Energy Research & Social Science 70 (2020) 101665

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

In pursuit of a homegrown biofuel: Navigating systems of partnership, stakeholder knowledge, and adoption of *Brassica carinata* in the Southeast United States

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ARTICLE INFO

Keywords:
Brassica carinata
Technology adoption
Extension
Oilseed
Biofuel

ABSTRACT

An emerging off-season crop in the Southeast United States (SE US) may provide farmers and industry with a climate-friendly means of enhancing the region's agricultural and bioenergy landscapes. Carinata (*Brassica carinata*) is an industrial oilseed that serves as a feedstock for renewable jet fuel and promises producers financial and soil health benefits. The likelihood of carinata adoption among producers depends on how well this technology fits within the region's complex cultural and socio-economic conditions. This paper examines factors shaping adoption among producers in the SE US, taking into consideration theories of technology adoption that place emphasis on both the individual and complex systemic factors. Findings indicate respondents perceive agronomic and economic benefits of adopting carinata into seasonal rotations, but previous growers largely fail to link carinata to environmental benefits beyond the farmgate. Respondents identify barriers to carinata adoption at multiple scales. Unfamiliarity with carinata leads as a major barrier and respondent narratives reflect wide-ranging perceptions defying analytical categorization. Respondents identify solutions to overcome critical adoption barriers, such as industry responsibility, research on carinata variety improvement, and land grant extension activities. Results reinforce the complex interconnectivity of factors influencing adoption decision-making and highlight the importance of clearly defining stakeholder roles within the public-private partnership promoting carinata expansion. The study highlights opportunities and challenges of land grant extension systems that attempt to unite stakeholders across scales. Finally, the study discusses implications of the apparent disconnect between factors that influence producers' adoption decision-making locally and the global forces that drive the carinata market.

1. Introduction

Individual decision-making reflects the nature of our choices, the magnitude of our immediate needs, the uniqueness of past experiences, and the socioeconomic and environmental contexts in which we are embedded. Agricultural producers are no different. This study focuses on understanding the factors that drive decision-making among producers in the Southeast United States (SE US). Specifically, it explores what influences their willingness to adopt *Brassica carinata* (carinata) – an industrial oilseed relative of canola – into their existing crop rotations, given the crop's recent entry into the region. Carinata may represent a novel livelihood option for these stakeholders due to its benefits as both a local off-season cash crop and regional feedstock for a burgeoning biofuel industry. Study findings represent a subset of a larger public-private partnership project that aims to expand sustainable carinata production in the SE US in response to a changing climate. The European market's strong demand for climate-friendly fuel drives the current export of carinata seeds from growing regions around the world. However, widespread cultivation of carinata in the SE US may build the needed capacity for local processing and give rise to regional consumption of homegrown biofuel.

Globally, agricultural producers face endless choices with regards to their production systems. Like all of us, they make decisions based on their unique realities, navigating both the benefits and barriers of any given option. Carinata in the SE US serves as a case study to illuminate the factors that shape technology adoption among producers who

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https://doi.org/10.1016/j.erss.2020.101665
Received 21 January 2020; Received in revised form 10 June 2020; Accepted 17 June 2020

weigh the crop's unique attributes and limitations. Viewing producers as one of many stakeholder groups in this system, the study also incorporates perspectives from industry, academia, and agricultural advisors through land grant extension systems. Four questions guide this research: 1) What do carinata stakeholders in the states of Florida, Georgia, and Alabama perceive as benefits of growing the crop?; 2) Which barriers to adoption do carinata stakeholders identify and how do they perceive their importance?; 3) What solutions do carinata stakeholders identify to overcome barriers?; and 4) How do stakeholder groups share information and what is the potential for knowledge exchange to advance adoption?

The following section reviews background literature to ground the study in scholarship related to biofuels in the context of climate change, carinata production in the SE US, and agricultural technology adoption. These elements are tied together in a conceptual framework that guides this study. Next, we present the methods for data collection and analysis, and then we provide results in relation to the study's guiding questions. Finally, we discuss the findings and attempt to bridge a gap between theories of change that focus on decision-making at the individual level and those that encompass the larger socio-environmental and economic context in which carinata producers are embedded.

2. Background

2.1. Expanding biofuel feedstock in response to a changing climate

In the face of unprecedented challenges due to the growing effects of climate change, governments have proposed frameworks to guide economic development such as the United Nations (UN) Sustainable Development Goals (SDGs). A report from the UN Intergovernmental Panel on Climate Change (IPCC) issues a clarion warning against delayed action while highlighting opportunities for climate resilience and sustainability. Agriculture, forestry, and other land uses, for example, contribute approximately 23% of anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs), aside from the compounded GHG emissions from associated transportation [1]. Biofuel production from agricultural feedstocks may have the capacity to both contribute to and mitigate these emissions, depending on the feedstock and conversion technology used to produce these fuels.

As knowledge of processing options increases and as societies assess the social implications of various agricultural feedstocks, biofuel production systems have undergone technological transformations. Although first-generation biofuels produced from food-based sugars and vegetable oils have been successfully deployed, the effects of their production on food prices and their contribution to greenhouse gases are still debated [2,3]. Second-generation, lignocellulosic biofuels produced from non-food biomass necessitate the removal of most carbon residue from fields, resulting in the depletion of soil carbon. Recent studies suggest this production method, therefore, may result in higher than predicted life-cycle carbon emissions from these systems [4,5]. In addition, the expense to both produce chemically identical analogues to petroleum-based fuels and to break down recalcitrant feedstocks like cellulose has limited the competitive edge of advanced biofuels in fuel markets [6,7]. Nevertheless, improved market dynamics and advancements in technology may increase the demand for next-generation (i.e. advanced) biofuels.

Like other alternative energy sources, advanced biofuels are currently more expensive than petroleum. However, this competitive disadvantage will loosen as emission standards tighten. Some alternative energy sources include solar and electric technologies, which are especially viable solutions for ground transportation but not realistic options for aviation. Therefore, aviation is one sector that is already placing higher demands on advanced biofuels. As the aviation industry increases its sustainability targets and therefore its dependence on renewable jet fuels, market demand for advanced fuels is expected to grow [8,9]. For example, the Renewable Fuel Standard 2 (RFS2) has targeted advanced biofuels consumption to overtake conventional biofuels by 2022 and beyond. This ambitious goal includes a potential contribution of 49.8% from the SE US, constituting an estimated 10.46 billion gallons per year (GPY) [10]. Though achievement of this goal may prove challenging, jet fuel consumption by major airlines with hubs in the SE US is estimated at over 3.3 billion GPY [10]. Replacing these aviation fuels with advanced biofuels would help to achieve the goals set out by RFS2 and bring significant financial benefit to the region.

In addition to their viability in a changing marketplace, advanced biofuels derived from specific feedstocks have potential environmental benefits and may yield valuable co-products. For example, unlike biofuels derived from lignocellulosic feedstock, much of the biomass from industrial oilseed crops remains in the field after seeds are harvested. This enlarged carbon sink of oilseed crop fields may yield healthier soils and reduce carbon emissions. One such oilseed is carinata, a feedstock with highly desirable oil composition, meal nutritive value, and agronomic characteristics. Carinata's oil contains > 40% erucic acid, rendering it unfit for human consumption, but whose longer carbon chain permits easier and more energy efficient conversion to aviation fuel [11]. In addition, the crushing process for carinata oil yields a by-product of approximately 40% crude protein, a viable meal supplement for beef and dairy cattle [12]. Subsequent oil processing also yields valuable renewable co-products [13]. These market trends and technological advancements underscore the potential of, and need for, the SE US to generate regionally appropriate advanced biofuel feedstock, including carinata.

2.2. Carinata's global journey and establishment in the Southeast United States

Traditionally, primitive domesticated varieties of carinata have been cultivated for their edible leaves in the highlands of Ethiopia and Kenya [14], while modern varieties possess enough variation in agriculturally important traits to serve as an oilseed crop [15]. Early research into carinata as an oilseed crop began in Western Canada, where breeding trials focused on decreasing time to maturation and increasing yield [16,17]. However, Canadian producers typically planted carinata as a cover crop to protect the soil and promote water conservation in orchards [18]. Further studies [19] have affirmed carinata's potential as an oilseed alternative to canola in Western Canada, as well as its potential as a feedstock for biofuel and sustainable aviation fuel, particularly due to its drought tolerance and well-adapted growth in semi-arid environments [20,21]. Carinata's industry sponsor expanded production to the Northern Plains region of the United States, cultivating the crop on fallowed land in the summer months, before expanding production to the SE US in 2014 through existing industry partnerships (S. Fabijanski, personal communication, December 6, 2018). Currently, carinata has seen wide commercial production in Uruguay and Argentina, and its industry sponsor intends to expand preliminary production trials in Southern Europe and Southeastern Australia (L. Streit, personal communication, February 26, 2020).

Commercial production of carinata in the SE US first began with 4000 ha during the winter-spring growing seasons from 2015 to 2018 [22]. This expansion followed previous, small-scale industry-led attempts in 2014 that introduced the crop via individual contracts with interested early adopters. Multiple years of weather variability during early commercial production have provided ample learning opportunity to understand the cold tolerance aspects and limitations of the existing commercial variety. However, they have also proved challenging for producers who first began growing the crop (D. Lee, personal communication, October 11, 2017). Commercial production successes and challenges have also helped inform research to fine-tune optimum variety development and agronomic recommendations such as planting dates, fertility, and pest management for carinata in the SE US (C. Bliss, personal communication, September 22, 2017). Scaling up carinata

production in the SE US will require a deeper understanding of agronomic and cultural management practices [23], as well as fitting carinata into existing and diverse crop rotations in the region through further variety development [22].

Historically, row-crop production of corn, soybeans, peanuts, and cotton has long dominated agriculture in the SE US, currently providing over $2.5 billion in production value for the tri-state region [24]. These crops grow during the warm season, leaving fields typically underexploited in the winter months. During this fallow period, less than 10% of the region's arable land is planted with cover crops. The optimal growing season for carinata production in the SE US coincides with the winter months. This seasonality can provide advantages for farmers, including benefits from cover cropping and additional income during the "offseason." Taylor et al. [25] observed that carinata displayed higher than average yields than other oilseeds like canola and camelina, suggesting greater economic opportunity for increasing overall revenue. In addition, planting a crop on land that is otherwise fallow in the offseason may allow producers to reap the benefits of several ecosystem services. This boon may include the improvement of several metrics of soil quality, such as organic matter, soil structure, microbial biodiversity, while reducing soil erosion and compaction. For example, cover cropping during the offseason generally improves soil fertility by reducing overall nutrient leaching and increasing nutrient cycling [26,27,28,29]. Additionally, the glucosinolates present in carinata are potent bio-fumigants that may control soil borne diseases, insects, and weeds [30,31].

2.3. Agricultural technology adoption and decision-making

Identifying and responding to factors that guide adoption decision-making of carinata are key to its commercial success in the SE US. This study considers decision-making at the producer level as well as barriers and incentives to carinata adoption that may exist at higher scales. The adoption of new agricultural technologies is not a linear process of knowledge and technology transfer (i.e. pipeline delivery from researchers to farmers through extension professionals) [32,33]. Rather, scholars describe a complex "whirlpool" of social processes [34]. Indeed, when discussing producers' decision-making within the context of new technologies, different schools of thought have explained adoption patterns in diverse ways. Multiple frameworks assess producers (as individuals) and the contexts in which they are embedded, albeit to varying degrees.

On one end of the spectrum, *diffusion of innovations* theory relies heavily on aspects of human capital to describe an individuals' decisions to adopt a particular technology within a sphere of social influence [35]. According to this theory, those producers most likely to adopt ahead of the curve (innovators/early adopters), tend to have privileged qualities such as more education, higher social status, larger operations, exposure to social channels, and opinion leadership [35]. Due to their privileged positions, innovators and early adopters tend to express more interest in the technical aspects of an innovation, while early majority adopters are more concerned with its tangible benefits, typically financial in nature [36]. Within agriculture, an implication of this approach is that those working in extension are pressured to "segment" farmers and develop different messages for different types of adopters [37]. This may lead to a central criticism of the theory, which posits that marketing and outreach efforts may unequally favor innovators and early adopters under the assumption that their adoption decisions will convince others to follow suit. However, such an approach may leave other producers (the so-called "laggards"), who may truly benefit from the technology, largely ignored or marginalized [35,38].

At the other end of the spectrum lies an alternative theory: *agricultural innovation platforms* (AIPs). These scholars focus on innovation platforms that encompass the larger agricultural context in which technologies are implemented, treating this context as part of a complex socio-ecological system [39,40]. AIPs may be virtual, physical, or hybrid spaces in which diverse actors within a system learn [32], holistically diagnose problems, identify opportunities, and harness their collective capacities to accomplish common goals [41]. This framework has been used to approach multi-stakeholder concerns regarding natural resource management, institutional change, the alleviation of poverty, and the enhancement of value chains and food security [42] at various scales [32,43,44,45]. Osorio-García et al. [46] suggest that AIPs facilitated the adoption of best practices and an overall collective understanding of climate-smart agriculture. Their study focused on stakeholders in Colombia to determine how specific innovation options correspond to local conditions and priorities. In a South African case, AIPs were used to improve irrigation scheme management by providing an environment in which actors could engage, experiment, learn, and build adaptive capacity [47].

While other schools of thought on technology adoption and individual decision-making exist at various points on this spectrum, the present study refers to diffusion of innovations and AIPs to understand factors that may shape adoption from the perspective of the individual as well as the socio-economic contexts in which they exist. We incorporate elements of both schools of thought to evaluate the likelihood of carinata adoption. Such assessment requires an understanding of how this emerging technology fits within the cultural and socio-economic conditions of the SE US [48]. A systematic analysis of adoption must encompass an examination of factors that range from the characteristics associated with the proposed technology, to the production systems themselves and individual farmers' contexts, as well as relevant elements found beyond the farmgate [49]. Furthermore, farmer-specific characteristics and preferences, which vary widely among producers [50] can be assessed as related to feasibility, profitability, and acceptability of new practices [51].

The present study assumes the complexity of factors leading to producers' technology adoption decisions defies simple models or explanations. Rather, the research embraces the intricate levels of influence that various stakeholders and other factors have on producers' decision-making at the scale of the farmgate and beyond. Fig. 1 illustrates an adapted conceptual framework that guides this study. Liu et al. [52] present this conceptual framework to reflect their findings of a comprehensive review and synthesis of factors that may influence farmers' adoption of best management practices (BMPs). Their framework places emphasis on how relevant factors and stakeholders are situated at scales within and beyond the farmgate, illustrating the flow of information between these stakeholders, and placing specific emphasis on information providers and how they frame their messages for others. From the perspective of all actors in this system, socioeconomic and biophysical factors present within the farmgate and beyond coincide with heterogeneity and uncertainty.

Nkonya et al. [53] suggest that the efficacy of crop development programs highly depends on how extension educators and technical assistants involved in agricultural development understand and address the factors that affect technology adoption. According to Dalton [54], failing to incorporate any of those factors (e.g. production, consumption, and market traits), or focusing on the wrong factors, could lead to biased and inappropriate varietal or technology promotions. When examining the early adoption of genetically modified oilseed rape among farmers in Germany, Breustedt et al. [55] suggested that attitudes of neighbors toward a given crop are so crucial that individual farmers may not be entirely free in their technology choice. Similarly, Fatimah [56] examined jatropha expansion in Indonesia to discover that various beliefs and values held by scientists, government officials, producers and others shaped the trajectory of the crop's adoption. Within the United States, Singer et al. [57] indicated that the additional value offered by winter oilseed crops grown in the Midwestern Corn Belt might incentivize farmers to adopt these crops. However, within this same agricultural system, Sindelar et al. [58] concluded that several environmental, agronomic, and socioeconomic barriers limit the

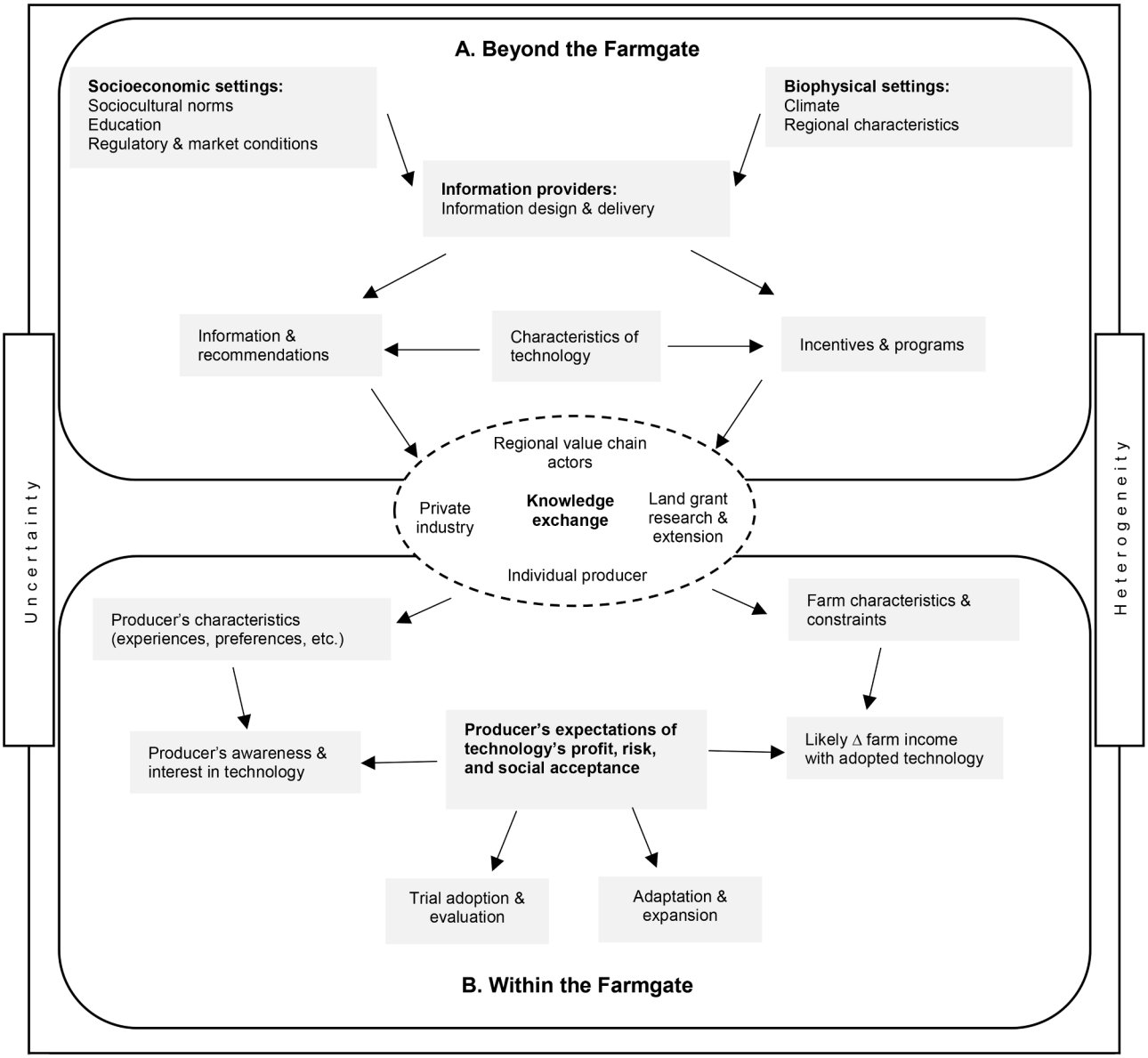

Fig. 1. Producer decision-making regarding agricultural technology adoption exists within an interconnected network of socioeconomic and environmental factors at the scales of the farmgate and beyond, framed by uncertainty and heterogeneity. Arrows show the proposed flow of information and influence between these elements. A system of knowledge exchange that permeates scales influences decision-making. Adapted from Liu et al. [52].

integration of winter oilseeds. These studies indicate the need for more comprehensive approaches to assessing the environmental and economic viability and sustainability of these intensified cropping systems within the US Corn Belt, other areas in the United States, and around the world.

Considering literature on the role of extension, neighbors, and the broader social system, we adapted the Liu et al. [52] framework to include an element related to the flow and management of information among stakeholders. Its addition allows us to explore the role of knowledge exchange and its relevance for understanding crop adoption patterns, particularly if viewing producer decision-making as being embedded in a complex socio-ecological system. As such, our study unites actors within the farmgate and beyond.

3. Methods

The scope of this study is a subset of a larger, university-led Coordinated Agricultural Project (CAP grant number 2016–11231) funded by the United States Department of Agriculture's National Institute of Food and Agriculture (USDA-NIFA). The 5-year-long (2017–2022) multidisciplinary project supports a public-private partnership that unites land grant universities and their extension systems in the SE US with an industry partner that has sole proprietary ownership of carinata germplasm as well as other partners associated with the production of carinata co-products. Exploratory in nature, this social research serves as the first step to inform a larger socioeconomic analysis that will randomly sample producers across the SE US to collect more generalizable data for quantitative economic modeling. The following subsections detail the steps of data collection and analysis.

3.1. Data collection

Data collection occurred over a two-year period, from September 2017 to September 2019 (University of Florida IRB #201701894). Table 1 illustrates the mixed-methods approach to gathering data from stakeholders involved in the expansion of carinata in the SE US.

Table 1
The research team utilized a mixed-methods approach to data collection from September 2017 to September 2019. These methods allowed the research team to engage carinata stakeholders involved at various stages of the crop's production and processing.

Timeline	2017	2018		2019	
Research Audience (Sampling size)	Key informants (n = 15)	Carinata event attendees (n = 34)	Previous carinata growers (n = 8)	Carinata event organizers (n = 7)	Producers (n = 4); extension faculty (n = 2); carinata agronomist (n = 1)
Data Collection Instrument	Semi-structured interview	Survey with ranking exercise	Semi-structured interview and sorting exercise	Semi-structured interview	Focus group

Interviews were conducted by phone, video chat or face-to-face and lasted between thirty minutes and two and a half hours, depending on depth of response. With participant consent, the research team recorded all semi-structured interviews and the focus group. As shown below, each of the five phases of data collection were cumulative so that findings from previous interviews were validated subsequently and re-explored over time to check for gaps and deepen understanding.

3.1.1. Interviews with key informants (Phase 1)

Fifteen key informants were selected based on their leadership positions within the university-led partnership, subsequently following a snowball sampling method for further recruitment. The interview instrument consisted of twenty-one questions derived from a series of collaborative planning sessions with project team members in August and September of 2017. Using participant responses as a base, the research team followed a process of secondary literature review to cross-check conflicting information.

3.1.2. Survey of carinata field day attendees (Phase 2)

Members of the research team attended four carinata-related events hosted by partnership-affiliated universities in Florida, Alabama, and Georgia between February and April 2018. They distributed surveys to attendees before the start of each event to capture their familiarity, opinions, and concerns with carinata before exposure to event programming. Respondents ranked their self-described "top five" barriers from a list of ten farm-level barriers to carinata adoption, which the research team identified from interviews with key informants.

3.1.3. Interviews and adoption barrier sorting with previous carinata growers (Phase 3)

As a result of collaborative discussions on the initial findings from key informant interviews and event surveys, questions were developed for previous carinata growers, or producers that had any experience growing the crop commercially, regardless of success. These included an expanded list of potential barriers to carinata adoption at the level of the farm and beyond. Between August and November of 2018, a member of the research team conducted semi-structured interviews with eight of these growers. To maximize respect for privacy, the research team relied on university extension and industry to broker interview times and locations. The interview instrument consisted of twenty questions, including two exercises. Producers selected their top three sources of information guiding production decision-making from factors randomized on a sheet of paper, and also a completed a sorting exercise in which they selected the "top five" barriers to adoption at the level of the farm gate, beyond the farm gate, and finally the top three barriers considering both categories. The research team member conducting the exercise presented cards with pictures representing each barrier in a random order, allowing the participating producer to perform the sorting by physically placing cards into piles. A facilitated discussion with each participant followed the sorting exercise to understand both their reasoning and potential solutions to these barriers.

3.1.4. Interviews with organizers of SE US carinata events (Phase 4)

Throughout July and August of 2019, a member of the research team conducted semi-structured interviews by phone with the organizers of carinata-related events held during the first two years of the university-led project (July 2017 – July 2019). The interview tool consisted of five main questions about factors that may have determined the success of each event, the planning process and lessons learned for future events, as well as the organizers' perspectives on engaging various stakeholders more adequately.

3.1.5. Focus group with producers and extension faculty (Phase 5)

Data collection concluded with a focus group in August 2019 that convened a diverse group of stakeholders. Four producers with mixed experience growing carinata, two extension agents familiar with the carinata, and one university agronomist met to discuss the crop. One member of the research team facilitated the focus group and presented participants with six main questions over a two-hour period, while another member of the research team took notes of conversation dynamics not captured in the recording. Background information on the expansion of carinata in the SE US and insights from the barrier sorting exercise with previous growers catalyzed the discussion, allowing participants to voice their own perceptions of barriers and their potential solutions.

3.2. Data analysis

Data collection and analysis attempted to capture the unique perspectives of key stakeholder groups associated with the adoption of the carinata crop in the SE US. The mixed-methods approach presented above allowed for the comparison of primarily qualitative and some quantitative responses, providing a pragmatic overview of stakeholders' attitudes, emotions, and concerns regarding factors shaping carinata's adoption among producers and the role of knowledge exchange in this process. A member of the research team transcribed each recording and focus group audio twice using Express Scribe Transcription Software (Pro v 7.03). Thematic analysis was used to sort qualitative responses into specific categories during the first review. Secondly, specific quotes were associated with themes and validated by two social scientists. Quantitative data from the carinata event survey was analyzed using a weighted scoring method [59]. Farm-level barriers with the highest ranked factor received a score of five and the lowest a score of one. This allowed for the visualization of the participant-identified importance of certain barriers. The survey also requested participants to list any other barriers to carinata adoption not included on the list. The research team presented this information to the larger project's working groups for discussion, following a collaborative process to compile a list of potential adoption barriers at the farm-level and beyond. The compiled list was used in the sorting exercise with previous growers. The research team analyzed this sorting exercise by assigning a point to each individual factor selected by a producer as part of their "top five" at the levels of the farm gate and beyond and their overall "top three" considering both categories. The highest-scoring barriers served as a point of reference for the analysis of interview responses, providing a framework to identify recurring themes among all participants in order to supplement a lack of statistical strength.

4. Results

The presentation of results follows the four original research questions, beginning with the identified benefits of growing carinata in the SE US, and followed by perceived barriers to adoption, presenting within-farmgate factors before those existing beyond the farmgate. The exact order of factors also follows the results of quantitative analysis derived from the barrier sorting exercise conducted with previous growers when available. Additional factors that received significant attention during interviews and the focus group also appear in the narrative. The section continues with stakeholder-identified solutions to some of these barriers and concludes with findings on the role of learning and knowledge exchange in the adoption of carinata in the SE US. Detailed demographic information was not collected; however, we identified all previous growers as men and three overall respondents were women. To clarify or emphasize certain points, the (n) number of respondents expressing a given idea is also included within the text.

4.1. Benefits of growing carinata

Carinata stakeholders that participated in the research process identified several perceived benefits of carinata production in the SE US. These benefits generally fell into two broad categories: agronomic benefits and economic benefits. Participants largely failed to acknowledge environmental benefits of carinata that may be seen at larger scales beyond the farm.

4.1.1. Agronomic benefits

Most agronomic benefits of carinata production centered on those related to winter cover cropping. Offering a broad perspective, a key informant referenced the "millions of acres in the Southeast that have no crops" during the winter months, identifying a need in the SE US that carinata might satisfy. Other key informants provided similar perspectives, with one speaking on the mindset of producers:

> There are a number of farmers conscious of the need of having a crop growing year-round. Why is that? It literally has to do with soil health, benefits, and partnerships. When you keep something green in that ground, then you are feeding carbon and you have more active soil bacteria and fungi. – Key informant, September 2017

Previous growers (n = 6) echoed this sentiment, speaking plainly about the perceived soil benefits of growing carinata. One felt he had "more nutrients in the soil than ever" after growing soybeans behind a carinata stand cleared with fire after frost damage incurred. However, he admitted not having data to back up this claim. Yet, other producers reported similar claims. For example, another farmer who successfully harvested his carinata perceived that his subsequent soybean harvest benefitted from planting a cover crop. Another producer commented on the improved vigor of his cotton crop after planting behind carinata, specifically mentioning its "extensive root system that rotted away and left great conditions for the cotton." Other producers (n = 2) focused more on the general importance of covering the soil during the winter months without providing specific reasons for doing so, and that carinata represented a crop that has potential to fit into existing crop rotations. Perceived agronomic benefits of carinata production also included the crop's capacity for nematode suppression. One previous grower who farms on sandy soils found this to be the most interesting aspect of the crop, although he was not sure if the soil benefits he documented resulted from nematode suppression or added nutrients. Similarly, an extension professional participating in the focus group, when expressing great interest in carinata, mentioned "certain mustards can help clean up some nematodes."

4.1.2. Environmental benefits

Beyond the ecosystem services that may render agronomic benefits for producers (e.g. soil health), participants in the research process rarely discussed environmental benefits of growing carinata that may be seen at a scale beyond the farm. One key informant working for carinata's industry sponsor elaborated the importance of carinata's low GHG production scheme, specifically stating that adhering to "specific standards is key to the crop's export to the European market." However, an extension professional participating in the focus group commented on how pressure to meet sustainability standards may have ultimately hindered initial research of the crop in the SE US. Furthermore, a key informant operating within the realm of academic research suggested those working in the public-private partnership should be cognizant of language used when communicating with producers, focusing more on the in-field benefits of the crop rather than concepts related to sustainability.

Also of note, no participant linked carinata or other biofuel feedstocks to the climate crisis or to effecting any positive impact to the global environment whatsoever. In fact, only one participant in the study referenced the climate crisis. This participant focused on the regional economic benefits that may result from carinata production in the SE US, but specifically stated that (said participant) did not believe such efforts would "save the climate or save the world." We elaborate further upon this topic in the next subsection.

4.1.3. Economic benefits

Participating stakeholders also referenced financial and overall economic benefits of growing carinata, as described in this subsection. Both key informants and previous growers (n = 10) at different stages of data collection mentioned that carinata may add another stream of revenue for producers. One of these producers elaborated that it was a crop suitable for both winter production in the SE US and benefited from effective marketing by its industry sponsor. He also observed "it is not much more expensive to maintain than a winter cover crop." Furthermore, although the SE US region is "choked with oats", he insisted there is a need for cover crop alternatives that have more profit potential. A key informant working within land grant extension claimed one of carinata's only true competitors in the SE US winter would be wheat, but stated, "wheat is consistently inconsistent as a winter cash crop. But there really wasn't anything else (available for producers), at least until carinata came along, that could supplant wheat." A previous grower summarized many of these perceptions, saying:

> People are looking for an alternative – really any alternative – that might show profit potential. The margins have been slim in the (agricultural) sector. There are some nice little blips that come along with crop markets. Cotton is kind of a bright spot, but it needs to be north of 80 cents for folks to really do well. I think (carinata) is just an opportunity where it can fit folks' schedules. We are blessed with a growing season that can handle it, even though we had two snows last year. There's a lot of opportunity. – Previous grower, August 2018

Participants discussed the potential regional economic benefits of growing carinata in the SE US. As referenced above, one key informant working in the private sector referred to the potential of carinata to fill a gap for energy security:

> There really aren't many petroleum resources or refineries in the Southeast, so it would be very complementary there […] I'm not one of those that believe we are going to save the climate or save the world. I really believe it is an economic driver, and the benefit that it would bring to local farmers and communities […] So we have the economic impact as well as energy security. – Key Informant, September 2017

Previous growers (n = 6) who participated in the research process also viewed the energy security of the SE US as being important, and that carinata may represent a solution to currently "unacceptable" diesel prices. "We tend to be at the mercy of others' fuel," one producer mentioned when talking about the strain of purchasing diesel at

perceived high prices. Another, referring specifically to Alabama, viewed a potential biofuel industry centered on carinata as a way of "revitalizing" its agricultural sector, as the state had "lost so much ground in agriculture. They need anything that can help make living off the land viable."

Carinata as a source for protein-rich animal feed was another benefit brought forward by stakeholders. One key informant associated with land grant research said the following:

> From an Animal Science perspective, we are lacking high-protein by-products in (the SE US). So, any crop that would provide a high-protein by-product would be very welcome in the industry. – Key Informant, October 2017

Previous growers who do not raise cattle did not expect to see direct benefit from a new, high-protein feed source. One producer involved in livestock production said his interest in the product "would depend on price points and performance factors." However, during the mixed-stakeholder focus group, an extension professional asked a farmer who also raised cattle "So, you would be a potential buyer of carinata feed?" The producer replied by nodding his head affirmatively.

4.2. Barriers to adopting carinata

Throughout data collection, the research team followed an iterative process to define and understand barriers to producers adopting carinata in the SE US and their perceived importance. Semi-structured interviews with key informants affiliated with the university-led project served as a base of understanding for the research team, providing wide-ranging barriers that were then presented in a survey to carinata field day attendees. Respondents of this survey (n = 34) ranked "unfamiliarity" with the crop as the highest barrier to adopting carinata or recommending it to someone else. It is important to note that those responding to this survey varied in their knowledge of the crop including those with no knowledge of carinata whatsoever. The research team discussed these findings with the larger project's working groups to collaboratively synthesize and interpret the results.

4.2.1. Barriers within the farmgate

Fig. 2 displays the results of the barrier sorting exercise conducted with previous growers. When sorting barriers within the farmgate, previous growers most frequently selected "negative prior experience" as a factor that may deter widespread adoption among producers in the SE US. Conversations with these producers as well as with key informants revealed these negative experiences may not only relate to previous attempts at growing carinata, but also negative experiences with other oilseeds. Some key informants and an extension professional participating in the focus group (n = 4) referred to the idea that industry pushed the carinata crop "too fast, too soon," referring to the company's commercial production leading up to 2014 before significant research in the SE US had occurred. Historical crop failures have given carinata a negative reputation among some in the SE US, a barrier that evidently seems to persist. In comparison to forays with other oilseed crops, one previous grower spoke positively of his experience with the carinata industry partner, saying the company, "hadn't done him wrong" like a canola company had. This sentiment echoed those brought forward by other key informants (n = 5), which suggests that a troubled history with oilseed companies in the SE US may make present day producers hesitant to sign contracts with the carinata industry.

In the barrier sorting exercise, previous growers also frequently selected unfamiliarity as a barrier to carinata adoption, both when considering solely within farmgate barriers and when viewing all factors cumulatively. Reponses from producers and key informants suggest that they characterize unfamiliarity in multiple ways, as seen in Fig. 3. Broadly, unfamiliarity may simply refer to the dearth of information about this crop among both farmers and scientists. Additionally, members of all participant groups (n = 16) called for research to mitigate the poor fit of carinata into existing crop rotations. Specifically, these respondents mention the challenges related to the timing of the carinata growing season, which might interfere with the planting and harvesting of summer cash crops.

Concerns emerged regarding various other agronomic factors, including effects on carinata's growth by chemicals used in the management of row crops. An example of this was a negative effect that herbicide application to peanut crops had on subsequent carinata grown in the same fields. The discussion of chemical pesticides and herbicides also frequently provoked producers to mention the prevalence of wild radish (*Raphanus raphanistrum*) in the SE US and the negative impact it may cause on carinata. In addition, one previous grower in North Florida commented on that region's soil quality, stating it "has the perfect environment to grow carinata in the winter, but the wrong soils." These factors may interact to constrain yields in the SE US. Indeed, several participants in the research process commented on the challenge of replicating high carinata yields attained in research plots on producers' fields.

Low selling price per bushel was another factor frequently chosen by previous growers when sorting within farmgate barriers and all factors cumulatively. However, these producers often failed to elaborate on this concern. In contrast, secondary data indicate that producers were offered between $8.00 to $10.00/bushel between 2014 and 2018, which some key informants (n = 6) referred to as a "good price."

Another frequently perceived barrier was the high demand of time and energy by carinata production. Participants (n = 4), regardless of their experience with the crop, suggested producers might prefer to spend the winter months pursuing other activities like recreational hunting. Others highlighted that carinata differs from typical cover crops because it requires significant management. Often, the time and energy sinks associated with carinata were related to equipment constraints due to the small size of carinata seeds. One key informant working for land grant extension drew parallels to his experience with canola in the SE US:

> The problem I saw with the adoption of canola is a lot of farmers are not prepared equipment-wise to deal with such a small seed or small grain. And because of that, they […] believe and feel with confidence that they can go out with their piece of equipment, fight a little bit, and do a good job. Well, some can and some can't […] It requires paying attention to the details. – Key Informant, September 2017

These barriers, as perceived by both key informants and previous growers, may largely relate to the concept of risk management. During interviews, key informants referred to the possible limited growing areas for some producers (n = 2), representing an opportunity cost of choosing to plant carinata, and that producers may have insufficient cash reserves to offset potential carinata crop failure (n = 3).

4.2.2. Beyond farmgate barriers

When considering barriers from beyond the farmgate and all factors cumulatively, previous growers most frequently chose limitations of crop insurance as a key barrier to carinata adoption. One previous grower simply stated, "no one really seems to understand how insurance works." Another argued that insurance was not worthwhile due to the perceived requirement of needing a certified growing history in his local area, and that managing to certify carinata might negatively impact their capacity to insure other crops. One producer participating in the focus group said, "Crop insurance is an issue. The importance of crop insurance really depends on the crop itself…it all comes back to the upfront cost and the potential loss."

Previous growers also frequently selected weather risks as a high-ranking barrier to adoption. Some (n = 4) referred to having experienced crop failures due to freeze damage. Not mutually exclusive to freeze damage, others (n = 3) mentioned that untimely rainfall delayed planting and harvesting. Many producers and key informants (n = 10)

Barriers within farmgate

Unfamiliarity
Low selling price
Poor fit into rotation
Equipment constraints
Difficulty getting high yield
Too much time & energy demanded
Limited growing area
Insufficient cash reserves to offset failure
Negative prior experience
Poor soil quality

Sorting results

Score	Within Farmgate Barriers
8	Negative prior experience
7	Unfamiliarity
6	Poor fit into rotation
5	Difficulty getting high yield
4	Low selling price

Score	Beyond Farmgate Barriers
7	Limitations of insurance
	Weather risks
5	Market proximity
4	Custom combining
	Visible evidence of success
	Quality of grain transport

Barriers beyond farmgate

Limitations of insurance
Market proximity
Custom combining
Visible evidence of success
Quality of grain transport
Smokestacking research
Weather risks
Petroleum price per barrel
Absence of policy incentives
Delays in certification
Pushback against feedstocks
Shipping to Europe

Cumulative sorting results considering all barriers

Score	All Barriers
5	Limitations of insurance
4	Unfamiliarity
3	Weather risks
2	Low selling price
	Visible evidence of success
1	Poor fit into rotation
	Equipment constraints
	Difficulty getting high yield
	Market proximity
	Custom combining

Barriers not appearing in this list were not selected by producers during the final round of sorting and received an overall score of 0.

Fig. 2. Scored responses from the barrier sorting exercise conducted with previous growers (n = 8) in the SE US. Respondents chose five barriers they considered most impactful to adoption at the levels of the farmgate and beyond, and three barriers when considering all factors cumulatively. Scores represent the number of times each factor was chosen by respondents during each round.

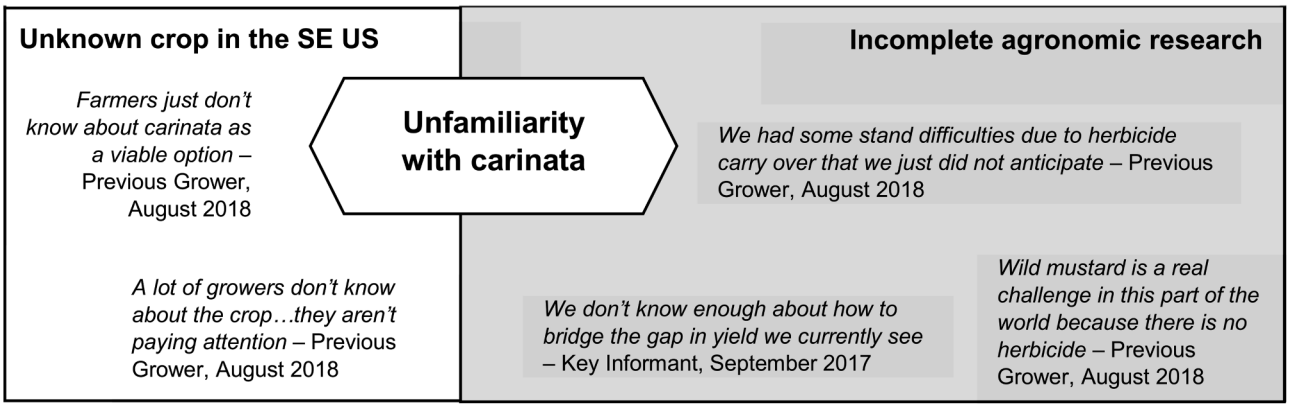

Fig. 3. "Unfamiliarity" as a barrier to carinata adoption in the SE US may take different forms. Stakeholders perceived that the crop is generally unknown to most in the SE US, and that much agronomic work remains incomplete, as highlighted by selected quotes from research participants.

Industry providing access to information and resources may overcome *limitations of insurance*, *equipment constraints*, and *lack of custom combining*.

- *If (industry) is taking production seriously in a particular area, why don't they invest in machinery to do the custom combining?* - Extension Professional (focus group), August 2019
- *People need some source of reassurance that there is effective crop insurance, so they don't feel like they'll go in the hole if they fail* - Previous Grower, November 2018

Research leading to improved and regionally appropriate varieties of carinata may overcome *weather risks*, *poor fit into established crop rotations*, and *difficulty attaining high yield*.

- *It's not that universities aren't doing the right research, but more research needs to be done* - Previous Grower, August 2018
- *We need more research done on cold tolerance and finding that sweet spot for planting time* - Previous Grower, August 2018

Land grant extension service providing platforms for stakeholder interaction and shared learning experiences may overcome *unfamiliarity* and provide *visible examples of success* with carinata.

- *Any contact whatsoever with folks who have successfully grown the crop would be the best information available* - Previous Grower, August 2018
- *We need to have some kind of community where our producers can interact. This generally happens at field days [...] so, a producer who is thinking about growing can hear what another grower's challenges were. That type of community is important when it comes to producers making decisions* - Key Informant, October 2017

Fig. 4. Carinata stakeholders provided self-described solutions to perceived adoption barriers throughout the research process. These solutions generally referred to the responsibilities of industry and business practices, the role of university-driven research, and land grant extension activities serving as a catalyst for stakeholder interaction and knowledge-exchange. The figure includes relevant quotations from research participants referring to these concepts.

highlighted carinata's poor cold tolerance as a persistent barrier to the crop's success as a winter crop in the SE US. One producer in Alabama summarized this notion by stating the following:

> The past fall we planted (carinata) and it was a pretty wet fall. We had a perfect stand. But […] it snowed twice in Central Alabama that year. Anyway, it tore our carinata up. We planted a little bit at the start, it would rain for a week or two, and then we continued planting. […] If we had planted it all a month earlier, it would have done better. – Previous Grower, September 2018

Market proximity, referring to the distance to facilities that store harvested carinata seed, also scored highly as a potential barrier to carinata adoption in the SE US. A producer stated his experience with carinata mirrored that with canola: he lacked on-farm storage, and the nearest handler was one with whom he did not like to do business. The next closest option was too far away to be feasible for shipment. A lack of custom combining options for carinata harvest also appeared as a perceived barrier to adoption. The extension professionals and producers in the focus group perceived that for many growers, "having the equipment to *plant* carinata isn't the issue. Harvesting is a different matter entirely." A producer with experience growing carinata related that he had difficulty finding someone with equipment to help with his harvest, saying, "they didn't want carinata mustard to run through their machines."

Producers also selected a lack of visible evidence of success with the carinata crop as a barrier to adoption. During interviews, producers (n = 5) frequently stated that examples of success with the crop would convince hesitant growers to make a first attempt. One participating grower said what is needed is to, "take a few people, do everything you can to make them successful, and then prop them up as examples."

Issues surrounding the small size of carinata seed arose in discussions of the quality of grain transport. Previous growers (n = 3) described the painstaking steps taken to seal their machinery, often using tape and other materials to prevent seed from leaking, which "flow out like water if you aren't careful" or "pour like BB's out of a box." Often, producers drew connections to the extra time and energy demanded by the crop when discussing this barrier. They also noted that oftentimes grain transport infrastructure was not prepared to handle such small seeds.

Key informants brought forward several perceived barriers to adoption that previous growers did not frequently select in the sorting exercise. For example, key informants (n = 2) raised concerns about the influence of petroleum prices on the demand for carinata and other biofuels, as well as, the historical pushback against purpose-grown feedstocks, which arguably reduce the agricultural land dedicated for food production. This group of respondents (n = 5) highlighted the lack of policy incentives for sustainability and green energy in the SE US as compared to the western United States. They were also critical of the export of carinata seed harvested in the SE US to Europe for processing (n = 3). Sentiments on this topic might contrast with those of producers. For example, one producer said, "they could ship (carinata) to the moon and it wouldn't make a difference to me."

Previous growers acknowledged other barriers, such as the impact of delays in sustainability certifications. As previously referenced, an extension professional in the focus group felt the sustainability requirements for carinata are an obstacle to understanding how the crop performed in the SE US. This participant expressed disappointment with researchers who "should have figured out how to properly attain

high yield first, then whittle down on nitrogen applications so it meets requirements." Another producer felt "smoke-stacking" research – or pursuing academic interests over the true needs of farmers – negatively affected their growing experience. This producer expressed frustration at both industry and land grant university researchers who they perceived as making decisions for them when they "really wanted to make (their) own agronomic decisions."

Finally, throughout the research process, participants (n = 6) frequently cited another perceived barrier existing beyond the farmgate, which the research team later came to refer to as "the chicken or the egg." This concept refers to a paralysis in progress of establishing a regional carinata bioindustry and related infrastructure in the SE US. A key informant working in industry put it this way:

> It's a chicken-or-the-egg thing. We have […] the airline folks on the demand side. They are saying they will buy whatever they get but aren't necessarily willing to put it on a contract. I have always been the type of person to think that if you want it, put a contract on it and then it will flow down the rest of the supply chain. Then on the other side, you have the producers […] who generally don't like to try new things until they know they can grow it and make money growing it. You also have crushing facilities that have to see that it will be worth their while to accept carinata, meaning they would have to take extra steps to clean out their facilities before and after crushes. However, to get that many acres, you have to get that many farmers. – Key Informant, October 2017

4.3. Stakeholder solutions to adoption barriers

Options for overcoming perceived barriers to adoption arose as central themes in interactions with key informants, extension professionals, and producers. Fig. 4 illustrates concepts and quotes from stakeholders regarding these proposed solutions. Although participants did not suggest solutions for all perceived barriers, their proposals fell into three categories: 1) Suggestions for industry and business practices; 2) the role of university and industry-driven research; and 3) land grant extension as a catalyst for information sharing among stakeholders.

When describing solutions to certain barriers to adoption, previous growers placed some responsibility on industry and their business practices. This view was particularly evident during discussions on the lack of custom combining options for carinata in the SE US (n = 3), which if addressed, could potentially alleviate equipment constraints during harvest time. In contrast, stakeholders did not provide a clear-cut solution to their perceived limitations of crop insurance for carinata. However, both producers and extension agents participating in the research process indicated that insurance options exist but vary from state to state. One previous grower stated that someone "needs to provide reassurance that there is effective crop insurance, so people won't feel like they'll go in the hole after failure."

Producers, key informants from various sectors, and extension professionals recognized the value of university and industry-led research and development in the areas of breeding and management practices as a means of overcoming barriers like weather risks, a perceived poor fit into existing crop rotations, and difficulty attaining high yield. Members of all participant groups (n = 17) highlighted the necessity of developing better, more regionally appropriate varieties of carinata that meet producers' needs. Additionally, participants appear to depend on peer-to-peer learning and knowledge exchange to overcome their unfamiliarity with carinata. Such approaches can improve adoption as reflected in the perspective of one extension professional in the focus group who suggested "unfamiliarity being one of the most frequently identified barriers may be the easiest to overcome."

4.4. Information flow and the roles of knowledge exchange and learning

This subsection presents a more thorough discussion of the dynamics of information sharing among stakeholders and the perceived importance that research participants placed on learning and knowledge exchange in the adoption of carinata in the SE US.

4.4.1. Information flow among carinata stakeholders

Participants in this study define "information" as any type of knowledge surrounding various aspects of carinata, including but not limited to its adoption, agronomy, and processing. Throughout interviews and the focus group, participants in the research process described the dynamics of information flow among carinata stakeholders. Previous growers (n = 8) were asked, "As a grower, how do you stay informed to effectively make decisions about your production system?" From a list of eight potential information sources, these participants selected their top three. "Extension" and "companies associated with the crop" were equally chosen most frequently, more so than "consultants" and "internet agriculture websites" which tied for second. Only two producers selected "neighbors," while one producer selected "trade magazines" and "coffee shop talk" respectively. No producers selected "television" as a source of information guiding their agronomic decision-making. During subsequent discussions, respondents frequently described the characteristics, perceived strengths and limitations, and other aspects of carinata stakeholders, ultimately referring to their role as purveyors of information on the crop. Discussions largely focused on carinata's industry sponsor, land grant extension professionals, and neighboring producers. They also highlighted possible contention and misunderstanding of the roles of extension within the public-private partnership promoting carinata in the SE US.

Previous growers (n = 6) spoke favorably about the agronomic support provided by industry agents, with many of them echoing sentiments of a producer who said they were "very present and great to work with." Key informants (n = 2) also referred to a single industry sponsor of carinata in the SE US as a positive factor for adoption. They perceived the company as being more organized than other crop promoters.

> Having the focus of (the industry sponsor), who is – compared to other crop developers – much better organized compared to others. Some crops I've worked with do not have a singular advocate that can work with it well. – Key Informant, October 2017

Previous growers (n = 2) referred to their specific county agents as important sources of support throughout the carinata growing season. Key informants from various sectors also expressed opinions on

Table 2
Key informants expressed varied expectations and concerns with regards to extension professionals' role as purveyors of information on carinata within the SE US.

Expectations of Extension's Role	Concerns of Extension's Role
"(Extension agents) are the tip of the spear to validation for farmers."	"There needs to be some level of congruency of the message […] being shared by state extension agents and (the industry sponsor's) agents. There needs to be a relationship between these two entities, because I've been in some of those meetings…and you don't want misunderstandings being aired in a producer meeting between research and extension. That can stymie confidence and create distrust."
"(Extension) will hopefully accept the idea of getting trained and being (the industry sponsor's) deputies. This is sort of like the Wild West. If extension accepts the fact that they are like deputies, then I think the chances of success are a lot better. If (extension) thinks they know how to do it better than (the industry sponsor), they don't."	

extension professionals as purveyors of information on carinata. These opinions sometimes reflected perceived expectations of extension's role, and others expressed concern regarding the handling of information. Table 2 provides quotations that exemplify these thoughts.

Finally, both key informants (n = 6) and previous growers (n = 5) referred to neighboring producers as important sources of information on carinata production. When asked who growers likely rely on most when deciding to adopt a new crop like carinata, one key informant responded by saying, "Neighbors for most growers. And extension, but that's research. They want to see real examples." Another key informant answered by saying that neighbors who successfully grow the crop will "serve as examples for others to follow," while another said neighbors are important sources of information because producers "like to get together and talk about technical things they are doing." Previous growers largely corroborated these thoughts from key informants, elaborating on the importance of shared learning experiences among producers that have interest or experience growing carinata. However, key informants (n = 2) also commented on the implications of negative growing experiences among producers, inferring that "bad news travels fast" and may deter growers from adopting the crop.

4.4.2. Learning and knowledge exchange as factors that shape carinata adoption

Participating stakeholders outlined how processes of knowledge exchange and opportunities for shared learning may serve as a guiding force for adoption of carinata. During the focus group, an extension professional noted that despite historical challenges in the SE US, examples of success with carinata do exist:

> When the crop first got started and we had so many failures with carinata, you couldn't help but hear farmers talking about the bad – that neighbors had bad experiences and so on. But now with the more recent rounds of production, you've heard a different dialogue among producers. To me, that shows promise with the crop. – Extension Professional (focus group), August 2019

Producers with experience growing carinata (n = 5) expressed a distinct desire to learn from others who had grown the crop successfully. When asked what would be helpful for future rounds of production, they responded that they wanted "to ask successful growers questions" and that they needed "to see examples of success on other growers' fields." One producer in North Florida said if he had "a neighbor also growing on sand" that could show him how to grow carinata effectively, they would be his best resource. He also added, "that's what my granddaddy always said I needed to do."

When discussing what might expand or widen adoption of the crop in the SE US, producers and extension professionals in the focus group often referred to the interactions between carinata stakeholders at extension-run events, like field days. This group viewed these interactions as positive, but also highlighted opportunities for improvement. Specifically, they expressed desire for such events to be held closer to potential growers and that extension should partner with producers when possible to grow large-scale test plots on producers' fields. By following this collaborative protocol, interested growers would be able to interact with the crop in regionally appropriate areas and assess realistic examples of how the crop may grow in their own fields.

The organizers of carinata events in the SE US (n = 6) reflected on their own experiences of hosting such interactions. Of these organizers, many (n = 4) stated that fostering communication between producers was a priority. However, when questioned about challenges surrounding the dynamics of these events, the organizers seemed to experience multiple pressures. For example, they are evaluated based on the number of attendees at educational events. Therefore, for reporting purposes, they typically prioritize quantity of participants over the quality of discussion content. As one organizer put it, "You can't put a number on that type of interaction and report it to your boss." The same organizer expressed regret that he did not have the training to facilitate small group discussions among producers because he valued their importance but felt unsure as to how to manage these conversations.

To overcome some of these perceived challenges, organizers (n = 4) highlighted the opportunity that may exist with presenting carinata alongside other relevant crops rather than hosting an event focused solely on carinata itself. One organizer felt extension had not effectively connected carinata to the cover crop benefits it may provide producers. Therefore, presenting it alongside other cover crop options may provide relevant context to interested growers. Another organizer who had hosted a field day exclusively focused on carinata said future events should be rebranded as "winter crop options for the Southeast," to connect better with the needs of producers. In general, organizers interviewed in July 2019 characterized the perceived benefits of this strategy as follows:

> "When carinata is featured alongside other crops, it puts it into context and makes it easier to think about feasible rotations."

> "Featuring multiple crops at once or combining events can be a way of introducing carinata to an already established community, as opposed to building a community from the ground up."

> "Having carinata featured alongside other crops really provides points of comparison. For example, they could see firsthand how real frost damage had impacted the crops differently."

> "Carinata is a new crop and nobody knows about it. Pairing it with crops that are more well-known gives attendees assurance that they will walk away with 'news they can use.'"

It is also worth noting that all previous growers and the extension professionals and producers participating in the focus group indicated that they want more conversations surrounding carinata to occur in the future and that they would be willing to participate in these ongoing discussions.

5. Discussion and conclusions

Within the landscapes of biofuel feedstock production and bioenergy, this study provides insights into the barriers and opportunities to carinata adoption within the SE US. The research reveals the complex socio-environmental and economic nature of carinata's trajectory of establishment and expansion in this region. The following section summarizes findings on perceived barriers to carinata adoption, highlighting their interconnectedness and links with AIP theories. Then, we discuss the potential for system approaches to enhance land grant extension services that aim to increase technology adoption. We also touch on the opportunities and challenges associated with the diverse stakeholder roles and expectations within the public-private partnership promoting carinata in the region. Finally, we acknowledge the apparent disconnects between the drivers of producers' adoption decisions and the economic and climate factors that guide the carinata market globally. To conclude, we consider the study's findings by reflecting on our adapted conceptual framework and provide final thoughts on carinata adoption in the SE US within the context of a changing global climate.

5.1. The complexity of disentangling adoption barriers

Artificially delineating adoption barriers into discrete categories presented an unexpected methodological challenge. Because many of these factors are linked within the minds of stakeholders, the process of disentangling them for the sake of this analysis proved difficult and sometimes counterproductive. For example, focusing solely on a specific adoption barrier like *equipment constraints* might isolate this factor from its critical connection to summer cash crops, which represent a vital economic driver to producers. In this case, farmers consider these equipment constraints within a complex system of integrated factors.

These considerations include the relatively reliable revenue stream generated from summer crops and the interest-laden capital investments in equipment needed to harvest them. Such risk assessment strategies employed by producers may prompt them to decline opportunities offered by carinata production if they perceive that adapting to this crop's planting schedule threatens the bottom line of their summer operations.

Furthermore, we learned that stakeholder groups perceived the weight of key adoption barriers differently, with some groups dismissing certain barriers while others focused heavily on them. For example, key informants associated with the public-private partnership perceived particular barriers as simpler to solve, such as *crop insurance*. However, it is not clear that these solutions are as apparent to the producers themselves, who rank this factor high on their list of barriers. Therefore, we note that any quantitative efforts to separate, rank, and list barriers to adoption only deepens our understanding when accompanied by in-depth qualitative data.

During our analysis, it also became apparent that certain barriers encompass various scales of analysis, spanning within-farmgate production and outward. One such example is the complex barrier of *unfamiliarity*, which can include a lack of basic agronomic knowledge on the crop at the field level circulating among producers to information about other stakeholders in the value chain within the SE US and beyond. In short, we found barriers across scales fabricated for this analysis are more permeable than expected. Similarly, Roesch-McNally et al. [60] highlight the systemic nature of agriculture, linking structural and in-field challenges to barriers beyond the field. Such complexity cautions against simple solutions that solely focus on individuals within the farmgate or those that only note factors at higher scales. Rather we point to the dynamic web of barriers that come in and out of play dependent on the perspective of the stakeholder and their position within the value chain.

5.2. Extension facilitating a systems approach: Opportunities and challenges

Key informants in this study revealed a dependence on early adopters, with the hope that their success would convince others to grow carinata over time. Such narratives reflect a reliance on diffusion of innovations theory [35]. However, Diederen et al. [61] point to challenges with this theory, suggesting that the complexity of an innovation itself, its industry dynamics, or the socio-environmental factors in which it is embedded may prevent a clear understanding of factors leading to adoption. Additionally, industry bias – or a technology supplier's preference toward innovative, wealthier clients – may lead to skewed adoption pathways away from those who may truly benefit from the crop [35,38]. Although we do not reject the relevance of theories like diffusion of innovations that place emphasis on the individual, we note that AIPs resonate more strongly in helping to understand the factors shaping technology adoption of carinata in the SE US.

The public-private partnership project structure provides extension and other actors with a platform to not only continue engagement with producers, but also to enhance the complex systemic connections between carinata stakeholders along the value chain in the SE US and beyond. Indeed, study respondents expressed an interest in shifting away from conventional approaches to knowledge exchange in which producers passively receive information from experts like researchers or industry advisors [62,63,64]. Instead, producers and other key informants proposed a system in which producer expertise actively contributes to the co-creation of knowledge in the vein of an AIP, guiding both carinata agronomic research and producer decision-making. Hoffman et al. [65] and Sumane et al. [66] emphasize the value of producer knowledge for sustainable agriculture due to its context-specific and holistic nature. This emerging dynamic supports scholarship which proposes that producers have the capacity to shift from consumers of agronomic information to purveyors of such knowledge [67].

Within land grant extension in the United States, Raison [68] argues that the traditional delivery system of transferring knowledge from experts to producers may no longer provide value. Instead, they envision the extension professional as a facilitator of knowledge exchange between community members to build social capital within agricultural systems. The results presented in this study also suggest land grant extension systems may facilitate this knowledge exchange among producers and other carinata stakeholders through various methods. These may include on-farm demonstrations of carinata with clearly defined roles for producers, researchers, and extension to enhance knowledge exchange [69]. Future studies of carinata expansion in the SE US should assess the value of participatory variety selection (PVS) among carinata stakeholders in the SE US. This process brings together agronomists, producers, and social scientists to collaboratively select crop traits deemed most important [70,71]. Kolech et al. [72] report on the effectiveness of the PVS approach among potato farmers in Ethiopia, noting its ability to capture factors and desired traits not addressed in conventional crop breeding programs. Applying PVS in the ongoing development of regionally specific varieties of carinata in the SE US may achieve similar results by addressing producers' concerns while providing them a pathway for involvement in the research process. Reminiscent of an AIP, this approach may also clarify confusion regarding specific practices and policies such as crop insurance for carinata or the handling of the crop post-harvest, perceived barriers that seem much better understood by members of the public-private partnership than by the producers themselves.

Although extension professionals may be well positioned to unite and facilitate interactions among carinata stakeholders in the SE US, they also face multiple challenges. For example, the study revealed the need for "un-learning" negative experiences with carinata. In such cases, extension agents are called to reframe the crop *as an opportunity* to producers who are biased against it. However, we found that the reward system for extension may disincentivize such deep conversations. Performance evaluations are based upon the quantity of attendees at field days or meetings over quality of discussion. Furthermore, many extension professionals see themselves as purveyors of "neutral" information as opposed to salespeople for specific products or crops. Even so, some respondents in this study noted that due to the scope of the industry partnership, extension agents should serve as "deputies" of carinata's corporate sponsor. This expectation may not resonate with the philosophies and guiding missions of state extension systems or individual agents. Finally, we note that extension professionals may be somewhat disconnected from market forces beyond the farmgate and may not be adequately informed to guide producer decision-making about higher-scale factors such as renewable fuel certification standards. Moving forward, efforts must focus on improving extension's capacity to facilitate learning among producers beyond immediate in-field agronomic factors. In addition, studies should examine the perceptions of roles within public-private partnerships, and how misaligned expectations may undermine specific actors' contributions to such partnerships.

5.3. Balancing roles within a public-private partnership

Both previous growers and key informants praised carinata's industry sponsor as an overall driver of adoption in the SE US. These respondents pointed to the company's close involvement with producers in the field and its provision of a single, clear market for the buying and selling of carinata seed. However, our research supports the claim that carinata's corporate sponsor represents just one stakeholder that engages producers in the SE US as part of the public-private partnership promoting the crop's adoption, and that the influence of private sector employees may bear significant weight on producer decision-making [73]. Private sector decisions ultimately guide the narrative associated with carinata in the SE US as a tiny oilseed with potential to both propel airplanes around the world and serve as an off-season cash crop.

However, this information may not exactly match the message of extension professionals, or even address the true concerns of producers.

Collaboration within any partnership assumes that the decisions of all parties are guided by different priorities and constraints. For extension, their decisions on information-sharing may be based on cultivating trust among growers in their regions, while corporate choices are oftentimes a proprietary means of remaining competitive at the marketplace. Due to proprietary control, the present study was limited by information constraints, which thwarted its power to glean broader insights into technology adoption. Social scientists were unable to ask carinata producers about acreage planted, associated yields, profit margins, and experienced a general lack of access to all previous growers. In contrast, most university research on carinata is open access. This disparity in information sharing and its effect on crop adoption warrants further examination.

As of late 2019, commercial production was suspended in the SE US after a larger company purchased carinata's original industry sponsor. These changes do not detract from the value of results from this study but bear weight on their application. For example, uncertainty about an already unfamiliar crop might increase among producers. A new corporate identity may also raise concerns about carinata market stability. Despite the unknown impact of these changes, this new reality may also present unique opportunities for the public-private partnership moving forward.

5.4. A missing link: The disconnect between local carinata adoption and global climate change adaptation

Key informants linked to carinata's industry sponsor emphasized the global forces, both social and economic, driving the carinata market. Production in the SE US represents just one growing region, which feeds into a larger system sustained by the market for low GHG renewable fuel in Europe. Despite the importance of carinata as a renewable biofuel feedstock internationally, most study respondents failed to make global linkages when discussing the crop's benefits. Specific climate factors bear weight on the future of agriculture in the SE US. Drought, for example, is predicted to persist and worsen in the SE US [74,75], and long-term climate change models estimate total farmland value may decrease 2.5–5% in the region, with varying state-level impacts [76]. The results of the present study of carinata stakeholders do not suggest that climate change is not of concern; however, at least from the perspective of producers, climate change may not be a central force in their decision-making regarding technology adoption. Rather, producers that participated in this study expressed clear interest in the agronomic and economic benefits of carinata not only to their individual operations but to the resilience of agriculture in the SE US in general, and expressed the need for continued agronomic research to reduce risk.

The apparent disconnect between the factors that guide producers' decision-making locally and the global forces that drive the carinata market may not necessarily hinder the crop's adoption in the SE US. As suggested by one key informant, it may warrant sensitivity surrounding buzz phrases like "climate change," requiring communication to focus more on the tangible, in-field benefits that producers may experience. Although some producers expressed the importance of sustainable energy security in the SE US, the relevance of such may ultimately depend on how it translates to the price they are offered at harvest in relation to perceived risk of carinata adoption. Indeed, analyses conducted by Moerkerken et al. [77] of Dutch farmers regarding energy-saving and GHG-reducing measures suggest external factors, such as economic hardship, largely motivate the environmental awareness of farmers in that region, and that campaigns centered on the benefits of adaptive innovation rather than climate mitigation may see larger success. Similarly, corn farmers in the Midwestern United States that perceive risk to their own operations may be more inclined to adaptive innovation [78].

To market carinata as a feedstock bound for the European market, producers in the SE US must follow certain management practices and comply with renewable fuel certification standards. For example, they must limit nitrogen application and the number of trips they make with tractors across the fields (to reduce GHG emissions) [22]. However, it is unclear whether producers internalize an association of these management conditions with championing climate change mitigation. It is possible that a failure to make this connection could limit the potential expansion of carinata precisely because growers are not envisioning its positive global contributions and may be motivated to increase yield regardless of the restrictions on management. At the same time, the avoidance of communicating these global climate benefits may be strategic and grounded in familiarity with the conservative political leanings often associated with the target producer audience. Morton et al. [79] suggest that studies seek to identify core values and beliefs that guide adaptive decisions in the face of climate change. A limitation of our study is that it did not specifically address "green" sustainability factors associated with carinata, or directly guide participants to consider larger, global issues. Therefore, the research design itself may have also contributed to the lack of attention to this topic. Future studies of carinata adoption among producers in the SE US should examine perceptions of global climate change and the degree to which carinata's mitigation potential motivates or deters adoption. Furthermore, this study primarily focuses on the perspectives of producers, extension professionals, and agronomists regarding the factors shaping adoption of carinata in the SE US. If future studies capture the viewpoints of stakeholder groups operating further along the value chain, they may more directly provoke consideration of global linkages.

5.5. Revision of the conceptual framework

In light of the study's findings, we reflect on the conceptual framework (Fig. 1) that guided our research. Our original adaptation of the framework presented by Liu et al. [52] emphasizes producer decision-making as being embedded in a complex socio-ecological system that unites actors within the farmgate and beyond through a shared process of knowledge exchange. Research findings suggest that various forms of engagement, particularly those occurring at extension-hosted field days, indeed provide opportunities to unite carinata stakeholders in the SE US to collaborate and promote knowledge co-creation. Perhaps uniting these actors in a system of "knowledge exchange" is too limiting; rather, using the term "collaborative stakeholder engagement" may better represent the findings of our research. As our results suggest, this collaborative engagement may prove important to addressing complex adoption barriers such as unfamiliarity with the crop.

Despite its effectiveness, the conceptual framework in its current state fails to capture the intricacies of relationships between stakeholders and how relationship dynamics may impact collaborative engagement and, consequently, producer decision making regarding carinata adoption. The nature of the public-private partnership guiding carinata's expansion in the SE US may bear significant weight on information delivery to producers from different members of the partnership. Specifically, future research should aim to assess matters of trust, power dynamics, and the perception of roles between partners. Should we be perceiving extension professionals as "deputies of private industry" or "neutral" purveyors of academic information? Our findings suggest not all carinata stakeholders would respond equally to this question, and such incongruency may undermine the efficacy of opportunities for shared learning and knowledge co-creation.

5.6. Concluding thoughts

Carinata may hold significant promise for producers in the SE US by providing additional cash flow and off-season cover crop benefits. The potential expansion of the crop and related biofuel industry in the United States and around the world is not a climate solution per se;

rather, it is one of many puzzle pieces that continue to reflect society's reaction to climate change. In the face of such a world-spanning crisis, it may be the choices of individuals that guide the success of resilience-oriented projects such as carinata production in the SE US. The public-private partnership project at the heart of this study highlights the opportunities and challenges of coordinating effective science and knowledge exchange between diverse stakeholders. However, the inclusion of a social science perspective in the project assists in navigating the interconnected nature of factors shaping adoption among producers, offering depth in understanding carinata stakeholders through narrative and qualitative methods. In short, the inclusion of social science in the fields of agriculture and bioenergy paves pathways between science and people and vice versa, an essential connection in the continued response to a changing environment, making partnerships for climate action possible.

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.

Acknowledgements

We would like to thank the United States Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA) for their support that made this research possible. Additionally, we would like to thank everyone that participated in the research process for their time and energy and for the invaluable information they shared with us.

Funding source

This work was supported by the United States Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA) Coordinated Agriculture Project grant program (grant number 2016-11231).

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