Methodology for USDA Feedstock Carbon Intensity Calculator (FD-CIC) as Used in "Technical Guidelines for the Production of Regenerative Agricultural Biofuel Feedstocks"

Office of the Chief Economist

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1 Introduction

The carbon intensity (CI) of transportation fuels can be reduced through the use of biofuels, which can have lower CI values than traditional fossil fuels. Life cycle analyses indicate that feedstock production—growing the biofuel crop—is the most carbon intensive stage of biofuel production (Xu et al., 2022). Adoption of certain regenerative, or low-carbon, agricultural practices[1] (e.g., cover crops, reduced till, no-till), and nutrient management (e.g., use of nitrification inhibitors, and improved nitrogen use efficiency) can both reduce nitrous oxide (N_2O) emissions and increase soil organic carbon (SOC) compared to feedstocks produced with business-as-usual (BAU) farming practices, resulting in a reduction of biofuel CI.

USDA published "Technical Guidelines *for Climate-Smart Agriculture Crops Used as* Biofuel Feedstocks" on January 17, 2025. The interim rule establishes guidelines for quantifying, reporting, and verifying the CI associated with the production of biofuel feedstock commodity crops grown in the United States. The rule facilitates recognition of the lower feedstock CI scores from adoption of specific low-carbon agriculture practices and nutrient management. In turn, lower CI scores for feedstocks may be recognized in clean transportation fuel programs and create new market opportunities for biofuel feedstock producers. As a companion to this rule, USDA's Office of the Chief Economist (OCE) collaborated with Argonne National Laboratory (ANL) to develop a USDA-specific version of the Feedstock Carbon Intensity Calculator (USDA FD-CIC) that estimates the feedstock crop-specific CI impacts of adoption of selected combinations of low-carbon practices and nutrient management. USDA FD-CIC includes updated modeling used to generate N_2O and SOC impacts, updated low-carbon practices, and regionalized CI estimates in lieu of national averages.

This version of USDA FD-CIC relies on data from ANL's 2025 R&D FD-CIC (Rev1). These data are subject to change in future updates to USDA FD-CIC and any other versions of the tool that are adopted for use under specific policies and programs.

The feedstock crop CI score estimated by USDA FD-CIC considers the net on-farm and upstream impacts from changes in N_2O emissions, SOC, and carbon dioxide (CO_2) emissions associated with nutrient management (including use of nitrification inhibitors), the adoption of selected low-carbon practices (reduced till, no-till, cover crops and grazed cover crops), upstream and on-farm fuel use, urea and lime emissions, and upstream impacts of fertilizer and other chemical use associated with the production of biofuel feedstocks. These impacts are all expressed in as carbon dioxide equivalent (CO_2e). The CI estimate the CO_2e impact per bushel of feedstock produced is based on the following on-farm and upstream sources of emissions[2]:

- SOC emissions and removals from adoption of low-carbon practices;

[1] Low-carbon agriculture practices are agricultural management, practices, systems, and technologies that have been demonstrated to generally reduce greenhouse gas emissions or increase soil carbon sequestration.
[2] Note that methane emissions from enteric fermentation are not considered within the boundaries of this analysis.

- Direct and indirect N_2O emissions from nutrient management—including fertilizer and manure applications as well as use of nitrification inhibitors—and impacts of adoption of low-carbon practices;
- CO_2e emissions from upstream and on-farm fuel use;
- CO_2 emissions from urea and lime application;
- Upstream CO_2e emissions from fertilizer production; and
- CO_2e emissions from manufacture and transportation of other chemicals used in production of the feedstock.

This technical document describes: 1) the modeling performed to generate the N_2O and SOC impacts of low-carbon and nutrient management practices; 2) the methods for developing the region- and crop-specific SOC, N_2O and CO_2 factors used to estimate CI scores; and 3) the methods used to calculate the feedstock CI scores in USDA FD-CIC. USDA developed the USDA FD-CIC methodology in collaboration with the Systems Assessment Center (SAC) at Argonne National Laboratory (ANL), Colorado State University's Natural Resource Ecology Laboratory, and ICF International.

2 Modeling the Changes in Soil Carbon and N_2O Emissions Impacts of Biofuels Feedstock Production

The SOC and N_2O impacts of feedstock production for a BAU baseline and a set of alternative low-carbon production management scenarios were simulated by Colorado State University (CSU) using the DayCent model (see Appendix B for a description of the DayCent modeling framework and its approach to uncertainty). DayCent is a process-based biogeochemical model that simulates carbon, nitrogen, and other nutrient fluxes in agroecosystems over long time scales. Key drivers of N_2O emissions and carbon sequestration estimates include soil moisture, soil texture, management practices (such as tillage, fertilization, and crop rotation sequences), and climate variables (such as temperature, precipitation, and solar radiation).

For each biofuel feedstock considered in this analysis—corn, soybeans, sorghum, and spring canola—CSU estimated N_2O emissions and SOC changes for a BAU baseline scenario developed from the U.S. Environmental Protection Agency (EPA) *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. GHG Inventory),[3] and additional scenarios associated with adoption of low-carbon practices (i.e., reduced till, no-till, cover crops, and grazed cover crops), and nutrient management (i.e., nitrification inhibitors. The analysis includes adoption of single low-carbon practices as well as stacking multiple practices for each feedstock. The DayCent modeling results were used to derive regional and crop-specific annualized changes in SOC accumulation and N_2O emissions for BAU and low-carbon practice adoption scenarios (e.g., tillage and cover crop scenarios) as well as implied emissions factors for direct and indirect N_2O emission from fertilizer and manure applications.

[3] EPA 2024.

2.1 Simulating the Business-as-Usual (BAU) Baseline

The BAU baseline scenario used for the analysis utilizes the model, methods and data inputs applied in the U.S. GHG Inventory. The DayCent model simulated baselines for SOC stock changes and soil N_2O emissions for U.S. agricultural lands under BAU production methods for corn, soybean, sorghum, and spring canola production using the U.S. Department of Agriculture's 2017 National Resources Inventory (NRI) (USDA-NRCS 2020). Baseline DayCent simulations are conducted on the USDA 2017 National Resources Inventory (NRI) points (USDA-NRCS 2020), with site conditions specific to those points and a set of management practices imputed to those points using a wide array of data sources (please see below for details on how management is imputed).

DayCent Initialization and Simulations

DayCent is initialized in three steps. In the first step, the model is run to a steady state condition (i.e., equilibrium) under native vegetation, historical climate data and the soil characteristics for the NRI survey locations. In the second step, the model simulates the expansion of agriculture following European settlement to the beginning of the NRI survey in 1979. This step captures the loss of SOC and N following conversion of native vegetation to cropland and includes varying time periods of land conversion depending on historical settlement patterns starting in the 1700s. In the third step, the model simulates the cropping histories in the NRI survey from 1979 to 2017, which have been extended through 2020 using the USDA National Agriculture Statistics Service (NASS) Crop Data Layer (CDL) (USDA-NASS 2021).

CSU simulated every NRI survey location with at least one of the biofuel crops (corn, soybean, sorghum, and canola) in the most recent five years of available crop history (2016-2020). The baseline projection replicated this five-year rotation over 30 years. CSU excluded NRI survey locations with recent grass-to-cropland conversions in the previous 20 years (2000 or later) because land use change has a much larger effect on trends in SOC stocks and, to a lesser extent, soil N_2O emissions, compared to changes in management practices. By excluding these points, CSU was able to ensure that N_2O and SOC changes were driven by management effects rather than the effects of land use change. In addition, lands enrolled in USDA's Conservation Reserve Program were excluded from the analysis as they are not actively used for crop production.

Imputation of Management Practices

For corn, soybeans, and sorghum rotations the BAU baseline scenarios use the cropland management data from the U.S. GHG Inventory.[4] These management data capture the current management practices on U.S. farmland, which includes a combination of conventional and low-carbon and nutrient management practices (e.g., BAU includes a mixture of intensive, reduced and no-till practices employed across the landscape, in addition to various fertilizer application rates, crop rotations, cover crop adoption, etc.). Management data are drawn from several sources in addition to the NRI data. The USDA Natural Resources Conservation Service (NRCS) Conservation Effects and Assessment Project (CEAP) provided spatial data on mineral fertilization, cover crop usage, as well as planting and harvest dates (USDA-NRCS 2022; USDA-NRCS 2018; USDA-NRCS

[4] Cropland management data from the US GHG Inventory were not used for canola is it is not included in the US GHG Inventory.

2012)[5]. Fertilizer data were also used from Agricultural Resource Management Surveys (ARMS) at the state scale (USDA-ERS 2020). Tillage and cover crop data were also informed by the Operational Tillage Information System (OpTIS) Data Product[6], which is derived from remote sensing imagery (Hagen et al. 2020). Cover crop data are also utilized from the USDA Census of Agriculture at the state scale (USDA-NASS 2012, 2017). See the U.S. GHG Inventory report (U.S. EPA 2024) for more information about the historical management data.

CSU made the following assumptions for the corn, soybeans, and sorghum BAU baselines:

- Cover crops were not planted before or after hay or pasture crops.
- Tillage was classified at the NRI point scale as a management system based on the U.S. GHG Inventory data that is statistically imputed from OpTIS and CEAP survey data using machine learning methods (U.S. EPA 2024). All crops in a rotation received the same tillage practice (i.e., no-till system had no-till in each year). Consequently, there is no intermittent tillage in the baseline. The exception was hay and pasture in rotation with annual crops, in which hay and pasture were not tilled in years following establishment.
- Fertilizer rates were based on CEAP and ARMS data as statistically imputed for 2016-2020 in the U.S. GHG Inventory (U.S. EPA 2024). The CEAP data were collected through surveys conducted on a sub-sample of the NRI point locations and were used to infer rates on individual fields. The ARMS data provided state-level fertilizer rates over two decades that were used to infer trends over time. Fertilizer sales data were used to constrain the total application of mineral fertilizer at the state scale (U.S.-EPA 2024, Brakebill and Gronberg 2017, AAPFCO 2013 – 2022). All fertilizer was assumed to be 80%/20% ammonium/nitrate. There were insufficient data to inform fertilizer application timing when the last U.S. GHG Inventory was compiled (U.S.-EPA 2024). All fertilizer was applied at the time of planting for all crop rotations, with the exception of the corn and hay/pasture (CHP) rotation, in which corn and grass hay received split applications. Corn received 25% at planting and 75% 40 days after planting, while grass hay received 50% at planting and 50% in June.
- The available manure for application to soils was estimated as described in the US EPA National Greenhouse Gas Emissions Report (US-EPA 2024). The proportion of area receiving manure application and rate of manure application were determined from USDA-NRCS CEAP Data (USDA-NRCS 2022) and ARMS (USDA-ERS 2020), using gradient boosted models (GBM). The models estimated manure application specific to state, year and crop in order to assign applications at individual NRI survey locations (USDA-NRCS 2020). Manure estimated from the GBMs were adjusted at the state scale to ensure that the amounts did not exceed the available manure for application to soils, i.e., the rate at each survey location in a state was adjusted slightly to ensure state level totals were the same as the amount available for application to soils according to US-EPA (2024).

Using the U.S. GHG Inventory baseline for the forward projection captures the current mixture of conventional and conservation practices. This approach limits over-estimation of SOC gains in the

[5] CEAP surveys are conducted at a subsample of NRI locations and collect detailed information on farm management practices.
[6] OpTIS data on tillage practices provided by Regrow Agriculture, Inc.

low-carbon practice adoption scenarios, which could occur if we assumed that all lands were under conventional management practices.

Due to differences in data availability, the BAU baseline scenario for spring canola was developed using a different method from that used for corn, soybeans and sorghum. For spring canola, CSU used expert opinion and best available data to develop management practices for the BAU baseline. Fertilizer inputs were determined using a yield-to-fertilizer ratio based on field trial data from Montana that had both yield and fertilizer rates. Spring canola yield data from Washington, Montana, Idaho and North Dakota were then used to develop a linear mixed effect model that predicts yield as a function of mean annual precipitation by state. CSU applied this model to the NRI points to estimate yields and determined the amount of fertilizer applied given the ratio of yield-to-fertilizer rate as discussed above. Tillage and cover crop management for spring canola were based on USDA-NRCS CEAP survey data (USDA-NRCS 2018) with additional data in the Midwest from OpTIS (Hagen et al. 2020; Regrow Agriculture, Inc). These data were used in a statistical imputation analysis using linear modeling methods and gradient boosting to identify management practices for NRI survey locations.

Crop Rotations

To differentiate generalized rotation effects on SOC and N_2O emissions, the four biofuel feedstocks were categorized into eleven rotation types based on the NRI survey (2016-2020) five-year crop rotation sequences (Table 1). The impact of low-carbon practice adoption in each rotation was simulated at the NRI survey points and then aggregated to MLRA. The eleven rotation types include:

1. Continuous corn (CC) with corn in the last five years of the cropping history;
2. Continuous soybeans (SS) with soybeans in the last five years of the cropping history;
3. Corn and soybeans (CS) with any combination of corn and soybeans in the last five years of the cropping history;
4. Corn and hay/pasture (CHP) with at least one year of corn and two years of hay or pasture (grass, alfalfa, etc.) in the last five years of the cropping history;
5. Soybeans and hay/pasture (SHP) with at least one year of soybeans and two years of hay or pasture (grass hay, alfalfa, etc.) in the last five years of the cropping history;
6. Corn, soybeans and hay/pasture (CSHP) with at least one year of soybeans, one year of corn, and two years of hay or pasture (grass hay, alfalfa, etc.) in the last five years of the cropping history;
7. Corn and other crops in rotation (CO) with a year or more of corn in the last five years of the cropping history;
8. Soybeans and other crops in rotation (SO) with a year or more of soybeans in the last five years of the cropping history;
9. Continuous Sorghum (SGSG) with sorghum in the last five years of the cropping history;
10. Sorghum and other crops in rotation (SGO) with sorghum in at least one of the last five years of the cropping history.
11. Spring canola and other crops in rotation (CaO) with canola in at least one of the last five years of the cropping history.

Table 1. Crop rotations in the analysis where crop abbreviations are corn (C), soybeans (S), sorghum (SG), Canola (Ca), hay/pasture (HP), and other crops (O).

Rotation	Abbreviation
Corn-soybeans	CS
Continuous corn	CC
Continuous soybeans	SS
Corn and hay/pasture	CHP
Soybeans and hay/pasture	SHP
Corn-soybeans and hay/pasture	CSHP
Corn and other crops	CO
Soybeans and other crops	SO
Continuous sorghum	SGSG
Sorghum and other crops	SGO
Spring canola and other crops	CaO

Some rotations are non-exclusive, so the same NRI survey point may be evaluated for multiple crop rotation types. For example, points with both soybeans and sorghum in rotation are defined as both Soybeans-Other and Sorghum-Other, and that NRI survey point would be used for assessing scenario effects for both rotation types.[7]

Biophysical Data

Weather data: CSU replicated the most recent eight years of weather data from PRISM (PRISM Climate Group 2022); this accounts for the timing of leap years and provides an offset with the crop rotation length to reduce crop year interactions that could produce artifacts in the projection. PRISM provides daily weather data on a 4km grid with daily minimum and maximum temperatures, in addition to daily precipitation, which are used in the DayCent model simulations. The time span was limited to 8 years to represent recent climatic conditions (IPCC 2023).

Soils data: CSU used the soils data from the US GHG Inventory. Soil profiles and associated edaphic characteristics are from the NRCS gSSURGO database (Soil Survey Staff 2020). These data include bulk density, pH, and soil texture, which are needed as input for the DayCent model simulations.

[7] This application is not double-counting effects, but rather assessing average impacts for individual crops that may be used in biofuel production. Total changes are not assessed in this analysis, such as the total amount of SOC stock change or total N_2O emission reductions, in which double-counting would be problematic.

2.2 Simulation of Low-Carbon and Nutrient Management Practice Scenarios

DayCent was used to simulate scenarios for adoption of single and stacked low-carbon and nutrient management practices. These scenarios were simulated at the NRI point to evaluate the impact of adopting cover crops, no-till, reduced tillage, and nitrification inhibitors. Table 2 lists the low-carbon and nutrient management scenarios that were modeled.

Table 2. Single practice scenarios in the analysis

Practice Type	Count	Scenario	Abbreviation
Cover Crop	1	Winter rye cover crop	ccR
	2	Winter rye cover crop grazed	ccRg
Tillage[8]	3	Reduced tillage	RT
	4	No-tillage with intermittent reduced tillage	NTRT
	5	No-tillage with intermittent intensive tillage	NTIT
Nutrient management	6	Nitrification inhibitors	NI

All scenarios have the same crop sequences, management events and timing, as well as weather and soils data as the BAU baseline, except for specific management interventions detailed below.

Cover Crop Scenarios (CcR and CcRg)

- Cover crops were simulated as winter rye.
- Cover crops were simulated every year except in years that have small winter grains (e.g., winter wheat) or perennial hay or pasture.
- Cover crop termination was simulated as a chemical/herbicide termination without biomass removal and soil disturbance. Tillage termination was evaluated in a previous study and resulted in decreases or no change in SOC stocks (Ogle et al., 2023) and thus was not included in this analysis.
- For grazed cover crops, a single intensive grazing event was simulated one month prior to cover crop termination. Grazing was assumed to remove 90% of cover crop biomass. A fraction of the carbon and nitrogen in the biomass removed is returned to the field as unmanaged manure and urine applications.

[8] Intensive tillage is defined as multiple tillage operations every year, including significant soil inversion (e.g., plowing, deep disking) and low surface residue coverage. No-till is defined as not disturbing the soil except through the use of fertilizer and seed drills and where no-till is applied to all crops in the rotation. The remainder of the cultivated area is classified as reduced tillage, including mulch tillage, strip tillage and ridge tillage (CTIC 2004).

- Planting and termination dates were consistent with the U.S. GHG Inventory in which cover crops were planted within a week after harvesting the previous crops and terminated within a week before the first tillage events or planting of the next crops (U.S. EPA 2024).
- Cover crops did not receive any fertilizer (U.S. EPA 2024).

Tillage Scenarios (RT, NTRT, and NTIT)

CSU simulated scenarios with conversion to continuous reduced tillage (RT), no-till with intermittent reduced tillage (NTRT) and no-till with intermittent intensive tillage[9] (NTIT) as noted below.

- Reduced tillage (RT): All NRI survey points with intensive full tillage (IT) in the baseline were converted to RT.
- No-till (NT): USDA used farmer adoption data to inform patterns of adoption of no-till. Based on a review of ARMS data, USDA decided to model no-till as an intermittent practice, assuming that no-till farmers would have a tillage event once every 5 years (e.g., for weed control or to reduce soil compaction). CSU simulated two different intermittent tillage scenarios, one with an intensive tillage event in the fifth year and one with a reduced tillage event in the fifth year (see below).
  - Intermittent no-till with reduced till (NTRT): All NRI points in the baseline were converted to NT with one year of RT in the fifth year. If the fifth year occurred on a hay/pasture crop, the reduced tillage event was moved to the next non-perennial crop in the rotation.
  - Intermittent no-till with intensive till (NTIT): All NRI points in the baseline were converted to NT with one year of intensive tillage in the fifth year. If the fifth year occurred on a hay/pasture crop, the intensive tillage event was moved to the next non-perennial (i.e., annual) crop in the rotation.
- Given that intensive tillage is common practice in sorghum systems, CSU simulated intermittent tillage for sorghum using the NTIT scenario. For other crops (corn, soybeans, spring canola), CSU simulated no-till using the NTRT scenario.
- DayCent classifies tillage using the soil carbon disturbance index described in USDA's *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* report (USDA Methods report). The soil carbon disturbance index assesses disturbance within the soil column (from 0-30 cm) during discrete tillage windows to determine impacts on decomposition and soil carbon.

[9] Farmers are incorporating occasional tillage in no-till systems to address problems with weed resistance (Lu et al. 2022), and possible other issues such as compaction of the soil. The specific tillage implements can vary so both a less intensive reduced tillage implement and more intensive full tillage implement were simulated to capture the variation.

Nitrification Inhibitors (NI)

CSU simulated application of nitrification inhibitors in conjunction with synthetic fertilizer. Note that there were no changes in nutrient management for NRI points where only manure was applied. For NRI survey locations where both manure and synthetic fertilizer are applied, nitrification inhibitors were only applied with the synthetic fertilizer. No changes to synthetic N application rates were assumed in the NI modeling scenarios.

2.2.1 Stacked Low-Carbon Practice Scenarios

CSU evaluated the full set of stacked low-carbon practices by simulating the adoption of two and three low-carbon and nutrient management practices by combining cover crops, tillage, and nutrient management options. Examples of two stacked practices include the adoption of cover crops (ccR) and no-till with reduced till (NTRT) for the NTRT_ccR scenario, and nitrification inhibitors (NI) and cover crops (ccR) for the NI_ccR scenario. Three stacked practices include scenarios such as combining cover crops, no-till with reduced till, and nitrification inhibitors, as NTRT_NI_ccR. The complete list of stacked practices with two and three combinations are listed below. There are no additional assumptions or modifications from the single practice definitions.

Two Practices

1. NI_ccR
2. RT_ccR
3. NI_ccRg
4. RT_ccRg
5. RT_NI
6. NTRT_ccR
7. NTRT_ccRg
8. NTRT_NI
9. NTIT_ccR
10. NTIT_ccRg
11. NTIT_NI

Three Practices

12. RT_NI_ccR
13. NTRT_NI_ccR
14. NTIT_NI_ccR
15. RT_NI_ccRg
16. NTRT_NI_ccRg
17. NTIT_NI_ccRg

2.3 Model Outputs

For each rotation type and scenario, model outputs and supporting scenario data are aggregated to the MLRA level using NRI survey area weights. The NRI uses a complex weighting system to produce statistically valid estimates of land use and natural resource conditions on U.S. non-federal lands. These weights are crucial for converting data collected at specific sample points into regional or national estimates. NRI-weighted results were then aggregated to the Major Land Resource Area (MLRA) level to maintain regional variability and statistical relevance while also adhering to data disclosure restrictions. Outputs are aggregated by rotation (across all years) for the impact on SOC.

For N_2O, the outputs are aggregated by crop type within each of the rotations (across years with the crop of interest) for each scenario. The reported outputs include:

1) Across all rotations by MLRA:

- Percentage of the area of each crop rotation relative to the total simulated area in each MLRA

2) Within each rotation by MLRA and scenario:

- Average annual area proportion of the crop and any "Other" crop/silage
- Average annual area proportion with a cover crop in any year
- Average annual delta SOC
- Average annual area proportion of full tillage (IT)
- Average annual area proportion of reduced tillage (RT)
- Average annual area proportion of no-tillage (NT)

3) Within each rotation and crop by MLRA and scenario:

- Average annual C in grain (yield) in gC/m^2
- Average annual aboveground biomass in gC/m^2
- Average annual belowground biomass in gC/m^2
- Average annual total biomass in gC/m^2
- The proportion of the total nitrogen available applied as fertilizer
- The proportion of the crop's total biomass to the rotation's total biomass
- Average annual total nitrogen sources in $g\ N/m^2$
- Average annual total N fertilizer in gN/m^2
- Average annual litter N in gN/m^2

3 Developing SOC, N_2O and CO_2 Impact Factors for Use in USDA FD-CIC

USDA developed region- and crop-specific SOC, N_2O and CO_2 impact factors based on the DayCent modeling results (See Section 2). The sections below describe the methods used to estimate the following impact factors which are subsequently used to estimate the feedstock CI in the USDA FD-CIC tool:

1. Soil carbon emissions and removals under low-carbon practice scenarios;
2. Implied emissions factors for direct and indirect N_2O emissions from fertilizer and manure applications;
3. Nitrogen Use Efficiency (NUE) adjustment factor;
4. Impact of nitrification inhibitors on N_2O emissions from synthetic fertilizer;
5. Impacts of low-carbon practice scenarios to direct and indirect N_2O emissions;
6. Impact of low-carbon practices on on-farm fuel use emissions;

The above emissions values and impact factors are used to estimate CI score calculations in USDA FD-CIC. Emissions values and impact factors utilize IPCC 100-year AR5 global warming potential (GWP) values in the current version of the tool. The sections below detail the methods for deriving these values and emissions factors. Please refer to Section 4 of this document for more information on how the emissions values and factors developed in this section are used in the tool to estimate the CI score.

3.1 SOC Impacts of Feedstock Production Under Low-Carbon Practice Scenarios

USDA used the DayCent model outputs to estimate the feedstock and MLRA-specific changes in SOC emissions and removals resulting from adopting one, two or three low-carbon practices compared to the BAU baseline.

DayCent outputs for changes in SOC are estimated as annual SOC changes for an entire crop rotation (see Table 1 in Section 2.1.1 for the complete list crop rotations that were simulated). Given that USDA FD-CIC CI scores are feedstock specific, it was necessary to estimate the portion of SOC that could be attributed to a specific biofuel feedstock. To do this, USDA assumed that SOC contribution is proportional to the crop biomass—meaning feedstock crops with greater above- and below-ground crop residue contribute more to annual SOC changes than those with lower biomass. We chose to estimate change in SOC (dSOC) using the biomass weighting method across the rotation because looking at changes in SOC on an annual basis is problematic given that SOC is not just impacted by what is happening in a given growing season. By using the biomass weighting method we are better able to capture rotational effects on dSOC.

This allocation process produced feedstock-specific dSOC values by crop and MLRA for each modeled low-carbon practice: reduced tillage, no-till, cover crops, nitrification inhibitors, and grazed cover crops. These crop-specific dSOC values were then normalized by yield to calculate annual dSOC per bushel of feedstock for each practice and MLRA combination.

To determine the SOC change from adoption of low-carbon practices, the crop- and practice-specific dSOC were compared to those of the BAU baseline. Specifically, the dSOC values are expressed in grams of CO_2e per bushel (gCO_2e/bu) and were estimated by subtracting the MLRA-crop- and practice-specific dSOC from the corresponding BAU baseline dSOC.

See Appendix C for more details on the methodologies used to convert DayCent SOC results into MLRA-, feedstock- and practice-specific annualized per-bushel impact values.

In addition to the previously described conversions, USDA also conducted outlier analyses on the MLRA and crop-specific dSOC values derived from DayCent. To ensure data quality, USDA removed any instances of outlying data and developed proxies for MLRAs with reported feedstock production where biogeochemical modeling data were not available. For more details on the outlier analysis, please see Appendix F.

3.2 Implied Emissions Factors for Direct and Indirect N_2O Emissions from Fertilizer and Manure Applications and Crop Residues

Total N_2O emissions from fertilizer, manure, and crop residues are calculated as the sum of direct N_2O emissions and indirect N_2O emissions. Direct N_2O emissions are directly released onsite from soils as a result of nitrogen inputs (synthetic fertilizer, manure, crop residues) and management practices. Indirect N_2O emissions result from nitrogen that is lost from the field via volatilization or leaching and subsequently converted to N_2O elsewhere in the environment. Direct and indirect N_2O emissions from synthetic fertilizer and manure application are estimated using MLRA-specific implied emissions factors (IEFs) derived from DayCent simulations. As described in Section 2 above, DayCent simulated BAU and low-carbon practice scenarios for each of the four biofuel feedstock crops. Modeled nitrogen input and N_2O emission values were used to develop IEFs for each BAU baseline scenario for each feedstock. IEFs represent the amount of direct and indirect N_2O emissions per unit of mineral N addition to the soil. The nitrogen inputs in the DayCent model simulations include synthetic N fertilization; mineralization of N from soil organic matter, crop residue and manure application, and asymbiotic N fixation.

The N_2O IEFs were calculated at the MLRA level for each crop using the NRI area-weighted annual average emissions, divided by the NRI area-weighted annual average of mineral nitrogen inputs. This method produced unique direct and indirect N_2O IEFs by crop and MLRA.

While inputs of nitrogen from manure and residues are not fully mineralized in the first year of application, validation runs performed by substituting applied synthetic N with manure N in simulated scenarios found no significant differences in N_2O emissions when estimates of emissions were annualized over the 30-year simulation period. The resulting IEFs were therefore used to represent the rate of N_2O emissions per unit of nitrogen applied to the soil from synthetic fertilizer and manure application.

To ensure that all counties where feedstock crops are grown are able to use the USDA FD-CIC tool, USDA developed proxies for MLRAs with reported feedstock production where biogeochemical modeling data were not available. For more details on how proxies were developed, please see Appendix F.

3.2.1 Aligning the Simulated IEFs with the Estimated National Average N_2O Emissions Factors

The estimated national average CIs for feedstocks are generated using fixed national average emissions factors for direct and indirect N_2O emissions. To ensure consistency between USDA FD-CIC estimates of "average" N_2O emissions for crop production and the estimated national average N_2O emissions, it was necessary to shift the distribution of IEFs generated by DayCent so that regional variation is maintained, but the national acreage-weighted mean IEF for total N_2O emissions (i.e. the sum of the direct IEF and the indirect IEFs) aligns with the total emissions factors used to generate the estimated national average emissions (see Table 4). To align the CSU-generated distributions across regions with the estimated national average emissions factors, an acreage-weighted mean IEF is calculated for each crop using the MLRA-specific IEFs calculated for the BAU baseline scenario and the crop acreage within each MLRA. The distributions of direct and indirect IEFs are then shifted, by crop, using a multiplicative adjustment factor to ensure that the revised acreage-weighted mean for the total IEF (i.e., the sum of the direct IEF and the indirect IEFs) equals the estimated national average emissions factor for total N_2O emissions (.01374). The factors used to adjust the direct and indirect IEFs by crop are shown in Table 5.

Table 4. Estimated National Average N_2O Emission Factors

Estimated national average N_2O emission factors, applied N (g N_2O-N/g N applied)	
Direct	0.01 (1%)
Indirect	0.00374 (.374%)
Total	**0.01374 (1.374 %)**

Table 5. Adjustment Factors for N_2O Emissions by Crop Type

Crop	**Acreage-weighted mean IEF for total N_2O emissions (i.e., sum of the direct IEF and indirect IEF) before adjustment (expressed as %)**	**Adjustment factor applied to DayCent estimates of direct IEF and indirect IEF for each region**
Spring canola	2.0469	0.6713
Corn	2.0542	0.6689
Sorghum	1.9200	0.7156
Soybeans	2.4636	0.5577

Figures 1and 2 below represent the adjusted total IEFs (i.e., the sum of the direct and indirect IEFs) from corn production and soybean production by region, expressed as percent of applied N released as N_2O-N.

Figure 1: Total N_2O emissions factors from corn production. Units are in (g N_2O -N/g N applied) and represent the percent of applied N that is released as N_2O-N.

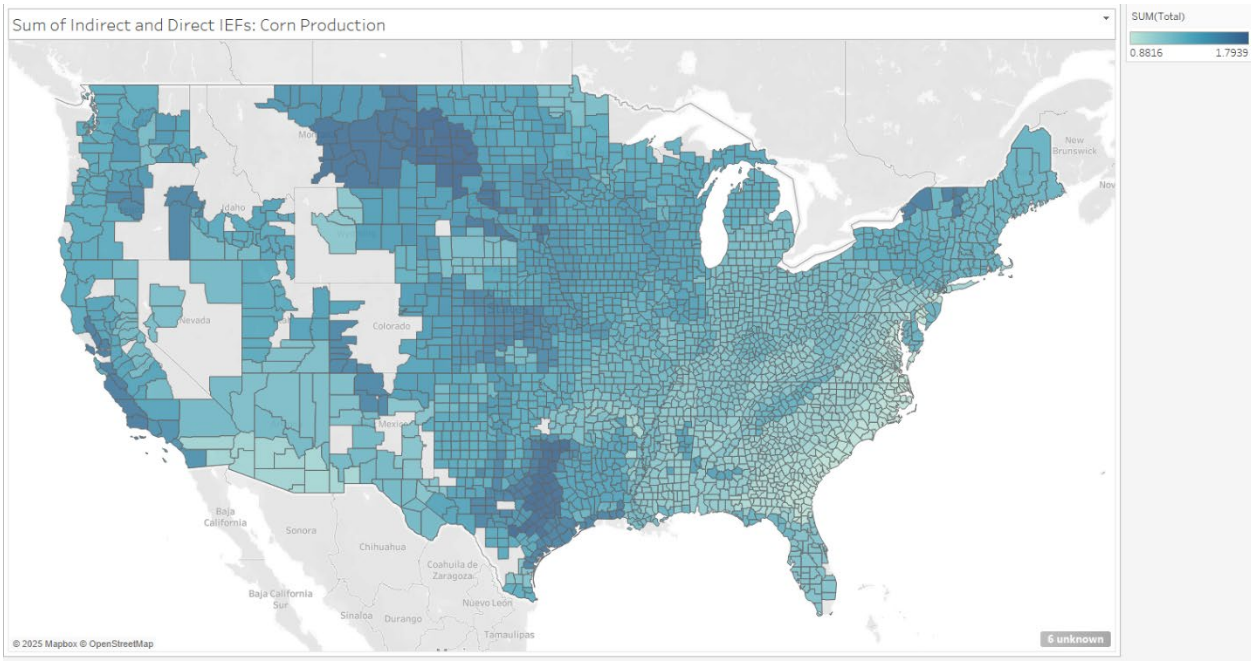
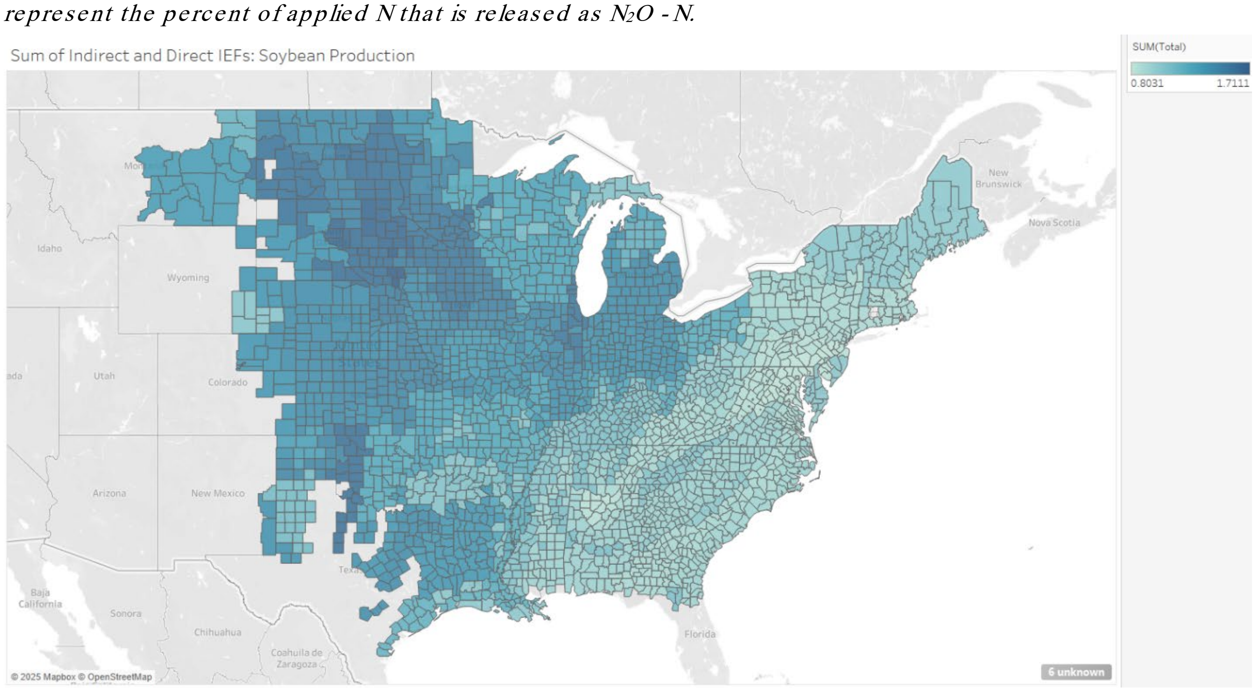


Figure 2: Total N_2O emissions factors from soybean production. Units are in (g N_2O -N/g N applied) and represent the percent of applied N that is released as N_2O -N.



3.3 Nitrogen Use Efficiency (NUE) Adjustment Factor

In addition to the differences between emissions factors used in the estimated national average and those used in USDA FD-CIC, as described above, there are also differences between the assumed average yield and N application estimated by the estimated national average and the simulated average yield and N applications derived from DayCent. Such differences generate a misalignment between the two about what constitutes the "average" applied N/bushel (or NUE) per crop, and about the resulting average N_2O emissions from applied N per bushel. Given the need for alignment with the estimated national average, for each crop USDA developed an NUE Normalization Factor (NNF) to account for differences between the NUE assumptions underlying the estimated national average and the implied NUE values in the DayCent-modeled BAU baseline. For instance, the estimated national average assumes a national average N application on corn of 155.7 lbs N/acre and an assumed average corn yield of 186 bushels/acre. The resulting NUE used to develop the estimated national average feedstock CI value for corn is 0.84 lb N applied/bushel corn.

The default N_2O emissions values associated with the estimated national average NUE for corn are presented in Table 6.

Table 6. Estimated National Average N_2O Emissions Associated with Estimated National Average NUE for Corn

N_2O Source	Default N_2O Emissions (g CO_2e/bu)
Direct N_2O	2171
Indirect N_2O	747

According to the literature and meetings with researchers and stakeholder groups, an NUE of 0.84 lb N applied/bushel corn is likely an underestimate of the true average NUE associated with corn production. An assessment of the DayCent simulation inputs and outputs suggests a national average NUE associated with current yields and management practices of 0.98 lb N applied/bushel corn.

Accordingly, USDA uses an NUE value of 0.98 lb. N applied/bushel of corn to represent the NUE efficiency level for corn that is associated with "average" national BAU emissions for corn. To normalize N_2O emission estimates from fertilizer applications in USDA FD-CIC, USDA developed a NUE Normalization Factor (NNF) that ensures that, when using the estimated national average N_2O emissions factors, USDA FD-CIC users with a user-defined NUE value of 0.98 lb. N applied/bushel of corn receive the default N_2O emissions levels shown above in Table 6. The NNF, is equal to (default NUE/USDA FD-CIC Threshold NUE) = 0.84/0.98= 0.86 and is used at several points in the USDA FD-CIC emissions calculations to align assumptions of "average" or baseline nitrogen management with the estimated national average emissions. Similar adjustments are made for the other crops, using crop-specific BAU NUE values arising from the DayCent simulations (see Table 7).

Table 7. DayCent Simulation BAU NUE Values by Crop Type

Crop	Threshold BAU NUE* (lb N applied/bushel)	National Default NUE (lb N applied/bushel)	NUE Normalization Factor
Corn	0.9774	0.8370	=0.8370/0.9774= 0.8563
Soybean	0.0988	0.1101	=0.1101/0.0988= 1.114
Sorghum	1.1585	.9913	=.9913/1.1585= 0.8557
Spring canola	2.8424	2.5819	=2.5819/2.8424=.9084

*Threshold BAU NUE values are derived using DayCent N inputs and DayCent yields from the BAU scenario.

3.4 Impact of Nitrification Inhibitors on N_2O Emissions from Fertilizer

The emissions reduction factors for Nitrification Inhibitors ($EEFRF_{NI}$) vary by crop, MLRA, and practice. These factors are calculated from the DayCent simulation results for nitrification inhibitor scenarios described in Section 2. The EEFRF factor represents the percent reduction in N_2O emissions when nitrification inhibitors are applied when compared to a comparable scenario that uses no nitrification inhibitors. For example, a nitrification inhibitor reduction value is calculated by comparing the percent N_2O reduction between the ccR_NTRT scenario and the ccR_NTRT_NI scenario. The nitrification inhibitor reduction factors are derived for each combination of low-carbon practice implementation, crop, and MLRA. Because the DayCent simulations assume that nitrification inhibitors were used with 100% of applied synthetic N, the USDA FD-CIC tool scales the EEFRF factor proportionally according to the user-defined percentage of synthetic fertilizer applied with nitrification inhibitors (see Section 4.3.1 for more details).

3.5 Impacts of Low-Carbon Practices on N_2O Emissions

USDA estimated the change in N_2O emissions relative to the BAU baseline from adopting one, two or three low-carbon practices using outputs from the DayCent model for each feedstock and MLRA. DayCent models changes in total system N (including the individual N pools of litter, fertilizer, manure, other N) for each feedstock crop under different crop rotations and low-carbon practices. This change in total system N between the BAU baseline and the low-carbon scenarios was used to estimate a percent change in direct and indirect N_2O emissions attributable to the adoption of low-carbon practices for each MLRA, crop and practice adoption scenario. Within the USDA FD-CIC tool, the percent change in N_2O emissions from adoption of low-carbon practices is applied to the direct and indirect N_2O emissions calculated from N additions, residues, and nitrification inhibitors (please see Section 4.4). See Appendix D for more details on the methodologies used to convert DayCent N_2O results into MLRA-, feedstock- and practice-specific annualized per-bushel impact values.

USDA conducted outlier analyses on the MLRA and crop-specific N_2O values derived from DayCent. To ensure data quality, USDA removed any instances of outlying data and developed proxies for MLRAs with reported feedstock production where biogeochemical modeling data were not available. For more details on the outlier analysis, please see Appendix F.

3.6 Impact of Low-Carbon Practices on On-Farm Fuel Use Emissions

Producing biofuels feedstock crops typically requires multiple field passes using different types of equipment. For example, tillage, planting, fertilization, pesticide application and harvesting require one (or more) field passes using different types of equipment depending on the local conditions and management practices used (e.g., tillage performed using moldboard flowing vs. chisel plowing vs. tandem disking or fertilizer applied using knife vs. spray application). Adoption of conservation practices can impact both the number of field passes and the equipment used, depending on the practice(s) adopted. In this step, USDA estimated the change in fuel use between the BAU baseline and the management practice. The percent change is applied to the default fuel use values in the USDA FD-CIC tool to estimate carbon emissions per bushel.

Fuel use for the following activities was estimated to develop both baseline fuel use impacts and changes in fuel impacts for conservation practice adoption for corn, soy, and sorghum feedstock production:

- Tillage (including conventional, reduced, and no-till)
- Planting
- Fertilizer application
- Pesticide application
- Cover crop planting
- Cover crop termination
- Harvesting

The following values were used to estimate the crop-specific fuel use for baseline and conservation practice adoption scenarios.

Table 3. Fuel use values in gallons of diesel per acre by crop and management practice.

Activity	Corn (gal/acre)	Soybeans(gal/acre)	Sorghum (gal/acre)	Canola (gal/acre)	Reference
Tillage and Planting: conventional till	5.4	5.4	5.4	5.4	CEAP
Tillage and Planting: reduced till	3.1	3.1	3.1	3.1	CEAP
Tillage and Planting: no-till	1.8	1.8	1.8	1.8	CEAP
Fertilizer application [10]	0.47	0.44	0.44	0.44	Average fuel use based on multiple sources

[10] Fuel use for fertilizer application assumes a single field pass for soybeans, sorghum and canola. Corn is assumed to have some split application in the baseline and is thus assigned an average of 1.068 field passes.

Activity	Corn (gal/acre)	Soybeans(gal/acre)	Sorghum (gal/acre)	Canola (gal/acre)	Reference
Pesticide fuel use	0.3	0.3	0.3	0.3	Average fuel use based on multiple sources—Jones, J., and J.K. O'Hara (Eds), (2023)
Harvesting (combine)	1.45	1	1.23 [11]	1.24	Corn, Soybeans, and Sorghum- Hanna (2005) Spring canola – Beattie (2020)
Cover crop planting	0.62	0.62	0.62	0.62	Average fuel use based on multiple sources—Jones, J., and J.K. O'Hara (Eds), (2023)
Cover crop termination (chemical)	0.3	0.3	0.3	0.3	Average fuel use based on multiple sources—Jones, J., and J.K. O'Hara (Eds), (2023)

The total fuel use (gal/acre) was calculated for each practice using the fuel use estimates in Table 8 as well as DayCent modeling outputs for adoption rates of practices. The change in fuel use from practice adoption was estimated by calculating a percent change from the BAU baseline. Additional details about the calculation steps used to generate the estimates for change in fuel use are in Appendix E: Methods for Estimating Change in Fuel Use.

[11] As no specific values were found for the fuel-use requirements for sorghum combine harvesting, the average of corn and soy combine harvesting was used.

4 Methods for Calculating the Feedstock CI in USDA FD-CIC

The CI score calculated in the USDA FD-CIC tool varies based on user location (state and county), crop (corn, soybeans, sorghum or spring canola), yield, nutrient management on the field (e.g., inputs of synthetic nitrogen and manure application, use of nitrification inhibitors), and adoption of low-carbon practices (reduced till, no-till, cover crops, grazed cover crops). This section describes how the values and emissions factors described in Section 3 are used in FD-CIC to estimate a field-specific CI based on user inputs. Table 9 describes the elements included in the CI score. The final CI score is the sum of the estimated CO_2e impact of each of these elements.

In order to provide results at a county scale, the CI impact factors which were calculated by MLRA in Section 3 were mapped to each county in the United States using a crosswalk provided by CSU. A representative MLRA was assigned to each county based on the MLRA that covers the largest share of the county's area. This mapping enables the USDA FD-CIC tool to utilize state and county drop-down menus for users.

Table 4. Elements of Carbon Intensity

CI Element	Components of CI Element	Description of Related Impact Factor	Application in USDA FD-CIC
Soil Organic Carbon Change	Soil carbon changes (dSOC/bu) resulting from adoption of low-carbon practices (Section 4.1)	DayCent model runs used to derive dSOC/bu relative to BAU.	SOC value assigned based on user selection of crop, location and low-carbon practices (cover crops & tillage).
Total N_2O emissions	Sum of direct and indirect N_2O emissions from fertilizer, biomass residue, and manure applications (section 4.3)	Direct and Indirect implied emissions factors (IEFs) are derived from DayCent model runs and used to calculate N_2O emissions per lb N applied. Nitrification emissions reduction factors (EEFRF) are also derived from DayCent model runs.	Direct and indirect IEFs are selected based on crop and location and applied to total N from synthetic N, residue N, and manure N. If user indicates use of a nitrification inhibitor, the direct and indirect emissions from synthetic fertilizer are reduced based on user-defined percent applied.

CI Element	Components of CI Element	Description of Related Impact Factor	Application in USDA FD-CIC
	Change in direct and indirect N_2O emissions from soils resulting from adoption of low-carbon practices (Section 4.4)	DayCent model runs used to derive the percent change in N_2O relative to BAU for low-carbon low-carbon practices.	N_2O percent change value selected based on user-specified crop, location, and low-carbon practices. Percent change is applied to emissions estimates generated using IEFs (see above).
On-Farm energy consumption	On-Farm energy consumption (Section 4.5)	Calculated % reduced fuel use informed by low-carbon practice scenario assumptions and applied to estimated national average.	Fuel use factor (%) selected based on user-specified crop, location, and low-carbon practices. Factor is applied to the estimated national average fuel use to adjust for fuel use changes from low-carbon practices.
Upstream nitrogen fertilizer emissions	Upstream fertilizer emissions (Section 4.6)	Estimated national average values for upstream fertilizer emissions are used.	Estimated national average value is adjusted based on distance of user-defined synthetic fertilizer additions and yield (NUE) from threshold average NUE value.
Upstream emissions from other on-farm chemical use	Upstream emissions from other on-farm chemical use (Section 4.7)	The estimated national average value for upstream emissions from other chemicals is used.	The estimated national average value for upstream emissions from other chemicals does not vary based on user selections.
CO_2 emissions from urea and lime	CO_2 emissions from urea (Section 4.8)	Estimated national average value for CO_2 emissions from urea is used.	Estimated national average values for CO_2 emissions from urea are adjusted based on distance of user-defined synthetic fertilizer additions and yield

CI Element	Components of CI Element	Description of Related Impact Factor	Application in USDA FD-CIC
			(NUE) from threshold average NUE value.
	CO_2 emissions from Lime (Section 4.9)	Estimated national average value for CO_2 emissions from Lime is used.	Estimated national average CO_2 emissions from lime are used and do not vary based on user selections.

Table 10. Estimated national average emissions estimates by CI element

Carbon Intensity Element	Corn	Soybeans	Sorghum	Canola
Emissions from manufacture and transportation of N fertilizer	**1280**	**168**	**1516**	**3103**
Soil carbon emissions/removals	**0**	**0**	**0**	**0**
Total N_2O emissions	**2918**	**5152**	**3357**	**9353**
Direct N2O emissions	2171	4462	2493	6975
Indirect N2O emissions	747	690	864	2378
Emissions from on-farm energy consumption	**818**	**1269**	**690**	**940**
diesel and gasoline	544	1031	685	900
other energy	274	238	5	41
Emissions from manufacture and transportation of other chemicals	**476**	**1068**	**597**	**1040**
CO_2 emissions from urea/lime	**537**	**31**	**278**	**1114**
CO2 emissions from urea	234	31	278	1114
CO2 emissions from lime	303	0	0	0
Estimated National Average Total Emissions/bushel	**6028**	**7688**	**6438**	**15551**

The inputs used in the generation of the estimated national average emissions can be found in table 11 (below).

Table 11. Input values used in generation of the estimated national average emissions.

Input Parameter	Units	Corn	Soybean	Sorghum	Spring Canola
Yield	Bushels/acre	186	53	72.6	2033.9 lbs /acre
Energy Use					
Diesel	Gallons/acre	7.2	3.7	3.8	3.0

Gasoline	Gallons/acre	1.3	0.9	0.3	0.0
Natural Gas	ft3/acre	90.7	9.5	0.6	4.5
Liquefied Petroleum	Gallons/acre	2.2	0.4	0.0	0.0
Electricity	kWh/acre	72.3	22.8	0.8	3.3
Nitrogen Fertilizer	lbs N/acre	155.7	5.8	72.0	105.0
Phosphorus Fertilizer	lbs P2O5/acre	55.4	24.0	15.3	32.5
Potash Fertilizer	lbs K2O/acre	56.5	39.4	2.7	11.7
Lime	lbs CaCO3/acre	573.0	0.0	0.0	0.0
Herbicide	g/acre	1314.7	1057.9	1340.0	508.8
Insecticide	g/acre	9.9	14.2	47.7	11.8
Sulfur	lbs/acre	2.9	1.9	.34	0.0
Fungicide	g/acre	23.9	21.9	0.0	35.9

A description of each of the methods used to calculate each of the CI elements based on user inputs is described below.

4.1 Soil Organic Carbon Changes from Adoption of Low-Carbon Practices

Change in SOC from adoption of low-carbon practices is a value derived from the DayCent model for each MLRA, crop, and low-carbon practice scenario. The previous sections (see sections 2.1 and 2.1.1) describe the methods for modeling SOC and allocating SOC changes to the feedstock. In USDA FD-CIC, the SOC value is selected based on user location (state/county), crop and low-carbon practice selections.

4.2 N_2O Emissions from Fertilizer and Manure

Direct and indirect N_2O emissions for crop production are calculated based on synthetic N application, N content of biomass residue, and N content of manure, together with the estimated IEFs described in section 3.3, which represent the percent of applied N that is emitted as N_2O-N. Total N_2O emissions reported in the CI score results are the sum of direct N_2O emissions and indirect N_2O emissions.

N contributions from fertilizer and manure are calculated based on the user-defined nitrogen inputs to USDA FD-CIC. N contributions from residue are derived from the estimated national average assumptions about N content of crop residue (Table 14).

Table 14. Estimated National Average Crop Residue and Biomass Residue by Crop Type

Crop	N in Crop Residue
Soybeans	557 g residue N/bushel
Corn	141.6 g residue N/bushel
Sorghum	149 g residue N/bushel
Canola	503.9 g residue N/bushel

The N_2O emissions from nitrogen additions are estimated using direct and indirect implied emissions factors (IEF) for N_2O, and are further adjusted by the NUE Normalization Factor (NNF) (see Section 3.2 and 3.3 for descriptions on how these factors were derived). The IEFs vary by crop and location. Direct and indirect IEFs do not vary by source of N (e.g., biomass residue and manure use the same region and crop-specific IEFs as applied synthetic N).

4.2.1 Impacts of Nitrification Inhibitors

N_2O emissions are also impacted by use of nitrification inhibitors. USDA FD-CIC allows users to enter the fraction of synthetic fertilizer that was applied with nitrification inhibitors. USDA-FD-CIC calculates the reduction in direct and indirect N_2O emissions from NI use by multiplying the user-specified fraction of synthetic fertilizer applied with a nitrification inhibitor to the enhanced efficiency reduction factor ($EEFRF_{NI}$). The $EEFRF_{NI}$ represents the percent reduction in emissions from use of nitrification inhibitors with 100% of applied synthetic N; the USDA FD-CIC tool uses the EEFRF factors and scales them back proportionally according to the user-defined fraction of synthetic fertilizer applied with an NI. While the DayCent simulations did not assume a lower rate of fertilizer application with the use of NIs, this practice is accommodated for in USDA FD-CIC by allowing users to enter the total pounds of synthetic N applied per acre, thus capturing any reduction in fertilizer rate.

The method used to derive the $EEFRF_{NI}$ factor is described in Section 3.4. The $EEFRF_{NI}$ factor varies by crop, MLRA, and practice. The reduction factors due to use of NIs are applied to synthetic N additions only, and not to N contributed through residue or N applied from manure application.

4.3 Change in Direct and Indirect N_2O Emissions from Soils Resulting from Adoption of Low-Carbon Practices

Adoption of low-carbon practices—reduced/no-till and cover crops—also results in impacts on direct and indirect N_2O emissions (See Section 3.1 for how the percent N_2O reduction factor was calculated from the DayCent modeling scenarios). Those N_2O impact factors vary by crop, region, and low-carbon practice combination. These impact factors are assumed to affect all sources of N_2O emissions, including synthetic fertilizer application, manure application, and biomass residue.

To estimate net N_2O emissions, including impacts resulting from adoption of low-carbon practices, the values calculated in Section 4.3 for direct and indirect N_2O emissions per bushel (based on N application and the direct and indirect IEFs) are multiplied by the percent N_2O reduction associated with the county, crop and practice combination entered by the user. Percent N_2O reductions are calculated separately for direct and indirect emissions.

Equation 1. Comprehensive calculation of direct and indirect N_2O emissions including fertilizer, residue and manure inputs; EEF impacts; and impacts of low-carbon practices

$$N_2O\ emissions_{direct}(g\ N_2O-N/bushel) = \left[NNF \times \left(Direct\ N_2O\ IEF\ (g\ N_2O-N/g\ N\ applied\ )\right) \times \left(\left(\frac{Synthetic\ N\ applied\ (g\ N\ applied/acre)}{yield\ (bushels/acre)}\right) \times \left(1 + NI_{frac} * EEFRF_{NI,direct}\right) + (Default\ N\ in\ crop\ residue\ (g\ N/bushel)) + \left(\frac{Manure/Amendment\ N\ applied\ (g\ N\ applied/acre)}{yield\ (bushels/acre)}\right)\right)\right] \times (1 + \%\ change\ Direct\ N_2O)$$

$$N_2O\ emissions_{indirect}(g\ N_2O-N/bushel) = \left[NNF \times \left(Indirect\ N_2O\ IEF\ (g\ N_2O-N/g\ N\ applied\ )\right) \times \left(\left(\frac{Synthetic\ N\ applied\ (g\ N\ applied/acre)}{yield\ (bushels/acre)}\right) \times \left(1 + NI_{frac} * EEFRF_{NI,indirect}\right) + (Default\ N\ in\ crop\ residue\ (g\ N/bushel)) + \left(\frac{Manure/Amendment\ N\ applied\ (g\ N\ applied/acre)}{yield\ (bushels/acre)}\right)\right)\right] \times (1 + \%\ change\ Indirect\ N_2O)$$

Where:

$N_2O\ emissions_{direct}$	*Direct N_2O emissions (g N_2O-N/bushel).*
$N_2O\ emissions_{indirect}$	*Indirect N_2O emissions (g N_2O-N/bushel).*
$Direct\ N_2O\ IEF$	*Amount of direct N_2O emitted per unit of N applied (g N_2O-N/g N applied).*
$Indirect\ N_2O\ IEF$	*Amount of indirect N_2O emitted per unit of N applied (g N_2O-N/g N applied).*
NI_{frac}	*Fraction of nitrogen applied with Nitrification Inhibitors (NI).*
$EEFRF_{NI,direct}$	*EEF reduction factor for direct N_2O emissions from 100% NI use.*
$EEFRF_{NI,indirect}$	*Emission reduction factor for indirect N_2O emissions from 100% NI use.*
Synthetic N applied	*Total amount of synthetic N fertilizer applied (g/acre).*
$Default\ N\ in\ crop\ residue$	*Default assumptions for amount of N retained in crop biomass residue after harvest (g N/bushel) (see table 14).*
NNF	*NUE Normalization Factor – scaling factor to align USDA FD-CIC average NUE assumptions with default NUE assumptions.*

Units are then converted into g CO_2e/bushel by multiplying by 1) a factor converting N_2O -N into N_2O and 2) N_2O global warming potential.

The total N_2O emissions estimate reported out in the results section of the tool represents the sum of the direct and indirect emissions calculated above.

4.4 Emissions from On-Farm Energy Consumption

As described in Section 3.7 and Appendix E, the DayCent simulations were used to calculate percent reductions in fuel use associated with the low-carbon soil management practices. Estimated national average on-farm energy emissions for diesel and gasoline use per bushel were multiplied by the percent change in fuel use associated with the user-defined crop and practice to determine the impacts of those practices on on-farm fuel use. The estimated national average emissions for diesel and gasoline on-farm energy consumption includes upstream and consumption emissions from fuel use. Emissions due to other on-farm energy (i.e., electricity) consumption for feedstock production are assumed to be held constant with the estimated national average in Table 10. Thus, the total estimated emissions from on-farm energy consumption is the sum of the adjusted emissions from gasoline and fuel use and the estimated national average emissions for other on-farm energy.

4.5 Upstream Emissions from Fertilizer

Upstream emissions associated with synthetic fertilizers are calculated by shifting the estimated national average upstream emissions based on the difference between the user-defined NUE and USDA's threshold "average" NUE, which varies by crop. Table 10 shows the estimated national average values that are also used in the USDA FD-CIC tool for purposes of calculating the CI

For corn, for instance, users with a user-defined NUE of .97 are assigned the estimated national average emissions for upstream emissions shown above (1350 g CO_2e/bushel). All other users receive an emissions estimate that is shifted to account for the distance of their NUE from the threshold of .97:

*Upstream N Emissions = Estimated National Average Upstream Emissions * (User-defined NUE/ Threshold NUE)*

4.6 Upstream Emissions from Manufacture and Transportation of Other Farming Chemicals

USDA FD-CIC uses the estimated national average estimate of per bushel emissions from manufacture and transportation of other farming chemicals and keeps it constant across practice scenarios. Table 10 shows the estimated national average values that are also used in the USDA FD-CIC tool for purposes of calculating the CI.

4.7 CO_2 Emissions from Urea

CO_2 emissions from urea are calculated by shifting the estimated national average urea emissions based on the difference between the user-defined NUE and USDA's threshold "average" NUE, which varies by crop. Table 10 shows the estimated national average emissions values from urea that are also used in the USDA FD-CIC tool for purposes of calculating the CI.

For corn, for instance, users with a user-defined NUE of .97 are assigned the estimated national average for CO_2 emissions from urea shown in Table 10 (245 g CO_2e/bushel). All other users receive an estimate of CO_2 emissions from urea that is shifted to account for the distance of their NUE from the threshold NUE:

*CO_2 emissions from urea = Estimated National Average CO_2 emissions from urea * (User-defined NUE/ Threshold NUE)*

4.8 CO_2 Emissions from Lime

USDA FD-CIC uses the estimated national average of per bushel emissions from lime application and keeps it constant across practice scenarios. This value represents an estimate of average lime application rates and frequencies over time. Table 10 shows the estimated national average values for lime emissions that are also used in the USDA FD-CIC tool for purposes of calculating the CI.

5 References

AAPFCO (2008-2022) Commercial Fertilizers: 2008-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

Allmaras, R.R., D.R. Linden, and C.E. Clapp. (2004) Corn-residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. Soil Science Society of America Journal, 68(4), 1366-1375. https://doi.org/10.2136/sssaj2004.1366

ANL (2023). R&D GREET 2023, Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. https://greet.anl.gov/

Beattie, A. (2020). The Farm Management Handbook 2020/21. Retrieved from Scottish Rural Development Programme Farm Advisory Service: https://www.fas.scot/downloads/farm-management-handbook-2020-21/

Brakebill, J.W. and Gronberg, J.M. (2017) County-Level Estimates of Nitrogen and Phosphorus from Commercial Fertilizer for the Conterminous United States, 1987-2012: U.S. Geological Survey data release, https://doi.org/10.5066/F7H41PKX.

CTIC. 2004. 2004 Crop Residue Management Survey. Conservation Technology Information Center. Available online at http://www.ctic.purdue.edu/CRM/.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel. 2001. "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.); Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press. Boca Raton, Florida. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." Global Biogeochemical Cycles, 24, GB1009, doi:10.1029/2009GB003544.

Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DayCent modeling package and additional procedures for parameterization, calibration, validation, and applications, in Methods of Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA.

Del Grosso, S. J., S. M. Ogle, C. Nevison, R. Gurung, W. J. Parton, C. Wagner-Riddle, W. Smith, W. Winiwarter, B. Grant, M. Tenuta, E. Marx, S. Spencer, and S. Williams. 2022. A gap in nitrous oxide emission reporting complicates long-term climate mitigation. Proceedings of the National Academy of Sciences 119:e2200354119.

EPA (2024). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 U.S. Environmental Protection Agency, EPA 430R-24004. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

Gurung, R. B., Ogle, S.M., Breidt, F.J., Williams, S.A., Parton, W.J. (2020) Bayesian calibration of the DayCent ecosystem model to simulate soil organic carbon dynamics and reduce model uncertainty. Geoderma 376: 114529.

Gurung RB, Ogle SM, Breidt FJ, et al. (2021) Modeling nitrous oxide mitigation potential of enhanced efficiency nitrogen fertilizers from agricultural systems. Science of The Total Environment. 2021/12/20/;801:149342.

Hagen, S. C., G. Delgado, P. Ingraham, I. Cooke, R. Emery, J. P. Fisk, L. Melendy, T. Olson, S. Patti, N. Rubin, B. Ziniti, H. Chen, W. Salas, P. Elias, and D. Gustafson. 2020. Mapping Conservation Management Practices and Outcomes in the Corn Belt Using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. Land **9**:408.

Hanna, M. (2005). Fuel Required for Field Operations. Iowa State University Extension. https://www.extension.iastate.edu/agdm/crops/pdf/a3-27.pdf

Iowa State University Extension and Outreach. (2001). Fuel required for field operations—Machinery management. https://store.extension.iastate.edu/product/Fuel-Required-for-Field-Operations-Machinery-Management

IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

Jones, J., and J.K. O'Hara (Eds), (2023). Marginal Abatement Cost Curves for Greenhouse Gas Mitigation on U.S. Farms and Ranches. Office of the Chief Economist, U.S. Department of Agriculture, Washington, DC.

Lu, C., Z. Yu, D. A. Hennessy, H. Feng, H. Tian and D. Hui. 2022. "Emerging weed resistance increases tillage intensity and greenhouse gas emissions in the US corn–soybean cropping system." Nature Food **3**(4): 266-274.

NASS (2024). NASS Quick Stats. National Agricultural Statistics Service, U.S. Department of Agriculture. https://quickstats.nass.usda.gov/.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." Ecological Modeling 205:453-463.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., Breidt, F.J., Del Grosso, S., Gurung, R., Marx, E., Spencer, S., Williams, S., Manning, D. (2023) "Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States." Scientific Reports 13(1):14564.

Parsons, S. (n.d.). AE-110. Estimating Fuel Requirements for Field Operations. Purdue University Cooperative Extension Service.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". Glob. Planet. Chang. 19:35-48.

Parton, W.J., E.A. Holland, S.J. Del Grosso, M.D. Hartman, R.E. Martin, A.R. Mosier, D.S. Ojima, and D.S. Schimel (2001) Generalized model for NO_x and N_2O emissions from soils. Journal of Geophysical Research. 106 (D15):17403-17420.

Prairie, A.M., A.E. King, and M.F. Cotrufo (2023). Restoring particulate and mineral-associated organic carbon through regenerative agriculture. Proceedings of the National Academy of Sciences, 120 (21). https://doi.org/10.1073/pnas.2217481120.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

Sumner, P. (2024). Grain sorghum: Harvesting, drying and storing. University of Georgia Extension. https://extension.uga.edu/publications/detail.html?number=C1017&title=grain-sorghum-harvesting-drying-and-storing

University of Nebraska-Lincoln. (n.d.) CropWatch. https://cropwatch.unl.edu/

USDA-ERS (2020) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-NASS (2012) 2012 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2017) 2017 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. US Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

USDA-NRCS (2018) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163.

USDA-NRCS (2020) Summary Report: 2017 National Resources *Inventory*. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2022) Conversation practice on cultivated croplands: A comparison of CEAP I and CEAP II survey data and modeling. United States Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/sites/default/files/2022-09/CEAP-Croplands-ConservationPracticesonCultivatedCroplands-Report-March2022.pdf.

U.S. Department of Agriculture, Natural Resources Conservation Service. (2022a). Reduction in Annual Fuel Use from Conservation Tillage. Conservation Effects Assessment Project (CEAP) Conservation Insight. https://www.nrcs.usda.gov/sites/default/files/2022-11/CEAP Croplands-2022-ConservationInsight-FuelSavingswithConservationTillage.pdf

U.S. Department of Agriculture, Natural Resources Conservation Service. (2022b). Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. U.S. Department of Agriculture, Agriculture Handbook 296. https://www.nrcs.usda.gov/resources/data-and-reports/major-land-resource-area-mlra

U.S. Department of Agriculture, National Agricultural Statistics Service. (2024). 2022 Census of Agriculture. https://www.nass.usda.gov/Publications/AgCensus/2022/index.php

U.S. Department of Agriculture, Natural Resources Conservation Service. (n.d.). Conservation Effects

Assessment Project (CEAP) Assessment. https://www.nrcs.usda.gov/ceap

U.S. Environmental Protection Agency (EPA) (2024) Inventory of U.S. Greenhouse Gas Emission and Sinks: 1990-2022. United States Environmental Protection Agency, EPA 430-R-24-004.

Xu, H., Ou, L., Li, Y., Hawkins, T. R., & Wang, M. (2022). Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States. *Environmental Science & Technology*, *56*(12), 7512–7521. https://doi.org/10.1021/acs.est.2c00289

Appendix A: Acronyms and Variable Definitions

General Acronyms:

Acronym	Definitions
BAU	Business-as-usual/Baseline
CI	Carbon intensity
CO_2	Carbon dioxide
GHG	Greenhouse gas
LRR	Land Resource Region
MLRA	USDA Major Land Resource Area
N_2O	Nitrous oxide
SOC	Soil organic carbon

Model/Tool/Source Acronyms:

Acronym	Definitions
ANL	Argonne National Laboratory
CSU	Colorado State University
DayCent	Daily Century model
FD-CIC	Feedstock Carbon Intensity Calculator
NRI	National Resources Inventory

Rotation Acronyms:

Acronym	Definitions
CC	Continuous corn
CHP	Corn-hay-pasture
CO	Corn-other
CS	Corn-soy
CSHP	Corn-soy-hay-pasture
SGSG	Continuous sorghum
SGO	Sorghum-other
SHP	Soy-hay-pasture
SO	Soy-other
SS	Continuous soy
CaO	Canola other

Scenario Acronyms:

Category	Acronym	Scenario
Cover Crop	ccR	Cover crop, Rye
Cover Crop	no ccR	BAU cover crop adoption
Tillage	RT	Reduced tillage
Tillage	NT	No-tillage
Tillage	NTRT	Intermittent NT with RT
Tillage	NTIT	Intermittent NT with intensive tillage
Tillage	AvgT	Current tillage mix
Fertilizer	stnd	Standard N application type
Fertilizer	BAU_FSN	Standard N application (mix of FN, FN/SN and SN) for corn
Fertilizer	NI	Nitrification inhibitor

SOC Allocation Variable Acronyms:

Acronym	Definitions
base	Baseline
$dSOC_{(rotation,MLRA)}$	Annualized change in SOC [Mg C/ha] by rotation and MLRA.
$M_{(crop,rotation,MLRA)}$	Proportion of the crop's root and residue biomass relative to the rotation's total root and residue biomass.
$CP_{(crop,rotation,MLRA)}$	Average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation.
$RP_{(rotation,MLRA)}$	Proportion of the area each crop rotation relative to the total simulated area in each MLRA.
$CY_{(crop,rotation,MLRA,practice)}$	Crop grain yield [g C/m^2] for the practice scenario.
$CY_{(crop,rotation,MLRA,base)}$	Baseline crop grain yield [g C/m^2].
$dSOC_{(rotation,MLRA,avgCC)}$	Annualized change in SOC [Mg C/ha] for BAU cover crop scenarios by rotation and MLRA.
$dSOC_{(crop,rotation,MLRA,avgCC)}$	Annualized change in SOC [Mg C/ha] for non-cover crop scenarios allocated by crop for each rotation and MLRA.
$dSOC_{(crop,rotation,MLRA,ccR)}$	Annualized change in SOC [Mg C/ha] for cover crop scenarios allocated by crop for each rotation and MLRA.
$RCY_{(crop,rotation,MLRA, practice)}$	Ratio of crop grain yields between practice and baseline scenarios.
$CRP_{(crop,rotation,MLRA)}$	Proportion of an MLRA's crop production that is attributable to a specific rotation.
$dSOC_{(crop,MLRA, practice)}$	Annualized change in SOC per ha for the practice scenario allocated by crop for each MLRA.
$Yield_{(crop,MLRA,base)}$	Average crop yield [bu/ha] for the MLRA.
$\Delta dSOC/bu_{(crop,MLRA, practice)}$	Final change in SOC [Mg C/bu] from practice adoption for the crop and MLRA.

Acronym	Definitions
$dSOC_{(crop,MLRA,base)}$	Annualized change in SOC [Mg C/ha] for the baseline scenario allocated by crop for each MLRA.
$bu_{(crop,MLRA)}$	Average crop-specific production data for the MLRA.
$dSOC_{(rotation,MLRA,avgccR)}$	Annualized change in SOC [Mg C/ha] for non-cover crop scenarios by rotation and MLRA.
$dSOC_{(rotation,MLRA,ccR)}$	Annualized change in SOC [Mg C/ha] for cover crop scenarios by rotation and MLRA.
$dSOC_{(crop,rotation,MLRA,\ practice)}$	Annualized change in SOC [Mg C/ha] allocated by crop for each rotation and MLRA.
$RCY_{(crop,MLRA,\ practice)}$	Ratio of crop grain yields between practice and baseline scenarios for the MLRA.
$dSOC/bu_{(crop,MLRA,\ practice)\ [CO2e/bu]}$	Final change in SOC [Mg C/bu] from practice adoption for the crop and MLRA converted to potential grams of CO_2 per bu.
$dSOC/bu_{(crop,\ practice)\ [CO2e/bu]}$ BC $Moisture_{crop\ grain}$	Final national weighted average change in SOC [Mg C/bu] from practice adoption for the crop converted to potential grams of CO_2e per bu. The assumed biomass carbon percentage (45%) of dry matter (Kwon 5/29/2025). The assumed moisture content for each modeled feedstock crop grain, provided by ANL (Kwon 5/29/2025). The moisture content assumptions are as follows: canola (8.5%), corn (15.5%), sorghum (14%), soy (13%).
g_to_lb	Conversion factor from grams to pounds. 1 lb = 453.59 g.
M^2_to_ha	Conversion factor from m^2 to hectare. 1 hextar = 10,000 m^2.
$Lb\_to\_Bu_{crop}$	Crop-specific factor from pounds to bushel. 1 bushel of corn or sorghum = 56 lbs; 1 bushel of soybeans = 60 lbs; 1 bushel of canola = 50 lbs.

N_2O Allocation Variable Acronyms:

Acronym	Definitions
base	Baseline
j	Number of crops in the rotation.
$N_{(crop,MLRA,\ practice)}$	Total Nitrogen (N) input values in grams N per meter^2 for the rotation.
$N_{(MLRA,rotation,crop,\ practice)}$	Total system nitrogen (N) values in grams N per m^2 from all N sources for the feedstock crop.
$CP_{(MLRA,rotation,crop)}$	Average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation.
Direct $N_2O_{(MLRA,rotation,\ practice)}$	Total direct N_2O emissions for the rotation [kg N_2O-N/ha].
Direct $N_2O_{(MLRA,rotation,crop,\ practice)}$	Direct N_2O emissions for the crop [kg N_2O-N/ha].
Indirect $N_2O_{(MLRA,rotation,\ practice)}$	Total indirect N_2O [kg N_2O-N/ha] emissions for the rotation.

Acronym	Definitions
Indirect $N_2O_{(MLRA,rotation,crop,practice)}$	Indirect N_2O [kg N_2O-N/ha] emissions for the crop for every rotation.
$fracN_{(fert,MLRA,rotation,crop,practice)}$	Nitrogen (N) input from crop synthetic fertilizer as a fraction of the total rotation N.
$N_{(fert,MLRA,rotation,crop,practice)}$	Nitrogen (N) input [g N/m^2] from synthetic fertilizer application for the feedstock crop.
$N_{(MLRA,rotation,practice)}$	Total Nitrogen (N) input values [g N/m^2] for the rotation.
$fracN_{(CR,MLRA,rotation,crop,practice)}$	Nitrogen (N) input from crop residue as a fraction of the total rotation N.
$N_{(CR,MLRA,rotation,crop,practice)}$	Nitrogen (N) values [g N/m^2] for the feedstock crop.
$fracN_{(MLRA,rotation,crop,practice)}$	Nitrogen (N) from crop synthetic fertilizer and crop residue as a fraction of the total rotation N.
Direct $N_2O_{(fert/CR,MLRA,rotation,crop,practice)}$	Direct N_2O emissions [kg N_2O-N/ha] from synthetic fertilizer and crop residues for the feedstock crop.
Indirect $N_2O_{(fert/CR,MLRA,rotation,crop,practice)}$	Indirect N_2O emissions [kg N_2O-N/ha] from synthetic fertilizer and crop residues for the feedstock crop.
Direct $N_2O_{(MLRA,rotation,practice)}$	Direct N_2O emissions [kg N_2O-N/ha] for the rotation.
Indirect $N_2O_{(MLRA,rotation,practice)}$	Indirect N_2O emissions [kg N_2O-N/ha] for the rotation.
Direct N_2O $yield_{(MLRA,rotation,crop,practice)}$	Direct N_2O emissions [kg N_2O-N*m^2/ha/g C]* for the crop, adjusted for changes in yield.
Indirect N_2O $yield_{(MLRA,rotation,crop,practice)}$	Indirect N_2O emissions [kg N_2O-N*m^2/ha/g C]* for the crop, adjusted for changes in yield.
DAYCENT $Yield_{(MLRA,rotation,crop,practice)}$	Crop simulated yield [g C/m^2].
i	The # of rotations in the MLRA that include the feedstock crop.
$CRP_{(crop,rotation,MLRA)}$	The proportion of an MLRA's crop production that is attributable to a specific crop rotation.
$RP_{(rotation,MLRA)}$	The proportion of the area each crop rotation relative to the total simulated area in each MLRA.
$CP_{(crop,rotation,MLRA)}$	The average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation.
DAYCENT $Yield_{(crop)}$	Crop-specific DayCent-modeled yield [g C/m^2].
MLRA Direct N_2O $yield_{(MLRA,crop,practice)}$	Direct N_2O [kg N_2O-N/unit yield] for the practice scenario aggregated by crop and MLRA.
MLRA Indirect N_2O $yield_{(MLRA,crop,practice)}$	Indirect N_2O [kg N_2O-N/unit yield] for the practice scenario aggregated by crop and MLRA.
% change MLRA Direct N_2O	% difference between practice-specific direct N_2O and the baseline (current practice adoption) scenario.
% change MLRA Indirect N_2O	% difference between crop, practice-specific indirect N_2O and the baseline (current practice adoption) scenario.

Acronym	Definitions
CSU % change MLRA Direct N_2O	% change in direct N_2O for the practice scenario aggregated by crop and MLRA.
CSU % change MLRA Indirect N_2O	% change in indirect N_2O for the practice scenario aggregated by crop and MLRA.
[% change MLRA Direct N_2O]$_{(practice)}$	% difference between spring application practice-specific direct N_2O and the spring baseline scenario.
[% change MLRA Indirect N_2O]$_{(practice)}$	% difference between spring application practice-specific indirect N_2O and the spring baseline scenario.
[% change MLRA Direct N_2O]$_{(FS2)}$	% difference between spring application practice-specific direct N_2O and the BAU N application timing baseline scenario.
[% change MLRA Indirect N_2O]$_{(FS2)}$	% difference between spring application practice-specific indirect N_2O and the BAU N application timing baseline scenario.
BC	The assumed biomass carbon percentage (45%) of dry matter (Kwon 5/29/2025).
$Moisture_{crop\ grain}$	The assumed moisture content for each modeled feedstock crop grain, provided by ANL (Kwon 5/29/2025). The moisture content assumptions are as follows: canola (8.5%), corn (15.5%), sorghum (14%), soy (13%).
g_to_lb	Conversion factor from grams to pounds. 1 lb = 453.59 g.
M^2_to_ha	Conversion factor from m^2 to hectare. 1 hextar = 10,000 m^2.
$Lb\_to\_Bu_{crop}$	Crop-specific factor from pounds to bushel. 1 bushel of corn or sorghum = 56 lbs; 1 bushel of soybeans = 60 lbs; 1 bushel of canola = 50 lbs.

Note: * = Because the final result for change in N_2O emissions is presented as a % change, a unit conversion to kg N_2O-N/g C was considered unnecessary and omitted

On-Farm, Fuel Use Variable Acronyms:

Acronym	Definitions
$FracTill_{Full\ (MLRA,rotation,crop,practice)}$	Fraction of area dedicated to full-till practices
$FracTill_{No\ (MLRA,rotation,crop,practice)}$	Fraction of area dedicated to no-till practices
$FracTill_{Reduced\ (MLRA,rotation,crop,practice)}$	Fraction of area dedicated to reduced till practices
$FracTill_{Intensive}$	Rate of fuel use for intensive till practices [gal/acre]
$FracTill_{No}$	Rate of fuel use for no-till practices [gal/acre]

Acronym	Definitions
$FracTill_{Reduced}$	Rate of fuel use for reduced till practices [gal/acre]
CCFuel	Fuel use from cover crop practices
$CCP_{(MLRA,rotation,crop,practice)}$	% of acres that have cover crop adoption
CC_{seed}	Rate of fuel use used for seeding [gal/acre]
CC_{chem}	Rate of fuel use used for chemical termination [gal/acre]
Fertilizer Fuel use	Total fuel used from fertilizer application process [gal/acre]
AvgSplit	% of acres where two fertilizer application passes are made
SinglePass	% of acres where one fertilizer application is made
FertilizerPass	Rate of fuel use per fertilizer pass [gal/acre]
$Frac_{Unfertilized}$	Fraction of land with no fertilizer application
Combine Harvesting Fuel Use_{corn}	Approximate rate of fuel use to harvest corn [gal/acre]
Combine Harvesting Fuel $Use_{soybeans}$	Approximate rate of fuel use to harvest soybeans [gal/acre]
Combine Harvesting Fuel $Use_{sorghum}$	Approximate rate of fuel use to harvest sorghum, proxy value based on average of corn and soybean rates [gal/acre]
Tillage Fuel Use	Fuel used for tillage practices [gal/acre]
Pesticide Fuel Use	Total fuel used from a single pesticide pass [gal/acre]

Appendix B. DayCent Modeling Framework

The DayCent ecosystem model (Parton et al. 1998, 2001; Del Grosso et al. 2001, 2011, 2022) has been used in this analysis. DayCent simulates biogeochemical carbon and nitrogen cycles between the atmosphere, vegetation, and soil, using a broad suite of environmental drivers. These drivers include soil characteristics, weather patterns, crop and forage characteristics, and management practices. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994) but has been refined to simulate dynamics at a daily time-step.

The DayCent model includes two plant residue pools (structural and metabolic litter), and three soil organic matter (SOM) pools (active, slow, and passive). The metabolic pool consists of easily decomposable plant residue, and the structural litter pool is composed of ligno-cellulosic plant materials. The three SOM pools represent a gradient in decomposability. The active pool, which represents microbial biomass and metabolites, turns over in months to years and includes both surface and soil components; the slow pool represents decomposed material with a mean residence time measured in decades and also includes both surface and soil components; the passive pool (highly processed, humified, and condensed material) has a turnover time of several hundred years and is solely represented in the soil. In the analysis done for USDA FD-CIC, the active surface and soil litter pools were omitted which ensures SOC gains estimated are more durable.

Carbon and nitrogen dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production. Nutrient supply is a function of external nutrient additions as well as litter and SOM decomposition rates. Increasing decomposition can lead to a reduction in soil organic carbon stocks due to microbial decomposition, and greater N_2O emissions by enhancing mineral nitrogen availability in soils. DayCent has been tested and applied in many studies; the most recent calibration associated with this version utilized Bayesian methods for soil C and N_2O emissions (U.S.-EPA 2024; Gurung et al. 2020, 2021).

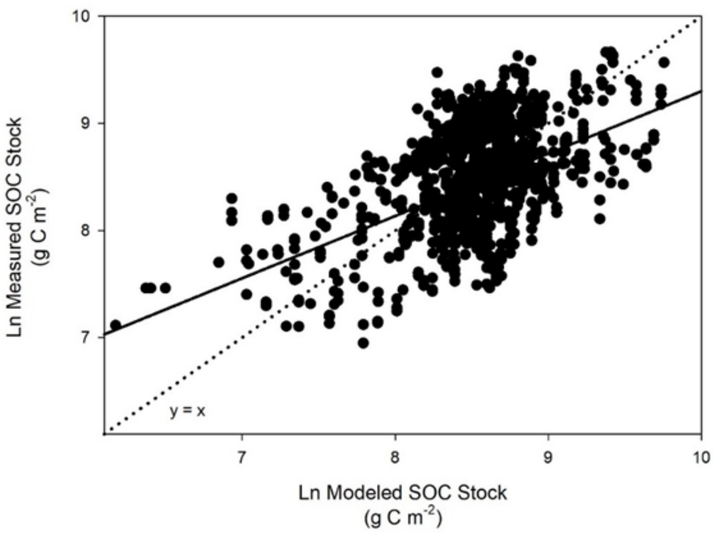
DayCent is used to approximate initial values of C and N in the plant and soil system for the biofuels feedstock analysis using the U.S. GHG Inventory framework and NRI survey data. First, the DayCent model is used to establish the initial conditions and carbon stocks for 1979, which is the first year of the NRI survey. Second, DayCent is used to simulate land use and management histories recorded in the 2017 NRI histories (USDA-NRCS 2020) extended through 2020 using USDA-NASS Crop Data Layer (CDL) (USDA-NASS 2021). Using these histories to establish initial conditions ensures that forward projection for the sustainable biofuels analysis is consistent with historical practices in US agricultural lands (US-EPA 2024). The forward simulations for the 30-year projection are described in sections above using the last 5 years of the NRI histories, which are replicated 6 times in this analysis.

Evaluating uncertainty is an integral part of the analysis and key uncertainties include uncertainty in the management activity data inputs (input uncertainty) and uncertainty in the model formulation and parameterization (model structural uncertainty) (Ogle et al. 2010; Del Grosso et al. 2010, Ogle et al. 2023). A Monte Carlo simulation was conducted to propagate uncertainty through the analysis with 10,000 iterations, and the mean of the results was provided as the output for this analysis.

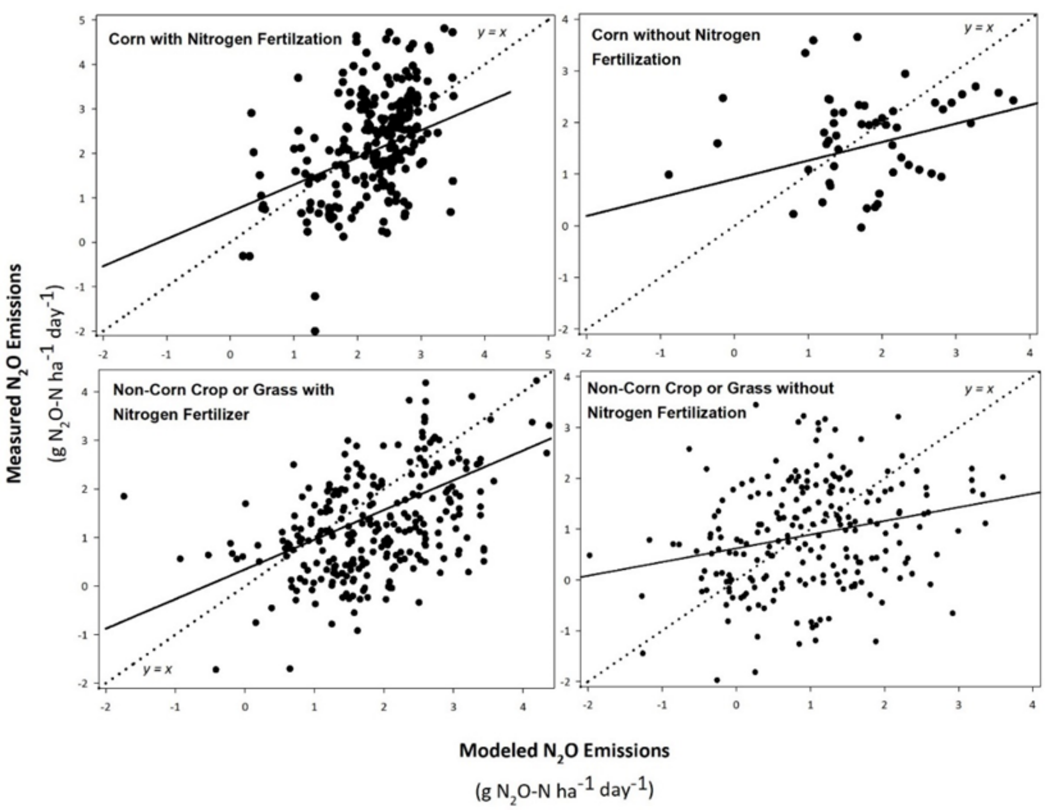
First, input uncertainty is based on the six imputations underlying the management data product that combines data from the CEAP survey, ARMS, OpTIS Data Product, Census of Agriculture and CTIC survey data. CSU randomly selected imputations for each of the 10,000 iterations in a Monte Carlo analysis to propagate this error.

Model structural uncertainty is the estimation error associated with model formulation and parameterization. This component is the largest source of uncertainty in this model-based analysis, accounting for more than 80 percent of the overall uncertainty in the final estimates (Ogle et al. 2010; Del Grosso et al. 2010). An empirically based procedure is applied to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments using linear mixed effect modeling techniques (Ogle et al. 2007). The modeled emissions are treated as a fixed effect in the statistical models along with other covariates that are significant based on the model fit in R, such as crop type, tillage practice and fertilization rates. The resulting relationships are used to make an adjustment to modeled values to address biases due to significant mismatches between the modeled and measured values (Figure B1). Random effects are included to capture the dependence in time series and data collected from the same site, which are needed to estimate appropriate standard deviations for parameter coefficients. The resulting mixed effect model is applied in the DayCent model framework using a Monte Carlo framework with 10,000 draws for parameter values in a joint probability distribution from the linear mixed-effect model. In this step, DayCent output is adjusted for bias and a level of precision is quantified according to the statistical model relationships. See US-EPA (2024) for more information about the DayCent modeling framework. The outputs of this analysis include the mean from the Monte Carlo analysis to inform the final score.

Figure B1. Relationship between DayCent model predictions and empirical observations of soil C stocks from 1406 observations from 69 long-term experiment sites and 145 NRI soil monitoring network sites (Spencer et al. 2011), and empirical observations of N2O emissions from 76 experimental sites with 857 observations. These figures are from US-EPA (2024).



y = x
Ln Measured SOC Stock
(g C m^{-2})
Ln Modeled SOC Stock
(g C m^{-2})



Corn with Nitrogen Fertilzation
Corn without Nitrogen Fertilization
Non-Corn Crop or Grass with Nitrogen Fertilizer
Non-Corn Crop or Grass without Nitrogen Fertilization
y = x
Measured N_2O Emissions
(g N_2O-N ha^{-1} day^{-1})
Modeled N_2O Emissions
(g N_2O-N ha^{-1} day^{-1})

Appendix C. Method for Allocation of SOC Across Feedstocks

Results from the DayCent model are reported as the annual change in soil organic carbon (dSOC) to 30-cm soil depth for each 5-year crop rotation simulated over 30 years. To apportion the dSOC from feedstock crop production among crops over a thirty-year simulation, USDA used a biomass- and frequency- based allocation method where dSOC is allocated based on both (a) the biomass of the feedstock crop as a percent of the total biomass of the rotation and (b) the amount of time any given feedstock crop is planted in the 5-year rotation. The biomass used for the allocation method comprises the total season accumulation of root and residue biomass. The SOC methodology described in this section applies to all modeled crop rotations (Allmaras et al., 2004; Prairie et al., 2023).

By allocating dSOC based on crop-specific biomass, it is assumed that feedstock crops which produce more biomass will result in greater dSOC due to the conversion of decayed feedstock crop residue into SOC. This method was adopted to capture rotational effects on dSOC.

A different approach was used for rotations that included rye cover crop production, as dSOC from cover crop production is due to the biomass of the cover crop (and not the feedstock crop). For cover crops, the dSOC between the rotation with cover crops and the same rotation without cover crops was estimated and then allocated to the feedstock crop(s) based on the frequency in the rotation. See below for the detailed formulas used.

Allocation of dSOC for scenarios without additional cover crop adoption

Equation C-1 uses the ratio of biomass from each crop among all crops in the rotation and the frequency of the crop in the rotation to return an annualized dSOC value that is allocated to the feedstock crop of interest.

Equation C-1. SOC allocation method for scenarios without additional cover crops

$$dSOC_{crop,rotation,MLRA,no\ ccR} = \frac{(dSOC_{rotation,MLRA,no\ ccR}) \times (M_{crop,rotation,MLRA})}{CP_{crop,rotation,MLRA}}$$

Where:

$no\ ccR$	BAU cover crop adoption.
ccR	High adoption of rye cover crop.
$dSOC_{crop,rotation,MLRA,\text{no ccR}}$	The annualized change in SOC [Mg C/ha] for non-cover crop scenarios allocated by crop for each rotation and MLRA.
$dSOC_{rotation,MLRA,no\ ccR}$	The annualized change in SOC [Mg C/ha] for non-cover crop scenarios by rotation and MLRA.
$M_{crop,rotation,MLRA}$	The proportion of the crop's root and residue biomass relative to the rotation's root and residue biomass over the 30-year period. This value is provided by DayCent.
$CP_{crop,rotation,MLRA}$	The average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation. This value is provided by DayCent.

Allocation of dSOC for Scenarios with Additional Cover Crop Adoption

The dSOC associated with cover crop adoption is allocated to feedstock crops in the rotation based on the frequency of the crop in the rotation. The change in SOC from cover crop adoption is assumed to be equal to the difference between cover crop scenarios (ccR) and non-cover crop scenarios (no ccR)[12]. Therefore, cover crop adoption should result in similar changes in dSOC/acre for all crops in the rotation.

Equation C- 2. SOC allocation method for scenarios with additional cover crops

$$dSOC_{crop,rotation,MLRA,ccR} = [(dSOC_{rotation,MLRA,ccR} - dSOC_{rotation,MLRA,no\ ccR}) + dSOC_{crop,rotation,MLRA,no\ ccR}]$$

Where:

$no\ ccR$	BAU cover crop adoption.
ccR	High adoption of rye cover crop.
$dSOC_{crop,rotation,MLRA,ccR}$	The annualized change in SOC [Mg C/ha] for cover crop scenarios allocated by crop for each rotation, and MLRA.
$dSOC_{rotation,MLRA,ccR}$	The annualized change in SOC [Mg C/ha] for cover crop scenarios by rotation, and MLRA. This value is provided by DayCent.
$dSOC_{rotation,MLRA,no\ ccR}$	The annualized change in SOC [Mg C/ha] for BAU cover crop scenarios by rotation, and MLRA. This value is provided by DayCent.
$dSOC_{crop,rotation,MLRA,no\ ccR}$	The annualized change in SOC [Mg C/ha] for non-cover crop scenarios allocated by crop for each rotation, and MLRA. This value is calculated in **Equation C- 1**.

Aggregating dSOC Estimates Across Rotations to Create a Crop-Specific Value for the MLRA

The crop-specific value for dSOC is constructed as a crop-specific weighted average of the rotation-specific values based on the acreage of each rotation within the MLRA. These values are then used to develop CI factors by MLRA, crop, and conservation practice.

DayCent modeled the rotation area proportion (RP) of the total MLRA area that is cropped in each of the eleven representative crop rotations. Additionally, DayCent also outputs the frequency of the feedstock crop versus any "other crop" within each rotation for each MLRA ($CP_{crop,rotation,MLRA}$). These two variables can determine how much of an MLRA's crop production is attributed to one rotation versus another.

Equation C- 3. The portion of the MLRA's crop production from each rotation

$$CRP_{crop,rotation,MLRA} = \frac{RP_{rotation,MLRA} \times CP_{crop,rotation,MLRA}}{\sum_0^i (RP_{rotation,MLRA} \times CP_{crop,rotation,MLRA})}$$

Where:

[12] This option does not take into consideration how often cover crops are adopted in the baseline scenario or in cover crop scenarios. It just considers any SOC accumulation in the baseline as "baseline" SOC and SOC accumulation associated with cover crop scenarios as "cover crop adoption".

i	The number of rotations in the MLRA that include the feedstock crop.
$CRP_{crop,rotation,MLRA}$	The proportion of an MLRA's crop production that is attributable to a specific rotation.
$RP_{rotation,MLRA}$	The proportion of the area of each crop rotation relative to the total simulated area in each MLRA. This value is provided by CSU.
$CP_{crop,rotation,MLRA}$	The average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation. This value is provided by DayCent.

Once this is calculated, the crop-rotation proportion can be applied to each rotation's dSOC value to develop a weighted average dSOC value for each crop, MLRA, and conservation scenario.

Equation C- 4. Aggregate rotation dSOC by MLRA

$$dSOC_{crop,MLRA,practice} = \sum_{0}^{i}(dSOC_{crop,rotation,MLRA,practice} \times CRP_{crop,rotation,MLRA})$$

Where:

i	The number of rotations in the MLRA that include the feedstock crop.
$dSOC_{crop,MLRA,practice}$	The annualized change in SOC [Mg C/ha] allocated by crop for each MLRA and practice.
$dSOC_{crop,rotation,MLRA,practice}$	The annualized change in SOC [Mg C/ha] allocated by crop for each rotation, MLRA and practice. This value is calculated in either **Equation C- 1** or **Equation C- 2**.
$CRP_{crop,rotation,MLRA}$	The proportion of an MLRA's crop production attributable to a specific rotation. This value is calculated in **Equation C- 3**

Accounting for Yield Changes from Conservation Practice Adoption

In addition to affecting SOC accumulation, conservation practice adoption can also affect crop yields. Crop, rotation, and MLRA-specific yields were estimated based on DayCent-modeled crop yield reported in g C/m². The following equation was used to convert crop yields from g C/m² to bu/ha.

Equation C- 5. DayCent Yield Conversion

$$Yield_{crop,rotation,MLRA,practice} = (\frac{(CY_{crop,rotation,MLRA,practice}/BC)}{(1 - Moisture_{crop})}) \div (g\_to\_lb \times m^2\_to\_ha) \div Lb\_to\_Bu_{crop}$$

Where:

$Yield_{crop,rotation,MLRA,practice}$	The crop grain yield [bu/ha] for the rotation, MLRA and conservation scenario.
$CY_{crop,rotation,MLRA,practice}$	The crop, rotation and MLRA-specific grain yield [g C/m^2] for the conservation scenario. This value is provided by DayCent.
BC	The assumed biomass carbon percentage (45%) of total crop dry matter (Kwon 5/29/2025).
$Moisture_{crop\ grain}$	The assumed moisture content for each modeled feedstock crop grain, provided by ANL (Kwon 5/29/2025). The moisture content assumptions are as follows: canola (8.5%), corn (15.5%), sorghum (14%), soybeans (13%).

g_to_lb	Conversion factor from grams to pounds. 1 lb = 453.59 g.
$m^2\_to\_ha$	Conversion factor from m^2 to hectare. 1 hectare = 10,000 m^2.
$Lb\_to\_Bu_{crop}$	Crop-specific factor from pounds to bushel. 1 bushel of corn or sorghum = 56 lbs; 1 bushel of soybeans = 60 lbs; 1 bushel of canola = 50 lbs.

Because the crop yields are modeled to be specific to a crop rotation, they need to be aggregated for each MLRA following a similar process as **Equation C- 6**.

Equation C- 6. Aggregate rotation change in crop yield by MLRA

$$Yield_{crop,MLRA,practice} = \sum_{0}^{i} (Yield_{crop,rotation,MLRA,practice} \times CRP_{crop,rotation,MLRA})$$

Where:

i	The number of rotations in the MLRA that include the feedstock crop.
$CRP_{crop,rotation,MLRA}$	The proportion of an MLRA's total crop production attributable to a specific rotation. This value is calculated in **Equation C- 3**.
$Yield_{crop,rotation,MLRA,practice}$	The crop grain yield [bu/ha] for the rotation, MLRA and conservation scenario. This value is calculated in **Equation C- 5**.
$Yield_{crop,MLRA,practice}$	The aggregated MLRA crop grain yield [bu/ha] for the conservation scenario.

Calculating Change in SOC per Bushel from Conservation Practice Adoption

To estimate the crop and MLRA-specific change in SOC resulting from conservation practice adoption, the dSOC per bushel under the baseline scenario is subtracted from dSOC per bushel of the conservation practice adoption scenario. The MLRA-specific conservation and baseline scenario dSOC/hectare values can be converted to dSOC/bushel values by dividing MLRA-specific dSOC/ha values by the MLRA-specific yield/hectare values (derived from the DayCent yield values in g/m^2).

Equation C- 7. Calculating the change in dSOC/bu from conservation practice adoption

$$dSOC/bu_{crop,MLRA,practice} = dSOC_{crop,MLRA,practice}/Yield_{crop,MLRA,practice} - dSOC_{crop,MLRA,base}/Yield_{crop,MLRA,base}$$

Where:

$dSOC/bu_{crop,MLRA,practice}$	The annualized crop and MLRA-specific change in SOC [Mg C/bu] for the conservation scenario.
$dSOC_{crop,MLRA,practice}$	The crop and MLRA annualized change in SOC [Mg C/ha] for the conservation scenario. This value is calculated in **Equation C- 4**.
$Yield_{crop,MLRA,practice}$	The average MLRA-specific crop yield [bu/ha] for the MLRA for the conservation scenario. This value is calculated in **Equation C- 6**

$dSOC_{crop,MLRA,base}$	The crop and MLRA annualized change in SOC [Mg C/ha] for the baseline scenario. This value is calculated in **Equation C- 4**.
$Yield_{crop,MLRA,base}$	The average MLRA-specific crop yield [bu/ha] for the baseline scenario. This value is calculated in **Equation C- 6**.

The dSOC value in grams C per bushel can be converted to grams of CO_2e per bushel by multiplying by conversion factors for carbon to carbon dioxide and megagrams to grams.

Equation C- 8. Calculating the change in dSOC/bu from practice adoption in g CO_2 per bu

$$dSOC/bu_{crop,MLRA,practice}\ [CO_2e/bu] = dSOC/bu_{crop,MLRA,practice} * \frac{1e^6 g}{1 Mg} * \frac{3.67\ g\ CO_2e}{1\ g\ C}$$

Where:

$dSOC/bu_{crop,MLRA,practice}\ [CO_2e/bu]$	The final change in SOC per bushel from practice adoption for the crop and MLRA converted to carbon intensity of potential grams of CO_2 per bushel.
$dSOC/bu_{crop,MLRA,practice}$	The annualized crop and MLRA-specific change in SOC [Mg C/bu] for the conservation scenario. This is calculated in **Equation C- 7**.

Appendix D. Method for Estimating the Percent Change in N_2O Emissions from Soils

Annual N_2O emissions were calculated for each crop and practice by multiplying the IEFs derived in Section 3.2 by the total N for each crop. To align with the estimated national average, which only estimates N_2O emissions from synthetic fertilizer and crop residues, all other N sources were excluded from this analysis.

Calculating Rotation N Input

For every MLRA, rotation, crop, and conservation practice combination, DayCent[13] modeled total soil nitrogen (N) values in grams N per meter squared (m^2) for (1) synthetic fertilizer application, (2) feedstock crop residue, and (3) all sources of N, including net mineralization, nitrogen deposition, and non-symbiotic soil N fixation. Because DayCent does not provide the N content of cover crops, this value is inferred for each practice by calculating the change in N from the baseline value.

Equation D- 1. Calculate change in DayCent Total N as compared to Total N in the baseline

$$\Delta N_{MLRA,rotation,practice} = N_{MLRA,rotation,crop,practice} - \sum_{0}^{j} N_{MLRA,rotation,crop,base}$$

Where:

$N_{MLRA,rotation,base}$	Total system nitrogen (N) input values [g N/m^2] for the BAU baseline and feedstock crop. This value is provided by DayCent.
$N_{MLRA,rotation,crop,practice}$	Total system nitrogen (N) input values [g N/m^2] from all N sources for the feedstock crop. This value is provided by DayCent.
$\Delta N_{MLRA,rotation,practice}$	The difference between practice and baseline total system nitrogen (N) [g N/m^2] for the feedstock crop.

Calculating N_2O Emissions for Each Feedstock Crop

To estimate total direct and indirect N_2O emissions for each feedstock, rotation, practice, and MLRA, the implied emission factors (in kg N_2O per hectare of nitrogen applied, kgha_N) are multiplied by the total nitrogen input. This total nitrogen includes the change in total nitrogen sources from the baseline scenario, the crop fertilizer nitrogen, and nitrogen from the feedstock crop litter.

[13] Only DayCent modeled manure application to soils.

D- 2. Calculate crop-specific direct and indirect N_2O

$$Direct\ N2O_{MLRA,rotation,crop,practice} = (N_{fert,MLRA,rotation,crop,practice} + N_{CR,MLRA,rotation,crop,practice} + \Delta N_{MLRA,rotation,practice}) \times DirectIEF_{MLRA,rotation,practice} \times 0.1$$

$$Indirect\ N2O_{MLRA,rotation,crop,practice} = (N_{fert,MLRA,rotation,crop,practice} + N_{CR,MLRA,rotation,crop,practice} + \Delta N_{MLRA,rotation,practice}) \times IndirectIEF_{MLRA,rotation,practice} \times 0.1$$

Where:

$Direct\ N2O_{MLRA,rotation\ crop,,practice}$	Direct N_2O emissions [kg N_2O-N/ha] for the rotation.
$Indirect\ N2O_{MLRA,rotation,crop,practice}$	Indirect N_2O emissions [kg N_2O-N/ha] for the rotation.
$N_{fert,MLRA,rotation,crop,practice}$	N input in grams N/m^2 from synthetic fertilizer application for the feedstock crop. This value is provided by DayCent.
$N_{CR,MLRA,rotation,crop,practice}$	N values in grams N/m^2 from feedstock crop residue. This value is provided by DayCent.
$\Delta N_{MLRA,rotation,practice}$	The difference between practice and baseline total system nitrogen (N) [g N/m^2] for the feedstock crop.
$DirectIEF_{MLRA,rotation,practice}$	Implied emissions factor for direct N_2O. This value is provided by DayCent.
$IndirectIEF_{MLRA,rotation,practice}$	Implied emissions factor for indirect N_2O. This value is provided by DayCent.
0 .1	Conversion factor for converting from gm^2 to kgha.

Aggregating N_2O per Hectare Estimates Across Rotations

The rotation-specific N_2O per unit yield was aggregated to determine average N_2O factors per MLRA, crop, and conservation scenario. This aggregation considers how frequently each rotation occurs within the MLRA.

DayCent outputs the area proportion of the total MLRA area that is cropped in each of the 10 representative crop rotations ($RP_{rotation,MLRA}$). Additionally, DayCent provides the frequency of the feedstock crop versus any "other crop" within each rotation for each MLRA ($CP_{crop,rotation,MLRA}$). In combination, these two variables determine how much of an MLRA's crop production is attributed to one rotation versus another.

Equation D- 3. Calculation for the portion of the MLRA's crop production from each rotation

$$CRP_{crop,rotation,MLRA} = \frac{RP_{rotation,MLRA} \times CP_{crop,rotation,MLRA}}{\sum_0^i (RP_{rotation,MLRA} \times CP_{crop,rotation,MLRA})}$$

Where:

i	The # of rotations in the MLRA that include the feedstock crop.
$CRP_{crop,rotation,MLRA}$	The proportion of an MLRA's crop production that is attributable to a specific crop rotation.

$RP_{rotation,MLRA}$	The proportion of the area each crop rotation relative to the total simulated area in each MLRA. This value is provided by CSU.
$CP_{crop,rotation,MLRA}$	The average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation. This value is provided by DayCent.

The crop-specific direct and indirect N_2O is then multiplied by the proportion of area covered by each crop (spatial) and the crop frequency (temporal) within the rotation. This provided the crop-specific direct and indirect N_2O, accounting for spatiotemporal variability within rotations.

Equation D- 4. Aggregate rotation direct and indirect N2O yield by MLRA

$$MLRA\ Direct\ N2O_{MLRA,crop,practice} = Direct\ N2O_{MLRA,rotation,crop,CSA} \times CRP_{crop,rotation,MLRA}$$

$$MLRA\ Indirect\ N2O_{MLRA,crop,practice} = Indirect\ N2O_{MLRA,rotation,crop,CSA} \times CRP_{crop,rotation,MLRA}$$

Where:

$Direct\ N2O_{MLRA,rotation,crop,practice}$	Direct N_2O emissions [kg N_2O-N/ha] for the rotation. This is calculated in Equation **D- 2**.
$Indirect\ N2O_{MLRA,rotation,crop,practice}$	Indirect N_2O emissions [kg N_2O-N/ha] for the rotation. This is calculated in Equation **D- 2**.
$CRP_{crop,rotation,MLRA}$	The proportion of an MLRA's crop production that is attributable to a specific crop rotation.
$MLRA\ Direct\ N2O_{MLRA,crop,practice}$	Direct N_2O [kg N_2O-N/unit yield] for the conservation scenario aggregated by crop and MLRA.
$MLRA\ Indirect\ N2O_{MLRA,crop,practice}$	Indirect N_2O [kg N_2O-N/unit yield] for the conservation scenario aggregated by crop and MLRA.

Accounting for Impacts of Yield Changes from Conservation Practice Adoption

In addition to affecting N_2O emissions, conservation practice adoption can also affect crop yields. Crop, rotation, and MLRA-specific yield were estimated based on modeled grain yield in g C/m². The following equation was used to convert yields from g C/m² to bu/ha. This equation is identical to **Equation C- 5** used in the SOC calculation.

Equation D- 5. DayCent Yield Conversion

$$Yield_{crop,rotation,MLRA,practice} = (\frac{(CY_{crop,rotation,MLRA,practice}/BC)}{(1 - Moisture_{crop})}) \div (g\_to\_lb \times m^2\_to\_ha) \div Lb\_to\_Bu_{crop}$$

Where:

$CY_{crop,rotation,MLRA,practice}$	The crop grain yield [g C/m²] for the conservation scenario. This value is provided by DayCent.
$Yield_{crop,rotation,MLRA,practice}$	The crop grain yield [bu/ha] for the rotation and conservation scenario.
BC	The assumed biomass carbon percentage (45%) of dry matter (Kwon 5/29/2025).

$Moisture_{crop\ grain}$	The assumed moisture content for each modeled feedstock crop grain, provided by ANL (Kwon 5/29/2025). The moisture content assumptions are as follows: canola (8.5%), corn (15.5%), sorghum (14%), soy (13%).
g_to_lb	Conversion factor from grams to pounds. 1 lb = 453.59 g.
$m^2\_to\_ha$	Conversion factor from m² to hectare. 1 hectare = 10,000 m².
$Lb\_to\_Bu_{crop}$	Crop-specific factor from pounds to bushel. 1 bushel of corn or sorghum = 56 lbs; 1 bushel of soybeans = 60 lbs; 1 bushel of canola = 50 lbs.

Because the crop yields are modeled to be specific to a crop rotation, they need to be aggregated for each MLRA. This process is the same for both SOC and N_2O. **Equation D-6** is the same as **Equation C-6** in the SOC section.

Equation D-6. Aggregate rotation change in crop yield by MLRA

$$Yield_{crop,MLRA,practice} = \sum_{0}^{i} (Yield_{crop,rotation,MLRA,practice} \times CRP_{crop,rotation,MLRA})$$

Calculating Percent Change in N_2O Emissions Between Baseline and Conservation Scenarios

Similarly to dSOC changes from conversation practice adoption, the change in N_2O emissions from practice adoption was estimated by subtracting the BAU baseline from a given conservation practice scenario. However, unlike how dSOC changes were estimated, changes in N_2O emissions form practice adoption were then divided by the BAU baseline emissions to estimate a percent change in emissions that was then applied to the estimated national average N_2O emissions. This step was necessary to ensure that the USDA FD-CIC tool was consistent with the estimated national average.

D-7. Change in direct and indirect N2O emissions from conservation practice adoption

$$\%\ change\ MLRA\ Direct\ N2O = \frac{MLRA\ Direct\ N2Obu_{MLRA,crop,practice} - MLRA\ Direct\ N2Obu_{MLRA,crop,base}}{MLRA\ Direct\ N2Obu_{MLRA,crop,base}}$$

$$\%\ change\ MLRA\ Indirect\ N2O = \frac{MLRA\ Indirect\ N2Obu_{MLRA,crop,practice} - MLRA\ Indirect\ N2Obu_{MLRA,crop,base}}{MLRA\ Indirect\ N2Obu_{MLRA,crop,base}}$$

Where:

$MLRA\ Direct\ N2Obu_{MLRA,crop,practice}$	Direct N_2O [kg N_2O-N/unit yield] for the conservation scenario aggregated by crop and MLRA.
$MLRA\ Indirect\ N2Obu_{MLRA,crop,practice}$	Indirect N_2O [kg N_2O-N/unit yield] for the conservation scenario aggregated by crop and MLRA.
$\%\ change\ MLRA\ Direct\ N2O$	% difference in Direct N_2O [kg N_2O-N/ha/unit yield] between the conservation the baseline (current practice adoption) scenarios.
$\%\ change\ MLRA\ Indirect\ N2O$	% difference in Indirect N_2O [kg N_2O-N/ha/unit yield] between the conservation and the baseline (current practice adoption) scenarios.

Appendix E. Methods for Estimating Change in Fuel Use

Change in fuel consumption resulting from adoption of low-carbon practices was estimated as a percentage change from the BAU baseline for each feedstock crop and rotation. Fuel use for crop rotations were aggregated to develop a weighted average fuel use rate for each feedstock crop, MLRA, and practice.

Estimating Fuel Use Changes Resulting from Adoption of Conservation Practices

Conservation practice adoption was assumed to impact baseline fuel use if adoption of a specific conservation practice included changes to one or more of the following variables:

1. Tillage practice used
2. Cover crop adoption
3. Number of times fertilizer is applied

Using these criteria, it was assumed that adopting any of the following conservation practices (either alone or in combination with other practices) would result in fuel use changes:

- ccR (cover crop adoption)
- RT (reduced tillage)
- NT (no-tillage)
- NTRT (no-till with reduced till once every 5 years)
- NTIT (no-till with intensive till once every 5 years)

Using the same criteria, it was assumed that adoption of the following conservation practice would not affect fuel use relative to baseline:

- NI (nitrification inhibitor)

For practices where adoption was assumed to impact fuel use, the impact was estimated by multiplying the specific fuel impacts by the number of acres where the practice was adopted.

Specific fuel use rates for each crop and practice are included in Table 8. Baseline adoption rates for cover crop adoption, tillage, and no-fertilization use were provided by the DayCent model. Similar to the process for SOC and N_2O, crop rotations were aggregated to generate a single weighted average fuel use rate for each feedstock crop, MLRA, and practice by using the crop proportions and rotation proportions provided by DayCent.

Estimating Baseline Fuel Use

Baseline crop, MLRA and rotation-specific tillage fuel use was estimated as follows:

Equation E- 1. Fuel use from tillage practices

$$\begin{aligned} \textit{Tillage Fuel Use} &= \left(FracTill_{Intensive_{MLRA,Rotation,Crop,practice}} * TillFuel_{Intensive}\right) \\ &+ \left(FracTill_{NO_{MLRA,Rotation,Crop,practice}} * TillFuel_{No}\right) \\ &+ \left(FracTill_{Reduced_{MLRA,Rotation,Crop,practice}} * TillFuel_{Reduced}\right) \end{aligned}$$

Where:

$\textit{Tillage Fuel Use}$	Fuel used for tillage practices [gal/acre].

$FracTill_{Intensive_{MLRA,Rotation,Crop,practice}}$	Fraction of area dedicated to full-till practices.
$FracTill_{No_{MLRA,Rotation,Crop,practice}}$	Fraction of area dedicated to no-till practices.
$FracTill_{Reduced_{MLRA,Rotation,Crop,practice}}$	Fraction of area dedicated to reduced till practices.
$TillFuel_{Intensive}$	Rate of fuel use for intensive till practices [gal/acre].
$TillFuel_{No}$	Rate of fuel use for no-till practices [gal/acre].
$TillFuel_{Reduced}$	Rate of fuel use for reduced till practices [gal/acre].

Baseline crop, MLRA, and rotation-specific fuel use for cover crop use was estimated as follows:

Equation E- 2. Fuel use from cover crop practices

$$CCFuel = CCP_{MLRA,Rotation,CropCSA} * (CC_{seed} * CC_{chem})$$

Where:

$CCFuel$	Fuel use from cover crop practices [gal/acre].
$CCP_{MLRA,Rotation,Crop,practice}$	% of acres that have cover crop adoption.
CC_{seed}	Rate of fuel use for seeding [gal/acre].
CC_{chem}	Rate of fuel use used for chemical termination [gal/acre].

Baseline crop, MLRA, and rotation-specific fuel use for fertilizer application was estimated as follows:

Equation E- 3. Fuel use from fertilizer application

$$Fertilizer\ Fuel\ Use = \Big(AvgSplit\ \cdot 2 \cdot FertilizerPass \cdot \big((1 - FracUnfertilized)\big) + \big(SinglePass \cdot FertilizerPass \cdot (1 - FracUnfertilized)\big)\Big)$$

Where:

$Fertilizer\ Fuel\ Use$	Total fuel used from fertilizer application process [gal/acre].
$AvgSplit$	% of acres where two fertilizer application passes are made.
$SinglePass$	% of acres where one fertilizer application is made either in fall or spring.
$FertilizerPass$	Rate of fuel use per pass [gal/acre].
$Frac_{Unfertilized}$	Fraction of land with no fertilizer application.

Scenarios with 2 fertilizer passes:

Equation E- 4. Fertilizer use in scenarios with two passes

$$Fertilizer\ Fuel\ Use = 2 * FertilizerPass * (1 - Frac_{Unfertilized})$$

Where:

$Fertilizer\ Fuel\ Use$	Total fuel used from fertilizer application process [gal/acre].
$FertilizerPass$	Rate of fuel use per pass [gal/acre].
$Frac_{Unfertilized}$	Fraction of land with no fertilizer application.

Baseline crop, MLRA, and rotation-specific fuel use for combine harvesting was estimated as follows:

Equation E- 5. Combine harvesting fuel use for sorghum

$$Combine\ Harvesting\ Fuel\ Use_{sorghum} = \frac{Combine\ Harvesting\ Fuel\ Use_{corn} + Combine\ Harvesting\ Fuel\ Use_{soybeans}}{2}$$

Where:

$Combine\ Harvesting\ Fuel\ Use_{corn}$	Approximate rate of fuel use to harvest corn [gal/acre].
$Combine\ Harvesting\ Fuel\ Use_{soybeans}$	Approximate rate of fuel use to harvest soybeans [gal/acre].
$Combine\ Harvesting\ Fuel\ Use_{sorghum}$	Approximate rate of fuel use to harvest sorghum, proxy value based on average of corn and soybean rates [gal/acre].

Baseline crop, MLRA, and rotation-specific total baseline fuel use was estimated as follows:

Equation E- 6. Total fuel use

$$Total\ fuel\ use = Tillage\ Fuel\ Use + CCFuel + Fertilizer\ Fuel\ Use + Pesticide\ Fuel\ Use + Combine\ Harvesting\ Fuel\ Use\_crop$$

Where:

$Tillage\ Fuel\ Use$	Fuel used for tillage practices [gal/acre].
$CCFue$	Fuel use from cover crop practices [gal/acre].
$Fertilizer\ Fuel\ Use$	Total fuel used from fertilizer application process [gal/acre].
$Pesticide\ Fuel\ Use$	Total fuel used from a single pesticide pass [gal/acre].

Appendix F. Outlier Analysis and Proxy Values

A multi-step process was followed to remove outlier results from the DayCent results. The method for identifying and eliminating outlier values is described below.

1) MLRA data points were removed from the dataset if their baseline dSOC/bu value fell outside two standard deviations of the mean. Table F-1 shows the number of MLRAs eliminated for each feedstock.

Table F-1. Summary of Removed MLRAs

Crop	Count of MLRAs
Corn	8
Soybeans	7
Sorghum	3
Spring canola	1

2) For remaining MLRAs (those within two standard deviations), a mean and standard deviation for each crop and practice dSOC/bu, percent change in direct and indirect N_2O, direct and indirect N_2O IEFs, and percent change in fuel use values were calculated. MLRAs which had values outside of 2 standard deviations of the mean for that crop, practice, and CI attribute were replaced with the value at two standard deviations.
3) For outlier MLRAs removed in step 1, proxy values were derived as described below.

Developing dSOC and N_2O Proxies for Outlier MLRAs and MLRAs Without Data

NASS production data for corn, soy, sorghum, or canola over the past five years was used to determine which MLRAs should be assigned CI scores for biofuel feedstock production in USDA FD-CIC. When the MLRAs with NASS production data were compared to those with DayCent-modeled values for SOC and N_2O, three different combinations were observed:

1) The MLRA had both NASS production data and modeled DayCent values. In these cases, the values were kept. In cases where values had been dropped as part of the outlier analysis (as described in step 1, above), USDA developed the proxy values using the method described below.
2) The MLRA had modeled N_2O and SOC values from DayCent but no NASS production. In these cases, the MLRAs were dropped.
3) The MLRA had NASS production data but no modeled N_2O and SOC values from DayCent. In many cases no modeled values were present for an MLRA because there were too few NRI points in an MLRA and the model results were masked for data privacy. In these cases, the proxy method (described below) was used to generate values for the MLRA.

For all missing MLRAs (i.e., MLRAs that were dropped as part of the outlier analysis and MLRAs where NASS production data exist but which have no modeled SOC or N_2O values), average values for dSOC/bu, percent change N_2O, and fuel use percent change were applied based on the Land Resource Region (LRR) in which each MLRA is located (USDA 2022b). Each MLRA was mapped to one of the 28 unique LRRs. Challenges with a lack of data are less pertinent at the LRR-level since they encompass a wider geographic area than MLRAs. This same process was also conducted for the N_2O IEFs described in section 3.3. In total, proxy values were developed for 73 unique MLRAs. In addition, proxy values were used for the 19 MLRAs that were struck as part of the outlier analysis (described above). Note that data were available for the majority of canola, corn, sorghum, and soybeans production areas. See Table F-2 below for a specific breakdown of the share of data available, proxied, and not included in USDA FD-CIC, and Figures F1-F4 that show data availability mapped across all MLRAs and crops included in USDA FD-CIC.

Table F-2: Data availability, proxy data, and data not included for each crop in USDA FD-CIC[1]

Status	**Canola**	**Corn grain**	**Sorghum grain**	**Soybeans**
Data available	97.29%	99.13%	99.83%	99.43%
Proxied	2.19%	0.84%	0.11%	0.56%
Not included in USDA FD-CIC	0.52%	0.03%	0.06%	0.00%
Grand Total	**100%**	**100%**	**100%**	**100%**

[1] Please note that for canola, the table shows both spring and winter canola production because NASS, which is the source for that data, does not distinguish between those canola types. Based on a geographic analysis, many of the MLRAs not included in USDA FD-CIC are likely to produce winter canola.

Figure F1: Corn Data Availability and Production by MLRA

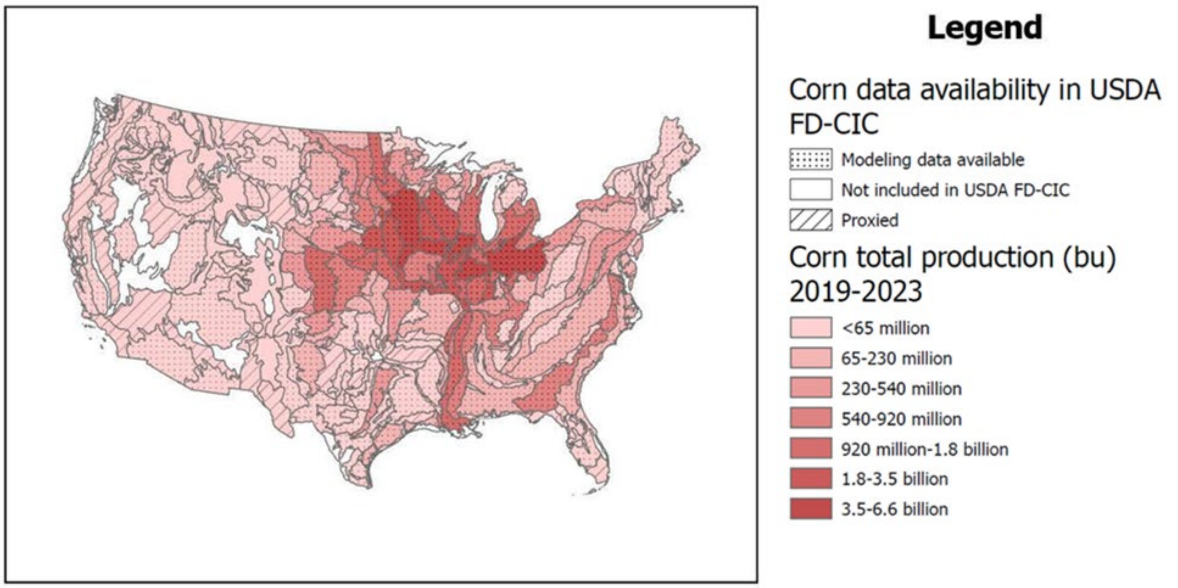


Figure F2: Soybean Data Availability and Production by MLRA

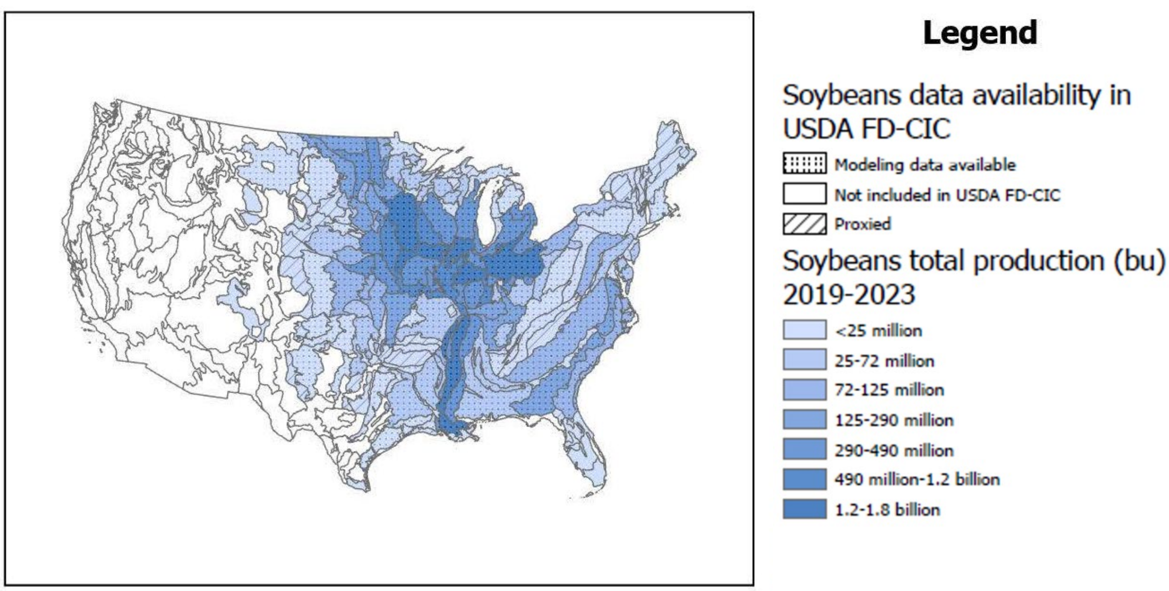


Figure F3: Sorghum Data Availability and Production by MLRA

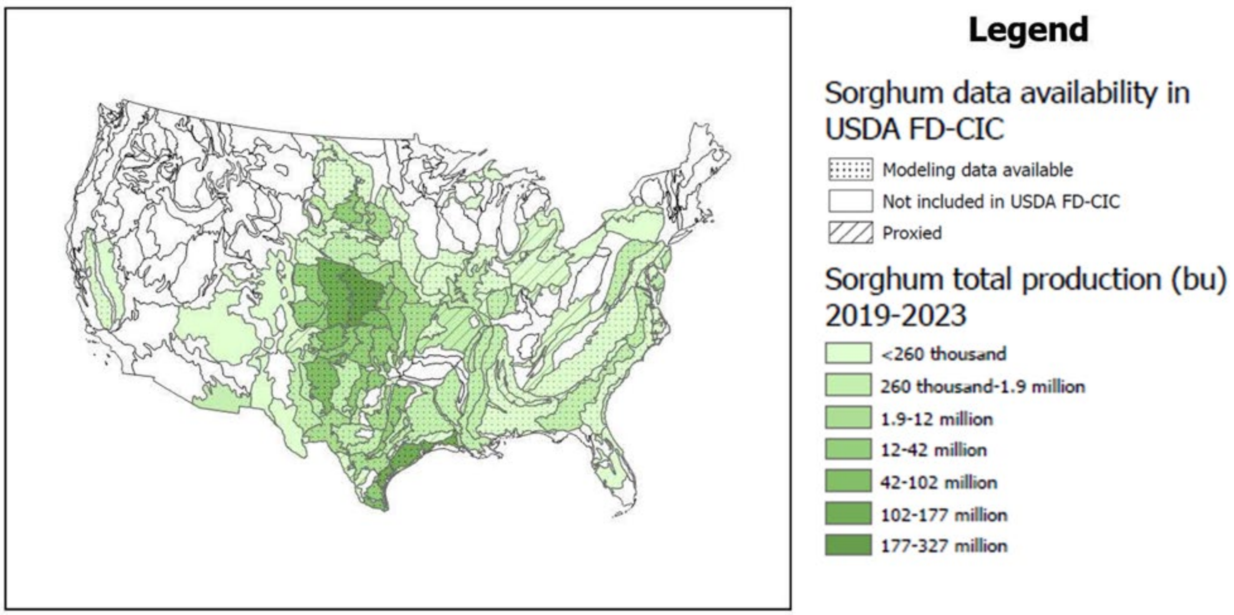
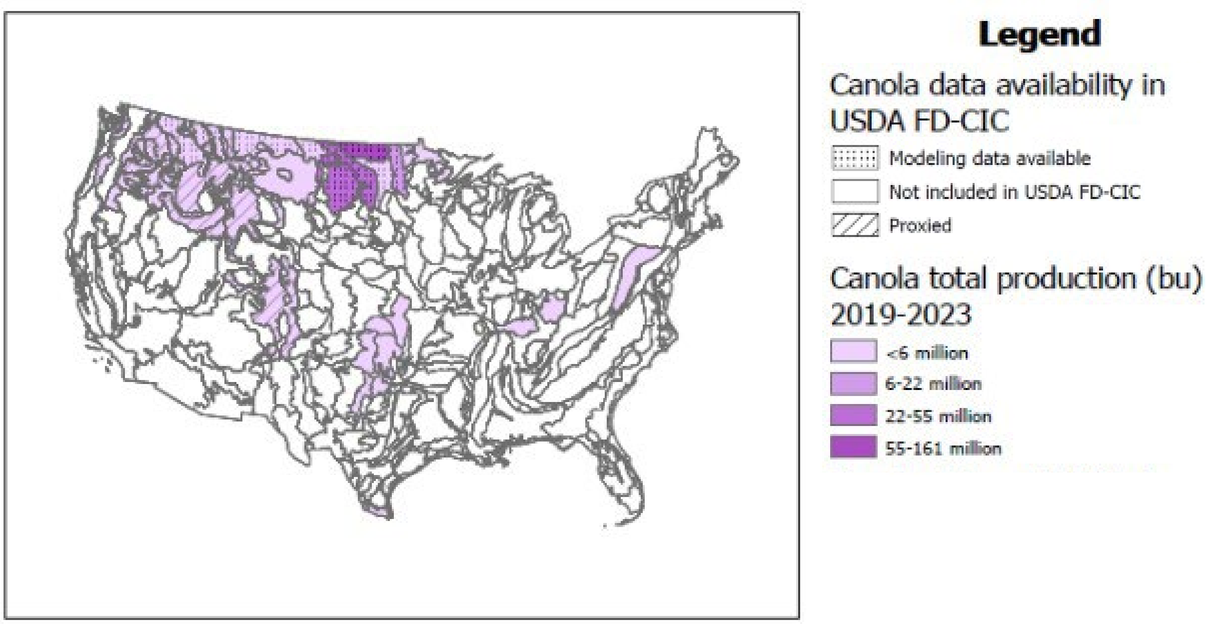


Figure F4: Canola Data Availability and Production by MLRA[2]



[2] Please note that for canola, the map shows both spring and winter canola production because NASS, which is the source for that data, does not distinguish between those canola types. Based on a geographic analysis, many of the MLRAs not included in USDA FD-CIC are likely to produce winter canola.