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

Regulatory agencies such as California Air Resources Board (CARB) adopts 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 the plant's revenue directly to its CI score through LCFS credit trading.

Besides 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 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, the Systems Assessment Center has developed a tool - the Feedstock Carbon Intensity Calculator (FD-CIC). The first version of the FD-CIC with the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model 2020 release accounts for user-specific, farm-level input data for corn production, coupled with the life-cycle inventory (LCI) data of key farming inputs from the GREET model (Wang *et al* 2020).

2. Brief Description of the FD-CIC

The system boundary of FD-CIC covers the cradle-to-farm-gate activities, including upstream emissions related to farming input manufacturing and feedstock production (Fig. 1). The FD-CIC tool helps stakeholders to assess effects of changing farm-level input parameters on corn CI scores in the biofuel LCA context.

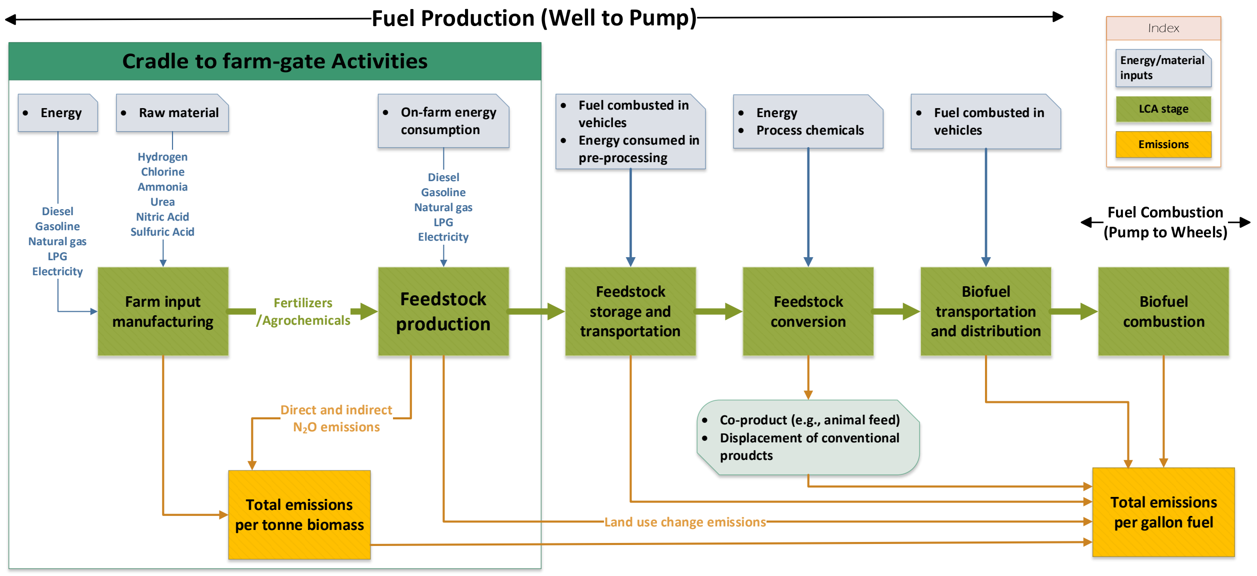


Figure 1: The system boundary of FD-CIC (i.e. cradle-to-farm-gate activities) compared to a complete supply chain of a biofuel.

Key parameters affecting biofuel feedstock CI include corn yield, fertilizers/chemicals application rates, and agronomic practices. Corn yield is related to the total volume of ethanol produced per area of land by coupling with the corn-grain-to-ethanol conversion rate (2.88 gallon of ethanol per bushel of corn). The corn yield also determines the amount of corn residue left on the farm field, which affect N_2O emission and soil organic carbon (SOC) sequestration potentials.

Inclusion of agronomic practice as a key parameter in FD-CIC reflects the current interest in evaluating the CI of the biofuel feedstock produced by various sustainable land management practices such as: i) nitrification inhibitor use to reduce fertilizer-induced N_2O emissions, ii) conservation tillage adoption to increase SOC and reduce on-farm energy uses in tilling, iii) manure application to improve soil quality by adding organic carbon and nutrients, and iv) cover cropping to increase residue carbon and nutrients in soils and reduce soil erosion.

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. However, since the FD-CIC focuses on the cradle-to-farm-gate activities, it does not include LUC emissions in CI calculation but has a lookup table for SOC sequestration potentials of diverse farming practices to address great opportunities for CI reductions.

Currently, two versions of FD-CIC are available, namely the dynamic version and the standalone version. The dynamic version interacts with the GREET model (in particular, GREET1, the fuel cycle model of GREET) by directly reading the LCI data of key farming inputs from the model. The dynamic version suits well when users want to change the default settings of the GREET model as related to farming inputs. For example, if the users want to assess the impact of using regional electricity grid mix, 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 key farming inputs. The interacting feature also enables the CI values to be updated with annual GREET release. The standalone version suits well for users who are not familiar with the GREET model and contains the default LCI data for key farming inputs from the GREET model. It is worth mentioning that the interacting feature will only work if users have GREET version 2020 or later and keep the GREET1 excel file in the same folder as with the FD-CIC tool.

3. Use of FD-CIC

3.1 Introduction worksheet

The structure of the FD-CIC tool is presented in the Introduction worksheet (Fig. 2) that defines the color schemes of cells for different types of parameters used in the FD-CIC and provides the key references that support the development of the FD-CIC.

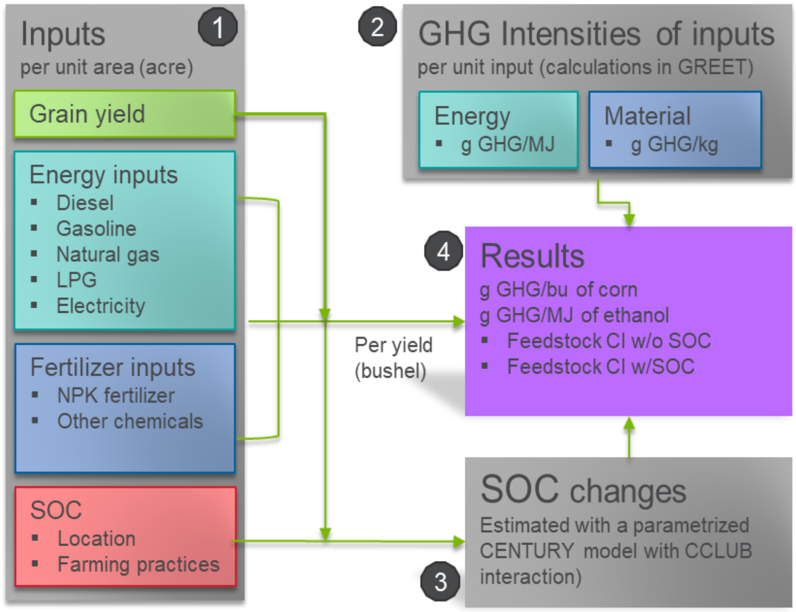


Figure 2: Structure of FD-CIC

3.2 Inputs worksheet

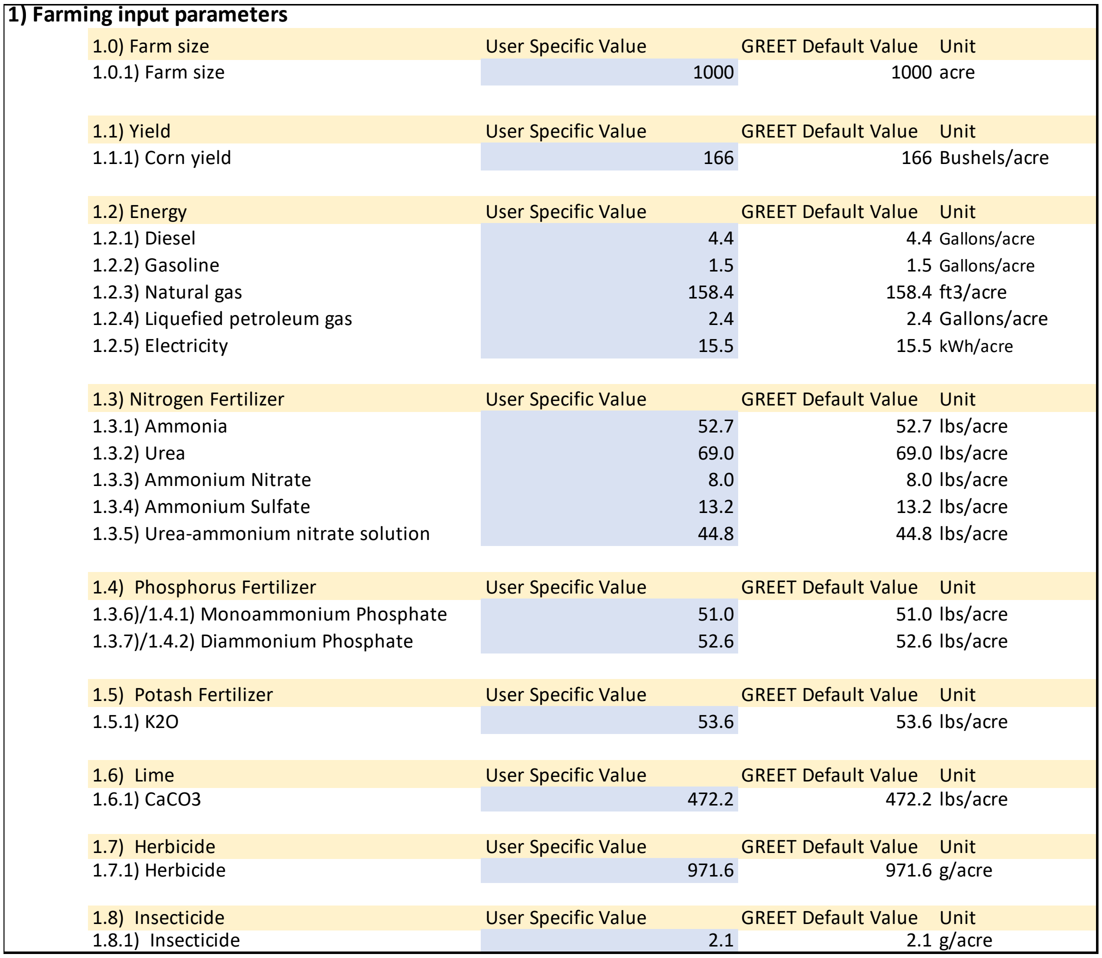
3.2.1 Farming input parameters

In the Inputs worksheet, users need to provide key information on corn yield, energy consumption, and fertilizer/chemical uses (Fig. 3). In particular, the energy use from all on-farm operations, including field preparation, tilling, fertilizer/chemical application, grain drying, and corn irrigation, should be included. 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 FD-CIC tool uses U.S. customary units by default (e.g. pound per acre or bushel per acre), 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 per British Thermal Unit of energy), so that the CI coefficients obtained from the GREET model can be utilized.

It is noteworthy that herbicide and insecticide types are not differentiated because of their small contribution to the overall feedstock CI (< 2%).

As shown in Figure 3, GREET default values reflecting US average corn farming are provided as the baseline scenario. Users can modify the blue cells to build their specific case and compare the results with the GREET default scenario. Please note that in the GREET model, the amount of fertilizers applied is measured by the amount of nutrients in fertilizer; but in FD-CIC, the amount of fertilizers applied is the actual compound application rates.



1) Farming input parameters

1.0) Farm size	User Specific Value	GREET Default Value	Unit
1.0.1) Farm size	1000	1000	acre
1.1) Yield	User Specific Value	GREET Default Value	Unit
1.1.1) Corn yield	166	166	Bushels/acre
1.2) Energy	User Specific Value	GREET Default Value	Unit
1.2.1) Diesel	4.4	4.4	Gallons/acre
1.2.2) Gasoline	1.5	1.5	Gallons/acre
1.2.3) Natural gas	158.4	158.4	ft3/acre
1.2.4) Liquefied petroleum gas	2.4	2.4	Gallons/acre
1.2.5) Electricity	15.5	15.5	kWh/acre
1.3) Nitrogen Fertilizer	User Specific Value	GREET Default Value	Unit
1.3.1) Ammonia	52.7	52.7	lbs/acre
1.3.2) Urea	69.0	69.0	lbs/acre
1.3.3) Ammonium Nitrate	8.0	8.0	lbs/acre
1.3.4) Ammonium Sulfate	13.2	13.2	lbs/acre
1.3.5) Urea-ammonium nitrate solution	44.8	44.8	lbs/acre
1.4) Phosphorus Fertilizer	User Specific Value	GREET Default Value	Unit
1.3.6)/1.4.1) Monoammonium Phosphate	51.0	51.0	lbs/acre
1.3.7)/1.4.2) Diammonium Phosphate	52.6	52.6	lbs/acre
1.5) Potash Fertilizer	User Specific Value	GREET Default Value	Unit
1.5.1) K2O	53.6	53.6	lbs/acre
1.6) Lime	User Specific Value	GREET Default Value	Unit
1.6.1) CaCO3	472.2	472.2	lbs/acre
1.7) Herbicide	User Specific Value	GREET Default Value	Unit
1.7.1) Herbicide	971.6	971.6	g/acre
1.8) Insecticide	User Specific Value	GREET Default Value	Unit
1.8.1) Insecticide	2.1	2.1	g/acre

Figure 3: Farm-level inventory required by FD-CIC

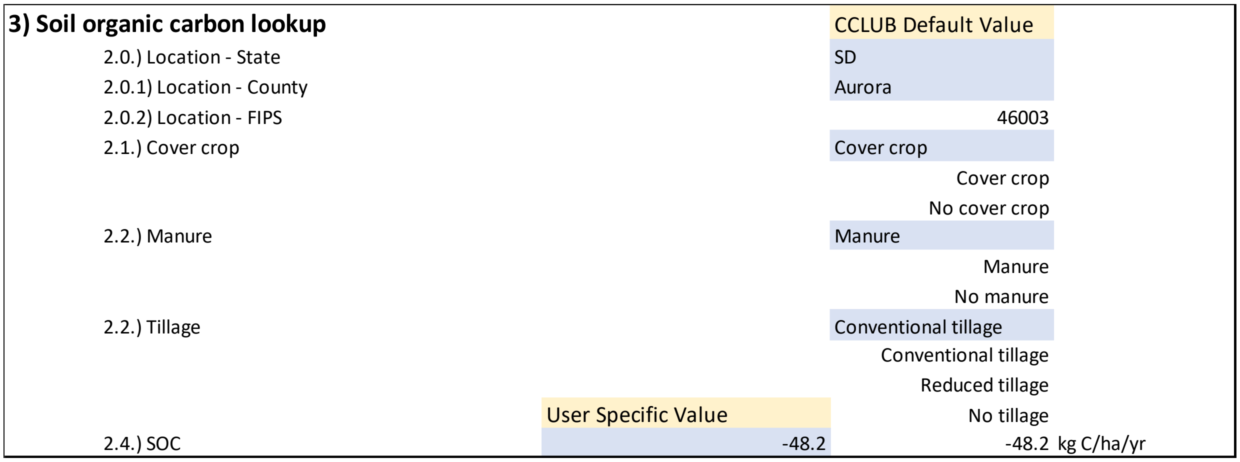
The FD-CIC also provides a few options for users to choose from. Users can choose whether to show results for CO_2 emissions only or for GHG emissions, by modifying cell “GHG_of_concern” in the Inputs worksheet. Additionally, by modifying cell “Nfertilizer_source” in the Inputs worksheet, users can also choose green ammonia as the nitrogen fertilizer building block, which is the ammonia produced by obtaining N_2 from cryogenic distillation and H_2 from low-temperature electrolysis using renewable electricity. More information on other alternative pathways to produce low-carbon ammonia can be found in Liu *et al* (2020a).

3.2.2 Soil organic carbon lookup

Currently, the corn ethanol CI calculated for regulations does not account for SOC changes in corn farms due to different land management practices, which is either sequestrated as SOC (i.e., increase in SOC) or emitted as CO_2 (i.e., decrease in SOC). The change in SOC due to the change in practices in corn farms can be significant and consideration of SOC in CI scoring can incentivize conservation practices that are tied to carbon sequestration and abatement. For example, growing of cover crops and application of manure in corn farms contribute positively to SOC stock increase, leading to net carbon sequestration compared to cases where cover crops and manure are not applied. On the other hand, the growth of cover crops and manure applications are associated with additional herbicide/energy use and associated emissions due to herbicide/energy manufacturing. These emission burdens also need to be accounted for (Liu *et al* 2020).

The FD-CIC provides a lookup table for the SOC sequestration potentials corresponding to different farming practices based on default simulation results using county-level corn yield record, soil, and climate information (Liu *et al* 2020). Therefore, the farm-level yields of cover crop and major crops (e.g. corn and soybean) provided by users would not affect the SOC change per hectare but the SOC change per bushel of corn. That is, SOC estimates in the FD-CIC are developed at the U.S. county level, not at the farm level.

As indicated by the SOC lookup table (Fig. 4), the users can look up the potential SOC changes. It should be noted that positive SOC values represent CO_2 emissions while negative values represent SOC sequestration.



3) Soil organic carbon lookup		CCLUB Default Value	
2.0.) Location - State		SD	
2.0.1) Location - County		Aurora	
2.0.2) Location - FIPS		46003	
2.1.) Cover crop		Cover crop	
		Cover crop	
		No cover crop	
2.2.) Manure		Manure	
		Manure	
		No manure	
2.2.) Tillage		Conventional tillage	
		Conventional tillage	
		Reduced tillage	
	User Specific Value	No tillage	
2.4.) SOC	-48.2	-48.2	kg C/ha/yr

Figure 4: Soil organic carbon look-up table

2.3 Intensities of Inputs worksheet

In the Intensities of Inputs worksheet, the GHG emissions related to farming inputs manufacturing (e.g. fertilizers and energy sources) are all based on the LCI emission results from the GREET model to maintain the transparency of CI calculation in FD-CIC.

The dynamic version has a control button named "Read from GREET" while the standalone version does not. This function enables the interaction between the FD-CIC and the GREET model, as described in Section 1. This "Read from GREET" button will only work if users have GREET version 2020 or later. Moreover, the GREET1 excel file should be in the same folder of one's computer as with the FD-CIC tool. Please note that "ton" stands for short ton in this worksheet.

If the users update cell "GHG_of_concern" and "Nfertilizer_source" in the Inputs worksheet, the Intensities of Inputs worksheet needs to be updated by pressing the "Read from GREET" button for the dynamic version. For the standalone version, if the users update cell M3 and M8, then a re-calculation is needed by pressing F9.

2.4 Results worksheet

The FD-CIC tool estimates the emissions of CO_2, CH_4, and N_2O combined with their 100-year global warming potentials (GWP) of 1, 30, and 265, respectively. N_2O emissions from soils and biomass are calculated mainly on the basis of the emission factors approach developed by the

Systems Assessment Center (Wang *et al* 2012, Xu *et al* 2019) and Intergovernmental Panel on Climate Change (Dong *et al* 2006), using emission factors from various nitrogen sources defined by the GREET model. As an example, to calculate the N_2O emission due to ammonia fertilizer application, the application rate of ammonia is multiplied by the ratio of nitrogen in ammonia to calculate the application rate of ammonia-nitrogen. The emission factor of 1.325% is then applied, which is the percentage of nitrogen in nitrogen fertilizer and biomass that is converted to nitrogen in N_2O (N_2O-N), which can be further converted to N_2O (Xu *et al* 2019). For those who are familiar with GREET N_2O calculations for biofuels, nitrogen fertilizer usage there in GREET is presented in the mass of nutrients, not the mass in compounds as in FD-CIC. The latter was done intentionally so that farming inputs can be entered into the FD-CIC by users without any conversion outside of it.

For Monoammonium Phosphate (MAP) and Diammonium Phosphate (DAP), which serve as both nitrogen and phosphorus sources, the tool employs more complex calculations (Fig. 5).

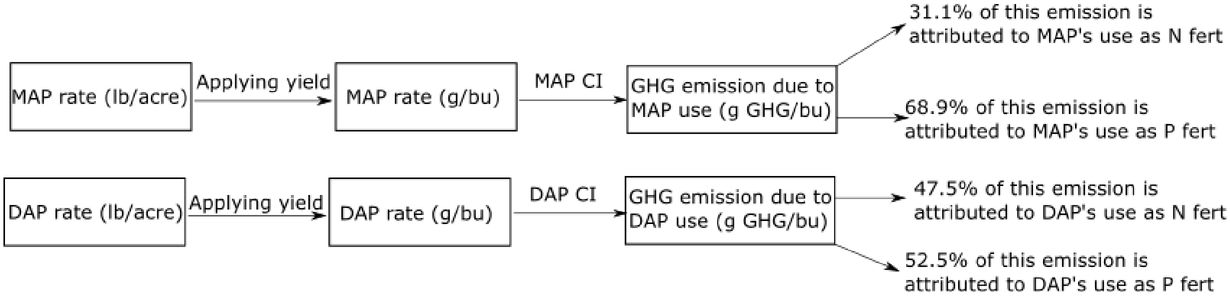


Figure 5: Calculations associated with MAP and DAP

In the Results worksheet, the FD-CIC tool reports both GREET default and user-specific CI for corn for comparison. The tool provides figures for comparison as well. The contribution from each emission source is also calculated and depicted in a pie chart.

The FD-CIC tool also translated the feedstock CI into ethanol CI based on per MJ of corn ethanol produced by applying the corn-grain-to-ethanol conversion rate (2.88 gallon of ethanol per bushel of corn) and the lower heating value of ethanol (80.5 MJ per gallon, lower heating value based) as the volume-to-energy unit conversion factor. This feature helps users to understand how the variations in feedstock-level CI can propagate through the bioethanol supply chain.

4. References

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