations in carinata seed prices while evaluating farm-level eco-efficiency, we considered two carinata price scenarios. In Scenario 1 (S1), the carinata price was $441 per metric ton whereas the same was $320 per metric ton under Scenario 2 (S2). The S1 price is based on the original commercial contracted price established by Agrisoma Biosciences in South Georgia in 2017, while the S2 price is derived from the average canola price (Karami et al., 2022). We calculated the net present value (NPV) for each of 292 crop rotations under both scenarios. The 292 four-year crop rotations remain the same under S1 and S2, enabling us to assess the impacts of carinata seed prices on the eco-efficiency of farms. Please see Karami et al. (2022) for more details on farm-level costs, incomes, and yields.

2.3. Life cycle assessment (LCA)

LCA is a methodology employed to assess the environmental impacts of various products and services throughout their entire life cycle, including stages such as raw material acquisition, manufacturing, utilization, end-of-life treatment, recycling, and final disposal (Wall and Pell, 2020). Fig. 1 illustrates the overall system boundary used to estimate the total CO_2e emissions associated with carinata-based SAF production. The process begins with cultivating carinata seeds on farmland and their subsequent transport to a storage facility. The seeds are then processed to extract crude oil, which is further transported to a biorefinery. At the biorefinery, hydro-processed esters and fatty acids (HEFA) conversion technology (Alam et al., 2021) is employed to convert the crude oil into carinata-based SAF. The resulting SAF is then transported to the demand centers for utilization or storage. In this study, we adopted a “cradle-to-farm” approach. The current study concentrated on farm-level environmental impacts to maintain methodological consistency with the LCAs conducted for other crops of corn, cotton, peanut, soybean, and wheat, which are part of selected crop rotations. Moreover, this approach is beneficial to compare our results with a multitude of other studies that also explore the environmental impacts of energy crops on farm-level practices (Solinas et al., 2015).

The functional unit is 1 ha for each crop rotation. Table 1 reports the input requirements to produce crops for 1 ha of agricultural land in South Georgia. We integrated the farm-level input data (Table 1) with GREET® Model 2019 to estimate the total global warming potential (GWP) in CO_2e of selected crops on a hectare basis. GaBi ts software was used to assess the environmental impacts of cotton, peanut, and wheat. GREET® Model 2019 was used for farm-level LCA of corn, soybean, and carinata. Neither GaBi ts nor GREET® Model 2019 has all six crops in their database; each has data for only three out of six crops. Consequently, we had to use both software due to the lack of needed data in either one of them.

Carinata farming operations involve using various chemicals to protect the crop from detrimental factors. Typically, farmers apply 1.5 Liter/ha of Prevathon® (chlorantraniliprole) as a pesticide. Glyphosate, ethalfluralin, and saflufenacil serve as herbicides, with application rates of 1.7, 2.62, and 0.05 kg/ha, respectively. The fungicide Priaxor® Xemium®, applied at a rate of 1 L/ha, is the sole fungicide used for carinata. Other detailed information about agrochemicals used for corn, cotton, peanuts, soybean, and wheat is reported by Karami et al. (2022).

2.4. Data envelopment analysis (DEA)

There are two different approaches for measuring efficiency: parametric and non-parametric. A parametric approach, such as the stochastic frontier approach (SFA), has three main limitations. First, it needs a specific functional form to define the efficient frontier. Second, it relies on a specific probability distribution to estimate the efficiency level. Lastly, any misspecification can lead to errors in estimating efficiency (Dong et al., 2014). On the other hand, a non-parametric approach, such as DEA, does not require assumptions about probability distributions or functional forms (Dong et al., 2014). As a result, it is well-suited for analyses with limited information. Consequently, this study applies the non-parametric DEA approach to evaluate production efficiency.

In DEA, efficiency is the production level at which the lowest inputs produce the highest output (Barbero and Zofío, 2023). There are three primary efficiency measurements within DEA: technical efficiency (TE), allocative efficiency (AE), and total economic efficiency (EE). Fig. 2 illustrates the relationship among these three efficiency measurements for a decision-making unit (DMU) at point P. $S\acute{S}$ is the unique isoquant of a fully efficient firm that consumes inputs of x_1 and x_2 to produce y. The input price ratio is $A\acute{A}$.

Per Coelli (2016), the formulas for calculating TE, AE, and EE for a DMU at point P are as follows:

$$TE = 0Q/0P \tag{1}$$

$$AE = 0R/0Q \tag{2}$$

$$EE = 0R/0P \tag{3}$$

It is vital to incorporate environmental and economic information into a cohesive framework to assess the efficiency of sustainability projects. A key advantage of DEA is its ability to integrate multiple indices into a single measurement, eliminating the need for subjective weight assignments among these indicators (Cabrera-Jiménez et al., 2022). Therefore, DEA facilitates sustainability assessments by integrating various environmental indicators and classifying alternatives in terms of their estimated efficiency scores (Cabrera-Jiménez et al., 2022). The merits of DEA provide a viable pathway to estimate an efficiency indicator considering both environmental and economic factors, such as eco-efficiency, which is a metric jointly evaluating economic and environmental performances (Arabi et al., 2014) and is computed using Equation 1 (TE) in this study.

Some studies have leveraged DEA to analyze economic and environmental impacts (Mardani et al., 2018; Wang et al., 2019; Xian et al., 2019; Zerafati et al., 2022). There are two approaches to modeling emissions using the DEA method. The first approach views emission as either a joint output or a byproduct in an explicit emission function (Ebert and Welsch, 2007). The second approach views emission as an input (quasi-input) to produce the desired output (Ebert and Welsch, 2007). Due to DEA's flexibility in functional form between inputs and outputs (Imran et al., 2018), we applied the second approach with a formulation of a single-input single-output TE index in Equation (1), initially introduced by Farrell (1957). The TE metric has been widely employed in DEA literature (Atici and Podinovski, 2015; Li et al., 2018; Mosbah et al., 2020; Pan et al., 2021). In our case, specifically, we apply the DEA method and assess eco-efficiency using the amount of CO_2e emissions and NPV as input and output, respectively. A DMU is efficient if no other DMU can give more output with the same or lesser input. Crop rotations represent DMUs in this study, and we seek the most efficient rotation or DMU by implementing DEA. We estimated the efficiency of the crop rotations using DEAP software (Coelli, 1996).

[1] Carinata cannot be sowed after peanut; there should be at least a two-year gap between carinata crops, and corn cannot be sowed after carinata or wheat (Karami et al., 2022).

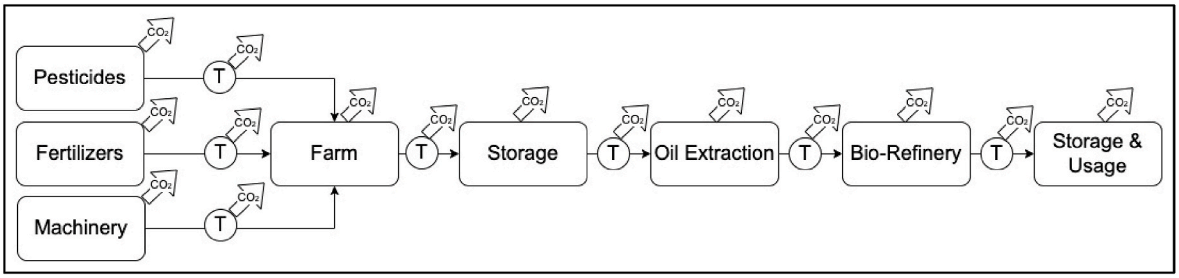

Fig. 1. | System boundary of carinata-based sustainable aviation fuel.

Table 1
Farm-level inputs for different crops in South Georgia.

	Inputs	Corn*	Cotton*	Peanut*	Soybean*	Carinata**	Wheat*
Fertilizers (kg/ha)	N	269	100.9	0	0	89.7	89.7
	P	112.1	78.5	0	44.8	0	44.8
	K	224.2	78.5	0	89.7	0	44.8
	Lime	1100	740	1120	740	0	560
	Inoculant	0	0	5.6	3.9	0	0
	Boron	0	0	0.6	0.6	0	0
	Phosphoric Pentoxide	0	0	0	0	44.8	0
	Potassium Oxide	0	0	0	0	89.7	0
	Sulphur	0	0	0	0	28	0
Chemicals (liter/ha)	Insecticide	0.9	1.1	23.5	0.2	0.08	0.1
	Herbicide	7.0	3.1	6.1	17.6	4.41	5.7
	Fungicide	0.8	2.6	12.4	0.9	0.3	0.3
Fuels	Diesel (liter/ha)	69.6	121.2	160	63.6	219.6	62.8
	Electricity (MJ)	90.6	90.6	67.9	56.6	11.3	11.3

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

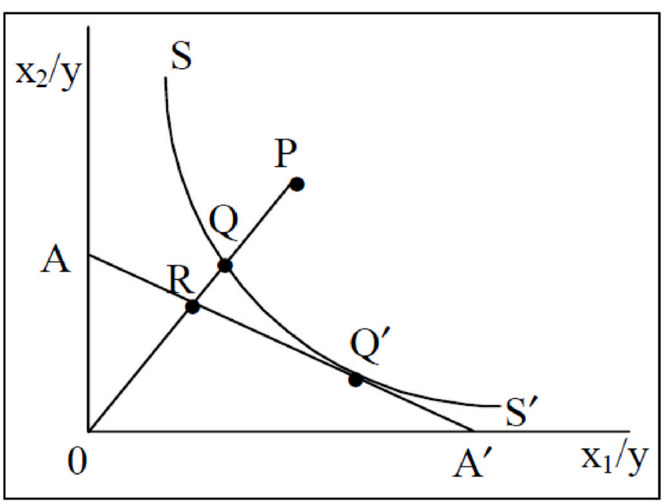

Fig. 2. | Technical, allocative, and economic efficiencies (Coelli, 2016).

3. Results

3.1. Economics of crop rotations

The average NPVs over four years under Scenarios S1 and S2 are \$2428/ha and \$2077/ha, respectively, primarily led by differences in carinata prices (Table 2). Consequently, the difference between the average NPVs between the rotations that include carinata and those without it stands at \$260/ha for S1 and -\$91/ha for S2. Within Scenario S1, the rotation “corn-fallow-corn-carinata-soybean-fallow-corn-wheat” is the most profitable rotation with an NPV of \$2996/ha. Meanwhile, under Scenario S2, the rotation “corn-fallow-corn-wheat-soybean-fallow-corn-wheat” has the highest NPV of \$2838/ha. All of the above calculations are based on an interest rate of 6% and an inflation rate of 2% (Karami et al., 2022).

Table 2
| NPV (\$/ha) of crop rotations with/without carinata under different scenarios (S1 and S2).

Scenarios	Average NPV		Difference
	with carinata	without carinata	(with carinata) – (without carinata)
S1	2428	2168	260
S2	2077	2168	−91

3.2. LCA of crop rotations

Using farm-level input data (Table 1), we estimated CO_2e emissions per hectare for individual crops (Fig. 3). Corn stands out as the highest emitter of CO_2e/ha, emitting 3389 kg of CO_2e/ha, followed by wheat at 2521 kg of CO_2e/ha, peanuts at 1440 kg of CO_2e/ha, and soybeans at 1130 kg of CO_2e/ha. In contrast, carinata and cotton exhibit the lowest carbon emissions among the six crops, with 819 kg of CO_2e/ha and 294 kg of CO_2e/ha, respectively. Fig. 4 further illustrates the percentage breakdown of CO_2e emissions for each crop.

Fig. 4 illustrates that fertilizer application is the primary source of CO_2e emissions for most crops, except peanuts. Specifically, corn, which necessitates 1705 kg/ha of fertilizers, stands out with a significant 98.6% of its CO_2e emissions from fertilizer usage. Soybeans follow closely behind at 96.3%, with wheat at 85.1% and cotton at 83.5%. Conversely, pesticide application is the primary source of CO_2e emissions for peanuts, accounting for 60.1%. Pesticide-related CO_2e emissions for other crops are comparatively minimal. Fossil fuel as a CO_2e emissions source was most noteworthy in carinata at 40.0%, followed closely by peanuts at 39.9%. In summary, the estimated CO_2e emission results from Figs. 3 and 4 show that corn and wheat have the highest

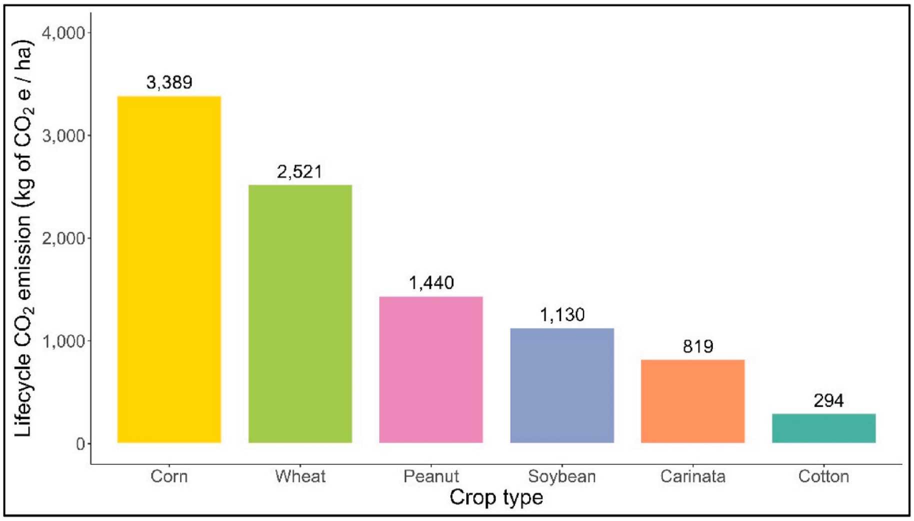

Fig. 3. | LCA at the farm level for different crops in South Georgia.

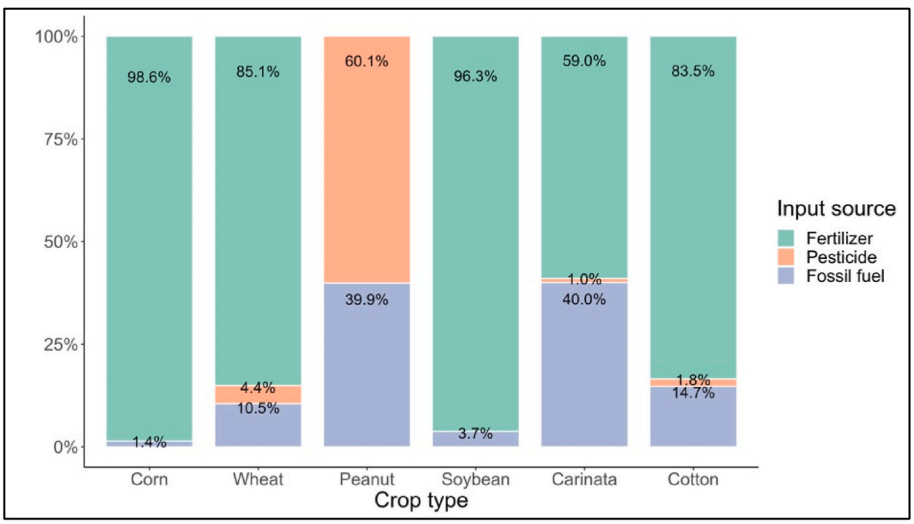

Fig. 4. | Share of inputs in farm-level LCA.

Table 3
| Top 20 crop rotations with the lowest CO_2e emissions for S1 and S2.

Year 1		Year 2		Year 3		Year 4		kg of CO_2e/ha
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	
cotton	fallow	cotton	fallow	soybean	fallow	cotton	fallow	2012
cotton	fallow	cotton	fallow	cotton	fallow	soybean	fallow	2012
cotton	fallow	cotton	fallow	peanut	fallow	cotton	fallow	2322
cotton	fallow	cotton	fallow	cotton	fallow	peanut	fallow	2322
cotton	carinata	cotton	fallow	soybean	fallow	cotton	fallow	2831
cotton	fallow	cotton	carinata	soybean	fallow	cotton	fallow	2831
cotton	fallow	cotton	fallow	soybean	carinata	cotton	fallow	2831
cotton	fallow	cotton	fallow	soybean	fallow	cotton	carinata	2831
cotton	carinata	cotton	fallow	cotton	fallow	soybean	fallow	2831
cotton	fallow	cotton	carinata	cotton	fallow	soybean	fallow	2831
cotton	fallow	cotton	fallow	cotton	carinata	soybean	fallow	2831
cotton	fallow	cotton	fallow	cotton	fallow	soybean	carinata	2831
cotton	carinata	cotton	fallow	peanut	fallow	cotton	fallow	3141
cotton	fallow	cotton	carinata	peanut	fallow	cotton	fallow	3141
cotton	fallow	cotton	fallow	peanut	fallow	cotton	carinata	3141
cotton	carinata	cotton	fallow	cotton	fallow	peanut	fallow	3141
cotton	fallow	cotton	carinata	cotton	fallow	peanut	fallow	3141
cotton	fallow	cotton	fallow	cotton	carinata	peanut	fallow	3141
cotton	carinata	cotton	fallow	soybean	fallow	cotton	carinata	3651
cotton	carinata	cotton	fallow	cotton	fallow	soybean	carinata	3651

CO_2e emissions due to their substantial fertilizer requirements. In contrast, cotton has the lowest CO_2e emissions among the six selected crops due to its more moderate fertilizer usage. Similarly, carinata, our crop of interest, ranks as the second-lowest emitter of CO_2e because it requires fewer fertilizers than corn and wheat, and its contribution from pesticide and fossil fuel usage is notably lower than that of peanuts.

Table 3 shows results for the top 20 rotations out of the total 292 crop rotations over four years in terms of the amount of CO_2e emissions. Notably, the rotations "cotton-cotton-soybean-cotton" and "cotton-cotton-cotton-soybean" exhibit the lowest CO_2e emissions (2012 kg of CO_2e/ha). It is worth noting that although neither of these rotations incorporates carinata, 16 out of the top 20 rotations do include carinata. The lowest CO_2e emissions rotation involving carinata is "cotton-carinata-cotton-fallow-soybean-fallow-cotton-fallow," which ranks fifth and has CO_2e emissions totaling 2831 kg of CO_2e/ha. In addition, corn and winter wheat do not appear in any of the top 20 rotations in terms of the total CO_2e emissions over four years due to their relatively high fertilizer application rates (Figs. 3 and 4).

In addition to assessing the top 20 crop rotation results, Fig. 5 shows how the presence of carinata potentially reduces CO_2e emission from a more comprehensive perspective. Specifically, Fig. 5 illustrates the amount of CO_2e emission for all 292 rotations grouped by the number of winter wheat rotations over four years. We grouped all 292 crop rotations by the number of rotations involving winter wheat because winter wheat directly competes with carinata, both being winter crops, and it also exhibits the second highest CO_2e emissions across all the crops. The x-axis labels in Fig. 5 employ an abbreviation format to represent the quantities of rotations involving carinata (C) and wheat (W) over a four-year span. For example, "2C–1W" signifies two carinata rotations and one wheat rotation within a four-year cycle. The results show that including more winter wheat in the rotations results in significantly higher CO_2e emissions compared to including more carinata rotations. To put this into perspective, a comparison of the mean CO_2e emissions between "2C–0W" and "0C–4W" rotations reveals that carinata could potentially reduce the CO_2e emissions as much as 7745 kg of CO_2e/ha over a four-year rotation cycle.

3.3. DEA of crop rotations

The relationship between CO_2e emissions (input factor of DEA) and NPVs (output factor of DEA) for all 292 crop rotations under the respective high carinata price scenario (S1) and low carinata price scenario (S2) is shown in Fig. 6. In each price scenario, we classified the total of 292 crop rotations based on the number of rotations that incorporate carinata. Since the y-axis and x-axis represent NPVs and CO_2e emissions, respectively, we identified crop rotations situated in the top-left portion of each graph to be desirable crop rotations, implying those scenarios have higher NPVs and lower CO_2e emissions.

Fig. 6 shows that, in Scenario S1, the rotations involving carinata for two years out of four years (green dots) tend to have relatively high NPV and lower CO_2e emissions compared to rotations with only a year of carinata (blue dots) or rotation without carinata (red dots). Conversely, in Scenario S2, where carinata prices are not sufficiently high to distinguish carinata's profitability from other crops, including more rotations with carinata (both green and blue dots) does not yield greater profitability than rotations without carinata. However, it is worth noting that despite the unclear profitability for carinata relative to other crops under S2, incorporating more carinata rotations results in reduced CO_2e emissions. Between S1 and S2, given the same level of emissions, rotations with carinata under S1 have higher NPV than carinata rotations under S2, as carinata prices under S1 are higher than carinata prices under S2.

One key implication in Fig. 6 is that, due to the unclear profitability of carinata rotations relative to other crops, it is necessary to not only consider whether carinata rotations have been implemented but also to account for what crop rotations are involved in the rotations. The following eco-efficiency result can provide a more comprehensive evaluation of the trade-offs between CO_2e emissions and NPVs across 292 crop rotations.

The top 20 eco-efficient rotations for S1 and S2 are reported in Table 4 and Table 5, respectively. The estimated eco-efficiency ranges from 0 to 1. If an efficiency equals one, a rotation is considered efficient (i.e., the rotation emits the least CO_2e given an NPV level); if an efficiency equals zero, a rotation is not efficient (i.e., the rotation emits the most CO_2e given an NPV level). The rotation with the highest eco-efficiency level under S1 is "cotton-carinata-cotton-fallow-soybean-fallow-cotton-carinata," which includes two years of carinata rotations out of four years (Table 4). On the other hand, the most efficient rotation under S2 is "cotton-fallow-cotton-fallow-soybean-fallow-cotton-fallow," which does not include carinata in the rotation (Table 5). Although carinata rotations do not have the lowest environmental impacts overall (Table 3), carinata makes the most eco-efficient rotation under S1 (Table 4) and the fifth most eco-efficient rotation under S2 (Table 5). This further shows that the higher the carinata price, the more eco-

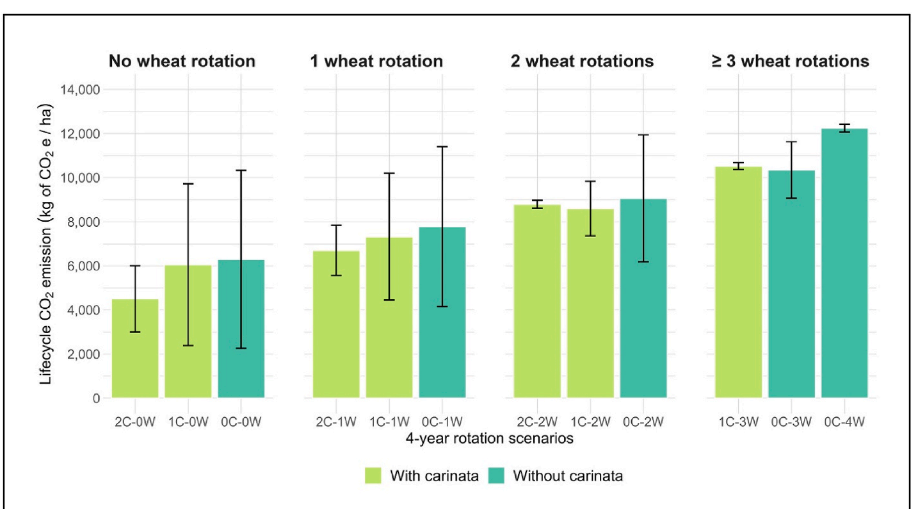

Fig. 5. | LCA of the considered rotations. Note: the error bars denote ± one standard deviation around the mean. The abbreviation of the x-axis labels denotes the numbers of rotations for carinata (C) and wheat (W) over a four-year period. For instance, 2C–1W indicates two carinata rotations and one wheat rotation over a four-year period.

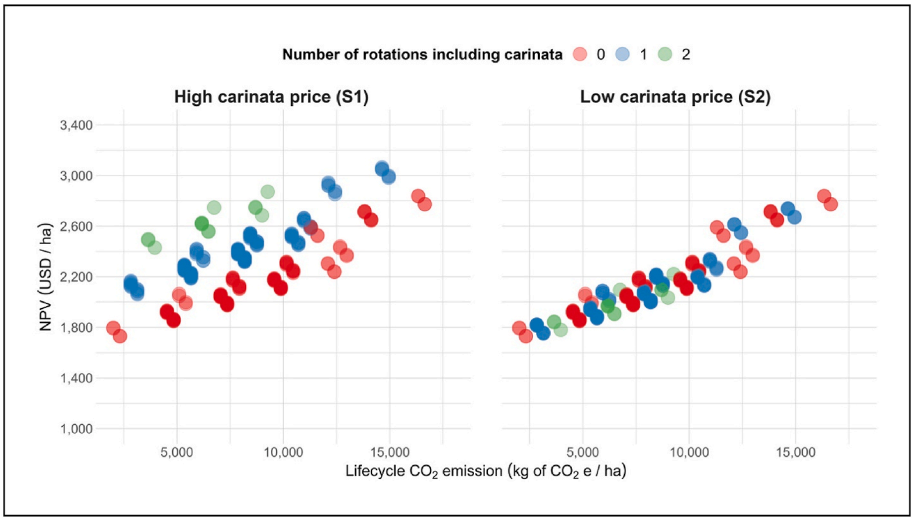

Fig. 6. | CO_2e emissions versus NPV under different carinata seed prices (S1 and S2).

Table 4
Eco-efficiency levels of top 20 rotations by data envelopment analysis (S1).

Year 1		Year 2		Year 3		Year 4		Eco-Efficiency
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	
cotton	carinata	cotton	fallow	soybean	fallow	cotton	carinata	1.000
cotton	carinata	cotton	fallow	soybean	fallow	cotton	fallow	0.962
cotton	fallow	cotton	carinata	soybean	fallow	cotton	fallow	0.957
cotton	fallow	cotton	fallow	soybean	carinata	cotton	fallow	0.951
cotton	fallow	cotton	fallow	soybean	fallow	cotton	carinata	0.946
cotton	carinata	cotton	fallow	cotton	fallow	soybean	carinata	0.944
cotton	carinata	cotton	fallow	cotton	fallow	soybean	fallow	0.901
cotton	fallow	cotton	fallow	soybean	fallow	cotton	fallow	0.898
cotton	fallow	cotton	carinata	cotton	fallow	soybean	fallow	0.895
cotton	fallow	cotton	fallow	cotton	carinata	soybean	fallow	0.890
cotton	fallow	cotton	fallow	cotton	fallow	soybean	carinata	0.885
cotton	carinata	cotton	wheat	soybean	fallow	cotton	carinata	0.872
cotton	carinata	cotton	fallow	soybean	wheat	cotton	carinata	0.871
cotton	carinata	cotton	fallow	corn	fallow	soybean	carinata	0.841
cotton	carinata	cotton	fallow	peanut	fallow	cotton	carinata	0.834
cotton	carinata	cotton	wheat	soybean	fallow	cotton	fallow	0.831
cotton	fallow	cotton	fallow	cotton	fallow	soybean	fallow	0.830
cotton	carinata	cotton	fallow	soybean	wheat	cotton	fallow	0.829
cotton	carinata	cotton	fallow	soybean	fallow	cotton	wheat	0.828
cotton	wheat	cotton	carinata	soybean	fallow	cotton	fallow	0.827

efficient are the carinata rotations. Interestingly, 18 out of 20 of the most eco-efficient rotations include carinata under S1 (Table 4); in contrast, the same is true for 16 out of 20 rotations under S2 (Table 5). When there are more carinata in the four-year rotation, it is expected to have a higher level of eco-efficiency under both scenarios and across all 292 crop rotations. For S1, the difference in eco-efficiency levels between rotations with and without carinata rotations was around 0.125. However, for S2, the eco-efficiency difference was much lower, i.e., 0.020, because of a lower carinata seed price and, in turn, lower NPV.

To better understand the effects of carinata price on the eco-efficiency level of crop rotations, we compare eco-efficiency levels across rotations with and without carinata under different price scenarios and the number of wheat rotations. For the between-price-scenario comparison, rotations are more efficient under S1 (Fig. 7) than in S2 (Fig. 8). Namely, if the carinata price is low (S2), planting carinata becomes less eco-efficient. For the within-price-scenario comparison, rotations are more efficient when there are more carinata occurrences over four-year rotations. The eco-efficiency is notably lower when there are more wheat occurrences over four-year rotations. This finding suggests planting carinata is more eco-efficient than its potential competing winter crop (i.e., wheat).

4. Discussion

Our results indicate that the difference between the average NPVs for the rotations with and without carinata under S1 and S2 are \$260/ha and -\$91/ha, respectively. The \$351/ha difference between the two scenarios is in sync with other studies that have analyzed the economics of including bioenergy crops in traditional crop rotations. Styles et al. (2008) showed that gross margins were critically dependent on the farm-level price of feedstock. A 50% price subsidy and an area subsidy of €80/ha increased the farm-level profitability by €144/ha. Similarly, Faasch & Patenaude (2012) found that the profitability of energy crops in rotation with conventional crops depends on the prices. The profitability was higher by €260/ha for crop rotations in the presence of a subsidized price for the energy crops. Spiegel et al. (2018) also recommended a floor price over 24 years for rotating energy crops with conventional crops. The policy could help increase the farmers' profitability by €2826/ha or €118/ha/year. Similar to S2 (no contract price) in our current study, Cubins et al. (2019) concluded that there would be at least a \$236/ha loss for corn-soybean rotation if pennycress is included in current agricultural systems in the midwestern United States. The primary source of the loss was a 40% higher amount of labor and

Table 5
Eco-efficiency levels of top 20 rotations by data envelopment analysis (S2).

Year 1		Year 2		Year 3		Year 4		Eco-Efficiency
Summer	Winter	Summer	Winter		Winter	Summer	Winter	
cotton	fallow	cotton	fallow	soybean	fallow	cotton	fallow	1.000
cotton	fallow	cotton	fallow	cotton	fallow	soybean	fallow	0.996
cotton	fallow	cotton	fallow	peanut	fallow	cotton	fallow	0.835
cotton	fallow	cotton	fallow	cotton	fallow	peanut	fallow	0.833
cotton	carinata	cotton	fallow	soybean	fallow	cotton	fallow	0.721
cotton	fallow	cotton	carinata	soybean	fallow	cotton	fallow	0.720
cotton	fallow	cotton	fallow	soybean	carinata	cotton	fallow	0.720
cotton	fallow	cotton	fallow	soybean	fallow	cotton	carinata	0.719
cotton	carinata	cotton	fallow	cotton	fallow	soybean	fallow	0.718
cotton	fallow	cotton	carinata	cotton	fallow	soybean	fallow	0.718
cotton	fallow	cotton	fallow	cotton	carinata	soybean	fallow	0.717
cotton	fallow	cotton	fallow	cotton	fallow	soybean	carinata	0.717
cotton	carinata	cotton	fallow	peanut	fallow	cotton	fallow	0.626
cotton	fallow	cotton	carinata	peanut	fallow	cotton	fallow	0.626
cotton	fallow	cotton	fallow	peanut	fallow	cotton	carinata	0.625
cotton	carinata	cotton	fallow	cotton	fallow	peanut	fallow	0.624
cotton	fallow	cotton	carinata	cotton	fallow	peanut	fallow	0.624
cotton	fallow	cotton	fallow	cotton	carinata	peanut	fallow	0.624
cotton	carinata	cotton	fallow	soybean	fallow	cotton	carinata	0.566
cotton	carinata	cotton	fallow	cotton	fallow	soybean	carinata	0.564

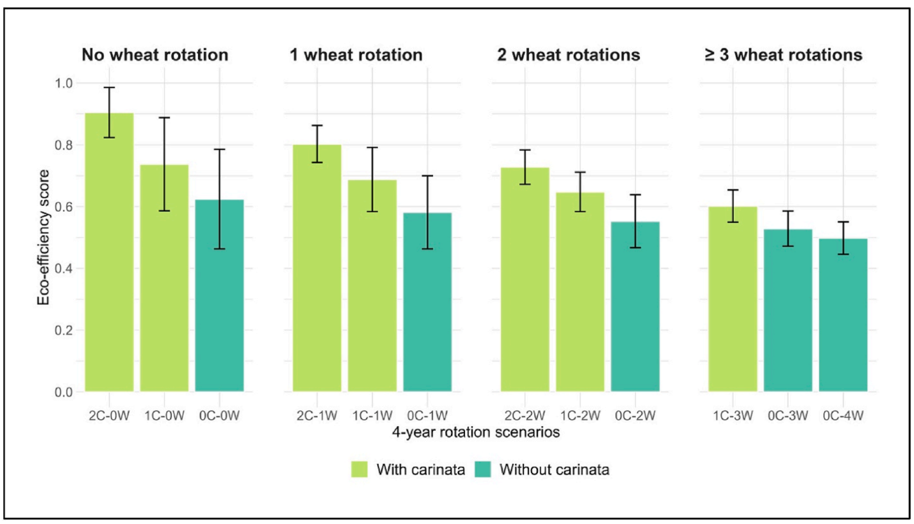

Fig. 7. Carinata effect on the eco-efficiency level of rotations (S1). Note: the error bars denote ± one standard deviation around the mean. The abbreviation of the x-axis labels denotes the number of rotations for carinata (C) and wheat (W) over a four-year period. For instance, 2C–1W indicates two carinata rotations and one wheat rotation over a four-year period.

equipment needed for double cropping compared to the conventional crop rotations.

We performed a detailed LCA to estimate CO_2 emission for each crop. Accordingly, corn had the highest emissions, with 3389 kg of CO_2e/ha (Fig. 3). Kim et al. (2009) concluded that corn emissions across different states were between 3000 and 4500 kg of CO_2e/ha, and other studies, such as Canter et al. (2016) and Obnamia et al. (2019), found similar results. We also showed that the emission of peanuts is 1440 kg of CO_2e/ha (Fig. 3). This finding is in sync with McCarty et al. (2014), who estimated 1422 kg of CO_2e/ha for peanuts, and Nikkhah et al. (2015), who estimated 1200 kg of CO_2e/ha for peanuts. Our estimate for soybean was 1130 kg of CO_2e/ha (Fig. 3). Moeller et al. (2017) estimated a similar amount of 1151 kg of CO_2e/ha. Rajaeifar et al. (2014) and Vunnava and Singh (2020) also had similar results for soybean.

For cotton, estimated CO_2e emissions vary across different studies. For instance, Jewell (2016) concluded that the estimated emission of cotton was 112 kg CO_2e per metric ton of fiber (or 150 kg of CO_2e/ha). However, Singh et al. (2019) concluded that the estimated emission of cotton production is between 593 kg of CO_2e/ha and 1230 kg of CO_2e/ha. This shows that the emissions of cotton vary dramatically from one farming system to another. It is also the same for wheat. Shrestha et al. (2020) found that wheat farm-level emission varies between 846 and 1410 kg of CO_2e/ha. However, Taki et al. (2018) estimated a higher amount of 1526 kg of CO_2e/ha. Few other studies, like Ghasemi-Mobtaker et al. (2022), concluded that wheat has a high farm-level environmental impact of around 3301 kg of CO_2e/ha.

Our results showed that carinata is the second least carbon-emitting crop in the region. According to LCA results, carinata rotations have around 12% lower environmental impacts under both scenarios. Monti et al. (2009) showed that a 50% increase in environmental benefits can be achieved by substituting conventional rotation with energy crops in Italy. Borzecka-Walker et al. (2011) also concluded that willow for biofuel production emits up to 56% less greenhouse gas compared to most conventional crops in Poland. Fazio and Monti (2011) obtained comparable results for the second-generation biofuels from switchgrass, with an environmental impact of 42% less than corn and 5% less than wheat. In a similar study, Berti et al. (2017) concluded that winter camelina had lower environmental impacts than conventional corn by

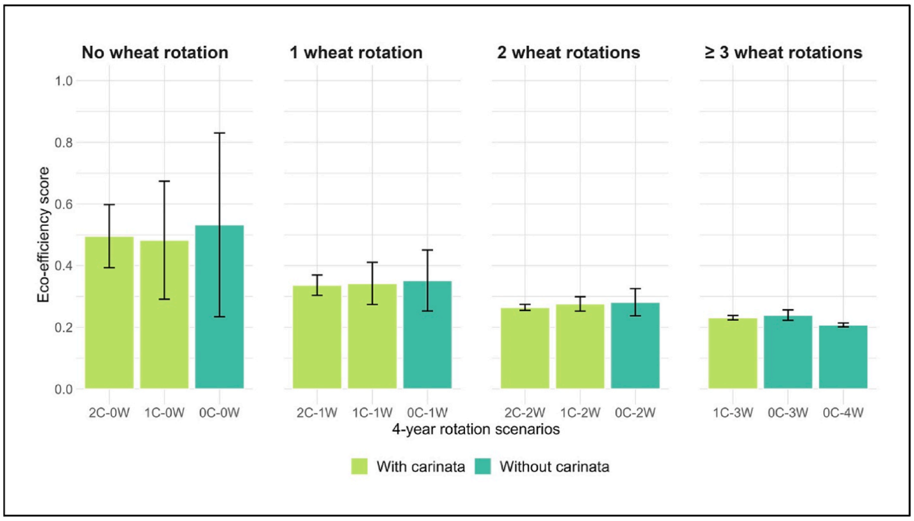

Fig. 8. Carinata effect on the eco-efficiency level of rotations (S2). Note: the error bars denote ± one standard deviation around the mean. The abbreviation of the x-axis labels denotes the number of rotations for carinata (C) and wheat (W) over a four-year period. For instance, 2C–1W indicates two carinata rotations and one wheat rotation over a four-year period.

71% and soybean by 53% in North Dakota and Minnesota. Camelina double cropping could also decrease soybean monocropping environmental impacts by around 40%. In a more recent study, Cecchin et al. (2021) assessed the environmental impacts of a corn-soybean rotation with and without winter cover crops of camelina, pennycress, and rye. They showed that energy crops could decrease the environmental impacts by around 3% when they did not receive N-fertilization. In contrast, the corn-soybean rotation had up to 11% lower environmental impacts when the winter crops were fertilized with N. There are also other studies, like O'Keeffe and Thrän (2020), Vatsanidou et al. (2020), and Marzban et al. (2022), who concluded that energy crops could improve farm-level environmental impacts.

For the current study, several reasons make carinata-based crop rotations better from an environmental perspective. First, carinata requires few chemicals as it outcompetes several winter weeds (Seepaul et al., 2019). This results in the CO_2e emissions of carinata production being one of the lowest (Fig. 3). Second, it is not possible to sow corn after winter wheat or carinata in Georgia because winter crops are harvested in June (Karami et al., 2022). This means that peanuts, soybeans, and cotton are summer crop choices after winter wheat and carinata. Moreover, Fig. 3 shows that corn has the highest impact of 3389 kg of CO_2e/ha. Therefore, the harvest and planting schedules of winter/summer crops made it less possible for carinata rotations to include corn (only 14 crop rotations out of 292 rotations have corn and carinata) which is a crop with the highest CO_2e emission. Third, most carinata rotations do not include peanuts because current, non-herbicide tolerant carinata varieties cannot come after peanuts sprayed with IMI products such as Cadre (Seepaul et al., 2019). Only 40 rotations out of 292 have both carinata and peanuts. We also know that peanut is the second most carbon-emitting summer crop after corn (Fig. 3). Peanut needs the highest amounts of insecticides, fungicides, inoculants, and boron among all crops (Table 1). Carinata decreases the environmental impacts of the rotation because of excluding peanuts from the rotation. Fourth, carinata has more possible rotations with soybean (52 crop rotations) and cotton (166 crop rotations). Soybean and cotton have the lowest emissions per hectare compared to other summer crops (Fig. 3). Thus, carinata comes in crop rotation with the crops that emit lower CO_2e at the farm level.

DEA results show that rotations with carinata are relatively more eco-efficient in the region. Carinata makes the most eco-efficient rotation in cotton-cotton-soybean rotation. Several reasons can explain the higher eco-efficiency of carinata rotations. First, carinata has a lower CO_2e emission per hectare than winter wheat (Fig. 3). Second, carinata has a higher profit per hectare ($369 versus $135). Third, carinata can only be in rotations with cotton and soybean rather than corn and peanuts (Karami et al., 2022). Cotton and soybean emit lower CO_2e than corn and peanuts (Fig. 3). There are some studies (Masuda, 2016; Vásquez-Ibarra et al., 2020) that combined LCA and DEA to investigate the eco-efficiency; however, there is no comparable study that has analyzed eco-efficiency for an oilseed energy crop in rotation with other crops. Therefore, we cannot directly compare our results with the existing studies to a larger extent.

5. Conclusion

In this study, we used the farm-level data of crops in South Georgia, United States, to find the most eco-efficient crop rotation with and without carinata, a winter oilseed crop for SAF production. We first determined the potential crop rotations in the study area with and without carinata. Then, we estimated the NPVs of the selected rotations, followed by calculating the CO_2e emissions of the selected crop rotations using LCA. Finally, we determined the eco-efficiency scores of each crop rotation using DEA. Our results indicate that carinata has a higher profit under the contract price and lower CO_2e emissions than winter wheat. We also noticed that carinata is included in rotations with summer crops with lower CO_2e emissions. This further decreases the overall environmental impacts of carinata rotations more than the other rotations, which do not include carinata. Consequently, carinata rotations are eco-efficient due to higher profits and lower environmental impacts.

In this study, we have assumed that all the farmers would adopt similar agronomy practices across all the crops over a four-year rotation period. However, this is an improbable case because farmers adopt different practices based on their knowledge, perspectives, and financial resources. We hope that future research will build upon this study, considering several agronomy practices that farmers adopt at the landscape level to develop more insights about the eco-efficiency of bioenergy crops in the region. We have also assumed that crop prices remain constant over time in our study. This assumption can also be relaxed in future studies. Finally, this study focuses on the farm level only. It is critical to evaluate the eco-efficiency at the supply chain level. Future studies could deliberate to ensure that bioenergy development is inherently sustainable over time.

Our study will support the use of carinata-based SAF production in the Southern United States and will advance the agenda of federal and state governments to reduce the overall carbon impacts of the aviation sector through cleaner technologies while supporting rural economies and improving the flow of ecosystem services.

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CRediT authorship contribution statement

Omid Karami: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yu-Kai Huang:** Writing – review & editing, Visualization. **Puneet Dwivedi:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix 1

Year 1		Year 2		Year 3		Year 4	
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
cotton	wheat	cotton	wheat	peanut	wheat	cotton	wheat
cotton	wheat	cotton	wheat	peanut	wheat	cotton	carinata
cotton	wheat	cotton	wheat	peanut	wheat	cotton	fallow
cotton	wheat	cotton	wheat	peanut	fallow	cotton	wheat
cotton	wheat	cotton	wheat	peanut	fallow	cotton	carinata
cotton	wheat	cotton	wheat	peanut	fallow	cotton	fallow
cotton	wheat	cotton	carinata	peanut	wheat	cotton	wheat
cotton	wheat	cotton	carinata	peanut	wheat	cotton	fallow
cotton	wheat	cotton	carinata	peanut	fallow	cotton	wheat
cotton	wheat	cotton	carinata	peanut	fallow	cotton	fallow
cotton	wheat	cotton	fallow	peanut	wheat	cotton	wheat
cotton	wheat	cotton	fallow	peanut	wheat	cotton	carinata
cotton	wheat	cotton	fallow	peanut	wheat	cotton	fallow
cotton	wheat	cotton	fallow	peanut	fallow	cotton	wheat
cotton	wheat	cotton	fallow	peanut	fallow	cotton	carinata
cotton	wheat	cotton	fallow	peanut	fallow	cotton	fallow
cotton	carinata	cotton	wheat	peanut	wheat	cotton	wheat
cotton	carinata	cotton	wheat	peanut	wheat	cotton	carinata
cotton	carinata	cotton	wheat	peanut	wheat	cotton	fallow
cotton	carinata	cotton	wheat	peanut	fallow	cotton	wheat
cotton	carinata	cotton	wheat	peanut	fallow	cotton	carinata
cotton	carinata	cotton	wheat	peanut	fallow	cotton	fallow
cotton	carinata	cotton	fallow	peanut	wheat	cotton	wheat
cotton	carinata	cotton	fallow	peanut	wheat	cotton	carinata
cotton	carinata	cotton	fallow	peanut	wheat	cotton	fallow
cotton	carinata	cotton	fallow	peanut	fallow	cotton	wheat
cotton	carinata	cotton	fallow	peanut	fallow	cotton	carinata
cotton	carinata	cotton	fallow	peanut	fallow	cotton	fallow
cotton	fallow	cotton	wheat	peanut	wheat	cotton	wheat
cotton	fallow	cotton	wheat	peanut	wheat	cotton	carinata
cotton	fallow	cotton	wheat	peanut	wheat	cotton	fallow
cotton	fallow	cotton	wheat	peanut	fallow	cotton	wheat
cotton	fallow	cotton	wheat	peanut	fallow	cotton	carinata
cotton	fallow	cotton	wheat	peanut	fallow	cotton	fallow
cotton	fallow	cotton	carinata	peanut	wheat	cotton	wheat
cotton	fallow	cotton	carinata	peanut	wheat	cotton	fallow
cotton	fallow	cotton	carinata	peanut	fallow	cotton	wheat
cotton	fallow	cotton	carinata	peanut	fallow	cotton	fallow
cotton	fallow	cotton	fallow	peanut	wheat	cotton	wheat
cotton	fallow	cotton	fallow	peanut	wheat	cotton	carinata
cotton	fallow	cotton	fallow	peanut	wheat	cotton	fallow
cotton	fallow	cotton	fallow	peanut	fallow	cotton	wheat
cotton	fallow	cotton	fallow	peanut	fallow	cotton	carinata
cotton	fallow	cotton	fallow	peanut	fallow	cotton	fallow
cotton	wheat	cotton	fallow	corn	wheat	peanut	wheat
cotton	wheat	cotton	fallow	corn	wheat	peanut	fallow
cotton	wheat	cotton	fallow	corn	carinata	peanut	wheat
cotton	wheat	cotton	fallow	corn	carinata	peanut	fallow

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(*continued*)

Year 1		Year 2		Year 3		Year 4	
cotton	wheat	cotton	fallow	corn	fallow	peanut	wheat
cotton	wheat	cotton	fallow	corn	fallow	peanut	fallow
cotton	carinata	cotton	fallow	corn	wheat	peanut	wheat
cotton	carinata	cotton	fallow	corn	wheat	peanut	fallow
cotton	carinata	cotton	fallow	corn	fallow	peanut	wheat
cotton	carinata	cotton	fallow	corn	fallow	peanut	fallow
cotton	fallow	cotton	fallow	corn	wheat	peanut	wheat
cotton	fallow	cotton	fallow	corn	wheat	peanut	fallow
cotton	fallow	cotton	fallow	corn	carinata	peanut	wheat
cotton	fallow	cotton	fallow	corn	carinata	peanut	fallow
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corn	fallow	corn	wheat	peanut	fallow	corn	wheat
corn	fallow	corn	wheat	peanut	fallow	corn	carinata
corn	fallow	corn	wheat	peanut	fallow	corn	fallow
corn	fallow	corn	carinata	peanut	fallow	corn	wheat
corn	fallow	corn	carinata	peanut	fallow	corn	fallow
corn	fallow	corn	fallow	peanut	fallow	corn	wheat
corn	fallow	corn	fallow	peanut	fallow	corn	carinata
corn	fallow	corn	fallow	peanut	fallow	corn	fallow
cotton	wheat	cotton	wheat	cotton	wheat	peanut	wheat
cotton	wheat	cotton	wheat	cotton	wheat	peanut	fallow
cotton	wheat	cotton	wheat	cotton	carinata	peanut	wheat
cotton	wheat	cotton	wheat	cotton	carinata	peanut	fallow
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cotton	wheat	cotton	wheat	cotton	fallow	peanut	fallow
cotton	wheat	cotton	carinata	cotton	wheat	peanut	wheat
cotton	wheat	cotton	carinata	cotton	wheat	peanut	fallow
cotton	wheat	cotton	carinata	cotton	fallow	peanut	wheat
cotton	wheat	cotton	carinata	cotton	fallow	peanut	fallow
cotton	wheat	cotton	fallow	cotton	wheat	peanut	wheat
cotton	wheat	cotton	fallow	cotton	wheat	peanut	fallow
cotton	wheat	cotton	fallow	cotton	carinata	peanut	wheat
cotton	wheat	cotton	fallow	cotton	carinata	peanut	fallow
cotton	wheat	cotton	fallow	cotton	fallow	peanut	wheat
cotton	wheat	cotton	fallow	cotton	fallow	peanut	fallow
cotton	carinata	cotton	wheat	cotton	wheat	peanut	wheat
cotton	carinata	cotton	wheat	cotton	wheat	peanut	fallow
cotton	carinata	cotton	wheat	cotton	fallow	peanut	wheat
cotton	carinata	cotton	wheat	cotton	fallow	peanut	fallow
cotton	carinata	cotton	fallow	cotton	wheat	peanut	wheat
cotton	carinata	cotton	fallow	cotton	wheat	peanut	fallow
cotton	carinata	cotton	fallow	cotton	fallow	peanut	wheat
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cotton	fallow	cotton	wheat	cotton	wheat	peanut	wheat
cotton	fallow	cotton	wheat	cotton	wheat	peanut	fallow
cotton	fallow	cotton	wheat	cotton	carinata	peanut	wheat
cotton	fallow	cotton	wheat	cotton	carinata	peanut	fallow
cotton	fallow	cotton	wheat	cotton	fallow	peanut	wheat
cotton	fallow	cotton	wheat	cotton	fallow	peanut	fallow
cotton	fallow	cotton	carinata	cotton	wheat	peanut	wheat
cotton	fallow	cotton	carinata	cotton	wheat	peanut	fallow
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cotton	fallow	corn	carinata	peanut	fallow	cotton	wheat
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Year 1		Year 2		Year 3		Year 4	
cotton	fallow	corn	fallow	peanut	wheat	cotton	wheat
cotton	fallow	corn	fallow	peanut	wheat	cotton	carinata
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cotton	fallow	corn	fallow	peanut	fallow	cotton	carinata
cotton	fallow	corn	fallow	peanut	fallow	cotton	fallow
cotton	wheat	cotton	wheat	soybean	wheat	cotton	wheat
cotton	wheat	cotton	wheat	soybean	wheat	cotton	carinata
cotton	wheat	cotton	wheat	soybean	wheat	cotton	fallow
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Year 1		Year 2		Year 3		Year 4	
cotton	fallow	cotton	fallow	corn	carinata	soybean	fallow
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cotton	fallow	corn	wheat	soybean	wheat	cotton	carinata
cotton	fallow	corn	wheat	soybean	wheat	cotton	fallow
cotton	fallow	corn	wheat	soybean	carinata	cotton	wheat

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Year 1		Year 2		Year 3		Year 4	
cotton	fallow	corn	wheat	soybean	carinata	cotton	fallow
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cotton	fallow	corn	wheat	soybean	fallow	cotton	fallow
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cotton	fallow	corn	fallow	soybean	carinata	cotton	fallow
cotton	fallow	corn	fallow	soybean	fallow	cotton	wheat
cotton	fallow	corn	fallow	soybean	fallow	cotton	carinata
cotton	fallow	corn	fallow	soybean	fallow	cotton	fallow

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