ANL/ESD-21/12 Rev. 2

FEEDSTOCK CARBON INTENSITY CALCULATOR (FD-CIC)

Users' Manual and Technical Documentation

Energy Systems and Infrastructure Analysis Division

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FEE**D**STOCK **C**ARBON **I**NTENSITY **C**ALCULATOR **(FD-CIC)**

Users' Manual and Technical Documentation

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1. Introduction

The carbon intensities (CIs) of biofuels are determined with the life cycle analysis (LCA) technique, which accounts for the energy/material uses and emissions during the complete supply chain of biofuel including feedstock production and fuel conversion stages.

Regulatory agencies such as California Air Resources Board (CARB) adopt LCA to calculate biofuel CIs. The Low Carbon Fuel Standard (LCFS) program developed by CARB allows individual biofuel conversion facilities to submit their own biofuel CIs with their facility input data and incentivizes the reduction in the CI specific to that particular facility compared to a reference fuel's CI (Liu *et al* 2020). Such an incentive program has driven innovations in biorefineries to reduce their greenhouse gas (GHG) emissions by linking their revenue directly to its CI score through LCFS credit trading.

Besides the biofuel conversion stage, different farming practices for feedstock growth can result in significant CI variations for feedstocks, thus for biofuels. To provide evidence-based research findings, the U.S. Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) has supported the Systems Assessment Center of the Energy Systems and Infrastructure Analysis Division at Argonne National Laboratory to examine CI variations of different farming practices to grow agricultural crops for biofuel production. Meanwhile, the ARPA-E has launched the Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management (SMARTFARM) program to develop technologies and data platforms that enable an accurate measurement of key farming parameters that can help robust accounting of the GHG benefits of sustainable, low-carbon agronomic practices at farm level.

A transparent and easy-to-use tool for feedstock-specific, farm-level CI calculation of feedstocks is especially helpful. With the ARPA-E support, we have developed a tool - the Feedstock Carbon Intensity Calculator (FD-CIC). The first version of FD-CIC was released with the GREET® model in 2020 so that corn feedstock producers can use this publicly available tool to quantify corn grain CIs with farm-level input data and management practices. In the 2021 version, we expanded the tool's capabilities by including additional feedstocks such as soybean, sorghum, and rice. Like corn, it calculates the farm-level CI for these feedstocks by allowing user-defined farm-level farming inputs and incorporating the GHG emission intensities of these inputs from GREET (in particular, GREET1, the fuel cycle model of GREET). In the 2022 version, we included the CI calculation of important international feedstocks such as Canadian corn and Brazilian sugarcane.

In the 2023 version, we incorporate the multi-year crop rotation worksheets to account for multi-year LCA for common crop rotations, including corn-soybean (CS), continuous corn (CC), and corn-corn-soybean (CCS). Moreover, we redesign the input and result worksheets for single-year domestic crop farming. Furthermore, we update the assumption and calculation associated with the Right source, Right rate, Right time, and Right place (4R) practice.

Currently, dynamic and standalone versions of FD-CIC are available. The dynamic version interacts with the GREET model by directly reading the life-cycle inventory (LCI) data of key farming inputs from it. This version suits well when users want to change the GREET default settings that affect the GHG emission intensities of farming inputs. For example, if the users want to assess the impact of using a regional electricity grid mix to produce key farming inputs, instead of the U.S. average grid mix, they can modify the grid mix in the GREET model and utilize the interacting feature in the FD-CIC to re-read the updated CI values for those key farming inputs. The interacting feature also enables the CI values to be updated with the annual GREET release.

The standalone version is built for users who are not familiar with the GREET model and contains the GREET default LCI data for key farming inputs.

2. Description of FD-CIC

2.1 System boundary and key parameters

The system boundary of FD-CIC covers the cradle-to-farm-gate activities, including upstream emissions related to farming input manufacturing and feedstock production (Figure 1).

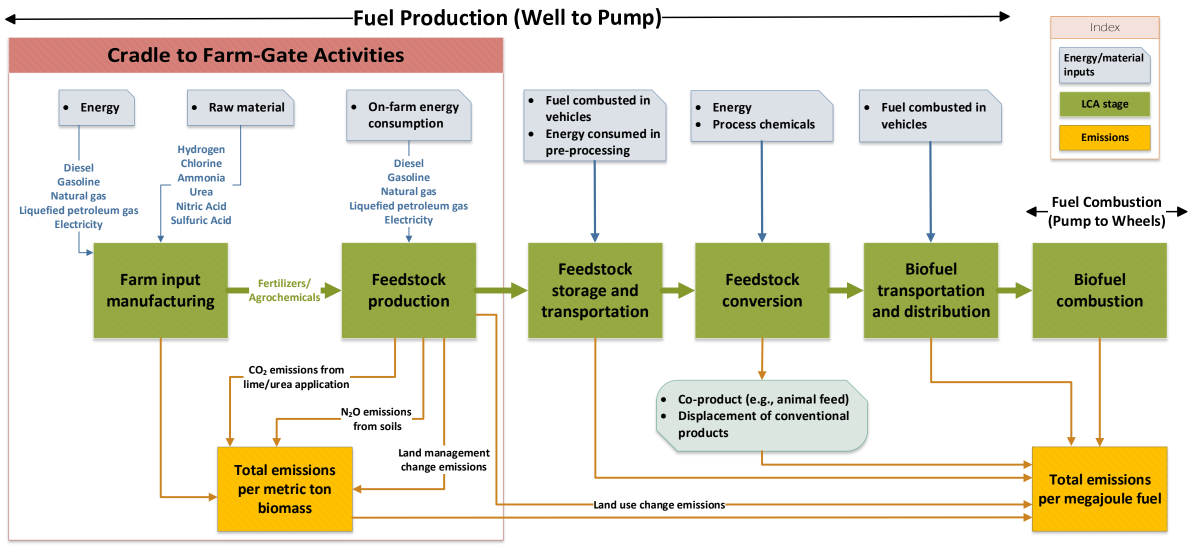

Figure 1: The system boundary of FD-CIC (i.e. cradle-to-farm-gate activities) compared to a complete supply chain of a biofuel (Modified from Liu *et al* (2021)).

The FD-CIC helps stakeholders assess the effects of changing farm-level input parameters on feedstock CI scores in the biofuel LCA context. Key parameters affecting feedstock CI include crop yield, fertilizers/chemicals application rates, and agronomic practices. Three key sources of GHG emissions from feedstock production are accounted for in FD-CIC, as detailed in the following three subsections.

2.2 Emissions from farming inputs and on-farm energy consumption

Farming inputs and on-farm energy consumption are the main LCI data required to estimate the GHG emissions associated with their upstream manufacturing and on-farm use. In FD-CIC, the users need to enter the usage amount per acre for fertilizer/chemical inputs and common energy carriers – diesel, gasoline, natural gas, liquefied petroleum gas, and electricity. If farms have not used a specific energy/fertilizer type, as defined in FD-CIC, the value for the specific type should be set to zero.

The GREET default farming input data are provided as references, which are derived from:

- Publicly available data and reports from U.S. Department of Agriculture (USDA)'s: National Agricultural Statistics Service (NASS), Economic Research Service (ERS), and Office of the Chief Economist.
- USDA ERS periodically compiled on-farm energy consumption data at the U.S. state level from the Agricultural Resource Management Survey (ARMS) for corn, soybean, and rice.
- National Sorghum Grower compiled on-farm energy consumption for sorghum.

Considering that the GREET default data for corn and soybean farming were originally derived from USDA statistics, which already factored in the effects of typical crop rotations (e.g., a corn-soybean rotation) on inputs and yields, we have chosen to use the GREET defaults as reference values for multi-year crop rotations as well. In an ideal scenario, USDA statistics for farming inputs, such as fertilizers, should differentiate between the impacts of various crop rotations for a specific crop.

2.3 Soil nitrous oxide emissions from nitrogen inputs

Two sources of nitrogen inputs to soil are considered in GREET and FD-CIC, namely, nitrogen from fertilizer application and nitrogen in crop residues left in the field after harvest. The content of nitrogen in crop residues was estimated using the harvest index and nitrogen contents of above- and below-ground biomass (Wang 2007). The nitrogen content in the fertilizers was determined by considering the user-specified application rate and the nitrogen content of the specific type of nitrogen fertilizer being used.

As with GREET, FD-CIC calculates soil nitrous oxide (N_2O) emissions associated with feedstock production using empirically derived emission factors (EFs), which assumes a linear relationship between nitrogen inputs and soil N_2O emissions. By default, FD-CIC employs a 1% N_2O EF to estimate the direct N_2O emissions from soil for crops other than flooded rice. For flooded rice production, the direct N_2O EF is 0.4% (IPCC 2019).

In addition to the direct N_2O emissions, N_2O can also be produced through indirect processes, which include the volatilization of nitrogen fertilizers, and the leaching and runoff of nitrate from fertilizers. GREET and FD-CIC adopt the indirect N_2O EFs from IPCC (2019) refinements, as summarized in Table 1.

Table 1. Indirect N_2O EFs (kg N_2O-N per kg N) in IPCC 2019 refinement

	Aggregated[1]		Disaggregate[1]		
Emission factor	**Default value**	**Uncertainty range**	**Climate zone**	**Default value**	**Uncertainty range**
EF_{leach} (leaching/runoff)	**0.011**	0 - 0.02			
$Frac_{leach}$	**0.24**		Wet	**0.24**	0.01 - 0.73
			Dry	**0**	
EF_{vol} (Volatilization)	**0.010**	0.002 – 0.018	Wet	**0.014**	0.011 – 0.017
			Dry	**0.005**	0.000 – 0.011
$Frac_{vol}$ from synthetic nitrogen fertilizer	**0.11**	0.02 – 0.33			
$Frac_{vol}$ from all organic nitrogen fertilizers applied, and dung and urine deposited by grazing animals	**0.21**	0.00 – 0.31			

[1] The values in bold is adopted in FD-CIC.

The total N_2O EFs (combining both direct and indirect emissions) used in FD-CIC for nitrogen derived from various sources are calculated using Eq. 1:

$$Total\ EF = Direct\ EF + Frac_{vol} * EF_{vol} + Frac_{leach} * EF_{leach} \quad \textbf{Eq. 1}$$

By default, it is 1.264% for crop residue, 1.374% for synthetic nitrogen fertilizers, and 1.474% for organic nitrogen fertilizers.

2.4 Soil organic carbon sequestration

Feedstock production can be managed to enhance soil organic carbon (SOC) sequestration with conservation farming practices, by either increasing carbon inputs to soils (via crop residues) and/or reducing carbon losses from soils (Paustian *et al* 2019). Without properly accounting for the change in SOC, the benefits introduced by the adoption of conservation practices tied to carbon sequestration and abatement may not be adequately quantified and incentivized.

FD-CIC accounts for the potential SOC changes associated with changes in farming practices, which are modeled using a parameterized version of the process-based CENTURY model at the U.S. county level (Liu et al 2020). The SOC changes are derived with a relative approach by comparing the difference in SOC stocks between baseline and alternative farming practices, in the unit of kilogram (kg) carbon per hectare per year. Thus, the user-specific yield data would not affect the SOC change per hectare, but the SOC change per bushel of feedstock produced. In this study, a baseline practice is set as a 2-year rotation of corn and soybean with reduced tillage.

The simulated SOC changes are incorporated to FD-CIC in the form of lookup tables. Once the users select the location of the farm, the crop rotation, and land management practices, such as tillage, cover crop, and manure, the corresponding SOC change results will be displayed. Note that positive SOC values represent CO_2 emissions while negative values represent SOC sequestration. For single-year LCA and SOC accounting, it is assumed that any farming options selected in the "Inputs_DomesticCrops" sheet are applied only to the selected crop in cell C3, therefore, all SOC gains and losses are attributed to this crop, by assuming there is no practice change in other crops (ANL 2023).

The detailed methodology for multi-year LCA and SOC allocation is discussed below in Section 2.5 Multi-year LCA methodology.

Note that as an important component in biofuel LCA, land use change (LUC)-induced emissions have been incorporated into biofuel CI calculation to account for SOC sequestration/GHG emissions associated with the shift in land use and land-cover for large-scale biofuel feedstock production. Such LUC-induced direct and indirect emissions are included in the Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) module of the GREET model (Kwon et al 2021).

2.5 Multi-year LCA methodology

To derive the crop-specific CI value, the landscape-based multiyear LCA results need to be allocated to individual crops involved in the rotation. As indicated in Figure 2, here are two major sources of GHG emissions from a crop-rotation. The first is GHG emissions associated with the production and consumption of farming energy and chemical inputs and is quantified based on the user-specific farm-level inputs for each crop in the rotation. The second part is the SOC change (ΔSOC, in g CO_2 equivalent (CO_2e)/acre/year) and additional GHG emissions associated with land management changes (LMC GHG, in g CO_2e/acre/year), which is quantified by allocating ΔSOC and LMC GHG between main crops in the selected rotation, based on crop-specific allocation factor, according to Eq. 2, using corn as an example:

$$(\Delta\text{SOC} + \text{LMC GHG})\ \text{allocated to corn} = (\Delta\text{SOC} + \text{LMC GHG}) * \text{number of year in rotation} * \text{allocation factor for corn} \quad \textbf{Eq. 2}$$

To derive the crop-specific allocation factor, the crop-specific allocation factor, Eq. 3 is applied, using corn as an example:

$$\text{Allocation factor for corn} = \frac{\text{Corn C inputs}}{\text{Corn C inputs} + \text{soybean C inputs}} \quad \textbf{Eq. 3}$$

where the crop-specific carbon (C) inputs are defined as the C content in aboveground residue and underground root biomass. They are calculated based on county-level crop yields, which are used to derive the amount of plant residue and root biomass returned to soil. With the carbon content of plant residue and root biomass, the crop-specific carbon (C) inputs for each crop can be quantified, in kg C/acre/year. For a 3-year rotation, such as corn-corn-soybean, the 1^{st} and 2^{nd} year corn are treated as different crops, and their allocation factors are derived separately.

The crop-specific LCA result (in g CO_2e/acre) is then calculated using Eq. 4, using corn as an example:

$$\begin{aligned}\text{Corn CI, landscape} &\\ &= \text{GHG emissions from corn farming inputs} \\ &+ (\Delta\text{SOC} + \text{LMC GHG}) \text{ allocated to corn}\end{aligned} \quad \textbf{Eq. 4}$$

Normalizing the landscape-level crop-specific LCA result with crop yield (in bu/acre), the per bushel crop-specific CI can be calculated in Eq. 5, in the unit of g CO_2e/bu, using corn as an example:

$$\text{Corn CI, bu} = \frac{\text{Corn CI, landscape}}{\text{Corn yield}} \quad \textbf{Eq. 5}$$

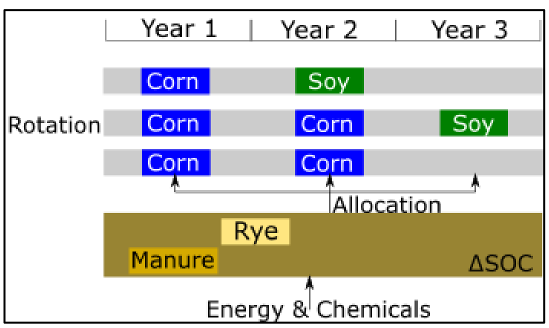

Figure 2: Allocation method employed in multi-year LCA.

3. Use of FD-CIC

3.1 Overview worksheet

The "Overview" worksheet contains the basic information regarding the organization of the FD-CIC, defines the color schemes for different types of parameters, and provides the key references that support the development of the FD-CIC.

3.2 Feedstock Selection worksheet

In the "Feedstock Selection" sheet, we differentiated between domestic and international feedstocks. Depending on users' interest in domestic vs international crops, and/or single vs multi-year LCA, they will be directed to the corresponding input sheets.

The users can activate/deactivate the stochastic simulation function by clicking the "Load Stochastic Toolkit"/ "Unload Stochastic Toolkit" button. In FD-CIC, we incorporated stochastic simulation capability to perform uncertainty analysis on feedstock CI estimates, leveraging the stochastic simulation capability of the GREET model (Subramanyan and Diwekar 2005). More details will be discussed below in Section 3.8 Stochastic simulation function.

The dynamic version has a control button named "Interact with GREET" while the standalone version does not. This function enables the interaction between the FD-CIC and the GREET model. Moreover, the GREET1 excel file should be put in the same folder on user's computer as with the FD-CIC tool to make this function work.

3.3 Inputs_DomesticCrops worksheet

In the previous FD-CIC designs, we included separate worksheets - "Inputs", "Intensities of Inputs", and "Results" for each feedstock considered.

However, as more feedstocks are being added to the tool, we redesign the input and result worksheets in FD-CIC 2023 for the sake of conciseness, so that a single "Inputs_DomesticCrops" worksheet handles the modelling of all domestic feedstocks.

In this worksheet, the user needs to first specify the crop they are interested in from the dropdown list and specify the location of the farm. Then, the user needs to click the "Update Management Options" button to update the management practices available for the crop of interest. For example, the 4R practice is only applicable to corn farming, therefore, when crops other than corn is selected, the selectors related 4R management practices would be greyed out (Figure 3).

After completing the left panel, the user needs to click the "Calculate Crop" button to update the calculation. This action will: 1) load the GREET default farming inputs for the crop of interest; 2) pre-fill the "User Specific Value" column with the GREET default values, based on which the user can make modifications (in the blue cells).

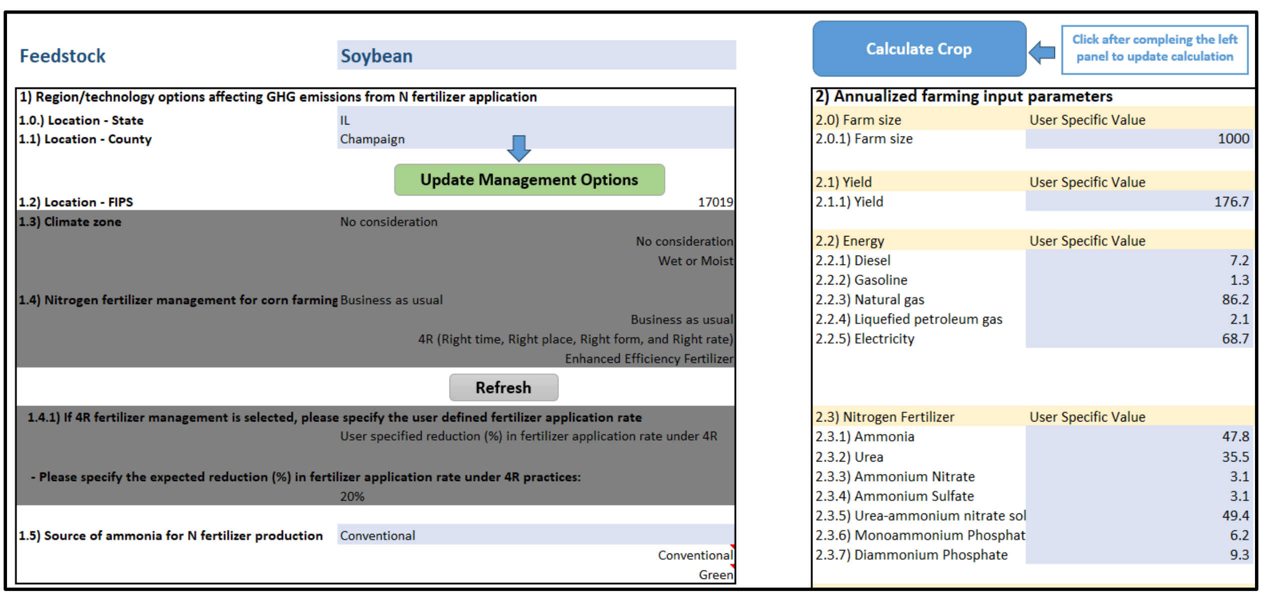

Figure 3: Land management practices and input panel in "Inputs_DomesticCrops" sheet

The FD-CIC tool uses U.S. customary units by default (e.g., pound per acre, short ton), followed by intermediate calculations to translate them into the GREET customary units for CI calculation (i.e., grams of GHG emitted per short ton of fertilizer or British Thermal Unit of energy), so that the CI coefficients obtained from the GREET model can be utilized. The units for fertilizers are in pounds of nutrient contents per acre, instead of pounds of products per acre. We have implemented this design because the manufacturing of herbicides and insecticides makes a relatively minor contribution to the overall CI of the feedstock, accounting for less than 2% of the total CI. If a user has a specific need to model the herbicide mix for their particular crop, they will need to utilize the dynamic version of FD-CIC. This involves making adjustments in the GREET model and then reloading the updated GREET upstream CI for the herbicide mix into FD-CIC.

3.3.1 Corn Specific Options

FD-CIC provides several regional/technological options for users to choose from and explore their impacts on the cradle-to-farm gate GHG emissions for corn farming:

Disaggregated N_2O EFs based on climate zone information

FD-CIC provides the option for the users to adopt the disaggregated direct soil N_2O EFs by climate zones (i.e. wet or dry) for corn farming, according to a meta-analysis of field experiment data collected from nine major corn-producing states (Xu *et al* 2019), as shown in Figure 4 and Table 1. It is worth mentioning that the IPCC (2019) also provided disaggregated direct N_2O EFs by climate. However, we chose not to employ their values since they are not crop specific and thus may not represent direct N_2O emissions from corn farming in U.S. Midwest, where corn-soybean rotation is a representative agricultural rotation.

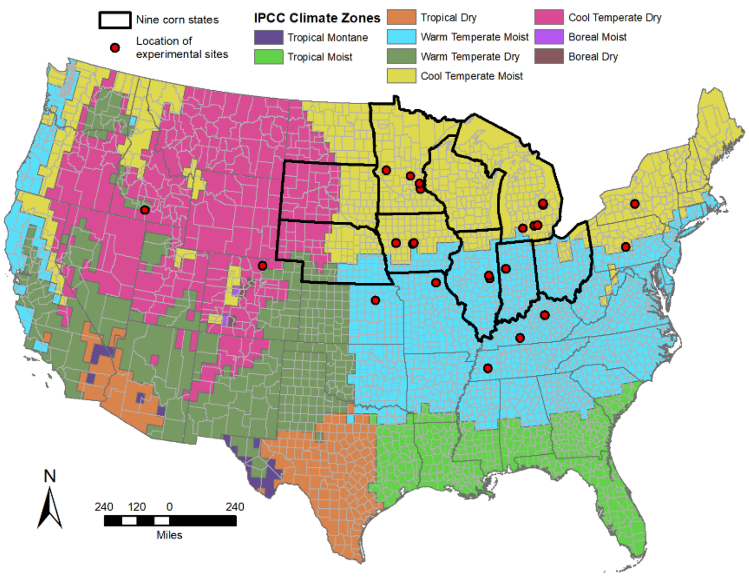

Figure 4: IPCC climate zone for the conterminous U.S and location of field experiments included in the expanded database of Xu *et al* (2019).

Table 2: The direct N_2O EFs (kg N_2O-N per kg N) disaggregated from Xu *et al* (2019) for corn farming

By climate	Mean[1]	Standard deviation	Sample size	Standard error	95% Confidence interval

Wet	**0.01**	0.012	200	0.0008	0.002
Dry	**0.005**	0.0039	94	0.0004	0.0008

[1] The values in bold is adopted in FD-CIC.

[2] The EFs are calculated as arithmetic averages of measurements from each experimental site to represent the entire climate zone, instead of weighted averages using crop production capacity as the weighting factor

To switch to climate zone specific N_2O EF, the user needs to specify the county in which their farm is located and then click the "Update Management Options" button. The dropdown list in item "1.3) Climate zone" would be updated based on the county selected. For example, if the farm is in Illinois, the dropdown list will be updated to "No consideration, Wet or Moist"; on the other hand, if the farm is in Arizona, the dropdown list will be updated to "No consideration, Dry". If the user selects "No consideration" from the dropdown list, the default direct N_2O EF will be used in the calculation, as has been discussed in Section 2.3 Soil nitrous oxide emissions from nitrogen inputs. Otherwise, the climate zone specific direct N_2O EF will be used, as summarized in Table 2**Error! Reference source not found.**.

Applying Enhanced Efficiency Fertilizer (EEF)

EEF reduces fertilizer-induced N_2O emissions but incurs additional GHG emissions in its upstream production. Nitrification inhibitor (NI) is a type of EEF, which slows down the nitrification process in which fertilizers are broken down to nitrates and N_2O. According to Thapa *et al* (2016), NI reduces N_2O emissions compared to conventional nitrogen fertilizer by 30%. This empirical value is adopted by FD-CIC. Nevertheless, FD-CIC has not accounted for the GHG emissions associated with the production and transportation of NI since it contributes only a minor proportion to the cradle-to-farm-gate GHG emissions for corn farming.

To explore the impact of EEF on farm-level corn CI, the user needs to select "Enhanced Efficiency Fertilizer" from the dropdown menu in item "1.4) Nitrogen fertilizer management for corn farming".

Using 4R (Right time, Right place, Right form, and Right rate) nitrogen fertilizer management

This management practice enhances nitrogen use efficiency while reducing direct N_2O emissions. In the previous version of FD-CIC, we employed a simplified nitrogen balance approach, as detailed in Eagle *et al* (2020) and assumed that whenever nitrogen inputs are managed by 4R practices, the nitrogen balance should be close to zero, which may be too optimistic and not practically feasible. Therefore, in FD-CIC 2023, we update our assumptions regarding the 4R practice. Evidence suggested that the right fertilizer rate is the most important factor in 4R management (Millar *et al* 2010). This process requires the estimation of "nitrogen need" from historical corn yields, crop rotations, and soil characteristics so that the economic optimum nitrogen rate for each field is determined and applied to soils without surplus nitrogen, which is vulnerable to environmental losses. Nehring (2020) suggested that the nitrogen fertilizer application rate can, on average, be reduced by 14% under 4R practice relative to the overapplied rate without 4R practice. The N_2O emission reduction resulting from 4R practices is determined by considering the reduction in nitrogen fertilizer input and the N_2O emissions that have been avoided as a result..

In FD-CIC, we incorporated the technological option "4R (Right time, Right place, Right form, and Right rate)” under item “1.4) Nitrogen fertilizer management for corn farming”. When the 4R practice is chosen, the N2O emission calculation will not utilize the user-specific nitrogen fertilizer rate. Instead, it will apply the reduced GREET default nitrogen rate. The default reduction stands at 14%, but the user has the flexibility to adjust this default value by selecting "User-specified reduction (%) in fertilizer application rate under 4R" in item 1.4.1).

We structure the implementation of the 4R practice in this manner to enable users to investigate how 4R can potentially reduce the CI of corn production, even if they are not currently employing 4R practices on their farms.

Cover cropping and animal manure application

Winter cover cropping in a corn-soybean rotation is considered as a conservation practice to improve SOC stock and provide agronomic benefits to subsequent cash crops (Marcillo and Miguez 2017). Incorporating cover crops into corn-soybean rotation would have the following GHG implications: 1) additional farming energy use; 2) additional herbicide requirement; 3) additional N_2O emissions from nitrogen content in cover crop biomass returned to soil; 4) improved SOC stock. Animal manure can be used as organic nitrogen and phosphorus fertilizer to improve soil fertility. Applying manure to corn fields would have the following GHG implications: 1) additional transportation and application energy use; 2) additional N_2O emissions from nitrogen content in manure added to soil; 3) improved SOC stock. It is noteworthy that N in manure has a higher N_2O emission factor (1.474 %), as compared to that in synthetic nitrogen fertilizer (1.374%).

Qin *et al* (2015) have compiled the energy and material inventory data attributable to winter rye cultivation, and the energy consumption data for manure transportation and application and implemented those into the GREET model. In FD-CIC, we assumed that diesel is consumed during cover crop planting, and manure transportation and application, as with Qin *et al* (2015). For cover crop planting and manure application, GREET by default employs the marginal allocation method, in which their emission burdens are allocated to corn stover. However, in FD-CIC, we allocated all benefits and burdens associated with the implementation of scenarios to corn grain, since we treated corn stover as waste left in the field to reflect the current and near-future practice, as with Liu *et al* (2020). To calculate on-field N_2O emissions, we implicitly assumed that the N_2O emissions from nitrogen content in manure and rye cover crops would not be affected by whether 4R or EEF is practiced.

Given that cover cropping and manure application practices are not yet widely adopted by farmers, (Liu *et al* 2021), we provided two sets of GREET default values in FD-CIC by letting the users decide whether they would like to include cover crop and/or manure in the default CI calculation. This accommodates the prevailing farming practices and offers flexibility in the analysis.

If the user chooses to include cover crop and/or manure in the default CI calculation by clicking the corresponding buttons, the GREET default values adopted from Qin *et al* (2015) for cover cropping and manure application will pop-up and be used for default corn CI calculation. Otherwise, zero values will pop-up as defaults, indicating that no cover crop/manure is implemented (Figure 5).

In addition, the user can independently choose whether cover crop/manure is practiced on their farm by incorporating their farm-specific parameters in the "User Specific Value" column to precisely reflect their own practices.

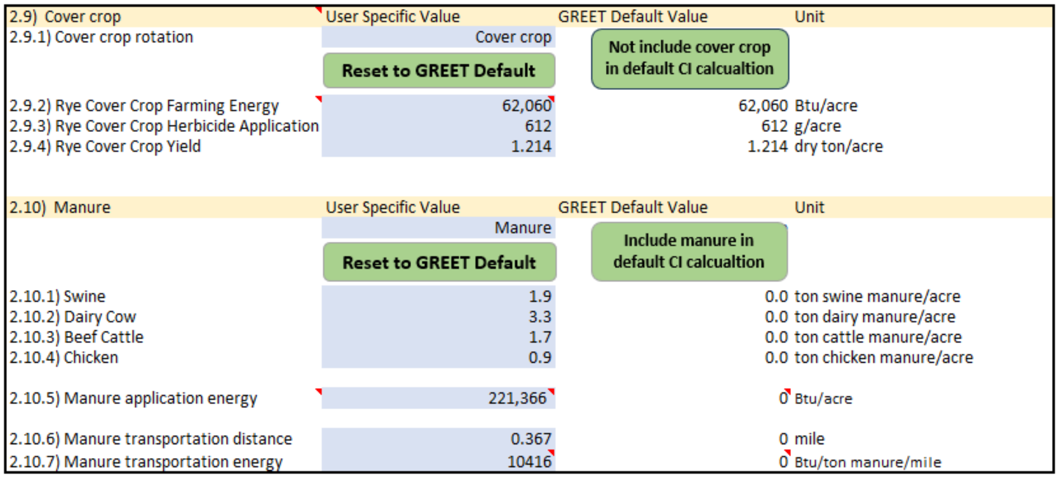

Figure 5: Parameters for cover cropping and manure application as sustainable practices for corn farming

Application of low-carbon nitrogen fertilizer

This provides an option for users to choose whether to use grey or green ammonia as the nitrogen fertilizer building block. Grey ammonia is the ammonia produced from conventional steam methane reforming of natural gas, which is a GHG intensive process and the GREET default ammonia production option. On the other hand, green ammonia is the ammonia produced by obtaining N_2 from cryogenic distillation and H_2 from low-temperature electrolysis using renewable electricity (Lee *et al* 2022). This option is enabled for other domestic crops as well.

3.3.2 Rice Specific Options

Methane (CH_4) emission is a particular concern for rice cultivation. In FD-CIC, annual CH_4 emissions (per area) from rice fields are calculated by multiplying daily EFs by the cultivation period of rice, with Eq. 6Eq. 7 - Eq. 8 adopted from the IPCC (2019):

$$\boldsymbol{CH_4 = EF_i \times d_i} \qquad \textbf{Eq. 6}$$

$$EF_i = EF_c \times SF_w \times SF_p \times SF_o \qquad \textbf{Eq. 7}$$

$$\boldsymbol{SF_o = (1 + \sum_i ROA_i \times CFOA_i)^{0.59}} \qquad \textbf{Eq. 8}$$

Where CH_4 is the annual methane emission (kg CH_4 ha^{-1}); EF_i is the daily EF for a specific condition i (kg CH_4 ha^{-1} d^{-1}) and d_i is the cultivation days of rice for a specific condition i. EF_c is the baseline EF for continuously flooded fields without organic amendments. SFw is the scaling factor to account for the differences in water regime during the cultivation period. SF_p is the scaling factor to account for the differences in water regime in the pre-season before the cultivation period. SF_o is the scaling factor that varies with both the type and amount of organic amendment applied. ROA_i is the application rate of organic amendment i, in dry weight for straw and fresh weight for others (Mg ha^{-1}). $CFOA_i$ is the conversion factor for organic amendment i in terms of its relative effect to straw applied shortly before cultivation. The values for the above-mentioned parameters can be found in Table 3.

Table 3. The EF (kg CH_4 ha^{-1} d^{-1}) and coefficients to calculate annual CH_4 emissions from U.S. rice farming

	Disaggregate

Emission factor	Application domain	Default value[1]	Uncertainty range
EF_c[2]	North America	**0.65**	0.44 – 0.96
d (days)	North America	**139**	110 – 165
SF_w	Continuously flooded	**1.00**	0.73 – 1.27
	Single drainage period	**0.71**	0.53 – 0.94
	Multiple drainage periods	**0.55**	0.41 – 0.72
	Regular rainfed	**0.54**	0.39 – 0.74
	drought prone	**0.16**	0.11 – 0.24
	Deep water	**0.06**	0.03 – 0.12
SFp	Non flooded pre-season <180 d	**1.00**	0.88 – 1.12
	Non flooded pre-season >180 d	**0.89**	0.80 – 0.99
	Flooded pre-season (>30 d)	**2.41**	2.13 – 2.73
	Non-flooded pre-season >365 d	**0.59**	0.41 – 0.84
CFOA	Straw incorporated shortly (<30 days) before cultivation	**1.00**	0.85 – 1.17
	Straw incorporated long (>30 days) before cultivation	**0.19**	0.11 – 0.28
	Compost	**0.17**	0.09 – 0.29
	Farm yard manure	**0.21**	0.15 – 0.28
	Green manure	**0.45**	0.36 – 0.57

[1] The values in bold is adopted in FD-CIC.

[2] CH_4 emission is not CH_4-C kg emission.

It should be noted that *SFp*, however, is only used to estimate CH_4 emissions during the rice growing period and cannot be used to quantify CH_4 emissions that occurred before the cultivation period or after harvest (i.e., outside of rice growing season, such as CH_4 emission during winter flooding period).

3.4 Results_DomesticCrops worksheets

FD-CIC estimates the GHG emissions in the unit of carbon dioxide equivalent (CO_2e) by combining the amount of CO_2, biogenic CH_4, fossil CH_4, and N_2O with their 100-year global warming potentials of 1, 28, 29.8, and 273, respectively, according to IPCC Sixth Assessment Report (AR6). It reports both GREET default and user-specific CI for comparison purposes.

3.5 Multi-year Inputs and Results sheet

Similar to the "Inputs_DomesticCrops" sheet, the user first needs to specify the location of the farm, and then the management practices applied to the farm (Figure 6). At present, users are limited to selecting from three prevalent crop rotations available in the dropdown menu of item 1.1). These rotations include corn-soybean (CS), continuous corn (CC), and corn-corn-soybean (CCS). The reason for this limitation is that FD-CIC exclusively contains pre-simulated SOC data for these specific crop rotations. The user also has the freedom to determine whether they wish to incorporate the effects of SOC on crop CI. They can make this selection by opting for "Yes" to include SOC or "No" to exclude it in item 1.6).

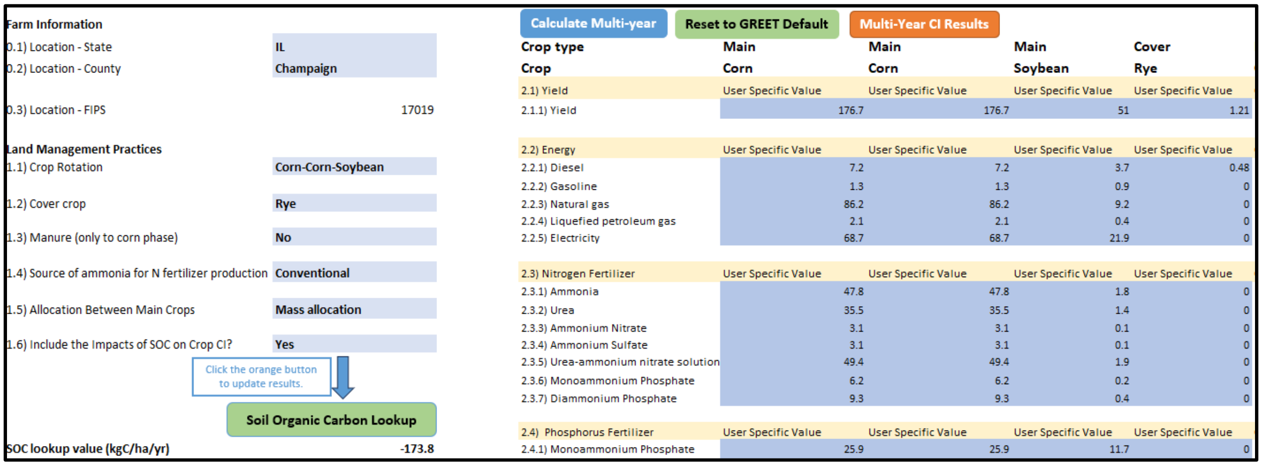

Figure 6: Land management practices and input panel in "Multi-year Inputs" sheet

After the user completes the left panel, as depicted in Figure 6, they should click the "Soil Organic Carbon Lookup" button to read the pre-simulated SOC change for the selected rotation and practices from the lookup table. Then, the user should fill their farm-specific inputs into the "User Specific Value" columns on the right panel (in the blue cells) and then click the "Calculate Multi-year" button. If the user has already made changes in the "User Specific Value" columns but would like to reset their inputs to GREET default values, they can click the "Reset to GREET Default" button.

The results can be viewed in the "Multi-year Results" worksheet by clicking the "Multi-year CI Results" button. Two types of results are presented: 1) landscape-based LCA results over the two or three years of crop rotation, in grams of GHG emissions per acre of cropland; and 2) crop-specific LCA results under different crop rotations, in grams of GHG emissions per bushel (bu) of a specific crop.

3.6 Intensities of Inputs worksheet

In the "Intensities of Inputs" worksheets, the GHG emissions related to farming inputs manufacturing (e.g., fertilizers and energy sources) are read from the GREET model to maintain the transparency of CI calculation in FD-CIC. The CI of these farming inputs may fluctuate from year to year owing to updates in the GREET model. These updates encompass changes in inventory data used to produce these inputs and variations in the upstream GHG emissions associated with the energy and materials employed in their production.

The breakdown of CI for each chemical/energy carrier is also presented. If a user prefers to utilize their own CI values for chemicals or energy carriers instead of relying on the values from the GREET model, they have the option to replace the data in the highlighted orange cells with their custom values. Nevertheless, this method is considered less preferable.

Nitrogen Fertilizer	Inputs	Value	Unit	Contributions	CI of product	Unit
Conventional Ammonia	Natural gas	27.961	mmBtu/ton	Inputs	351,561	g GHG/ton
	Electricity	0.189	mmBtu/ton		24,258	g GHG/ton
	Hydrogen	0.000	ton/ton		0	g GHG/ton
	Nitrogen	0.000	ton/ton		0	g GHG/ton
				Emissions from input c	419,299	g GHG/ton
				Process emissions	1,318,129	g GHG/ton
				T & D (ammonia as fin	28,326	g GHG/ton
				T & D (ammonia as Int	17,855	g GHG/ton
				Total	2,141,573	g GHG/ton ammonia (final fertilizer)
					2,131,102	g GHG/ton ammonia (intermediate to fertilizer)
Urea	Natural gas	3.981	mmBtu/ton	Inputs	52,920	g GHG/ton
	Electricity	0.456	mmBtu/ton		58,626	g GHG/ton
	Ammonia	0.567	ton ammonia/ton		1,208,335	g GHG/ton
				Emissions from input c	237,060	g GHG/ton
				Process emissions	-665,269	g GHG/ton
				T & D	46,691	g GHG/ton
				Total	938,362	g GHG/ton

Figure 7: Overview of the "Intensities of Inputs" worksheet

In GREET 2023, we updated the inventory data for manufacturing key fertilizer and herbicide ingredients. We also updated the herbicide ingredient mixes for major crops by collecting data from USDA NASS (Liu and Cai 2023). These updates have been incorporated into FD-CIC 2023.

3.7 International Feedstock worksheets

Regional expansion of FD-CIC includes the CI calculation of Canadian corn and Brazilian sugarcane to address current efforts in developing clean fuel policies in countries other than the United States. For example, the Canadian government is developing the Clean Fuel Standard (CFS) to reduce the CI of fuels and energies used in Canada. Similar to CARB'S LCFS, CFS aims to stimulate investments and innovations in low-CI fuels while enabling low-cost compliance. We have communicated with staff from Environment and Climate Change Canada and recognized the importance of GREET/FD-CIC expansion to include key Canadian feedstock such as corn for Canadian CFS. Since such an expansion is beneficial to the ARPA-E effort as well, we collaborated with stakeholders and obtained the Canada-specific farming inputs for corn production and the relevant GHG emissions intensities of manufacturing those inputs from GHGenius model (https://www.ghgenius.ca/).

In addition, the sugarcane production in Brazil as a feedstock for bioethanol has been introduced into FD-CIC since 2021, based on data from Wang *et al* (2012). The Brazilian government launched the National Biofuels Policy (RenovaBio) in 2017. We gathered the most current inventory data for sugarcane farming and ethanol production, obtained via RenovaBio, encompassing data from 67 sugarcane mills in the 2019/2020 period. Using this data, we have made updates to both the GREET and FD-CIC models for the year 2023 (Liu *et al* 2023).

It's important to mention that for international feedstocks, we have retained their distinct "Input," "Intensities of Inputs," and "Results" sheets. This is because these international feedstocks involve the use of different types of chemicals compared to U.S. domestic crops. Additionally, the production of these inputs is associated with varying upstream greenhouse gas emissions. As such, they necessitate separate data sheets to accurately account for these differences.

3.8 Stochastic simulation function

This function requires users to assign probability density functions for key farming inputs parameters, specify the number of samples required and the sampling technique to be used, and define the forecast variables based on which the stochastic simulations are performed.

To load the Stochastic Toolkit or unload it, the users should click "Load Stochastic Toolkit" or "Unload Stochastic Toolkit" on the "Feedstock Selection" worksheet. After loading the stochastic toolkit, it will be loaded to the "Add-ins" section in the excel Ribbon.

If experiencing any issues when loading the stochastic module, please follow the instruction below: Open FD-CIC tool → Go to File → Go to Options → Go to Add-ins → Scroll down to the bottom section "Manage: Excel Add-ins" and click "Go…" → Click "Browse" and select the "STOCHASTIC.xla" file in your local GREET folder → Click "OK" → Save the new version on your local drive.

3.8.1 Assign probability distribution functions to the input variables

To assign a probability distribution function, the users need to select an input variable with numeric value in excel, click the "Cell Input" tab in the stochastic toolkit, select a probability distribution function for the input variable (Figure 8) and parameterize the selected distribution (Figure 9). The users would then be asked to set a name for the variable or click "Cancel" to use location instead of name. It is recommended, however, to use the defined name approach. After successfully assigning a probability distribution function to the input variable, the cell turns green and the variable is automatically added to the "Dist_Spec" sheet. The users need to repeat the process until all the input variables participating in the stochastic simulations are defined. To delete the distribution from a cell, users can select that cell and click the "Delete Distribution" tab in the stochastic toolkit.

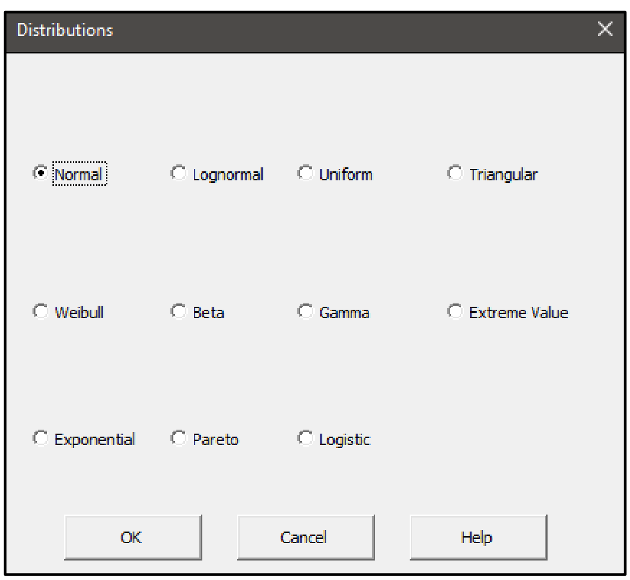

Figure 8: A list of probability distribution function for users to choose from

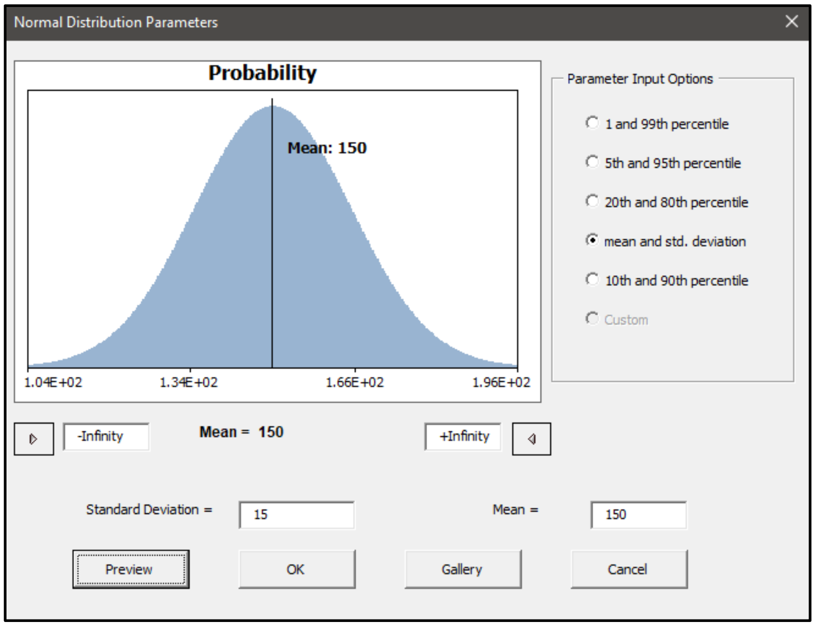

Figure 9: Parameters for a normal distribution. Note that parameters depicted in this panel would be different when users choose different probability distribution functions in the previous step.

3.8.2 Specify the number of samples and the sampling technique

To specify the number of samples and the sampling technique, the users need to click the "Sampling" tab in the stochastic toolkit. The users can choose between four different sampling techniques and enter the number of samples (Figure 10). An overview of the four sampling techniques is provided in Subramanyan and Diwekar (2005).

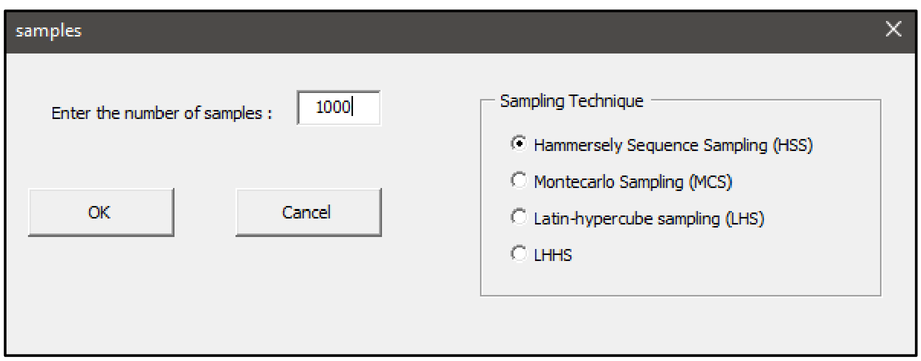

Figure 10: Specification of the number of samples and the sampling technique

3.8.3 Define the forecast variables

To define forecast variables, the users need to go to the "Forecast_Specs" sheet, type in the sheet and cell addresses of the forecast variables, and the names defined for the forecast variables (if applicable).

3.8.4 Run stochastic simulation

To run the stochastic simulation, the users need to click the "Run Simulation" tab in the stochastic toolkit and set the seed automatically or manually. After completing the simulation run, an Excel workbook will be generated to display the results from the stochastic simulation. Statistical values such as the mean, standard deviation, and 0th to 100th percentile are calculated automatically for each forecast variable. The users can save the output Excel file to the directory of their choice. Depending on the sampling technique and the number of samples specified, this process can take a few minutes to complete, with a progress bar displaying the percentage of completion.

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