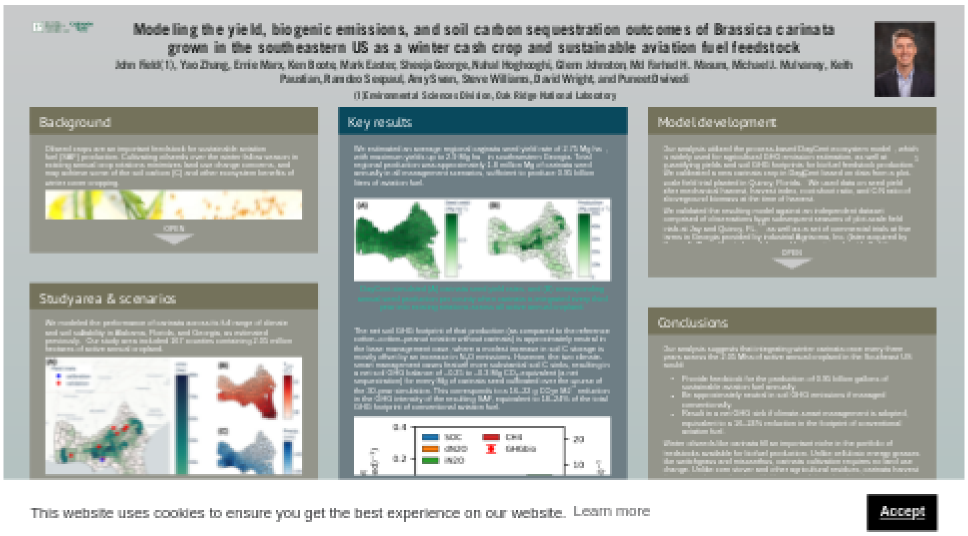
Modeling the yield, biogenic emissions, and soil carbon sequestration outcomes of Brassica carinata grown in the southeastern US as a winter cash crop and sustainable aviation fuel feedstock



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BACKGROUND

Oilseed crops are an important feedstock for sustainable aviation fuel (SAF) production. Cultivating oilseeds over the winter fallow season in existing annual crop rotations minimizes land use change concerns, and may achieve some of the soil carbon (C) and other ecosystem benefits of winter cover cropping.

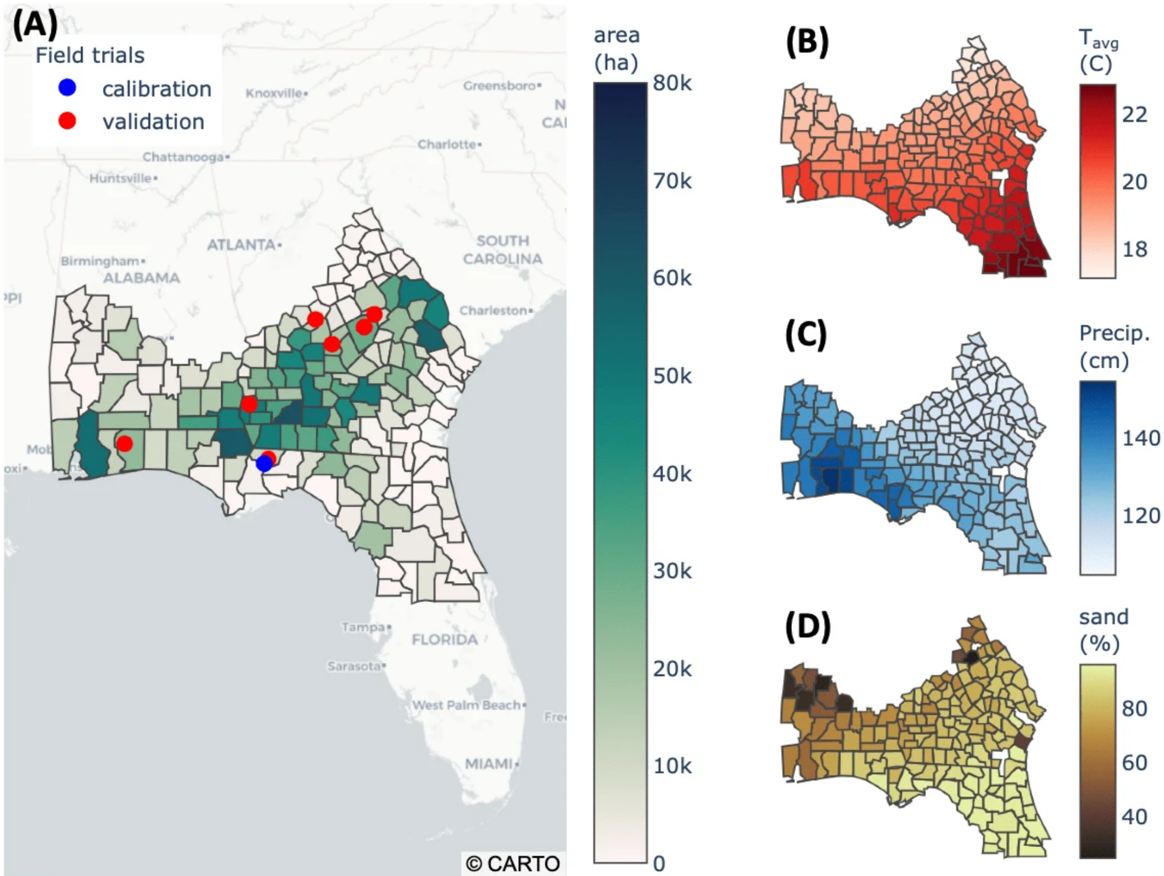
Carinata flowers, pods, and seed

Brassica carinata (known as Ethiopian mustard or simply 'carinata') is a non-food oilseed crop that can be grown during winters in the Southeast US to produce SAF feedstock and a high-protein livestock feed co-product. Integrating carinata into existing annual crop rotations can generate an additional revenue stream for landowners, while potentially increasing soil C storage and reducing nitrogen losses. The Southeast Partnership for Advanced Renewables from Carinata (SPARC) is a USDA-funded research consortium to advance carinata production and associated SAF and bioproduct supply chains in the region.

There is only limited data on carinata yields in the region, however, and no long-term measurements of associated changes in soil C storage or nitrous oxide (N_2O) emissions, the main greenhouse gas (GHG) impacts from agriculture. In this study[2] we used field trial data to calibrate a carinata crop in DayCent, and estimate the production potential of winter carinata across the tri-state region of Alabama, Florida, and Georgia. We also estimated associated changes in soil C storage and emissions of nitrous oxide (N_2O) to establish initial expectations for the climate performance of carinata and carinata-derived SAF.

STUDY AREA & SCENARIOS

We modeled the performance of carinata across its full range of climate and soil suitability in Alabama, Florida, and Georgia, as estimated previously.[2] Our study area included 167 counties containing 2.05 million hectares of active annual cropland.



Study area characteristics. (A) Cultivated cropland area, with locations of carinata trials used for DayCent model calibration (blue marker) and validation (red markers). (B) Average air temperature and (C) annual total precipitation. (D) Average sand content of the surface soil layer, considering cropland areas only.

We modeled all annual cropland as being under a cotton–cotton–peanut rotation, a commonly-practiced rotation in the region. We assumed that carinata could be integrated every third year within that rotation, over the winter between the two cotton crops. We also assumed that carinata would be planted in mid-November, fertilized with nitrogen at a rate of 90 kg N ha^{-1} in a split application, reach physiological maturity in early May, and be harvested after a three-week dry-down period ending in late May. Building off these general assumptions, we evaluated three different specific management scenarios:

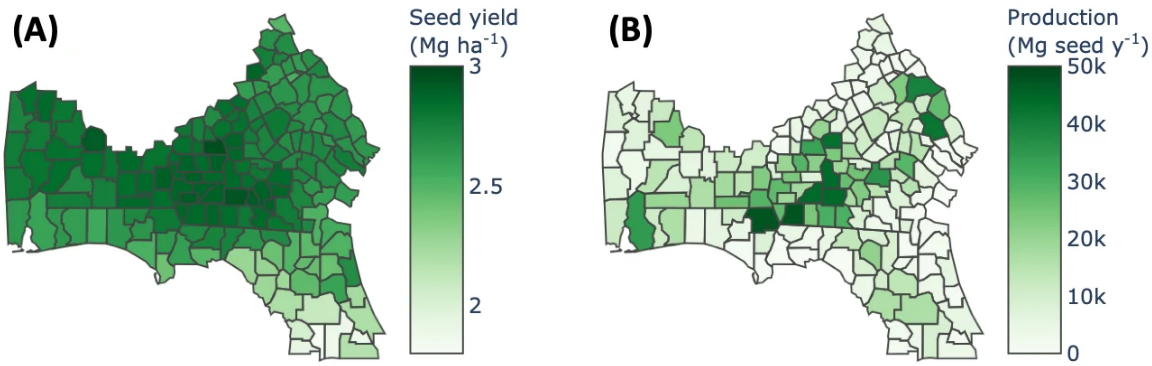
1. A **base** case that involved conventional field preparation (two passes with a disk) prior to planting.
2. A **no-till** climate-smart management case in which the disking is omitted.
3. A **poultry litter** climate-smart management case in which half of the nitrogen is supplied in the form of a poultry litter amendment (rather than synthetic fertilizer).

DayCent is a one-dimensional model, and multiple point simulations must be run to capture the heterogeneity in soils, climate, and land use history across the study area. Based on a GIS intersect of the SSURGO soil, PRISM weather, and NLCD land cover spatial databases, we specified a set of 30,720 unique point simulations necessary to represent the study area. Each of these simulations involved a model initialization step, followed by 30-year forward simulations

(2020–2050) of the three different carinata management scenarios, as we as a reference case of continued cotton–cotton–peanut rotation. In total this involved 11.1 million simulation-years run via batch execution on the Colorado State University Natural Resource Ecology Laboratory computing cluster. The results shown in subsequent figures reflect average yields and GHG emissions over the 30-year simulation, aggregated to county or regional scale.

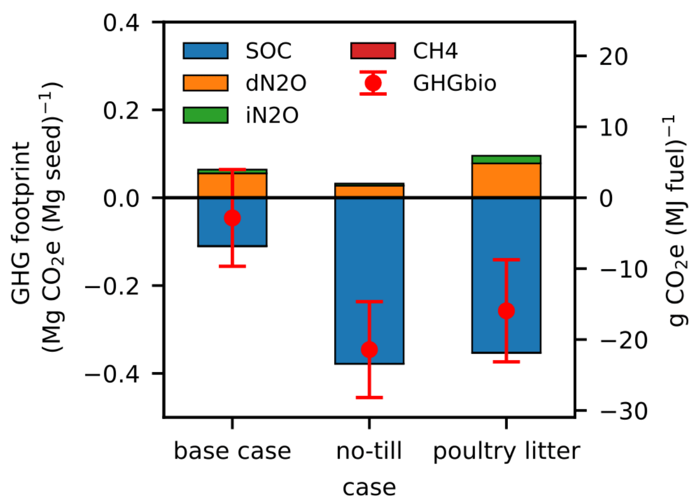
KEY RESULTS

We estimated an average regional carinata seed yield rate of 2.75 Mg ha^{-1}, with maximum yields up to 2.9 Mg ha^{-1} in southwestern Georgia. Total regional production was approximately 1.8 million Mg of carinata seed annually in all management scenarios, sufficient to produce 0.95 billion liters of aviation fuel.



DayCent-simulated (A) carinata seed yield rates, and (B) corresponding annual seed production per county when carinata is integrated every third year into existing rotations across all active annual cropland.

The net soil GHG footprint of that production (as compared to the reference cotton–cotton–peanut rotation without carinata) is approximately neutral in the base management case, where a modest increase in soil C storage is mostly offset by an increase in N_2O emissions. However, the two climate-smart management cases feature more substantial soil C sinks, resulting in a net soil GHG balance of –0.25 to –0.3 Mg CO_2-equivalent (a net sequestration) for every Mg of carinata seed cultivated over the course of the 30-year simulation. This corresponds to a 16–22 g CO_2e MJ^{-1} reduction in the GHG intensity of the resulting SAF, equivalent to 18–24% of the total GHG footprint of conventional aviation fuel.

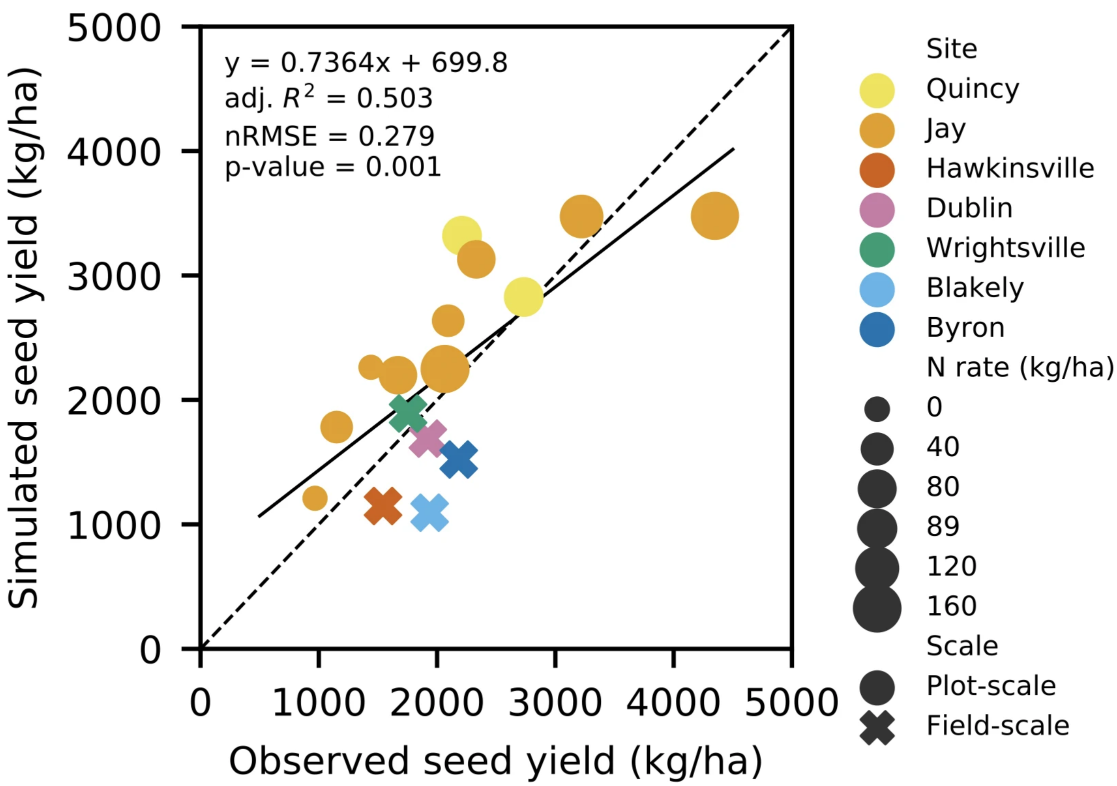


Soil GHG footprint per Mg of seed production, also expressed in units of global warming intensity (g CO2e (MJ fuel)-1) for the resulting carinata–SAF. Red error bars denote ±2SD of field-to-field variability.

MODEL DEVELOPMENT

Our analysis utilized the process-based DayCent ecosystem model[4], which is widely used for agricultural GHG emission estimation, as well at quantifying yields and soil GHG footprints for biofuel feedstock production.[5] We calibrated a new carinata crop in DayCent based on data from a plot-scale field trial planted in Quincy, Florida.[6] We used data on seed yield after mechanical harvest, harvest index, root:shoot ratio, and C:N ratio of aboveground biomass at the time of harvest.

We validated the resulting model against an independent dataset comprised of observations from subsequent seasons of plot-scale field trials at Jay and Quincy, FL,[7,8] as well as a set of commercial trials at five farms in Georgia provided by industrial Agrisoma, Inc. (later acquired by Nuseed). The calibrated model was able to capture about half of the observed variability in carinata yields across sites–years–treatments, with a normalized root mean squared error of 0.28.



DayCent model validation results against an independent yield dataset of plot-scale field trials at Jay and Quincy, Florida plus a set of field-scale commercial trials (Hawkinsville, Dublin, Wrightsville, Blakely, and Byron, Georgia).

CONCLUSIONS

Our analysis suggests that integrating winter carinata once every three years across the 2.05 Mha of active annual cropland in the Southeast US would:

- Provide feedstock for the production of 0.95 billion gallons of sustainable aviation fuel annually.
- Be approximately neutral in soil GHG emissions if managed conventionally.
- Result in a net GHG sink if climate-smart management is adopted, equivalent to a 16–24% reduction in the footprint of conventional aviation fuel.

Winter oilseeds like carinata fill an important niche in the portfolio of feedstocks available for biofuel production. Unlike cellulosic energy grasses like switchgrass and miscanthus, carinata cultivation requires no land use change. Unlike corn stover and other agricultural residues, carinata harvest does not reduce soil carbon. Unlike any cellulosic feedstock, carinata oil can be cheaply upgraded to drop-in aviation fuel. Our results support carinata as potential win–win–win for feedstock production, farmer revenues, and soil health improvement in this region.

Monitoring a carinata field trial

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ABSTRACT

Sustainable aviation fuels (SAF) produced from lipid feedstocks are an increasingly mature and low-cost option for aviation sector decarbonization. Ethiopian mustard (Brassica carinata) is a non-food oilseed crop that can be grown on winter fallow land in the southeastern US and used as a feedstock for SAF, with a high-protein livestock feed co-product. Integrating carinata into existing annual crop rotations produces an additional revenue stream for landowners, with potential co-benefits for soil carbon and other ecosystem services. The Southeast Partnership for Advanced Renewables from Carinata (SPARC) is a USDA-funded research consortium to advance carinata production and associated SAF and bioproduct supply chains in the region.

A SPARC research team used the DayCent ecosystem model to estimate the potential production of carinata across the tri-state region of Alabama, Florida, and Georgia, and assess associated changes in soil carbon storage and emissions of nitrous oxide (N2O), the main biogenic greenhouse gas (GHG) emissions from agriculture. First, we calibrated DayCent to reproduce the phenology, harvest index, productivity response to nitrogen application, root-to-shoot biomass ratio, and tissue nitrogen content data observed for a set of carinata field trials in the region. Next, we simulated the integration of carinata into a typical cotton/peanut rotation across the 2.3 million hectares of annual cropland within the climate suitability range for this crop, grown once every third winters. We show an annual production potential of greater than 1 billion liters of SAF from this feedstock in the region. Our base carinata production case is approximately neutral in biogenic GHG emissions, with modest soil carbon sequestration that offsets the associated small increase in N2O emissions. However, adopting conservation management practices such as no-till establishment or poultry litter soil amendments result in a more substantial net soil carbon sink, reducing the GHG footprint of carinata-derived SAF by up to 20 grams of CO2-equivalent per megajoule of fuel. This work supports SPARC's ongoing efforts to develop improved carinata varieties and management practices that simultaneously improve the economics and ecosystem service value of carinata production.

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