U.S. DEPARTMENT OF AGRICULTURE

ICF International

White Paper

Methodology for Determining the Feedstock Carbon Intensity of Climate Smart Agriculture Practice Adoption in USDA FD-CIC

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Overview

The process of developing the U.S. Department of Agriculture Feedstock Carbon Intensity Calculator (USDA FD-CIC) entailed two main steps.

First, to estimate how climate-smart farming practices impact soil organic carbon and nitrous oxide emissions, scenarios were generated from two agrosystem models (DAYCENT and SALUS). In general, the models simulated the effect of climate-smart agriculture (CSA) practices on greenhouse gas (GHG) emissions over a thirty-year cropping period. The models simulated these effects regionally across the United States for a) various combinations of climate-smart farming practices, b) various crops within a rotation, and c) various rotations.

Second, there was post-processing of the output from DAYCENT and SALUS to a) apportion the GHG emissions within and across rotations to specific feedstocks and b) develop a method for determining the carbon intensity of biofuels that source climate-smart feedstocks. There was additional post-processing undertaken (not using output from DAYCENT or SALUS) to determine how climate-smart farming practices would impact on-farm fuel use and upstream GHG emissions from fertilizer production.

This white paper focuses on the second of these two steps. Detailed overviews of the first of these two steps, with extensive descriptions of DAYCENT and SALUS, are contained in companion white papers.

1 Background

High-Level Summary

One way to reduce the greenhouse gas (GHG) intensity of transportation fuels is through the use of biofuels, which can have lower carbon intensity (CI) values than traditional fossil fuels. Life cycle analyses indicate that feedstock production, or growing the biofuel crop, is the most carbon intensive stage of biofuel production (Xu et al., 2022). Adoption of climate smart agricultural (CSA) practices can both reduce GHG emissions and increase soil carbon sequestration resulting in reduced on-farm CI scores compared to feedstocks produced with business-as-usual farming practices.

USDA's Office of the Chief Economist (OCE) worked with the Systems Assessment Center (SAC) at Argonne National Laboratory (ANL) to develop a USDA version of the Feedstock Carbon Intensity Calculator (FD-CIC). USDA FD-CIC estimates crop-specific, GHG impacts of CSA practice adoption relative to a baseline cropping system employing business-as-usual (BAU) farming practices at the USDA/NRCS Major Land Resource Area (MLRA) level.

This document describes the methods employed to estimate the net, on-farm and upstream GHG changes from nitrous oxide (N_2O) emissions, changes in soil organic carbon and carbon dioxide (CO_2) equivalent emissions from diesel fuel combustion associated with the adoption of CSA practices to produce biofuel feedstocks.

The geographic units analyzed by the process-based models described in this methodology are MLRAs. These units were chosen as MLRA boundaries are determined by local plant growing conditions. See Major Land Resource Area (MLRA) | Natural Resources Conservation Service for further information.

USDA/ICF quantified CSA adoption impacts on three feedstock production emission categories:

- Direct and indirect N_2O emissions
- Soil organic carbon sequestration
- Fossil CO_2 equivalent emissions due to changes in on-farm fuel use

Additionally, upstream GHG emissions from changes in fertilizer application rates were also estimated by Argonne National Laboratory using values from Argonne National Laboratory's Research and Development version of Greenhouse gases, Regulated Emissions, and Energy use in Technology (R&D GREET) model.

GHG emissions for three crops (field corn, soybeans, and sorghum) were modeled under a business-as-usual (BAU) baseline practice[1] and CSA scenarios at the MLRA-level. The CSA scenarios modeled use of one or more specified CSA practices. When the GHG emissions are divided by the number of bushels produced, as in USDA FD-CIC, they represent a change in CI that results when CSA practices are undertaken. Changes in feedstock CI were quantified on both a per bushel and per acre of crop produced basis. The change in CI accounts for both changes in net GHG emissions and changes in yield.

The estimated changes in CI resulting from adoption of one or more CSA practices for a specified crop and geography (MLRA) were incorporated into the USDA FD-CIC. The results were converted into county-level parameter values in USDA FD-CIC, so that each county within an MLRA has the same value. USDA FD-CIC is distinct from the version of FD-CIC maintained by Argonne National Laboratory (ANL FD-CIC).[2]

The CSA practices incorporated into USDA FD-CIC include:

- No-till
- Reduced till
- Rye cover crops
- Nitrification inhibitors
- Split in-season fertilizer application (for corn and sorghum only)
- Spring-only fertilizer application (for corn only)

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[1] The business-as-usual baseline practices are defined as crop, crop rotation and MLRA specific current adoption rates of conventional tillage, reduced tillage, no-tillage and cover crop adoption from NRI data points. For corn, baseline practice also includes the national average nitrogen application timing, with timing characterized as fall application, split fall/spring application and spring application.

[2] The 2023 documentation of ANL's version of FD-CIC is available at this link: https://greet.anl.gov/publication-fd-cic-tool-2023-user-guide

Overview of Process and Data Sources

SOC values were derived from output from the Daily Century (DAYCENT) model and N_2O emissions were derived from output primarily from DAYCENT, but baseline corn N fertilizer application was derived from both DAYCENT and the System Approach for Land Use Sustainability (SALUS) model.

DAYCENT is a process-based biogeochemical model that simulates carbon, nitrogen, and other nutrient fluxes in agroecosystems over long time scales. Key drivers of GHG emissions and carbon sequestration estimates include soil moisture, soil texture, management practices (such as tillage, fertilization, and crop rotation), and climate variables (such as temperature, precipitation, and solar radiation).

SALUS is a process-based biogeochemical model that simulates carbon, nitrogen, and other nutrient fluxes in agroecosystems over multiple growing seasons. Key drivers of GHG emissions and carbon sequestration estimates include soil water balance, carbon balance and other nutrient balance, crop genotypes, management practices (such as crop sequencing, planting and harvesting dates, fertilization, irrigation, and tillage) and climate variables (such as temperature, precipitation, and solar radiation). More detailed documentation about DAYCENT and SALUS are provided in separate white papers.

The DAYCENT model was the main model used to estimate direct and indirect N_2O emissions as well as annualized changes in SOC accumulation for baseline and CSA adoption for corn, soybeans, and sorghum.

SOC Changes

SOC data from the DAYCENT model were reported as the annualized total change in SOC for 10 representative 5-year crop rotations for each CSA scenario in each MLRA to a 30-cm soil depth. The 30-cm soil depth was chosen to be consistent with the U.S. GHG Inventory (EPA, 2024), and is the standard soil depth modeled in DAYCENT, as described in further detail in the DAYCENT companion document. The 10 five-year rotations were chosen as they are representative of current U.S. cropping practices and typical rotation length. The 10 rotations modeled are described in more detail in footnote 3. The scenarios were replicated over a 30-year projection period (i.e., the 5-year crop rotations were modeled for six consecutive terms). An annualized 30-year period was used to both capture that soil carbon changes occur over longer periods of time (up to 30 years) and linearize the change in SOC.

N_2O emissions

N_2O emissions in the DAYCENT model were delivered from Colorado State University (CSU) as crop-specific annual N_2O emissions from four nitrogen (N) input sources. To ensure consistency with Argonne National Laboratory's Research and Development version of Greenhouse gases, Regulated Emissions, and Energy use in Technology (R&D GREET) model, in this analysis, we estimated the two N input sources that R&D GREET attributes to biofuel production:

- Synthetic nitrogen application

- Nitrogen from crop residue decay

A modified approach was used to estimate baseline N_2O emissions from corn N fertilizer application. Nitrogen fertilizer application in DAYCENT was modeled using only spring application or split spring application for all three crops. However, current N fertilizer practices for corn include a combination of fall application, split fall/spring application and spring application (which can impact N_2O emissions). To estimate the baseline emissions associated with current corn N fertilizer practices, SALUS model output, which included both fall and spring N fertilizer application for corn, was used. For more details on how DAYCENT and SALUS model outputs were used to establish baseline N_2O emissions for corn, please see section 3.7.

Emissions from On-Farm Fuel Use

Changes in CO_2 equivalent emissions from on-farm diesel fuel use were calculated by estimating the number of field passes under each CSA scenario compared to a BAU scenario. The change in the number of passes was then multiplied by average equipment per-acre, fuel-use values based on literature (USDA 2022a; Jones 2023; University of Nebraska-Lincoln n.d.; Parsons n.d.; Iowa State University Extension and Outreach 2001; Hanna 2005; Sumner 2024).

Upstream Emissions

Upstream emissions from changes in fertilizer use were also included in the on-farm crop CI value. For example, as split-application of fertilizer in the spring can be more efficient, split in-season fertilizer CSA scenarios reduced overall N application by 10 percent. As such, GHG emissions from upstream fertilizer production were also reduced by 10 percent.

Estimation of GHG Impacts

SOC changes and N_2O emissions were model outputs generated for representative rotations[3] of three feedstock crops: field corn, soybeans, and sorghum. DAYCENT modeled various scenarios, including a baseline scenario with BAU farming practices and CSA scenarios with the adoption of one, two, or three CSA practices.

The categories of GHG emissions assigned to crop-based biofuels in R&D GREET are: upstream N fertilizer production, direct N_2O emissions, indirect N_2O emissions, emissions from on-farm energy use, emissions from other chemicals, CO_2 emissions from urea, and CO_2 emissions from lime. Direct methane emissions are not attributed to crop-based biofuels in R&D GREET for corn, soybeans, and sorghum since they are de minimis. (Methane emissions are attributed to crop-based biofuels from indirect crop and livestock production, but this is modeled separately in GREET's Carbon Calculator for Land Use Change in Biofuels model).

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[3] Including continuous corn (CC), corn-hay-pasture (CHP), corn-other (CO), corn-soy (CS), corn-soy-hay-pasture (CSHP), continuous sorghum (SGSG), sorghum-other (SGO), soy-hay-pasture (SHP), soy-other (SO), continuous soy (SS), and wheat-wheat spring canola (WWSC).

To summarize what we describe in greater detail subsequently, carbon intensity (CI) factors in grams of carbon dioxide equivalent (CO_2e) per bushel and per acre were estimated using the model outputs and National Agricultural Statistics Service (NASS) data on crop yields (data years 2018-2023, NASS 2024). The changes were quantified relative to the relevant MLRA baseline scenario for each CSA practice and MLRA combination. The estimated GHG impacts of adopting one or more CSA practices for a specified crop and geography (MLRA) were incorporated into the USDA FD-CIC.

In summary, the county-level feedstock CI factors in USDA FD-CIC were calculated in two steps. For the first step, USDA calculated the difference between the feedstock CI with CSA practices and the feedstock CI under BAU farming practices. The following paragraphs further detail how the feedstock CI with CSA practices and feedstock CI under BAU farming practices were derived. Second, USDA subtracted the difference calculated in step one from the national average baseline feedstock CI for each crop. The national average baseline feedstock CIs are used in the R&D GREET model. This step ensures a consistent baseline between USDA FD-CIC and the R&D GREET model.

The methodologies used to estimate the GHG impacts are described in the following sections.

2 Soil Organic Carbon (SOC) Methodology

As described above, results from the DAYCENT model are reported as the annualized change in soil organic carbon (dSOC) to 30-cm soil depth for each 5-year crop rotation modeled for 30 years. The approach described in this section was used to allocate the dSOC to individual feedstock crops within USDA FD-CIC.

2.1 Allocating SOC Emissions Across Feedstocks

The SOC methodology described in this section apply to all of the modeled crop rotations. To apportion the dSOC from feedstock crop production among crops over a thirty-year rotation, a biomass-based allocation method was used where dSOC is allocated 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.

For the “no-till” scenarios in USDA FD-CIC, the 5-year DAYCENT rotations used were four years of no-till followed by one year of reduced till for corn and soybeans. For sorghum, the 5-year DAYCENT rotation used was four years of no-till followed by one year of conventional till. These rotations were selected because they were most representative of the adoption of tillage practices according to USDA data from the Agricultural Resources Management Survey. The “reduced till” scenarios in DAYCENT for the three crops were modeled as continuous reduced till over five years.

This approach assumes that feedstock crops that produce more biomass will result in greater dSOC from the conversion of decayed feedstock crop residue into SOC. This method is adopted to ensure consistency with SOC methodologies previously established by Argonne National Laboratory and by expert recommendation on feasible approaches that could be followed to allocate SOC emissions among feedstocks when using DAYCENT output.

A different approach was used for 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 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 a dSOC value that is allocated to the feedstock crop of interest. See Appendix B for a description of how this equation is derived.

Equation 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.
$dSOC_{crop,rotation,MLRA,\mathrm{no\ ccR}}$	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 total biomass relative to the rotation's total biomass over the 30-year period. Total biomass includes above and belowground biomass. 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 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)[4].

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

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

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[4] 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”.

Where:

$no\ ccR$	BAU cover crop adoption.
ccR	High adoption of rye cover crop.
$dSOC_{crop,rotation,MLRA,\mathrm{ccR}}$	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 1.

2.2 Account for Changes in Yield from CSA

In addition to affecting SOC accumulation, CSA adoption can also affect crop yields. Yields impact both feedstock and fuel CI.

A two-step process was used to estimate the MLRA-level yield impacts of CSA adoption scenarios for each feedstock.

1. Crop, rotation, and MLRA-specific yield changes between the baseline and CSA scenarios were estimated based on modeled changes (from DAYCENT) in grain yield in g C/m^2. The change in yields between the baseline and CSA scenarios at the MLRA-level is represented as a ratio, as determined by Equation 3.
2. The change in yield in Step 1 was applied to the MLRA average yield. MLRA-specific average yield was estimated using an MLRA weighted average of the last 5 years of crop production for each of the biofuel feedstock crops using NASS yield data from 2019 to 2023 (NASS 2024). Averaging yields across years can control for year-to-year weather effects on yields, and five years was chosen since examining yields over longer time periods would not account for increases in productivity that occur over time.

Equation 3. Ratio of crop grain yield from CSA adoption vs. baseline

$$RCY_{crop,rotation,MLRA,CSA} = \frac{CY_{crop,rotation,MLRA,CSA}}{CY_{crop,rotation,MLRA,base}}$$

Where:

$RCY_{crop,rotation,MLRA,CSA}$	Ratio of crop grain yields between CSA and baseline scenarios.
$CY_{crop,rotation,MLRA,CSA}$	The crop grain yield [g C/m^2] for the CSA scenario. This value is provided by DAYCENT and SALUS.
$CY_{crop,rotation,MLRA,base}$	The baseline crop grain yield [g C/m^2]. This value is provided by DAYCENT and SALUS.

2.3 Aggregating Emissions Output Across Rotations

The rotation-specific dSOC is constructed by developing weighted average dSOC results based on the frequency of each rotation within each MLRA. These values are then used to develop CI factors by MLRA, crop, and CSA practice.

DAYCENT modeled the rotation area proportion (RP) of the total MLRA area that is cropped in each of the 10 representative crop rotations. The RP variables provided by CSU from DAYCENT were also used for SALUS. 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 4. 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 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 and SALUS.

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 CSA scenario.

Equation 5. Aggregate rotation dSOC by MLRA

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

Where:

i	The number of rotations in the MLRA that include the feedstock crop.
$dSOC_{crop,MLRA,CSA}$	The annualized change in SOC [Mg C/ha] allocated by crop for each MLRA.
$dSOC_{crop,rotation,MLRA,CSA}$	The annualized change in SOC [Mg C/ha] allocated by crop for each rotation and MLRA. This value is calculated in either Equation 1 or Equation 2.
$CRP_{crop,rotation,MLRA}$	The proportion of an MLRA's crop production attributable to a specific rotation. This value is calculated in Equation 4.

Similarly, a weighted average yield ratio can be calculated by applying the crop proportion weighting value to each rotation's yield ratio.

Equation 6. Aggregate rotation change in crop yield by MLRA

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

Where:

i	The number of rotations in the MLRA that include the feedstock crop.
$RCY_{crop,MLRA,CSA}$	Ratio of crop grain yields between CSA and baseline scenarios for the MLRA.
$RCY_{crop,rotation,MLRA,CSA}$	Ratio of crop grain yields between CSA and baseline scenarios. This value is calculated in Equation 3.
$CRP_{crop,rotation,MLRA}$	The proportion of an MLRA's crop production attributable to a specific rotation. This value is calculated in Equation 4.

2.4 Calculate Change in SOC per Bushel from CSA Practice

The final estimate for the crop and MLRA's change in dSOC resulting from CSA adoption is calculated by differencing the dSOC per bushel under CSA adoption from the baseline. The CSA and baseline dSOC per hectare may be converted to dSOC per bushel by dividing them by the MLRA-specific yield from NASS (NASS, 2024).

Equation 7. Final calc for the change in dSOC/bu from CSA adoption

$$dSOC/bu_{crop,MLRA,CSA} = (dSOC_{crop,MLRA,CSA} \times RCY_{crop,MLRA,CSA} - dSOC_{crop,MLRA,base})/Yield_{crop,MLRA,base}$$

Where:

$dSOC/bu_{crop,MLRA,CSA}$	The final change in SOC [Mg C/bu] from CSA adoption for the crop and MLRA.
$dSOC_{crop,MLRA,CSA}$	The annualized change in SOC [Mg C/ha] for the CSA scenario allocated by crop for each MLRA. This value is calculated in Equation 5.
$RCY_{crop,MLRA,CSA}$	Ratio of crop grain yields between CSA and baseline scenarios for the MLRA. This value is calculated in Equation 6.
$dSOC_{crop,MLRA,base}$	The annualized change in SOC [Mg C/ha] for the baseline scenario allocated by crop for each MLRA. This value is calculated in Equation 5.
$Yield_{crop,MLRA,base}$	The average crop yield [bu/ha] for the MLRA reported by NASS.

The dSOC value in grams C per bushel can be converted to grams of CO_2e per bushel by multiplying by a conversion factor.

Equation 8. Final calc for the change in dSOC/bu from CSA adoption in g CO₂ per bu

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

Where:

$dSOC/bu_{crop,MLRA,CSA}\ [CO_2e/bu]$	The final change in SOC per bushel from CSA adoption for the crop and MLRA converted to carbon intensity of potential grams of CO_2 per bushel.

2.5 Develop Proxies for MLRAs Without Modeled Data

Data outputs are not available for some MLRAs due to disclosure issues that arise when there are too few NRI points within the MLRA. There are 70 unique MLRAs that are missing modelling results but have recorded crop production across the three feedstock crops over the past 5 years (data years 2018-2023, NASS 2024). For these MRLAs, proxy values were generated using the average dSOC per bushel for each Land Resource Region (LRR) (USDA 2022b). Each MLRA is 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.

3 Nitrous Oxide (N_2O) Emission Methodology

For every MLRA, rotation, crop, and CSA practice combination, DAYCENT and SALUS[5] modeled soil nitrogen (N) values in grams N per meter squared (m^2) for (1) synthetic fertilizer application, (2) crop residues from all crops in any given rotation, (3) manure applied to soils as fertilizer, and (4) all other sources of N, including net mineralization, nitrogen deposition, and non-symbiotic soil N fixation. Synthetic fertilizer and crop residue N are the two sources of N that R&D GREET attributes to crop-based biofuels production. Since the other two N sources are not associated with crop-based biofuels production, they were excluded from this analysis. Aligning the N sources within USDA FD-CIC with the N sources in R&D GREET is important for internal consistency. This is because, as described previously, the change in GHG emissions in the modeled CSA scenarios is debited from the R&D GREET default value to arrive at a final parameter value.

3.1 Calculate Rotation N_2O and N Input

The rotation N input and N_2O emissions are calculated by summing all the crops in the rotation. This sum takes into account the differing frequency of crops in the rotation.

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[5] Only DAYCENT modeled manure application to soils. SALUS did not model manure application.

Equation 9. Sum DAYCENT N in rotation

$$N_{MLRA,rotation,CSA} = \sum_{0}^{j} N_{MLRA,rotationcrop,CSA} \times CP_{MLRA,rotation,crop}$$

Equation 10. Sum DAYCENT direct and indirect N_2O for all unique MLRA, rotation, and CSA practice combinations

$$Direct\ N2O_{MLRA,rotation,CSA} = \sum_{0}^{j} Direct\ N2O_{MLRA,rotation,crop,CSA} \times CP_{MLRA,rotation,crop}$$

$$Indirect\ N2O_{MLRA,rotation,CSA} = \sum_{0}^{j} Indirect\ N2O_{MLRA,rotation,crop,CSA} \times CP_{MLRA,rotation,crop}$$

Where there was only one crop in the rotation, e.g., continuous corn, the modeled total crop N is equal to the total rotation N.

Where:

j	The number of crops in the rotation.
$N_{MLRA,rotation,CSA}$	Total nitrogen (N) input values [g N/m^2] for the rotation.
$N\ _{MLRA,rotation,crop,CSA}$	Total system nitrogen (N) values [g N/m^2] from all N sources for the feedstock crop. This value is provided by DAYCENT and SALUS.
$CP_{MLRA,rotation,crop}$	The average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation. This value is provided by DAYCENT and SALUS.
$Direct\ N2O_{MLRA,rotation,CSA}$	Total direct N_2O emissions [kg N_2O-N/ha] for the rotation.
$Direct\ N2O_{MLRA,rotation,crop,CSA}$	Direct N_2O emissions [kg N_2O-N/ha] for the crop. This value is provided by DAYCENT and SALUS.
$Indirect\ N2O_{MLRA,rotation,CSA}$	Total indirect N_2O [kg N_2O-N/ha] emissions for the rotation.
$Indirect\ N2O_{MLRA,rotation,crop,CSA}$	Indirect N_2O emissions [kg N_2O-N/ha] for the crop for every rotation. This value is provided by DAYCENT and SALUS.

3.2 Allocate N_2O Emissions Among Feedstocks

DAYCENT and SALUS also output total direct and indirect N_2O emissions in kilograms per hectare N (kgha_N). DAYCENT cannot distinguish between N sources once N has entered the soil. Therefore, the proportions of N added to the soil were used to determine the amount of direct and indirect N_2O emissions attributed to synthetic fertilizer application and crop residues. This is the same mass balance-based allocation approach used for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA, 2024).

The direct and indirect N_2O from synthetic fertilizer and crop residues were allocated to each crop in the rotation by multiplying the rotation total N_2O emissions by the fraction of N input for each crop. The result is the allocated crop-specific direct and indirect N_2O emissions from fertilizer application and crop residue decay for each MLRA, rotation, and CSA scenario. Where there was only one crop in the rotation, e.g., continuous corn, the total N_2O emissions in the rotation will equal the N_2O emissions attributed to that crop.

Calculate crop-specific N fractions and rotation direct and indirect N_2O

Equation 11. Determine fraction of total N attributed to synthetic fertilizer

$$fracN_{fert,MLRA,rotation,crop,CSA} = \frac{N_{fert,MLRA,rotation,crop,CSA} \times CP_{MLRA,rotation,crop}}{N_{MLRA,rotation,CSA}}$$

Equation 12. Determine fraction of total N attributed to crop residues

$$fracN_{CR,MLRA,rotation,crop,CSA} = \frac{N_{CR,MLRA,rotation,crop,CSA} \times CP_{MLRA,rotation,crop}}{N_{MLRA,rotation,CSA}}$$

Equation 13. Determine the fraction of total N attributed to synthetic fertilizer and crop residues

$$fracN_{MLRA.rotation,crop,CSA} = fracN_{fert,MLRA,rotation,crop,CSA} + fracN_{CR,MLRA,rotation,crop,CSA}$$

Where:

$fracN_{fert,MLRA,rotation,crop,CSA}$	N input from crop synthetic fertilizer as a fraction of the total rotation N.
$N_{fert,MLRA,rotation,crop,CSA}$	N input in grams N/m^2 from synthetic fertilizer application for the feedstock crop. This value is provided by DAYCENT and SALUS.
$CP_{MLRA,rotation,crop}$	The average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation. This value is provided by DAYCENT and SALUS.
$N_{MLRA,rotation,CSA}$	Total N input values in grams N/m^2 for the rotation. This is calculated in Equation 8.
$fracN_{CR,MLRA,rotation,crop,CSA}$	N input from crop residue as a fraction of the total rotation N.
$N_{CR,MLRA,rotation,crop,CSA}$	N values in grams N/m^2 for the feedstock crop. This value is provided by DAYCENT and SALUS.
$fracN_{MLRA.rotation,crop,CSA}$	N from crop synthetic fertilizer and crop residue as a fraction of the total rotation N.

Equation 14. Allocate rotation direct and indirect N_2O to the crops in the rotation

$$Direct\ N2O_{fert/CR,MLRA,rotation,crop,CSA} = Direct\ N2O_{MLRA,rotation,CSA} \times fracN_{MLRA.rotation,crop,CSA}$$

$$Indirect\ N2O_{fert/CR,MLRA,rotation,crop,CSA} = Indirect\ N2O_{MLRA,rotation,CSA} \times fracN_{MLRA.rotation,crop,CSA}$$

Where:

$Direct\ N2O_{fert/CR,MLRA,rotation,crop,CSA}$	Direct N_2O emissions [kg N_2O-N/ha] from synthetic fertilizer and crop residues for the feedstock crop.
$Indirect\ N2O_{fert/CR,MLRA,rotation,crop,CSA}$	Indirect N_2O emissions [kg N_2O-N/ha] from synthetic fertilizer and crop residues for the feedstock crop.
$Direct\ N2O_{MLRA,rotation,CSA}$	Direct N_2O emissions [kg N_2O-N/ha] for the rotation. This is calculated in Equation 10.
$Indirect\ N2O_{MLRA,rotation,CSA}$	Indirect N_2O emissions [kg N_2O-N/ha] for the rotation. This is calculated in Equation 10.
$fracN_{MLRA.rotation,crop,CSA}$	N from crop synthetic fertilizer and crop residue as a fraction of the total rotation N. This is calculated in Equation 12.

3.3 Account for Changes in Yield from CSA

Crop yield can impact feedstock CI scores. The direct and indirect rotation-specific CI factors in kg N_2O-N per ha are divided by the crop-specific DAYCENT modeled yield to account for changes in yield from CSA adoption.

Equation 15. Adjust Direct and Indirect crop N_2O to account for changes in yield

$$Direct\ N2Oyield_{MLRA,rotation,crop,CSA} = \frac{Direct\ N2O_{fert/CR,MLRA,rotation,crop,CSA}}{DayCENT\ Yield_{MLRA,rotation,crop,CSA}}$$

$$Indirect\ N2Oyield_{MLRA,rotation,crop,CSA} = \frac{Indirect\ N2O_{fert/CR,MLRA,rotation,crop,CSA}}{DayCENT\ Yield_{MLRA,rotation,crop,CSA}}$$

Where:

$Direct\ N2Oyield_{MLRA,rotation,crop,CSA}$	Direct N_2O emissions [kg N_2O-N*m^2/ha/g C][6] for the crop, adjusted for changes in yield.
$Indirect\ N2Oyield_{MLRA,rotation,crop,CSA}$	Indirect N_2O emissions [kg N_2O-N*m^2/ha/g C][6] for the crop, adjusted for changes in yield.
$DayCENT\ Yield_{MLRA,rotation,crop,CSA}$	Crop simulated yield [g C/m^2]
$Direct\ N2O_{fert/CR,MLRA,rotation,crop,CSA}$	Direct N_2O emissions [kg N_2O-N/ha] from synthetic fertilizer and crop residues for the feedstock crop. This is calculated in Equation 14.

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[6] The final carbon intensity factor for N_2O emissions will be presented as a percent change, a unit conversion to kg N_2O-N/g C was considered unnecessary as it does not affect the percent change, and therefore was omitted.

$Indirect\ N2O_{fert/CR,MLRA,rotation,crop,CSA}$	Indirect N_2O emissions [kg N_2O-N/ha] from synthetic fertilizer and crop residues for the feedstock crop. This is calculated in Equation 14.

3.4 Aggregating Output Across Rotations

The rotation-specific N_2O per unit yield was aggregated to determine average CI factors per MLRA, crop, and CSA practice. 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 ($RP_{rotation,MLRA}$). This value is also used for SALUS. Additionally, DAYCENT and SALUS provide 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 16. 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 and SALUS.

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 17. Aggregate rotation direct and indirect N_2O yield by MLRA

$$MLRA\ Direct\ N2O_{MLRA,crop,CSA} = Direct\ N2Oyield_{MLRA,rotation,crop,CSA} \times CRP_{crop,rotation,MLRA}$$

$$MLRA\ Indirect\ N2O_{MLRA,crop,CSA} = Indirect\ N2Oyield_{MLRA,rotation,crop,CSA} \times CRP_{crop,rotation,MLRA}$$

Where:

$Direct\ N2Oyield_{MLRA,rotation,crop,CSA}$	Direct N_2O emissions [kg N_2O-N/unit yield][6] for the crop, adjusted for changes in yield. This is calculated in Equation 15.
$Indirect\ N2Oyield_{MLRA,rotation,crop,CSA}$	Indirect N_2O emissions [kg N_2O-N/unit yield][6] for the crop, adjusted for changes in yield. This is calculated in Equation 15.
$DayCENT\ Yield_{crop}$	Crop-specific DAYCENT modeled yield [g C/m^2]
$MLRA\ Direct\ N2O_{MLRA,crop,CSA}$	Direct N_2O [kg N_2O-N/unit yield] for the CSA scenario aggregated by crop and MLRA.
$MLRA\ Indirect\ N2O_{MLRA,crop,CSA}$	Indirect N_2O [kg N_2O-N/unit yield] for the CSA scenario aggregated by crop and MLRA.

3.5 Calculate Percent Change in N_2O emissions from CSA practice

The change in carbon intensity was determined as the difference between any given CSA practice scenario to its respective baseline (current practice adoption). The difference was estimated as a percent difference so it can be multiplied by the R&D GREET's national-level default baseline direct and indirect N_2O emission intensity parameters.

Equation 18. Change in direct and indirect N_2O emissions from CSA adoption

$$\%\ change\ MLRA\ Direct\ N2O = \frac{MLRA\ Direct\ N2O_{MLRA,crop,CSA} - MLRA\ Direct\ N2O_{MLRA,crop,base}}{MLRA\ Direct\ N2O_{MLRA,crop,base}}$$

$$\%\ change\ MLRA\ Indirect\ N2O = \frac{MLRA\ Indirect\ N2O_{MLRA,crop,CSA} - MLRA\ Indirect\ N2O_{MLRA,crop,base}}{MLRA\ Indirect\ N2O_{MLRA,crop,base}}$$

Where:

$MLRA\ Direct\ N2O_{MLRA,crop,CSA}$	Direct N_2O [kg N_2O-N/unit yield] for the CSA scenario aggregated by crop and MLRA.
$MLRA\ Indirect\ N2O_{MLRA,crop,CSA}$	Indirect N_2O [kg N_2O-N/unit yield] for the CSA scenario aggregated by crop and MLRA.
$\%\ change\ MLRA\ Direct\ N2O$	% difference between CSA-specific Direct N_2O [kg N_2O-N/ha/unit yield] and the baseline (current practice adoption) scenario.
$\%\ change\ MLRA\ Indirect\ N2O$	% difference between crop, CSA-specific Indirect N_2O [kg N_2O-N/ha/unit yield] and the baseline (current practice adoption) scenario.

3.6 Develop Proxies for MLRAs Without Modeled Data

Data outputs are not available for some MLRAs due to disclosure issues that arise when there are too few NRI points within the MLRA. There are 70 unique MLRAs that are missing modelling results but have recorded crop production across the three feedstock crops over the past 5 years (data years 2018-2023, NASS 2024). For these MRLAs, proxy values were generated using the average percent change in direct and indirect N_2O emissions for each Land Resource Region (LRR) (USDA 2022b).

Each MLRA is 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.

3.7 Adjust DAYCENT N_2O Results to Use a BAU Baseline for Corn

DAYCENT modelled N fertilizer with spring N fertilizer application for corn, sorghum, and soybeans. However, 2016 and 2022 USDA NASS survey data (REF) indicates that N fertilizer is currently applied to corn with a mix of fall, fall/spring split and spring application. As N application timing can impact N_2O emissions, with fall N application resulting in increased N losses compared to spring N application, ICF developed methodology to more accurately reflect current N practices for corn. The SALUS model was used to model fall, spring, and fall-spring split N application for two different corn rotations (corn-soy and continuous corn) at the MLRA level. A weighted average of these practices was used to estimate MLRA- and rotation-specific direct and indirect N_2O emissions for current N application timing. Fertilizer levels were chosen such that modeled yields were held constant in SALUS, which would limit the impact that the change would have on SOC fluxes. As is consistent with current practice, soybeans and sorghum were only modeled with spring N application.

A new baseline N_2O emissions level for corn was constructed in two steps. First, the emissions level corresponding to the percent change in direct N_2O emissions was calculated, where the change was between the two SALUS scenarios of a spring-only fertilizer application scenario and a scenario with both fall and spring application. Second, this emissions level was added to the DAYCENT N_2O baseline to establish a new baseline. The same approach was conducted for indirect N_2O emissions.

This new N application emissions scenario for corn implies that a spring N application can be established as a CSA practice for corn.

Equation 19. Apply fall-to-spring (F2S) adjustment to CSU CSA scenarios

$$CSU\ \%\ change\ MLRA\ Direct\ N2O \\ = [\%\ change\ MLRA\ Direct\ N2O]_{spring\ CSA} + [\%\ change\ MLRA\ Direct\ N2O]_{F2S}$$

$$CSU\ \%\ change\ MLRA\ Indirect\ N2O \\ = [\%\ change\ MLRA\ Indirect\ N2O]_{spring\ CSA} + [\%\ change\ MLRA\ Indirect\ N2O]_{F2S}$$

Where:

$CSU\ \%\ change\ MLRA\ Direct\ N2O$	% change in Direct N_2O for the CSA scenario aggregated by crop and MLRA.
$CSU\ \%\ change\ MLRA\ Indirect\ N2O$	% change in Indirect N_2O for the CSA scenario aggregated by crop and MLRA.
$[\%\ change\ MLRA\ Direct\ N2O]_{CSA}$	% difference between spring application CSA-specific direct N_2O and the spring baseline scenario.
$[\%\ change\ MLRA\ Direct\ N2O]_{F2S}$	% difference between spring application CSA-specific direct N_2O and the BAU N-application timing baseline scenario.
$[\%\ change\ MLRA\ Indirect\ N2O]_{CSA}$	% difference between spring application CSA-specific indirect N_2O and the spring baseline scenario.

$[\%\ change\ MLRA\ Indirect\ N2O]_{F2S}$	% difference between spring application CSA-specific indirect N_2O and the BAU N-application timing baseline scenario.

3.8 Adjust CSU Cover Crop Adoption Rates

DAYCENT includes MRLA-level data of cover crop adoption rates in its baseline estimates of soil carbon accumulation and nitrous oxide emissions by rotation and crop. DAYCENT derived cover crop adoption rates using data from the Operational Tillage Information System (OpTIS), supplemented with data from the USDA Conservation Effects Assessment Project (CEAP) and older versions of the USDA Census of Agriculture. At the national level, the 2022 Census of Agriculture shows lower cover crop adoption on average than DAYCENT (USDA 2024).

Because of the discrepancy in baseline cover crop adoption within DAYCENT and 2022 Census of Agriculture data, USDA revised the cover crop adoption rates to ensure consistency with the USDA Census of Agriculture and applied this adjustment to the DAYCENT cover crop practice cases.

The first step of the adjustment is to aggregate county-level cover crop rates of adoption from 2022 USDA Census of Agriculture into MLRA regions. Next, the differences between the 2022 Census of Agriculture cover crop adoption and the OpTIS cover crop data used by DAYCENT were calculated by MLRA. Cover-crop-only CSA cases for each rotation were used to estimate the absolute changes in dSOC, direct N_2O, and indirect N_2O that would result from the change in default cover crop adoption. The changes are then added or subtracted to the values provided by DAYCENT.

Equation 20. Cover crop area adjustment to CSU cover crop scenarios

$$Adj\_dSOC_{rotation,MLRA,ccR} = (USDA\_CCP_{MLRA} - CCP_{rotation,MLRA,base}) \times \frac{(dSOC_{rotation,MLRA,ccR\ only} - dSOC_{rotation,MLRA,base})}{(CCP_{rotation,MLRA,ccR\ only} - CCP_{rotation,MLRA,base})}$$

$$Adj\_\ MLRA\ Direct\ N2O = (USDA\_CCP_{MLRA} - CCP_{rotation,MLRA,base}) \times \frac{(MLRA\ Direct\ N2O_{MLRA,crop,ccR\ only} - MLRA\ Direct\ N2O_{MLRA,crop,base})}{(CCP_{rotation,MLRA,ccR\ only} - CCP_{rotation,MLRA,base})}$$

$$Adj\_\ MLRA\ Indirect\ N2O = (USDA\_CCP_{MRLA} - CCP_{rotation,MLRA,base}) \times \frac{(MLRA\ Indirect\ N2O_{MLRA,crop,ccR\ only} - MLRA\ Indirect\ N2O_{MLRA,crop,base})}{(CCP_{rotation,MLRA,ccR\ only} - CCP_{rotation,MLRA,base})}$$

Where:

$Adj\_dSOC_{rotation,MLRA,ccR}$	Adjustment to dSOC for high cover crop cases, by rotation and MLRA [Mg C/ha].

$Adj\_\ MLRA\ Direct\ N2O$	Adjustment to direct N_2O for high cover crop cases, by crop, rotation, and MLRA [kg N_2O-N/ha].
$Adj\_\ MLRA\ Indirect\ N2O$	Adjustment to indirect N_2O for high cover crop cases, by crop, rotation, and MLRA [kg N_2O-N/ha].
$USDA\_CCP_{MLRA}$	USDA cover crop area proportion from Census of Agriculture, by MLRA
$CCP_{rotation,MLRA,base}$	DAYCENT cover crop area proportion under base case practices, including BAU cover crop adoption, by rotation and MLRA.
$CCP_{rotation,MLRA,ccR\ only}$	DAYCENT cover crop area proportion for cases with cover crops as the single CSA practice, by rotation and MLRA.
$dSOC_{rotation,MLRA,ccR\ only}$	DAYCENT annualized change in soil organic carbon stocks for cover crops as the single CSA practice, by rotation and MLRA [Mg C/ha].
$dSOC_{rotation,MLRA,base}$	DAYCENT annualized change in soil organic carbon stocks for base case practices, including BAU cover crop adoption, by rotation and MLRA [Mg C/ha].
$MLRA\ Direct\ N2O_{MLRA,crop,ccR\ only}$	Direct N_2O [kg N_2O-N/ha] emissions for cases with cover crops as the single CSA practice, by rotation and MLRA. In
$MLRA\ Direct\ N2O_{MLRA,crop,base}$	Direct N_2O [kg N_2O-N/ha] for base case practices, including BAU cover crop adoption, by rotation and MLRA. In kg N_2O/ha.
$MLRA\ Indirect\ N2O_{MLRA,crop,ccR\ only}$	Indirect N_2O [kg N_2O-N/ha] emissions for cases with cover crops as the single CSA practice, by rotation and MLRA.
$MLRA\ Indirect\ N2O_{MLRA,crop,base}$	Indirect N_2O [kg N_2O-N/ha] for base case practices, including BAU cover crop adoption, by rotation and MLRA

4 On-Farm Fuel Use Methodology

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 CSA practices can impact both the number of field passes and the equipment used, depending on the practice(s) adopted.

Fuel use for the following activities was estimated to develop both baseline fuel use impacts and changes in fuel impacts for CSA 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 CSA practice adoption.

Table 1: Fuel use values in gallons of diesel per acre by crop and management practice.

Activity	**Corn (gal/acre)**	**Soy (gal/acre)**	**Sorghum (gal/acre)**	**Reference**
Tillage and Planting: conventional till	5.4	5.4	5.4	CEAP
Tillage and Planting: reduced till	3.1	3.1	3.1	CEAP
Tillage and Planting: no till	1.8	1.8	1.8	CEAP
Fertilizer application	Variable by MLRA[7]	0.44	0.44	Average fuel use based on multiple sources
Pesticide fuel use	0.3	0.3	0.3	Average fuel use based on multiple sources—MACC report
Harvesting (combine)	1.45	1	1.23[8]	Fuel Required for Field Operations—Machinery Management
Cover crop planting	0.62	0.62	0.62	Average fuel use based on multiple sources—MACC report
Cover crop termination (chemical)	0.3	0.3	0.3	Average fuel use based on multiple sources—MACC report

4.1 Estimate Baseline Fuel Use

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

Equation 21. Fuel use from tillage practices

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

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[7] As described in more detail in the current adoption of N practices and timing section.

[8] 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.

Where:

$Tillage\ Fuel\ Use$	Fuel used for tillage practices [gal/acre].
$FracTill_{Intensive_{MLRA,Rotation,Crop,CSA}}$	Fraction of area dedicated to full-till practices.
$FracTill_{No_{MLRA,Rotation,Crop,CSA}}$	Fraction of area dedicated to no-till practices.
$FracTill_{Reduced_{MLRA,Rotation,Crop,CSA}}$	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 22. 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].
$CCP_{MLRA,Rotation,Crop,CSA}$	% 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 23. Fuel use from fertilizer application

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

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: RF10split (CSU), _FSN (MSU), _SSN(MSU)

Equation 24. 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 25. 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 26. 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].

4.2 Estimate CSA Fuel-Use Changes

CSA practice adoption was assumed to impact baseline fuel use if adoption of a specific CSA practice changed 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 CSA 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)
- RF10split (split application with 10% reduction in N application)
- Fall to spring shift (only for corn)

Using the same criteria, it was assumed that adoption of the following CSA 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.

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Appendix A: Acronyms and Variable Definitions

General Acronyms:

Acronym	Definitions
BAU	Business as usual/Baseline
CI	Carbon intensity
CO_2	Carbon dioxide
CSA	Climate smart agriculture
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	ANL's Feedstock Carbon Intensity Calculator
MSU	Michigan State University
NRI	National Resources Inventory
SALUS	System Approach for Land Use Sustainability model

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
WWSC	Wheat-wheat spring canola

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
Fertilizer	CRF	Controlled release fertilizer
Fertilizer	PA	Precision application
Fertilizer	RF10split	Split fertilizer application with a 10% rate reduction
Fertilizer	FN	Fall nitrogen
Fertilizer	SN	Spring nitrogen
Fertilizer	Split	Spring split application nitrogen
Fertilizer	F2S	Switch from BAU_FSN to SN

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 total biomass (above and belowground) relative to the rotation's total biomass per unit area
$CP_{(crop,rotation,MLRA)}$	Average proportion of annual area of the feedstock crop and any "Other" crop/silage in the rotation

Acronym	Definitions
$RP_{(rotation,MLRA)}$	Proportion of the area each crop rotation relative to the total simulated area in each MLRA
$CY_{(crop,rotation,MLRA,CSA)}$	Crop grain yield [g C/m^2] for the CSA 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
$RCY_{(crop,rotation,MLRA,CSA)}$	Ratio of crop grain yields between CSA and baseline scenarios
$CRP_{(crop,rotation,MLRA)}$	Proportion of an MLRA's crop production that is attributable to a specific rotation
$dSOC_{(crop,MLRA,CSA)}$	Annualized change in SOC per ha for the CSA scenario allocated by crop for each MLRA
$Yield_{(crop,MLRA,base)}$	Average crop yield [bu/ha] for the MLRA
$\Delta dSOC/bu_{(crop,MLRA,CSA)}$	Final change in SOC [Mg C/bu] from CSA adoption for the crop and MLRA
$dSOC_{(crop,MLRA,base)}$	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
$dSOC_{(crop,rotation,MLRA,CSA)}$	Annualized change in SOC [Mg C/ha] allocated by crop for each rotation and MLRA
$RCY_{(crop,MLRA,CSA)}$	Ratio of crop grain yields between CSA and baseline scenarios for the MLRA
$dSOC/bu_{(crop,MLRA,CSA)\ [CO2e/bu]}$	Final change in SOC [Mg C/bu] from CSA adoption for the crop and MLRA converted to potential grams of CO$_2$ per bu
$dSOC/bu_{(crop,CSA)\ [CO2e/bu]}$	Final national weighted average change in SOC [Mg C/bu] from CSA adoption for the crop converted to potential grams of CO$_2$e per bu

N$_2$O Allocation Variable Acronyms:

Acronym	Definitions
base	Baseline
j	Number of crops in the rotation
$N_{(crop,MLRA,CSA)}$	Total Nitrogen (N) input values in grams N per meter^2 for the rotation

Acronym	Definitions
$N_{(MLRA,rotation,crop,CSA)}$	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 $N_2O_{(MLRA,rotation,CSA)}$	Total direct N_2O emissions for the rotation [kg N_2O–N/ha]
Direct $N_2O_{(MLRA,rotation,crop,CSA)}$	Direct N_2O emissions for the crop [kg N_2O–N/ha]
Indirect $N_2O_{(MLRA,rotation,CSA)}$	Total indirect N_2O [kg N_2O–N/ha] emissions for the rotation
Indirect $N_2O_{(MLRA,rotation,crop,CSA)}$	Indirect N_2O [kg N_2O–N/ha] emissions for the crop for every rotation
$fracN_{(fert,MLRA,rotation,crop,CSA)}$	Nitrogen (N) input from crop synthetic fertilizer as a fraction of the total rotation N
$N_{(fert,MLRA,rotation,crop,CSA)}$	Nitrogen (N) input [g N/m^2] from synthetic fertilizer application for the feedstock crop
$N_{(MLRA,rotation,CSA)}$	Total Nitrogen (N) input values [g N/m^2] for the rotation
$fracN_{(CR,MLRA,rotation,crop,CSA)}$	Nitrogen (N) input from crop residue as a fraction of the total rotation N
$N_{(CR,MLRA,rotation,crop,CSA)}$	Nitrogen (N) values [g N/m^2] for the feedstock crop
$fracN_{(MLRA,rotation,crop,CSA)}$	Nitrogen (N) from crop synthetic fertilizer and crop residue as a fraction of the total rotation N
Direct $N_2O_{(fert/CR,MLRA,rotation,crop,CSA)}$	Direct N_2O emissions [kg N_2O–N/ha] from synthetic fertilizer and crop residues for the feedstock crop
Indirect $N_2O_{(fert/CR,MLRA,rotation,crop,CSA)}$	Indirect N_2O emissions [kg N_2O–N/ha] from synthetic fertilizer and crop residues for the feedstock crop
Direct $N_2O_{(MLRA,rotation,CSA)}$	Direct N_2O emissions [kg N_2O–N/ha] for the rotation.
Indirect $N_2O_{(MLRA,rotation,CSA)}$	Indirect N_2O emissions [kg N_2O–N/ha] for the rotation.
Direct N_2O $yield_{(MLRA,rotation,crop,CSA)}$	Direct N_2O emissions [kg N_2O–N*m^2/ha/g C]* for the crop, adjusted for changes in yield
Indirect N_2O $yield_{(MLRA,rotation,crop,CSA)}$	Indirect N_2O emissions [kg N_2O–N*m^2/ha/g C]* for the crop, adjusted for changes in yield
DAYCENT $Yield_{(MLRA,rotation,crop,CSA)}$	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

Acronym	Definitions
$CP_{(crop,rotation,MLRA)}$	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 $yield_{(MLRA,crop,CSA)}$	Direct N_2O [kg N_2O-N/unit yield] for the CSA scenario aggregated by crop and MLRA
MLRA Indirect N_2O $yield_{(MLRA,crop,CSA)}$	Indirect N_2O [kg N_2O-N/unit yield] for the CSA scenario aggregated by crop and MLRA
% change MLRA Direct N_2O	% difference between CSA-specific direct N_2O and the baseline (current practice adoption) scenario
% change MLRA Indirect N_2O	% difference between crop, CSA-specific indirect N_2O and the baseline (current practice adoption) scenario
CSU % change MLRA Direct N_2O	% change in direct N_2O for the CSA scenario aggregated by crop and MLRA
CSU % change MLRA Indirect N_2O	% change in indirect N_2O for the CSA scenario aggregated by crop and MLRA
[% change MLRA Direct $N_2O]_{(CSA)}$	% difference between spring application CSA-specific direct N_2O and the spring baseline scenario
[% change MLRA Indirect $N_2O]_{(CSA)}$	% difference between spring application CSA-specific indirect N_2O and the spring baseline scenario
[% change MLRA Direct $N_2O]_{(FS2)}$	% difference between spring application CSA-specific direct N_2O and the BAU N-application timing baseline scenario
[% change MLRA Indirect $N_2O]_{(FS2)}$	% difference between spring application CSA-specific indirect N_2O and the BAU N-application timing baseline scenario

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

Acronym	Definitions
$\text{FracTill}_{\text{No}}$	Rate of fuel use for no-till practices [gal/acre]
$\text{FracTill}_{\text{Reduced}}$	Rate of fuel use for reduced-till practices [gal/acre]
CCFuel	Fuel use from cover crop practices
$\text{CCP}_{\text{(MLRA,rotation,crop,CSA)}}$	% 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 either in fall or spring
FertilizerPass	Rate of fuel use per fertilizer pass [gal/acre]
$\text{Frac}_{\text{Unfertilized}}$	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 $\text{Use}_{\text{soybeans}}$	Approximate rate of fuel use to harvest soybeans [gal/acre]
Combine Harvesting Fuel $\text{Use}_{\text{sorghum}}$	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: Explanation of SOC Allocation Methodology

In this analysis, we assume that the change in SOC (dSOC) is proportional to crop biomass. Therefore, the rotation's annualized 30-year change in SOC may be allocated between the crops in the rotation based on their biomass. For a single crop, this may be written as:

Equation A1:

$$dSOC_{crop} = A\ x\ BM_{crop}$$

Where A = a proportionality constant and BM_{crop} = crop biomass

The rotation's change in SOC may be written as a function of the dSOC contributions of each crop within the rotation. As an example, for a two-crop rotation:

Equation A2:

$$dSOC_{rotation} = dSOC_{crop1}\ x\ CP_1 + dSOC_{crop2}\ x\ CP_2$$

Where CP_1 and CP_2 refer to the crop area proportion variable provided by CSU which is assumed to represent the frequency of the crop in the rotation where:

$$CP_1 + CP_2 = 1$$

The rotation's dSOC may then be written as:

Equation A3:

$$dSOC_{rotation} = A\ x\ BM_1\ x\ CP_1\ x\ A\ x\ BM_2\ x\ CP_2$$

CSU also provides the biomass proportion (M_{crop}) for each crop in the rotation. This may be understood as:

Equation A4:

$$M_1 = \frac{BM_1\ x\ CP_1}{(BM_1CP_1 + BM_2CP_2)}$$

This may be re-arranged as:

$$BM_1 = \frac{M_1\ x\ (BM_1CP_1 + BM_2CP_{2)}}{CP_1}$$

Plugging this expression into Equation 1 we get:

$$dSOC_{crop} = A\ x\ \frac{M_1\ x\ (BM_1CP_1 +\ BM_2CP_2)}{CP_1}$$

Which simplifies to:

$$dSOC_{crop} = A\ x\ (BM_1CP_1 + BM_2CP_2)\ x\ \frac{M_1}{CP_1}$$

Substituting this for Equation A3, we see which is equal to **Equation 1**:

$$dSOC_{crop1} = dSOC_{rotation}\ x\ M_1/\ CP_1$$

Appendix C: CSA Scenarios Modeled by Crop

Table 2: Scenario list including cover crop applicability, tillage and fertilizer practice and timing by crop.

FD-CIC ID	Scenario Name	Cover Crop	Tillage	Fertilizer	Timing	Corn	Soy	Sorghum
1	base	no ccR	avgT	stnd	BAU_FSN	✓	✓	✓
2	F2S	no ccR	avgT	stnd	SN	✓		
3	RF10split	no ccR	avgT	RF10split	RF10split	✓	✓	✓
4	NI	no ccR	avgT	NI	BAU_FSN	✓	✓	✓
5	F2S_NI	no ccR	avgT	NI	SN	✓		
6	ccR	ccR	avgT	stnd	SN	✓	✓	✓
7	RF10split_ccR	ccR	avgT	RF10split	RF10split	✓	✓	✓
8	NI_ccR	ccR	avgT	NI	SN	✓	✓	✓
9	NTRT	no ccR	NTRT	stnd	BAU_FSN	✓	✓	✓
10	F2S_NTRT	no ccR	NTRT	stnd	SN	✓		
11	RF10split_NTRT	no ccR	NTRT	RF10split	RF10split	✓	✓	✓
12	NTRT_NI	no ccR	NTRT	NI	BAU_FSN	✓	✓	✓
13	F2S_NTRT_NI	no ccR	NTRT	NI	SN	✓		
14	NTRT_ccR	ccR	NTRT	stnd	SN	✓	✓	✓
15	RF10split_ccR_NTRT	ccR	NTRT	RF10split	RF10split	✓	✓	✓
16	NTRT_NI_ccR	ccR	NTRT	NI	SN	✓	✓	✓
17	RT	no ccR	RT	stnd	BAU_FSN	✓	✓	✓
18	F2S_RT	no ccR	RT	stnd	SN	✓		
19	RF10split_RT	no ccR	RT	RF10split	RF10split	✓	✓	✓
20	RT_NI	no ccR	RT	NI	BAU_FSN	✓	✓	✓
21	F2S_RT_NI	no ccR	RT	NI	SN	✓		
22	RT_ccR	ccR	RT	stnd	SN	✓	✓	✓
23	RF10split_ccR_RT	ccR	RT	RF10split	RF10split	✓	✓	✓
24	RT_NI_ccR	ccR	RT	NI	SN	✓	✓	✓
25	NT	no ccR	NT	stnd	BAU_FSN	✓	✓	✓
26	F2S_NT	no ccR	NT	stnd	SN	✓		
27	RF10split_NT	no ccR	NT	RF10split	RF10split	✓	✓	✓
28	NT_NI	no ccR	NT	NI	BAU_FSN	✓	✓	✓
29	F2S_NT_NI	no ccR	NT	NI	SN	✓		
30	NT_ccR	ccR	NT	stnd	SN	✓	✓	✓
31	RF10split_ccR_NT	ccR	NT	RF10split	RF10split	✓	✓	✓
32	NT_NI_ccR	ccR	NT	NI	SN	✓	✓	✓
33	NTIT	no ccR	NTIT	stnd	BAU_FSN	✓	✓	✓
34	F2S_NTIT	no ccR	NTIT	stnd	SN	✓		

FD-CIC ID	Scenario Name	Cover Crop	Tillage	Fertilizer	Timing	Corn	Soy	Sorghum
35	RF10split_NTIT	no ccR	NTIT	RF10split	RF10split	✓	✓	✓
36	NTIT_NI	no ccR	NTIT	NI	BAU_FSN	✓	✓	✓
37	F2S_NTIT_NI	no ccR	NTIT	NI	SN	✓		
38	NTIT_ccR	ccR	NTIT	stnd	SN	✓	✓	✓
39	RF10split_ccR_NTIT	ccR	NTIT	RF10split	RF10split	✓	✓	✓
40	NTIT_NI_ccR	ccR	NTIT	NI	SN	✓	✓	✓