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Development of R&D GREET 2023 Rev1 to Estimate Greenhouse Gas Emissions of Sustainable Aviation Fuels for 40B Provision of the Inflation Reduction Act

Energy Systems and Infrastructure Analysis Division

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Development of R&D GREET 2023 Rev1 to Estimate Greenhouse Gas Emissions of Sustainable Aviation Fuels for 40B Provision of the Inflation Reduction Act

prepared by

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April 2024

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ACKNOWLEDGEMENTS

This effort was supported by the Bioenergy Technologies Office of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, under Contract DE-AC02-06CH11357. Purdue University contributed to this study by generating results on induced land use changes, crop production, livestock production, and rice production with its GTAP-BIO model. ICF contributed to this study by developing emission profiles of crop production, livestock production, and rice paddy fields. We thank Farzad Taheripour and Ehsanreza Sajedinia of Purdue University for conducting GTAP-BIO simulations; and Kirsten Jaglo, Jason Jones, Georgia Kerkezis, Deanna Lizas, Kelly Summers, and Hazelle Tomlin of ICF for developing emission profiles of crop production, livestock growth, and rice cultivation. We are grateful to Jay Fitzgerald and Michael Shell of the Bioenergy Technologies Office of the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy for their support and guidance. The authors are solely responsible for the content of this publication.

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1 INTRODUCTION

The federal Interagency Working Group on sustainable aviation fuels (SAF) tasked Argonne National Laboratory with developing a modified version of the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model based on R&D GREET 2023. The goal of the new GREET version is to simulate the life-cycle greenhouse gas (GHG) emissions associated with seven sustainable aviation fuel (SAF) pathways for consideration under the 40B Provision of the Inflation Reduction Act – Sustainable aviation fuel credit. The Provision includes a new GHG-based tax credit to incentivize SAF production and reduce the costs of these fuels.

The GHG emissions — including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) — are accounted for based on their global warming potentials (GWPs) in accordance with the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). The seven SAF pathways are as follows:

1. Alcohol to jet with U.S. corn ethanol (corn ATJ-ethanol, corn ATJ-E)
2. U.S. soybean hydroprocessed esters and fatty acids (HEFA) to jet (soybean HEFA jet)
3. U.S. and Canadian canola HEFA to jet (canola HEFA jet)
4. Alcohol to jet with Brazilian sugarcane ethanol (sugarcane ATJ-ethanol, sugarcane ATJ-E)
5. Used cooking oil (UCO) HEFA to jet (UCO HEFA jet)
6. Tallow HEFA to jet (tallow HEFA jet)
7. Distillers corn oil HEFA to jet (distillers corn oil HEFA jet)

Argonne has modified R&D GREET 2023 to create an updated version — R&D GREET 2023 Rev1 — that addresses the life-cycle GHG emissions associated with the seven pathways for 40B use. This technical memo documents the modifications made in R&D GREET 2023 Rev1 and the key parameters that affect the life-cycle analysis (LCA) results for the seven SAF pathways. Key tasks include updating and expanding the indirect effects of the four pathways using dedicated feedstocks (corn, soybean, canola, and sugarcane). Purdue University and ICF assisted Argonne in assessing the indirect effects of these pathways. The Interagency Working Group also asked Argonne to address the effects of selected measures to mitigate GHG emissions associated with the seven pathways, particularly those aimed at reducing GHG emissions from SAF production facilities (including ethanol production facilities).

Argonne designed a SAF module, called 40BSAF-GREET 2024, as a user interface between R&D GREET 2023 Rev1 and foreground input parameters for conducting LCA of the seven SAF pathways. The 40BSAF-GREET 2024 tool allows users to estimate life-cycle GHG emissions for the seven SAF pathways with allowed changes in the key parameters of the pathways. Results from 40BSAF-GREET 2024 include (1) direct LCA results (D-LCA results), which are analogous to the core LCA results specified in the Carbon Offsetting and Reduction Scheme for International aviation (CORSIA) program of the International Civil Aviation Organization (ICAO) (ICAO, 2022); and (2) indirect effects (called *I-effects* here) that include (a) induced land use change (ILUC), (b) changes in non-feedstock crop production, and (c) changes in livestock emissions (both CH_4 emissions from enteric fermentation and CH_4 and N_2O emissions from manure management).

Section 2 of this technical memo presents D-LCA estimates, Section 3 describes I-effect simulations, and Section 4 addresses effects of selected GHG mitigation measures for SAF production.

We summarize the sample LCA results — comprising D-LCA results and I-effects for the seven SAF pathways (Table 1). These results are based on (1) default parameters in R&D GREET 2023 Rev1; (2) fossil natural gas (NG) providing energy for heat generation in ethanol and SAF plants; (3) hydrogen from NG steam methane reforming (SMR) for SAF production; and (4) U.S. average electricity generation, among other parameters. In addition, the GHG emissions of petroleum jet fuel is set to be 89 g/MJ in R&D GREET 2023 Rev1.

Table 1. Sample LCA results for the seven SAF pathways, including D-LCA results based on the default inputs in R&D GREET 2023 Rev1[a]

	Corn ATJ-E	Soybean HEFA	Canola HEFA	Sugarcane ATJ-E	UCO HEFA	Tallow HEFA	Distillers Corn Oil HEFA
Total LCA Results	**72.1**	**39.8**	**56.0**	**60.2**	**17.0**	**17.6**	**12.2**
Direct LCA	**61.0**	**23.5**	**32.3**	**54.3[b]**	**17.0**	**17.6**	**12.2**
I-effects	**11.1**	**16.2**	**23.7**	**5.9**			
ILUC	9.0	12.2	18.1	10.6			
Crop production	3.8	3.5	5.9	-3.0			
Livestock	-1.4	1.4	0.1	-1.6			
Rice methane	-0.3	-0.8	-0.3	-0.1			

[a] Results in g of CO_2- equivalent [CO_2e] CO_2, CH_4, and N_2O per MJ of SAF; lower-heating value based.

[b] The value here does not include potential GHG credit from exported electricity of sugarcane ethanol plants. The amount of exported electricity can vary significantly among sugarcane ethanol plants.

2 DIRECT LCA OF SEVEN SAF PATHWAYS WITH R&D GREET 2023 REV1

Table 2 lists the major D-LCA GHG emission contributors for the seven pathways. For the dedicated feedstock-derived fuels (corn, sugarcane, soybean, and canola), farming emissions associated with fertilizers, energy inputs, and N_2O emissions from nitrogen fertilizers contribute 38–56% of the total D-LCA value of each pathway. These emissions are directly related to the energy/fertilizer inputs and feedstock yield, as well as the upstream production of energy for farming and fertilizer inputs.

Table 2. D-LCA GHG emissions associated with the seven SAF production pathways

[gCO2e/MJ]	Corn ATJ-E	Soybean HEFA	Canola HEFA	Sugarcane ATJ-E	UCO HEFA	Tallow HEFA	Distillers corn oil HEFA
Farming							
Fertilizer production	8.2	1.5	6.4	3.6			
N2O emissions from fertilizers/fields	13.2	5.7	9.3	9.1			
CO_2 emissions from urea/$CaCO_3$	2.5	0.0	0.9	2.1			
Energy use	3.8	1.5	1.5	9.1			
Ethanol Production/Oil Extraction/Rendering	13.9	3.4	2.9	3.0	4.6	6.7	6.7
Materials use	1.8	0.1	0.2	0.7	0.0	0.0	0.0
Energy use	24.0	3.4	2.7	2.4	4.6	6.7	6.7
DDGS impacts	-11.9						
SAF Production	16.2	10.1	10.1	16.2	10.1	10.1	10.1
Natural Gas use	6.9	1.2	1.2	6.9	1.2	1.2	1.2
Electricity use	6.1	1.1	1.1	6.1	1.1	1.1	1.1
Hydrogen use	3.1	7.9	7.9	3.1	7.9	7.9	7.9
Transportation/Distribution and Others	3.2	1.3	1.1	11.2	2.2	0.7	0.7
D-LCA	**61.0**	**23.5**	**32.3**	**54.3**	**17.0**	**17.6**	**12.2**

In addition, Table 3 presents the farming and feedstock transportation related emissions for crop production on the basis of per-bushel of corn or soybean and per-metric ton (MT) of canola or sugarcane.

Since ethanol production requires significant process heat (provided by fossil NG), the corn ethanol production pathway has high emissions, primarily associated with energy use. However, sugarcane ethanol relies mainly on bagasse and straw to generate heat which only releases biogenic CO_2 and does not contribute to net GHG emissions.

Table 3. GHG emissions of crop production and transportation, in g CO_2e/bushel of corn or soybean and g CO_2e/MT of canola or sugarcane

	Corn	Soybean	Canola	Sugarcane
	g CO_2e/bushel corn	**g CO_2e /bushel soybean**	**g CO_2e /dry MT canola**	**g CO_2e /wet MT sugarcane**
N fertilizer production	1,367	182	194,511	3,761
Fertilizer-induced N_2O emissions	2,266	302	244,459	6,684
Crop residues (above and below ground) N_2O emissions	745	4,866	103,871	8,449
CO_2 from urea/$CaCO_3$	564	33	34,851	3,493
Other fertilizer production	495	1,145	45,166	2,172
Energy use	875	1,340	55,002	15,100
Transportation	227	337	13,516	0
Biomass burning	0	0	0	3,463
Total	**6,539**	**8,205**	**691,377**	**43,123**

Upgrading ethanol into jet fuel requires heat (provided by NG), hydrogen (H_2), and electricity. There is active project planning in the United States and other countries to convert ethanol to jet. We reached out to ATJ-E technology providers and project developers to obtain up-to-date energy balance data of ATJ-E conversion facilities. Based on the obtained data from multiple companies, we updated key data for ATJ-E conversion facilities (see Table 4 below). The updated inputs of NG, electricity, and hydrogen add 16.2 gCO_2e/MJ to the total D-LCA of ATJ-E pathways. For corn ethanol production, the co-produced dried distiller's grains with solubles (DDGS) displaces animal feed, providing emission credits for ethanol (and then for SAF).

Table 4. Major energy requirements for the ethanol upgrading process (ATJ-E) and products share (per MJ of combined liquid fuels)

		R&D GREET 2023 Rev1 Default
Inputs: MJ	Ethanol	1.01
	Electricity	0.05
	Natural gas	0.10
	Hydrogen	0.04
	Total	**1.20**
ATJ-E products shares	Jet fuel	95%
	Diesel fuel	5%
Energy conversion efficiency		84%

The HEFA process, used to convert oil into SAF and renewable diesel requires a significant input of H_2 to treat triglycerides in lipids, mainly to remove oxygen (hydrodeoxygenation) for production of "hydroprocessed esters and fatty acids."

Tallow, UCO, and distillers corn oil are by-products or waste streams, so no emissions are associated with upstream activities. For tallow and UCO, rendering processes require energy inputs to separate the lipid portion. For distillers corn oil, the oil extraction process in corn ethanol facilities requires electricity, which contributes to the emissions of distillers corn oil production.

Understanding the major contributors to emissions is helpful in selecting appropriate and effective GHG mitigation measures (presented in Section 4). Conventional energy inputs (fossil NG, H_2 from fossil NG SMR, and U.S. grid electricity — all included as defaults in R&D GREET 2023 Rev1) in different life-cycle stages can be displaced by lower-carbon energy inputs such as renewable natural gas (RNG), renewable H_2, and/or renewable electricity.

The following subsections provide simulation assumptions and data sources for each pathway.

2.1 CORN ATJ-E PATHWAY

The corn ATJ-E pathway includes three main processes: corn farming, ethanol production, and ATJ-E conversion. For the first two processes, R&D GREET 2023 Rev1 relies on the R&D GREET 2023 default conditions described in Lee et al. (2021). That study relied primarily on corn farming data from the U.S. Department of Agriculture (USDA) and ethanol production data from an industry survey. Corn yield and farming inputs such as fertilizer and energy use in R&D GREET 2023 Rev1 are based on 2019 data, as documented in Lee et al. (2021).

N_2O emissions are a significant source of corn farming GHG emissions. R&D GREET 2023 Rev1 takes the IPCC approach to estimating corn field N_2O emissions by considering total nitrogen (N) input to the soil and an N-to-N_2O conversion factor (1.264% in R&D GREET 2023 Rev1). N values include inputs from nitrogen fertilizers (396 g/bushel of corn in R&D GREET 2023 Rev1) and nitrogen in crop residues, calculated as follows. The N input to soil from above- and below-ground biomass is 141.6 g/bushel based on two-step calculations: the ratio of grain to above-ground biomass and the ratio of above-ground biomass to below-ground biomass (roots). Based on Wang (2008), the first ratio is 87% (dry matter based), with an N content of 0.6% for the above-ground biomass (i.e., corn stover). The second ratio is 22%, with an N content of 0.7% for the below-ground biomass (i.e., corn roots).

In 40BSAF-GREET 2024, we simulate corn ethanol production in dry mill ethanol plants with distillers corn oil extraction because this method represents the majority (roughly 92%) of U.S. corn ethanol production (RFA, 2024). For co-product emissions accounting, the default method for DDGS in R&D GREET 2023 Rev1 is the displacement method (i.e., system expansion). The default method for distillers corn oil is the marginal method (Wang et al. 2015), which allocates all emissions to ethanol except those associated with the distillers corn oil extraction process. Distillers corn oil is considered a by-product that can be used for renewable diesel (RD)/SAF production via a separate HEFA process.

Because R&D GREET 2023 Rev1 relied on dated process-modeling-based datasets, for the corn ATJ-E pathway, as mentioned above, Argonne consulted multiple industry sources to obtain the best available conversion dataset. Argonne used up-to-date values of the energy inputs (ethanol, NG, electricity, and hydrogen) in R&D GREET 2023 Rev1. Table 4 lists the input values in terms of MJ of energy inputs per MJ of liquid fuels combined. Note that ATJ-E product shares may vary. For the SAF share, it ranges from 90% to 98%, while the rest consists of diesel and naphtha. Regarding ethanol consumption in ATJ-E, the most recent data we obtained indicates a conversion rate of 1.01 MJ of ethanol per MJ of combined liquid fuels.

Note that R&D GREET 2023 Rev1 is configured based on the assumption that ethanol and SAF production are separate (i.e., two standalone facilities). If they are co-located, and surplus heat and electricity from ethanol production can be used to reduce NG and electricity inputs to the ATJ-E process, the values can be adjusted in the 40BSAF-GREET 2024 model.

2.2 SOYBEAN AND CANOLA HEFA

The soybean and canola HEFA pathways are based on the default input assumptions in R&D GREET 2023 Rev1, which relies mainly on Xu et al. (2022a). Because typical HEFA processes generate both SAF and RD, R&D GREET 2023 Rev1 used the energy input values from Xu et al. (2022a), who collected HEFA conversion process data from industry surveys. Xu et al. (2022a) also updated the farming parameters (e.g., crop yield, energy inputs, and fertilizer inputs) for soybean and canola production, which were derived mainly from a USDA database. For the oil extraction process, a mass-based allocation was used for oil and meals.

2.3 SUGARCANE ATJ-E

For the sugarcane ATJ-E pathway, we assume that ethanol upgrading takes place in the United States, while sugarcane farming and sugarcane ethanol production stages occur in Brazil. R&D GREET 2023 Rev1 includes major updates reflecting the state of the industry, including energy inputs, chemical requirements, and yields of sugarcane farming and energy balance of ethanol production (Liu et al. 2023). The study used datasets for 70 individual sugarcane mills that were collected from the Brazilian biofuel program, RenovaBio. A displacement method (also called the system expansion method) is applied to account for the emission impacts of co-produced electricity.

For the ethanol upgrading process, we used the values in Table 4 for the sugarcane ATJ-E.

2.4 UCO AND TALLOW HEFA

Tallow and UCO HEFA processes are also based on the default input assumptions in R&D GREET 2023 Rev1, which relies mainly on Xu et al. (2022a). Because these pathways use waste feedstocks, the system boundary starts at the collection and rendering processes. Xu et al. (2022a) collected data by means of a survey of 46 tallow-rendering operations and 61 UCO rendering facilities. The tallow-rendering process produces both rendered tallow and meat and bone meal (MBM); we employed a mass-based allocation process to allocate energy use and emissions associated with the rendering process.

2.5 DISTILLERS CORN OIL HEFA

Distillers corn oil is produced from corn ethanol plants through an oil-extraction process. As mentioned in Section 2.1 (corn ATJ-E pathway), production of distillers corn oil is responsible for the emissions from distillers corn oil extraction. Like other HEFA pathways, the distillers corn oil HEFA process relies on the study by Xu et al. (2022a).

3 INDIRECT EFFECTS

Indirect effects (I-effect) include ILUC emissions resulting from domestic and international land conversions, emissions due to changes in domestic and international non-feedstock crop production (including rice paddy field methane emissions) and emissions attributable to changes in domestic and international livestock production. These three I-effects are potentially induced by a biofuels program such as an incentive for SAF production. Historical GREET versions and R&D GREET 2023 Rev1 include ILUC emissions, while the other two indirect effects are included in 40BSAF-GREET 2024. Of the seven SAF pathways, the four that rely on dedicated feedstocks — corn, soybean, canola, and sugarcane — are subject to indirect effects as they are crops that are produced on dedicated land so additional production of them may lead to changes in other parts of the agricultural system.

Indirect effects are simulated using two steps: (1) changes in indirect effect activities, and (2) GHG emissions associated with changes in indirect effect activities. Purdue University configured its GTAP-BIO model to complete the first step. Argonne, together with ICF, completed the second step. Note that the indirect effects are amortized emissions over a 30-year period of the GTAP activity modeling results.

Below are the annual SAF production shock sizes used by Purdue in GTAP-BIO simulations.

- U.S. corn ATJ-E: 1 billion gal/yr.
- U.S. soybean HEFA: 0.5 billion gal/yr.
- U.S. and Canada canola (summer) HEFA: 0.5 billion gal/yr.
- Brazilian sugarcane ATJ-E: 1 billion gal/yr.

For this study, Purdue used the GTAP-BIO version based on global 2014 datasets (see Appendix A for details). GTAP-BIO simulations consider ATJ-E and HEFA conversion rates to simulate the feedstock demand, satisfying the SAF production shock volumes listed above. GTAP-BIO simulation results are presented in three Excel files available at the R&D GREET website.

Because the ATJ-E and HEFA conversion rates of specific projects may vary from those considered in the GTAP-BIO simulations, Argonne completed a two-step process to align these assumptions and to make direct LCA results and indirect effect results consistent. First, we adjusted the GTAP-BIO-based I-effects using a relative ratio of the updated ATJ-E and HEFA conversion rates for direct LCA in R&D GREET 2023 Rev1 and those in GTAP-BIO, following Equation (1).

$$I\_effects_{adj,GREET} = \frac{SAF\ conversion\ rate_{GREET}}{SAF\ conversion\ rate_{GTAP}} \times (I\_effects_{GTAP}) \qquad \text{Equation (1)}$$

Where,

$I\_effects_{GTAP}$ is the indirect effects of an SAF pathway based on the SAF conversion rate from GTAP-BIO;

$I\_effects_{adj,GREET}$ is the indirect effects of the SAF pathway corresponding to the GREET default SAF conversion rate after the conversion rate-based adjustment;

$SAF\ conversion\ rate_{GREET}$ is the SAF conversion rate of the SAF pathway, in units of MJ ethanol/MJ of total liquid fuel output for ATJ-E pathways or in units of ha/kg of total liquid fuel output for soybean and canola HEFA pathways, in R&D GREET 2023 Rev1; and

$SAF\ conversion\ rate_{GTAP}$ is the SAF conversion rate of the SAF pathway, in units of MJ ethanol/MJ of total liquid fuel output for ATJ-E pathways or in units of ha/kg of total liquid fuel output for soybean and canola HEFA pathways, that is considered in GTAP-BIO.

Table 5 lists SAF conversion rates from GTAP-BIO and R&D GREET 2023 Rev1 for the four SAF pathways that rely on dedicated feedstocks. We applied these conversion rates to adjust GTAP-BIO results for 40BSAF-GREET use.

Table 5. SAF conversion rates considered in GTAP-BIO and R&D GREET 2023 Rev1

	Conversion Rates		
Pathway	**GTAP-BIO**	**R&D GREET 2023 Rev1**	**Unit**
Corn ATJ-E	1.39	1.01	MJ of ethanol/MJ of total liquid fuel output
Sugarcane ATJ-E	1.28[a]	1.01	MJ of ethanol/MJ of total liquid fuel output
Soybean HEFA	1/549.1	1/446.2	ha/kg of total liquid fuel outputs
Canola HEFA	1/662.9	1/609.5	ha/kg of total liquid fuel outputs

[a] For the sugarcane ATJ-E, GTAP-BIO used a fuel yield of 1,313 MJ of total liquid fuels per metric ton of sugarcane. We converted the sugarcane consumption to ethanol consumption using the ethanol yield of 20.8 gal of ethanol per metric ton of sugarcane in R&D GREET 2023 Rev1, resulting in a conversion rate of 1.28 MJ ethanol/MJ total liquid fuels.

Table 6 summarizes the indirect effects after the conversion rate adjustments for the four SAF pathways considered. Subsections 3.1.1 through 3.1.4 describe the factors used to determine the results listed in the table.

Table 6. Adjusted indirect effects of the four SAF pathways (in g CO_2e/MJ of liquid fuels)

	Pathway			
	Corn ATJ-E	**Soy HEFA**	**Canola HEFA**	**Sugarcane ATJ-E**
ILUC	9.0	12.2	18.1	10.6
Non-Feedstock Crops	3.8	3.5	5.9	-3.0
Livestock	-1.4	1.4	0.1	-1.6
Rice Methane	-0.3	-0.8	-0.3	-0.1
Total	**11.1**	**16.2**	**23.7**	**5.9**

Table 7 summarizes the adjusted indirect effect results when converted to per bushel of corn, per bushel of soybean, per metric ton of canola, and per metric ton of sugarcane.

Table 7. Adjusted indirect effect results of the four SAF pathways (in g CO_2e per bushel of corn/soybeans and g CO_2e per metric ton of canola/sugarcane)

	Pathway			
	Corn Ethanol (Dry Mill w/ Distillers Corn Oil Extraction) ATJ-E	**Soy Oil HEFA**	**Canola Oil HEFA**	**Sugarcane ATJ-E**
ILUC	2,057.3	2,366.8	675,828.7	17,619.1
Non-Feedstock Crops	859.6	682.6	221,961.8	-5,005.0
Livestock	-322.8	263.9	2,745.4	-2,597.2
Rice Methane	-67.8	-155.9	-12,133.8	-240.2
Total	2,526.2	3,157.4	888,402.0	9,776.6

Second, Argonne set up the 40BSAF-GREET 2024 to adjust SAF project-specific indirect effects based on the project-specific conversion rate relative to the default in R&D GREET 2023 Rev1. Lower project-specific conversion rate means less feedstock is required to produce the same shock volume, and vice versa, resulting in reduced indirect effects. For corn and sugarcane ATJ-Ethanol pathways, the indirect effects are adjusted using Equation (2). For soybean and canola HEFA pathways, the indirect effects are adjusted using Equation (3).

$$I\_effects_{ATJ-Ethanol,adj,i} = \frac{Ethanol\ conversion\ rate_i}{Ethanol\ conversion\ rate_{GREET}} \times \frac{SAF\ conversion\ rate_i}{SAF\ conversion\ rate_{GREET}} \times (I\_effects_{ATJ-Ethanol,GREET}) \quad \text{Equation (2)}$$

$$I\_effects_{HEFA,adj,i} = \frac{SAF\ conversion\ rate_i}{SAF\ conversion\ rate_{GREET}} \times (I\_effects_{HEFA,GREET}) \quad \text{Equation (3)}$$

Where,

$I\_effects_{ATJ-Ethanol,GREET}$ is the indirect effects of an ATJ-Ethanol SAF pathway based on the GREET default SAF conversion rate in R&D GREET 2023 Rev1, following Equation (1);

$I\_effects_{ATJ-Ethanol,adj,i}$ is the adjusted indirect effects of the ATJ-Ethanol SAF pathway for project *i* after the project-specific conversion rate-based adjustment;

$I\_effects_{HEFA,GREET}$ is the indirect effects of a HEFA SAF pathway based on the GREET default SAF conversion rate in R&D GREET 2023 Rev1, following Equation (1);

$I\_effects_{HEFA,adj,i}$ is the adjusted indirect effects of the HEFA SAF pathway for project *i* after the project-specific conversion rate-based adjustment;

$Ethanol\ conversion\ rate_i$ is the project-specific ethanol conversion rate in bushel of corn per gallon of corn ethanol or wet tonne of Brazilian sugarcane per gallon of Brazilian sugarcane ethanol;

$Ethanol\ conversion\ rate_{GREET}$ is the GREET default ethanol conversion rate, which is 0.35 bu of corn per gallon of corn ethanol or 0.048 wet tonne of Brazilian sugarcane per gallon of Brazilian sugarcane ethanol.$SAF\ conversion\ rate_i$ is the SAF conversion rate of the SAF pathway, in units of MJ ethanol/MJ of total liquid fuel output for ATJ-E pathways or in units of kg of vegetable oil per kg of total liquid fuel output for soybean and canola HEFA pathways, for project *i*; and

$SAF\ conversion\ rate_{GREET}$ is the default SAF conversion rate of the SAF pathway that is considered in R&D GREET 2023 Rev1, as listed in Table 8.

Table 8. Default SAF conversion rates in R&D GREET 2023 Rev1

Pathway	GREET Default Conversion rate	Unit
Corn ATJ-E	1.01	MJ of ethanol/MJ of total liquid fuel output
Sugarcane ATJ-E	1.01	MJ of ethanol/MJ of total liquid fuel output
Soybean HEFA	1.27	kg of vegetable oil per kg of total liquid fuel output
Canola HEFA	1.27	kg of vegetable oil per kg of total liquid fuel output

3.1 ILUC GHG EMISSIONS

GTAP-BIO modeling considers an annual SAF production shock and simulates the resulting land use changes in hectares for each land conversion. In R&D GREET 2023 Rev1 (and 40BSAF-GREET 2024), the GTAP simulated land use changes are amortized over a period of 30 years, the same amortization period used in EPA's Renewable Fuel Standard and the California Low-Carbon Fuel Standard. The GTAP-BIO model ILUC results cover domestic and international land conversions that occur in response to a SAF fuel production shock: pasture or grassland conversion to cropland/and vice versa, conversion of cropland pasture to cropland and vice versa, conversion of forest to cropland and vice versa, and conversion from marginal unused land to cropland and vice versa.

GHG emissions occur because of changes in the soil carbon stock and overall carbon fluxes from conversion of one land type to another. For 40BSAF-GREET 2024, we take empirical carbon flux emission factors (expressed in metric ton of CO_2/ha/year) from the agro-ecological zone emission factor (AEZ-EF) model (Plevin et al., 2015; Taheripour et al., 2024) for 19 world regions across 18 AEZs; the model is used by GTAP-BIO for the ICAO CORSIA program. To mirror the CORSIA methodology (in which the AEZ-EF emission factors are applied to estimate ILUC GHG emissions), we implement the same AEZ-EF emission factors for both international and domestic ILUC (together with the GTAP-BIO ILUC results) using the Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) tool in R&D GREET 2023 Rev1.

CCLUB contains other emission factor sets, such as those developed using the CENTURY model — a process-based simulation model — for U.S. domestic cropland conversions (Liu. et al. 2023). These other emission factor sets in CCLUB can be used with GTAP ILUC results to estimate ILUC GHG emissions for pathways in R&D GREET 2023 Rev1.

3.1.1 Corn ATJ-E

For the corn ATJ-E shock of 1 billion gallons of SAF per year, GTAP-BIO results show that more than 246,000 hectares of cropland/pasture,[1] more than 68,000 hectares of grassland, and more than 20,000 hectares of forest are converted to cropland domestically and internationally across 18 AEZs over the 30-year simulation period. For cropland/pasture conversion, U.S. domestic conversion accounts for about 33%, followed by the EU (17%), Russia (17%), Brazil (8%), Canada (8%), and other world regions. For the grassland conversion, Sub-Saharan African countries dominate with 60%, followed by Brazil (11%), the United States (10%), and other world regions. For the forest conversion, Sub-Saharan African countries dominate with 48%, followed by Asia (22%), South America (16%), Brazil (13%), and other world regions. Note that the United States is estimated to have only a slight increase in forest land (1,600 hectares).

For the cropland/pasture conversion to cropland in the United States (the largest conversion share across regions), the AEZ-EF model emission factors vary from 27 metric tons of GHG emissions per hectare in AEZ 13 to 102 in AEZ 16. For the grassland conversion to cropland in Sub-Saharan African countries (the largest conversion share across regions), the AEZ-EF model emission factors vary from 45 metric tons of GHG emissions per hectare in AEZ 7 to 225 in AEZ 12. For the forest conversion to cropland in Sub-Saharan African countries, the AEZ-EF model emission factors vary from 382 metric tons of GHG emissions per hectare in AEZ 10 to 937 in AEZ 6. Note that the AEZ-EF emission factors are the same for the same land conversion type in the same AEZ of a specific world region, regardless of the SAF pathway. These AEZ-EFs are implemented in CCLUB.

By combining the GTAP-BIO-simulated ILUC for the three major land conversion types across the AEZ regions (within each world region) with the corresponding AEZ-EF emission factor, we estimated the ILUC GHG emissions of the corn ATJ-E pathway at 9.5 g CO_2e/MJ of SAF (Table 6 and Figure 1). Domestic ILUC GHG emissions account for 1.1 g CO_2e/MJ. Conversion from cropland/pasture to cropland, which accounts for 87% of the total domestic ILUC by acreage, is the dominant driver of domestic ILUC GHG emissions.

1 Cropland/pasture represents a land category that switches between cropland and pasture intermittently.

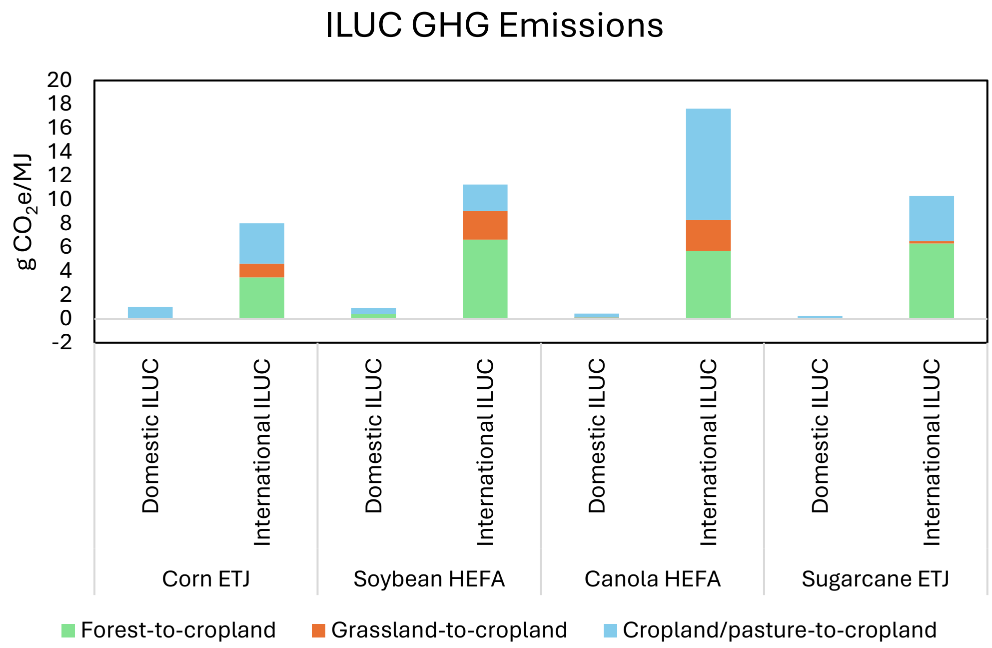

Figure 1. Domestic and international ILUC GHG emissions (g CO_2e/MJ) associated with conversion of forest to cropland, grassland to cropland, and cropland/pasture to cropland for four SAF pathways

Total ILUC GHG emissions of 8.4 g CO_2e/MJ are associated with international ILUC that occur across 18 world regions other than the United States. Conversion from forest to cropland and cropland/pastureland to cropland across the other world regions accounts for the most significant contribution to international ILUC GHG emissions: 3.7 and 3.5 g CO_2e/MJ, respectively. Forest conversion in Oceania countries (36%), South and Central America (23%), Brazil (21%), and Asia (16%) accounts for most of the conversion emissions, while conversion of cropland/pastureland to cropland in Brazil (44%), the EU (24%), Russia (10%), and Canada (6%) contributes the most GHG emissions from this ILUC type.

Although the scale of cropland/pasture conversion to cropland is about 15 times greater than that of forest conversion, the AEZ-specific emission factors for forest conversion are much greater than those for cropland/pastureland conversion. Across the global regions, the AEZ-specific emission factors for forest conversion vary from 2 times higher to as much as 35 times higher than those of the cropland/pasture conversion. For example, forest conversion in Canada in AEZ 13 results in 35 times more GHG emissions than cropland/pasture conversion in the same AEZ 13 region. As a result, these two land conversion types contribute similarly to the total ILUC GHG emissions for corn ATJ-E.

3.1.2 Soybean HEFA

For the soybean HEFA shock of 500 million gallons of SAF per year, GTAP-BIO results show that more than 55,000 hectares of cropland/pasture, more than 18,000 hectares of grassland, and about 2,000 hectares of forest are converted to cropland globally across 18 AEZs. For the cropland/pasture conversion, the U.S. conversion accounts for about 25%, followed by the EU (17%), Russia (17%), Brazil (13%), and other world regions. For the grassland conversion, Sub-Saharan African countries dominate (61%), followed by South America (11%), Brazil (10%), Asia (9%), and other world regions. For the forest conversion, the United States dominates (69%), followed by Asia, Brazil, and other world regions. Note that the Sub-Saharan African countries are estimated to see a slight increase in forested land (about 1,000 hectares).

Combining the GTAP-BIO-simulated ILUC for the three major land conversion types across the AEZ regions within each world region with the corresponding AEZ-EF emission factors, the ILUC GHG emissions of the soybean HEFA pathway are estimated to be 12.2 g CO_2e/MJ of SAF (Table 6 and Figure 1). Domestic ILUC GHG emissions account for 0.9 g CO_2e/MJ. Conversion from cropland/pasture to cropland and from forest to cropland accounts for almost all the domestic ILUC GHG emissions. For the corn ATJ-E pathway, the significant difference in the scale of ILUC between these two land conversion types and the significant differences in the AEZ-EF model emission factors for the two land conversions offset one another, resulting in similar amounts of domestic ILUC GHG emissions from these two land conversions.

GHG emissions associated with international ILUC account for 11.3 g CO_2e/MJ. Conversion from forest to cropland has the most significant contribution to international ILUC GHG emissions, resulting in 6.7 g CO_2e/MJ. Forest conversion — especially conversion of forest on peatland for palm oil production in Malysia and Indonesia — is the main source of international ILUC emissions (86%), followed by Brazil (7%), and rest of Asia (5%). The AEZ-EF model assumes a large share of forest on peatland in Southeast Asia. Conversion from grassland and conversion from cropland/pasture account for 2.4 and 2.2 g CO_2e/MJ, respectively.

3.1.3 Canola HEFA

For the canola HEFA shock of 500 million gallons of SAF per year, GTAP-BIO results show that more than 178,000 hectares of cropland/pasture, more than 24,000 hectares of grassland, and about 8,000 hectares of forest are converted to cropland domestically and internationally across 18 AEZs. For the cropland/pasture conversion, Canada accounts for 38%, followed by the EU (29%), Russia (12%), the United States (6%), and other world regions. For the grassland conversion, Sub-Saharan African countries dominate (70%), followed by South America (7%), Canada (7%), and other world regions. For the forest conversion, Sub-Saharan African countries account for 31%, followed by Canada, Brazil, Asia, the United States, and other world regions.

Combining the GTAP-BIO-simulated ILUC for the three major land conversion types across the AEZ regions within each world region with the corresponding AEZ-EF emission factors, the ILUC GHG emissions of the canola HEFA pathway are estimated at 18.1 g CO_2e/MJ of SAF (Table 6 and Figure 1). Domestic ILUC GHG emissions account for 0.4 g CO_2e/MJ, mostly due to conversion from cropland/pasture to cropland.

GHG emissions associated with international ILUC are estimated at 17.6 g CO_2e/MJ. Conversion from cropland/pasture to cropland accounts for 9.3 g CO_2e/MJ, primarily in the EU and Canada, which account for 43% and 39%, respectively, of the total emissions for this conversion. Forest conversion across the world regions is responsible for 5.6 g CO_2e/MJ, while grassland conversion accounts for 2.6 g CO_2e/MJ. For canola HEFA, forest conversion in Malysia and Indonesia accounts for 53% of the emissions from deforestation across all the world regions. Grassland conversion in Malysia and Indonesia accounts for 47% of the emissions associated with this land conversion across world regions.

Canola HEFA has higher ILUC GHG emissions than soybean HEFA for several reasons. First, canola is produced on land converted from regions with less multi-cropping and less unused land than regions cultivated with soybeans. Second, a large amount of canola is grown on land in Canada that has high soil carbon stocks in AEZ-EF, resulting in high ILUC GHG emissions. Third, based on GTAP-BIO, soybean production generates more market-mediated responses and thus more savings in consumption than canola. Fourth, GTAP predicts that canola involves more interaction with palm expansion than soybeans. Finally, the soybean HEFA pathway produces larger amounts of meals than the canola pathway, which offsets ILUC effects to some degree.

3.1.4 Sugarcane ATJ-E

For the sugarcane ATJ-E shock of 1.0 billion gallons of SAF per year, GTAP-BIO results suggest that more than 480,000 hectares of cropland/pasture, more than 161,000 hectares of grassland, and more than 38,000 hectares of forest are converted to cropland domestically and internationally across 18 AEZs. For the cropland/pasture conversion, Brazil accounts for 49%, followed by the EU (13%), Russia (29%), the United States (7%), Canada (5%), and other world regions. For the grassland conversion, Brazil dominates (65%), followed by Sub-Saharan African countries (30%), and other world regions. For the forest conversion, Sub-Saharan African countries account for 48%, followed by South America (34%), and other world regions.

Combining the GTAP-BIO-simulated ILUC for the three major land conversion types across the AEZ regions within each world region with the corresponding AEZ-EF emission factors, the adjusted ILUC GHG emissions of the sugarcane ATJ-E pathway are estimated to be 11.1 g CO_2e/MJ of SAF (Table 6 and Figure 1).

ILUC GHG emissions in the United States account for 0.3 g CO_2e/MJ, mostly associated with conversion from cropland/pasture to cropland. GHG emissions associated with non-U.S. ILUC are estimated at 10.8 g CO_2e/MJ. Forest conversion across the world regions is responsible for 6.9 g CO_2e/MJ, primarily from Sub-Saharan African countries (37%), South America (24%), Brazil (19%), and Asia (16%). Conversion from cropland/pasture to cropland accounts for 3.6 g CO_2e/MJ, primarily from the EU (42%), Russia (19%), Brazil (14%), and Canada (9%). Grassland conversion accounts for 0.4 g CO_2e/MJ globally.

3.2 EMISSIONS ASSOCIATED WITH CHANGES IN NON-FEEDSTOCK CROP PRODUCTION

3.2.1 Changes in Non-Feedstock Crop Production

For a given SAF feedstock, (e.g., U.S. corn), GTAP-BIO estimates annual production changes for more than 100 crops globally that result from U.S. corn production for SAF via ethanol. These non-feedstock crops[2] in GTAP-BIO comprise ten crop categories and 19 global regions for each of the four SAF production pathways. Changes in crop production of non-feedstock crops arise from market forces stemming from the increased demand for the SAF feedstock crop. For example, if more corn is demanded for SAF production, there may be some shifting of soybeans to corn production, and that supply of soybeans could be backfilled from soybeans grown elsewhere, or it might not be replaced one-to-one. These shifts in the production of soybeans and other crops from increased demand for corn have emissions impacts. The estimates for non-feedstock crop production are in units of metric tons of crop production change (based on the shock of each SAF production pathway).

3.2.2 GHG Emission Profiles of Non-Feedstock Crop Production

ICF developed the emission profiles for non-feedstock crop production for 29 key crops that represent over 60 percent of global crop production by acreage, and 13 domestic crops that represent the majority of crops grown domestically. Details of the ICF effort are presented in Appendix B. Emission sources for these crops include on-farm energy use, N_2O emissions from nitrogen fertilizer application, N_2O emissions from crop residue retention, and upstream emissions from farm inputs. ICF estimated upstream emissions for energy used on-farm and for fertilizer and pesticide manufacture and transportation. Different methods and data sources were used to estimate domestic and international crop production emission factors per acre of production. Per-acre emission factors were developed for 2021 and include CO_2, CH_4, and N_2O, converted to CO_2e using IPCC AR5 GWPs.

Emission factors were estimated by country and crop and then weight-normalized and aggregated to GTAP-BIO regions and crop categories. To perform the weighted aggregation, ICF used global crop production data for 2014 from FAOSTAT (2023) and the USDA National Agricultural Statistics Survey (NASS) (2024). To align with the 2014 baseline data used in GTAP-BIO, 2014 was selected as the data year. The final emission factors are presented in kg CO_2e per metric ton of crop produced. Figure 2 shows the emission factors by GTAP-BIO region and crop category. When emission factors are aggregated, East Asia, Japan, India, and China show higher emission impacts compared with other regions. The data for this figure and other figures in Section 3.2 are presented in Appendix C.

2 We call these crops *non-feedstock crops*, to differentiate them from crops used as feedstocks for SAF production, which are included in D-LCA simulations presented in Section 2.

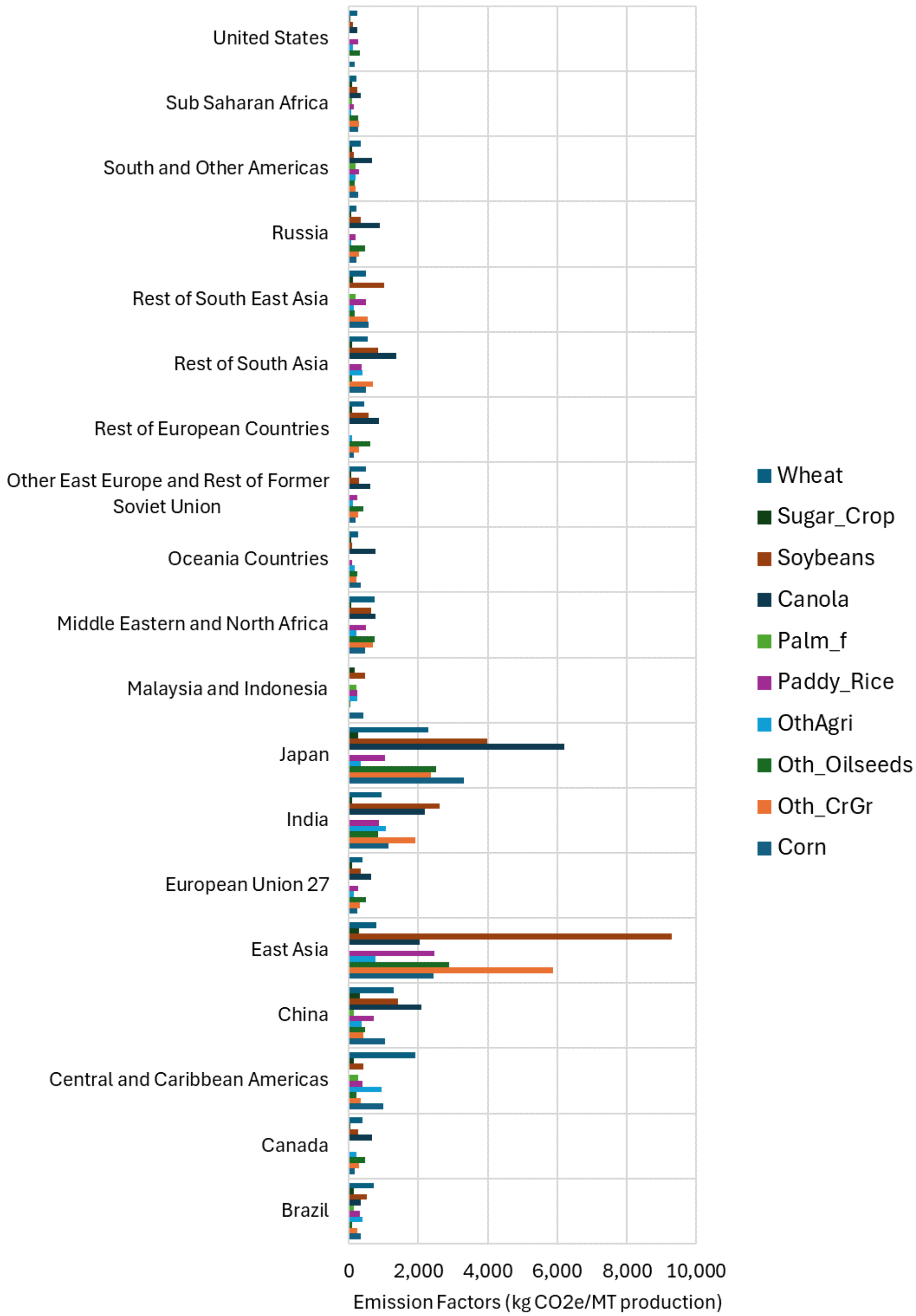

Figure 2. GHG emission factors estimated for GTAP regions and crop categories

3.2.3 Combining Changes in Crop Production and Emission Factors to Derive SAF Production-Induced Emission Intensities

Changes in crop production — in the form of activity change (estimated by GTAP-BIO in units of metric tons) — were mapped with the emission factors for crop production estimated by ICF for the GTAP-BIO regions and crop categories (in units of kg CO_2e per metric ton of crop produced). Based on the mapping, we calculate the total annual GHG emissions using Equation 3. Then, we developed indirect emission intensities of the biofuel shock scenario in units of grams GHG per MJ of biofuel production for each of the pathways (Equation 4), by dividing the annual total emissions by the annual total fuel production for each SAF pathway total: 123.42 PJ/year for Corn ATJ-E, 61.71 PJ/year for Soy HEFA jet, 61.71 PJ/year for Canola HEFA jet, and 160.47 PJ/year for Brazilian sugarcane ATJ-E, as shown in Table 6. These emission intensities are as per IPCC AR5 GWPs. Figure 3 shows the indirect emission intensities associated with changes in crop production across all regions and crops.

$$[indirect\ emissions]_{(region,\ category,\ pathway)} = [emission\ factors]_{(region,\ category)} \times [activity]_{(region,\ category,\ pathway)} \quad \text{Equation (3)}$$

Where,

$[emission\ factors]_{(region,\ category)}$ represents the emission factors for crop production in units of kg CO_2e per MT production (or for livestock production in units of kg CO_2e per USD production) for every crop category (or livestock category) and region;

$[activity]_{(region,\ category,\ pathway)}$ is the change in crop production in units of MT (or change in livestock production costs in units of million USD) for every crop category (or livestock category), regions, and pathway and

$[indirect\ emissions]_{(region,\ category,\ pathway)}$ are the total indirect emissions from crop production change (or livestock production change) for every crop category (or livestock category), regions, and pathway calculated in units of MT CO_2e.

$$[indirect\ emissions\ intensity]_{(region,\ category,\ pathway)} = \frac{[indirect\ emissions]_{(region,\ category,\ pathway)}}{[SAF\ production]_{(pathway)}} \quad \text{Equation (4)}$$

Where,

$[indirect\ emissions]_{(region,\ category,\ pathway)}$ are the total indirect emissions in units of MT CO_2e, as calculated by Equation 3;

$[SAF\ production]_{(pathway)}$ is the quantity of SAF fuels produced for each pathway, in units of MJ; and,

$[indirect\ emissions\ intensity]_{(region,\ category,\ pathway)}$ are indirect emissions estimated in units of MT CO_2e per MJ fuel produced for each crop category (or livestock category), region, and SAF pathway.

Figure 3. GHG emissions for non-feedstock crop production by region, major crop category, and pathway (in g CO_2e/MJ of SAF)

While performing the aggregation, we did not consider crop production for the SAF feedstock for each specific pathway to avoid double counting with direct LCA simulations (Section 2): for the corn ATJ-E pathway, we excluded corn production in the United States; for the Brazilian sugarcane ATJ-E pathway, we excluded sugarcane production in Brazil; for the soybean HEFA jet pathway, we excluded U.S. soybean production; and for the canola HEFA jet pathway, we excluded canola production in the United States and Canada from the calculation.

Emissions of non-feedstock crop production vary by crop category, region, and SAF pathway, as shown in Figure 3. For the corn ATJ-E pathway, the projected reductions in the United States contrast with identifiable increases in Brazil, China, India, and the Central and Caribbean Americas regions. For the soybean HEFA pathway, reductions are projected for the United States and increases are projected in Malaysia and Indonesia, Brazil, India, and China. For the canola HEFA pathway, emissions from the EU region increase and those from Canada decrease. In the Brazilian sugarcane ATJ-E pathway, significant emissions reductions are observed in Brazil. Aggregating the indirect emission impacts from crop production across regions and categories, we estimated them to be 3.8 g CO_2e/MJ for corn ATJ-E, 3.5 g CO_2e/MJ for soybean HEFA, 5.9 g CO_2e/MJ for canola HEFA, and -3.0 g CO_2e/MJ for sugarcane ATJ-E pathways (Table 6).

3.3 RICE PADDY FIELD METHANE EMISSIONS

3.3.1 Changes in Rice Production

Annual paddy rice production changes estimated by GTAP-BIO are classified by 19 global regions for every SAF production pathway. The production of rice in paddy fields results in methane emissions when the fields are flooded. Methane emissions from rice paddy fields is presented separately here because of its unique emissions process. The estimates are in units of metric tons of rice production.

3.3.2 Methane Emission Profiles for Rice Cultivation

ICF developed CH_4 emission factors for rice cultivation, per acre of rice grown. Details of the ICF effort are presented in Appendix B. International and domestic rice paddy CH_4 emissions were developed using multiple datasets. Domestic emissions are based on EPA's U.S. GHG Inventory 1990–2021 (EPA 2023). ICF derived the per-acre emission factors for international rice production by country using the IPCC Tier 1 methodology (IPCC 2019). Country-specific emissions data were aggregated to GTAP-BIO region estimates and converted to per-MT rice production using the same approach described in Section 3.2.2 and data from FAOSTAT and NASS. Figure 4 presents the final regional emission factors converted to CO_2 equivalence as per IPCC AR5 GWPs.

Emissions of N_2O from synthetic fertilizer applied to rice paddies and other rice production emissions were estimated as part of crop production estimates described in Section 3.2.2.

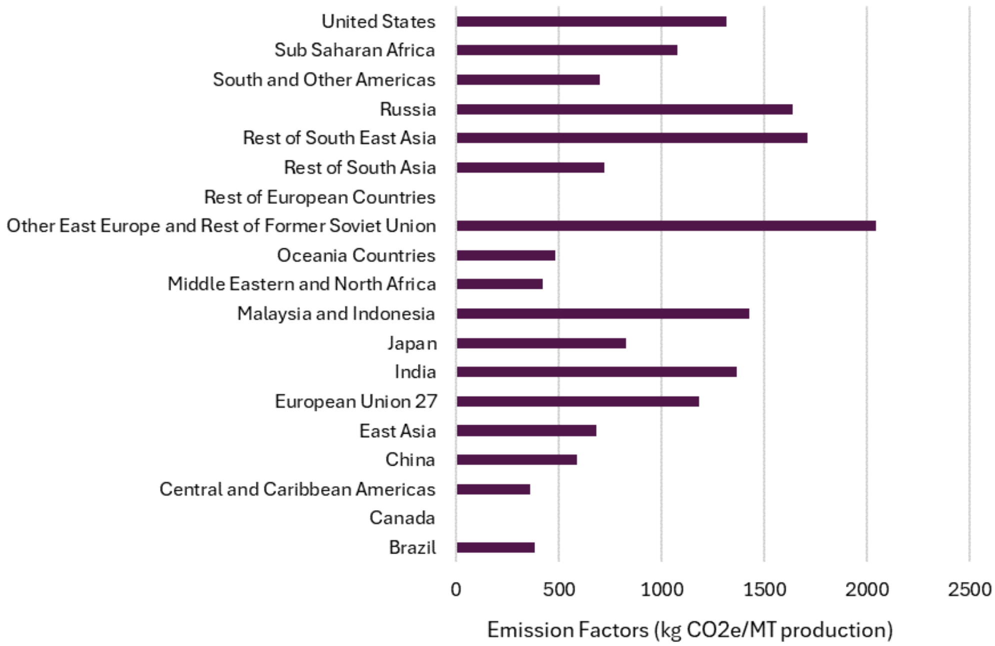

Figure 4. Rice paddy methane emission factors by country/region

3.3.3 Combining Changes in Rice Production and Paddy Field Emission Factors to Derive SAF Production-Induced Emission Intensities

Similar to the approach used to calculate crop production emissions, we calculated the methane emission intensity of SAF production by mapping rice production activity change by GTAP-BIO regions and using the corresponding emission factor, developed by ICF for the GTAP-BIO regions as per Equation 3. As Figure 5 shows, not all regions contribute to rice paddy emissions; rice is only grown in places with a suitable growing climate. Emission intensities vary across pathways. For the corn ATJ-E and Brazilian sugarcane ATJ-E pathways, we see a mix of increased and decreased emission intensities; for the soybean HEFA and canola HEFA pathways, we see decreased emission intensities across the regions.

Next, as per Equation 4, we calculate the net rice methane emission intensity considering the yearly total fuel production for each SAF pathway total: 123.42 PJ/year for Corn ATJ-E, 61.71 PJ/year for Soy ATJ-E, 61.71 PJ/year for Canola HEFA, and 160.47 PJ/year for Brazilian sugarcane HEFA pathways.

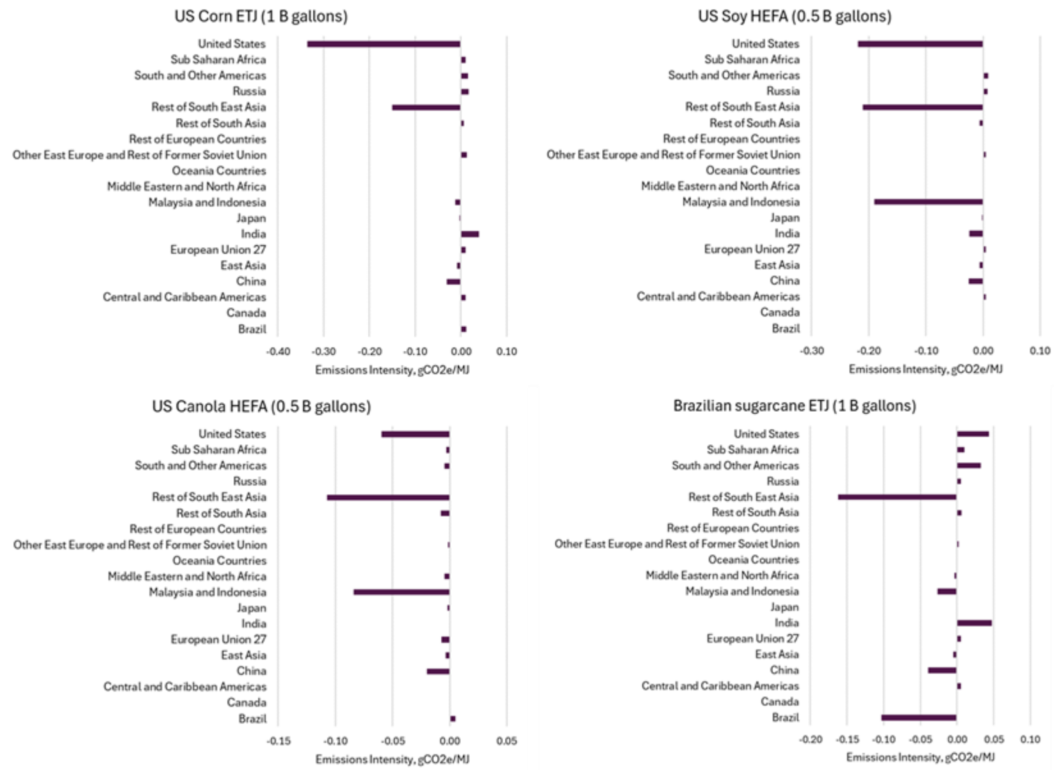

Figure 5. Emissions of rice paddy field CH_4 by region for four pathways

As summarized in Table 6, rice paddy CH_4 methane emissions that result from the SAF production shocks of corn ATJ-E, soybean HEFA, canola HEFA, and sugarcane ATJ-E reduce the I-effects and total LCA results by 0.3, 0.8, 0.3, and 0.1 g CO_2e/MJ of fuel, respectively.

3.4 EMISSIONS ASSOCIATED WITH CHANGES IN LIVESTOCK PRODUCTION

3.4.1 Changes in Livestock Production

GTAP-BIO estimates annual livestock production changes in units of U.S. dollars (2014 USD basis) for three livestock categories — dairy cattle, other ruminant animals (e.g., beef cattle, sheep, and goats), and non-ruminant animals (e.g., chickens and pigs) — and 19 global regions for each of the four pathways. Emissions from livestock arise from market-driven changes in the quantity and type of production driven by market forces. Namely, increased demand for agricultural crops can put direct pressure on grazing land, which could result in the overall reduction in livestock production due to higher prices and/or shifts in production to and from grazing to feed lots on the margin. Moreover, the production of feed coproducts (e.g., DDGS) changes the price and availability of feed types, which affects livestock production.

3.4.2 GHG Emission Profiles for Livestock Production

ICF developed the emission profiles for livestock production. Details of the ICF effort are presented in Appendix B. Emissions from livestock production do not include those from animal feed production. Livestock emissions here include CH_4 from enteric fermentation and CH_4 and N_2O from manure management presented in carbon dioxide equivalent (CO_2e) as per IPCC AR5 GWPs.

U.S. emissions factors per head of livestock species, for all livestock emission sources, are based on population and emissions data from EPA's U.S. GHG Inventory (EPA 2023). International livestock emissions for all livestock emissions sources are estimated based on population data from FAOSTAT, default emission activity data from the IPCC 2019 Refinement to the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*, and national economic classifications from the World Bank group.

To develop emissions per-production of dollar value (2014 USD from GTAP-Bio simulations), ICF used several U.S.-specific production price data sources, including USDA agricultural baseline projections, NASS statistics price data, and USDA agricultural marketing services (livestock, poultry, and grain market news). Because no consistent database of international production prices existed at the time of publication, U.S. price data were used for all countries.

ICF estimated the absolute emissions per livestock type (dairy cattle, other ruminants, and non-ruminants) using the U.S. and international emission factors described above and divided absolute emissions by the absolute production value of each GTAP-BIO sector using the U.S. price-per-head data to obtain emissions in CO_2e per USD of production value.

Figure 6 shows the aggregated livestock (enteric fermentation and manure management) emissions, classified by GTAP-BIO regions and categories.

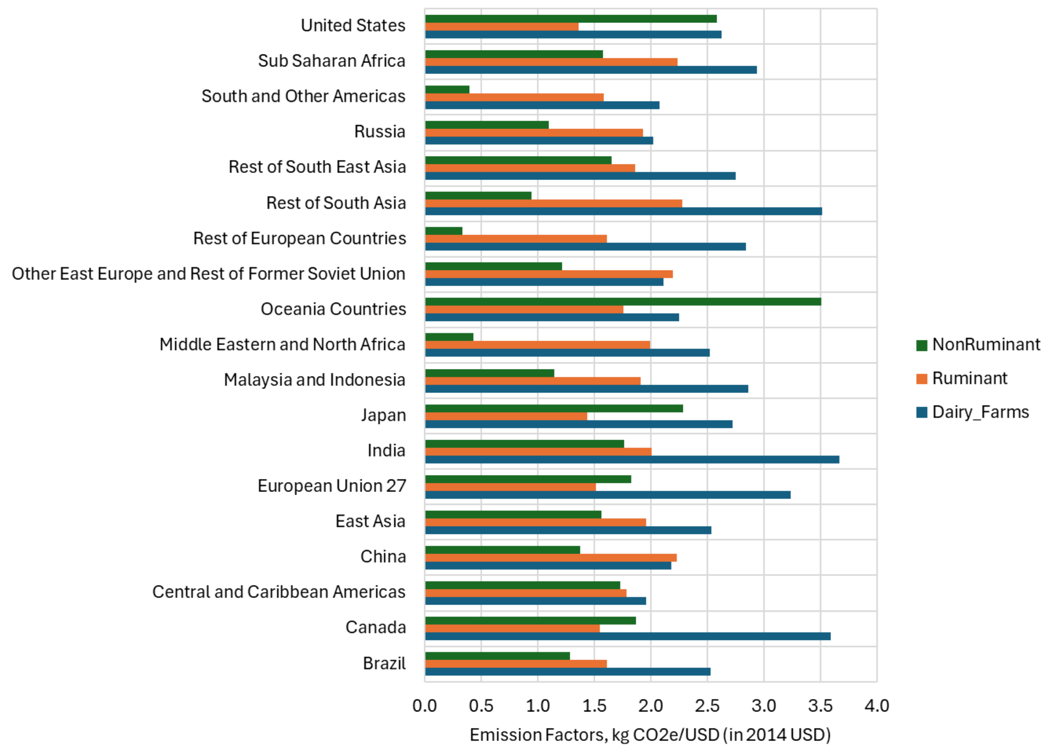

Figure 6. GHG emission factors for livestock production by GTAP-BIO regions and livestock categories

3.4.3 Combining Changes in Livestock Production and Emission Factors to Derive SAF Production-Induced Emission Intensities

A similar approach is taken for combining GTAP-BIO derived livestock production change with emission factors in units of kg CO_2e per USD [2014 USD] which are estimated by ICF for GTAP-BIO regions and livestock categories. The annual emissions by region and category are calculated using Equation (3). Next, the total emissions per region and livestock category were calculated based on Equation (4) for each SAF pathway. The same annual energy production for each SAF pathway mentioned in Section 3.4.1 was used to calculate the emission intensity associated with changes in livestock production for each SAF pathway.

Figure 7 shows the emission intensities for each of the four SAF pathways by region, presented in units of g CO_2e/MJ as per IPCC AR5 GWPs. Across all pathways, emission intensity changes in the United States and Brazil are the most significant, primarily because the changes in livestock production are significantly higher for these countries compared with other countries and regions. For the corn ATJ-E pathway, a reduction in emissions is observed for the United States due to a reduction in livestock production. For the soybean HEFA jet and canola HEFA jet pathways, emission increases are observed. For the Brazilian sugarcane ATJ-E, a reduction in emissions is observed for Brazil.

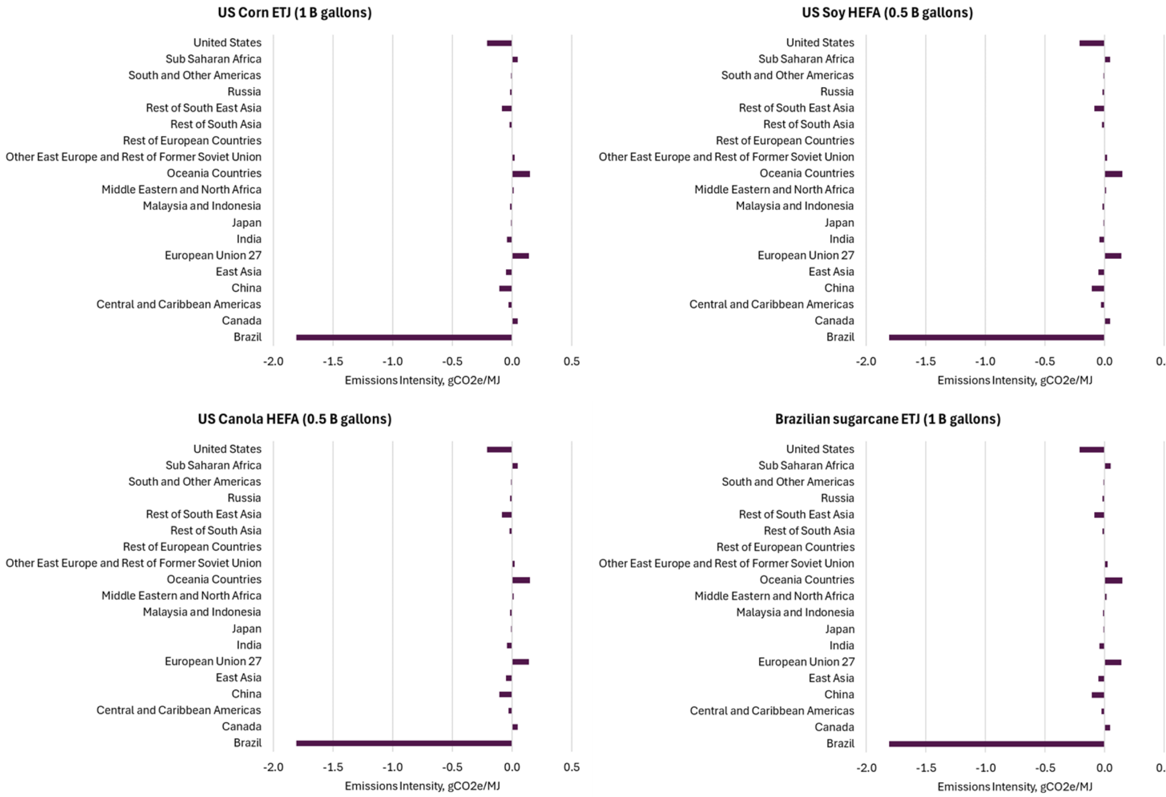

Figure 7. Livestock emission intensities by GTAP region and SAF pathway

Finally, the emission intensities were aggregated across the livestock categories and regions, to obtain the net GHG emissions from livestock production changes. As summarized in Table 6, the ILUC impacts from livestock production change for the pathways are estimated as -1.4 g CO_2e/MJ for Corn ATJ-E, 1.4 g CO_2e/MJ for Soy HEFA, 0.1 g CO_2e/MJ for Canola HEFA, and -1.6 g CO_2e/MJ for Sugarcane ATJ-E.

4 GHG REDUCTION POTENTIALS FOR SAF PRODUCTION

4.1 DEFAULT DATA FOR ENERGY INPUTS FOR ETHANOL AND SAF PRODUCTION IN R&D GREET 2023 REV1

In R&D GREET 2023 Rev1, the U.S. electricity mix is based on the "Annual Energy Outlook 2023" prepared by the U.S. Energy Information Administration, which represents U.S. electricity generation in 2022 (EIA 2023). Separate electricity conditions can be set for SAF production and corn ethanol production. 40BSAF-GREET 2024 has various regional electricity grid options based on EPA's Emissions & Generation Resource Integrated Database (eGRID) (EPA 2024).

As shown in Figure 8, the eGRID encompasses 27 regions.

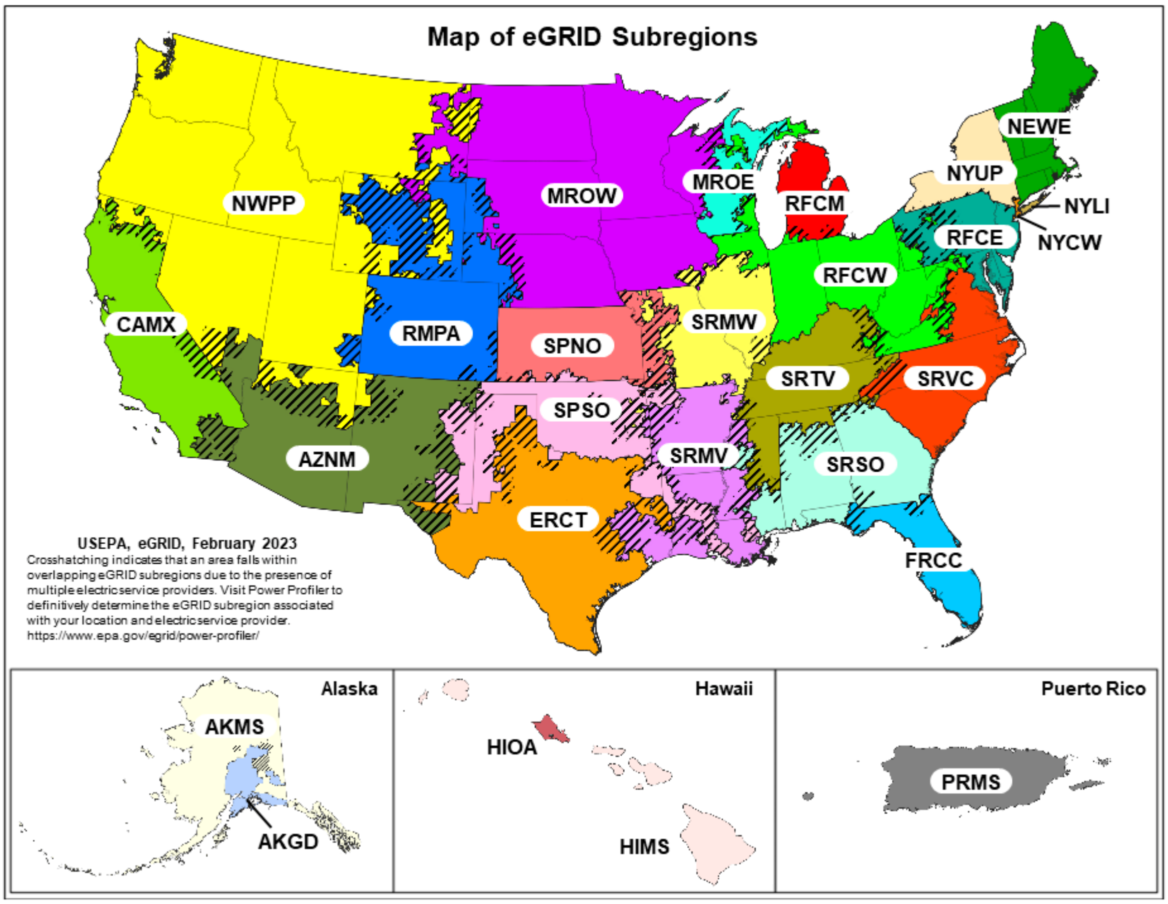

Figure 8. eGRID Regions (https://www.epa.gov/egrid/maps)

Figure 9 shows the electricity GHG intensities of the e-GRID regions in gCO_2e/kWh. The intensities are from the California Air Resources Board's *Proposed Amendments to the Low Carbon Fuel Standard Regulation* (CARB 2024), which presents eGRID 2021 data. The U.S. average transmission and distribution (T&D) loss of 4.9% is used for all cases. For the sugarcane

ATJ-E pathway, we assume that farming and sugarcane ethanol production occur in Brazil. Thus, instead of eGRID regions, sugarcane farming and sugarcane ethanol production use Brazil's electricity mix and GHG intensity.

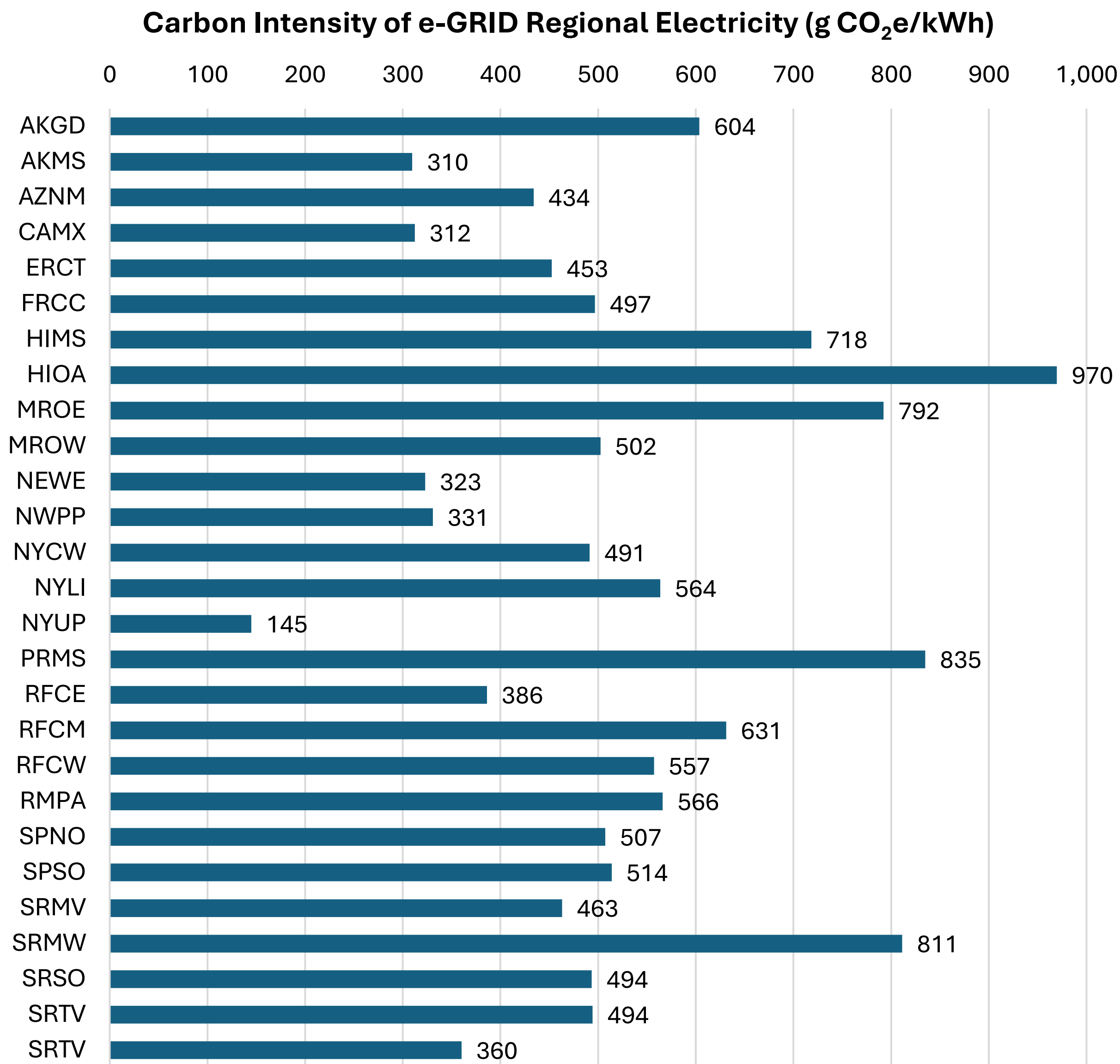

Figure 9. GHG intensities (g CO_2e/kWh) of the e-GRID regions

In R&D GREET 2023 Rev1, fossil NG and fossil NG-derived H_2 via SMR are used for process heat and H_2 by default.

4.2 GHG EMISSION REDUCTION POTENTIALS WITH CLEAN ENERGY SOURCES

Alternative heat sources could be used to replace fossil NG to reduce SAF GHG emissions. The process heat options in R&D GREET 2023 Rev1 include RNG from four different feedstocks (landfill gas, animal waste, wastewater sludge, and food waste). In 40BSAF-GREET 2024, only landfill gas RNG may be selected as an alternative to fossil NG for process heating/consumption. On the other hand, R&D GREET2023 Rev1 includes many other feedstocks for RNG production.

If a 45V modeled H_2 input is used for SAF production, the GHG intensity of the modeled H_2 (kg CO_2e/kg H_2) can be entered in 40BSAF-GREET 2024. Given that the 45V modeled H_2 carbon intensity includes only the well-to-gate emissions, additional emissions from compression and liquefaction (applicable to tube trailer and liquid truck) and H_2 transportation are included in 40BSAF-GREET 2024.

For corn ethanol production, users can apply carbon capture and geological sequestration (CCS) of CO_2 from the fermentation process. The major parameters in R&D GREET 2023 Rev1 that determine the emissions reduction are the amount of fermentation CO_2 (kg/gal of ethanol), the electricity requirement for CCS (kWh/ton CO_2), and the CO_2 capture rate (%). The R&D GREET 2023 default conditions are documented in Xu et al. (2022b). In 40BSAF-GREET 2024, users may enter a facility-level total of CO_2 captured and stored during the period of operation and use an eGRID region selected for corn ethanol production to calculate the emissions associated with electricity consumption for CCS.

Table 9 presents sample GHG emission reduction potentials (that can be achieved by using clean energy sources — such as hydrogen (from fossil NG SMR) and process heat (fossil NG) with lower carbon energy inputs — to replace conventional energy systems.

Table 9. Sample GHG emission reduction potentials (from base case GHG values in Table 2) by selecting different low-GHG energy input options[a]

Emission Changes [g CO_2e/MJ]	Ethanol Production	SAF Production: ATJ-E	SAF Production: HEFA
45V Modeled H_2 (1 kgCO_2e/kg H_2)	n/a	-4.2	-7.0
RNG (landfill gas) to replace fossil NG	-15.8	-9.1	-0.9
100% wind electricity	-3.6	-2.4	-1.1
CCS	-33.4	n/a	n/a

[a] Results in g CO_2e/MJ.

The GHG emission reduction options listed in Table 9 can be combined; for example, the impact of using lower-carbon hydrogen and process heat options can be added together.

For corn ethanol production, replacing fossil NG offers significant GHG emissions reductions. Use of landfill gas-derived RNG reduces GHG emissions by 15.0 gCO_2e/MJ compared with using fossil NG. CCS can significantly reduce emissions from the fermentation process of the corn ATJ-E pathway. By capturing high-purity CO_2 from ethanol facilities and sequestering it underground, the D-LCA value of corn ATJ-E can be reduced by around 36 gCO_2e/MJ (when 2.85 kg CO_2 is captured and stored per gallon of corn ethanol produced).

The ATJ-E pathway contributes significant emissions because of the use of fossil NG. Thus, by replacing the fossil NG used for SAF production with landfill gas-derived RNG that has lower upstream GHG emissions, the D-LCA value of the ATJ-E pathway can be substantially reduced — by 5.1 gCO_2e/MJ. Also for ATJ-E pathways, use of 45V modeled H_2 with the CI of 1 $kgCO_2e$/kg H_2 reduces GHG emissions by 4.2 gCO_2e/MJ for the corn ATJ-E LCA value.

In general, because HEFA pathways use relatively little NG, using RNG to replace fossil NG input for the HEFA process only offers a reduction of 0.9 gCO_2e/MJ. On the other hand, 45V modeled H_2 (with lower H_2 GHG emissions) can be used to replace conventional H_2 from NG SMR. The HEFA pathways consume H_2 at a relatively higher rate per MJ of fuel production compared with the ATJ-E process. If 45V modeled H_2 with 1 $kgCO_2e$/kg H_2 is used for the HEFA process, the emissions reduction can be as high as 7 gCO_2e/MJ.

Different electricity mixes can be used as well. However, the GHG emissions reduction impact is not as significant as other options. For example, when 100% wind electricity is used, the emissions reductions for corn ethanol production, ATJ-E, and HEFA are 3.6, 2.4, and 1.1 gCO_2e/MJ, respectively.

5 REFERENCES

California Air Resources Board (CARB), 2024, *Appendix B: CA-GREET4.0 Supplemental Document Proposed Amendments to the Low Carbon Fuel Standard Regulation*, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2024/lcfs2024/appb.pdf

Energy Information Administration (EIA), 2023, "Annual Energy Outlook 2023," https://www.eia.gov/outlooks/aeo/.

FAOSTAT (Food and Agriculture Organization of the United Nations), 2023, "Crops and Livestock Products Domain," https://www.fao.org/faostat/en/#data/QCL.

Intergovernmental Panel on Climate Change (IPCC), 2019, "Chapter 5: Cropland," in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use*. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch05_Cropland.pdf.

ICAO (International Civil Aviation Organization), 2022, *CORSIA Supporting Document, CORSIA Eligible Fuels – Life Cycle Assessment Methodology*, https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/CORSIA_Supporting_Document_CORSIA%20Eligible%20Fuels_LCA_Methodology_V5.pdf.

Lee, U., Kwon, H., Wu, M., and Wang, M., 2021,"Retrospective analysis of the US corn ethanol industry for 2005–2019: Implications for greenhouse gas emission reductions," *Biofuels, Bioproducts and Biorefining* 15(5):1318–1331.

Liu, X., Kwon, H., Wang, M., and O'Connor, D., 2023, "Life Cycle Greenhouse Gas Emissions of Brazilian Sugar Cane Ethanol Evaluated with the GREET Model Using Data Submitted to RenovaBio," *Environmental Science & Technology* 57(32):11814–11822.

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

Plevin, R. J., Gibbs, H. K., Duffy, J., Yui, S., and Yeh, S., 2015, Agro-Ecological Zone Emission Factor (AEZ-EF) Model (v47)*; GTAP Center, Department of Agricultural Economics*, Purdue University: West Lafayette, IN, USA.

Renewable Fuels Association (RFA), 2024, *2024 Ethanol Industry Outlook*, https://ethanolrfa.org/resources/annual-industry-outlook.

Taheripour, F., Mueller, S., Emery, I., Karami, O., Sajedinia, E., Zhuang, Q., and Wang, M., "*Biofuels Induced Land Use Change Emissions: The Role of Implemented Land Use Emission Factors*". Sustainability 2024, 16, 2729. https://doi.org/10.3390/su16072729,

U.S. Environmental Protection Agency (EPA), 2024, "eGrid mapping," https://www.epa.gov/egrid.

Wang, Z., Dunn, J. B., Han, J., and Wang, M. Q., 2015, “Influence of corn oil recovery on life-cycle greenhouse gas emissions of corn ethanol and corn oil biodiesel.” *Biotechnology for Biofuels* 8(2015):1–10.

Xu, H., Ou, L., Li, Y., Hawkins, T. R., and Wang, M., 2022a, “Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States.” *Environmental Science & Technology* 56(12):7512–7521.

Xu, H., Lee, U., and Wang, M., 2022b, “Life-cycle greenhouse gas emissions reduction potential for corn ethanol refining in the USA,” *Biofuels, Bioproducts and Biorefining* 16(3):671–681.

APPENDIX A: AN OVERVIEW OF GTAP-BIO MODEL

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Introduction

The GTAP-BIO model has been developed, improved, and frequently used during the past two decades to study the economic and environmental effects of biofuel production and policy. This appendix introduces the background of this model and its main features and explains a set of modifications that have been introduced in this model to evaluate the environmental impacts of the four Sustainable Aviation Fuel (SAF) pathways in this study.

Standard GTAP model

The GTAP-BIO model is an advanced extension of the standard Global Trade Analysis Project (GTAP) model. The original standard GTAP model is presented in Hertel (1997) with a full discussion of the theory, foundation of the behavioral equations, and the included accounting equations and market clearing conditions. The most recent version of the standard GTAP model is introduced in Corong et al. (2017). GTAP is a multi-region, multi-sector, Computable General Equilibrium (CGE) model which simulates production, consumption, and trade of all goods and services produced at a global scale. In this model, the economic activities and their corresponding supplies of goods and services are categorized, aggregated, and presented according to the International Standards Industrial Classifications (ISIC) and other related nomenclatures. Figure A1 represents the main components of this model and their links.

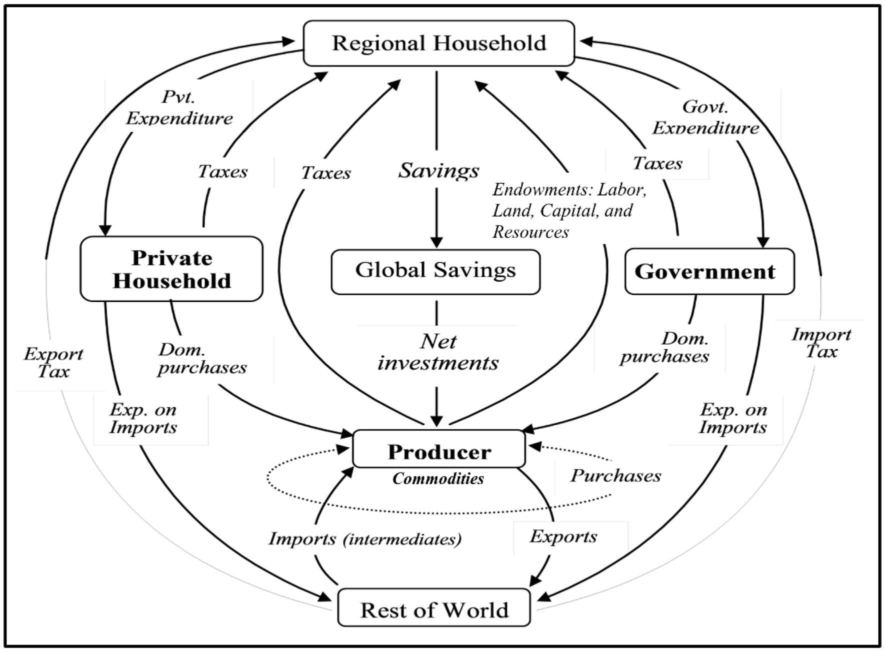

Figure A1. Schematic of GTAP Model (Hertel et al. 2010)

In the GTAP model, a regional household (e.g., the United States) collects all the incomes in its region and spends it over three expenditure categories including private household (consumer), government, and savings. In each sector of the GTAP model, a representative firm uses primary factors of production (including labor, land, capital, and natural resources) and intermediate inputs to produce a specific good or service. Producers pay wages, rental rates, or prices of resources to the regional household in return for the employment or use of land, labor, capital and natural resources. Producers are profit maximizer entities. They sell their outputs to other producers, (as intermediate inputs), private households, government, and investment. In this global CGE model, producers also export their tradable products or services to and import the intermediate inputs from other regions. In the GTAP model, the private household, a utility maximizer entity, spends its net incomes and purchases domestically produced or imported goods and services. Similarly, the government demands goods and services as well.

According to the observed trade patterns, the GTAP model follows the Armington hypothesis assuming that the tradeable goods and services are differentiated by region (imperfect substitutes). Following this assumption, the model traces bilateral trade flows among all countries/regions around the world. The regional household collects all taxes from economic entities and provides subsidies. The rest of the world gets revenues by exporting to private households, producers, and government. This rest of the world composite is made up of many other countries/regions – with the same explanation as mentioned above. Since GTAP is a global model, it takes into account the global savings and investments and a global market for capital resources.

Figure A2 shows the major components of a stylized simple one-region CGE model. The left box of this figure represents primary factors of production (land, labor, capital, and natural resources). Producers or economic sectors (classified into agriculture, industries, energy, and services in this stylized simple model) produce goods and services. Producers use a portion of their outputs as intermediate inputs. The rest could be used either by domestic users (as goods and services consumed by households or used by the government or used as capital goods) or foreign customers through trade (net of exports and imports).

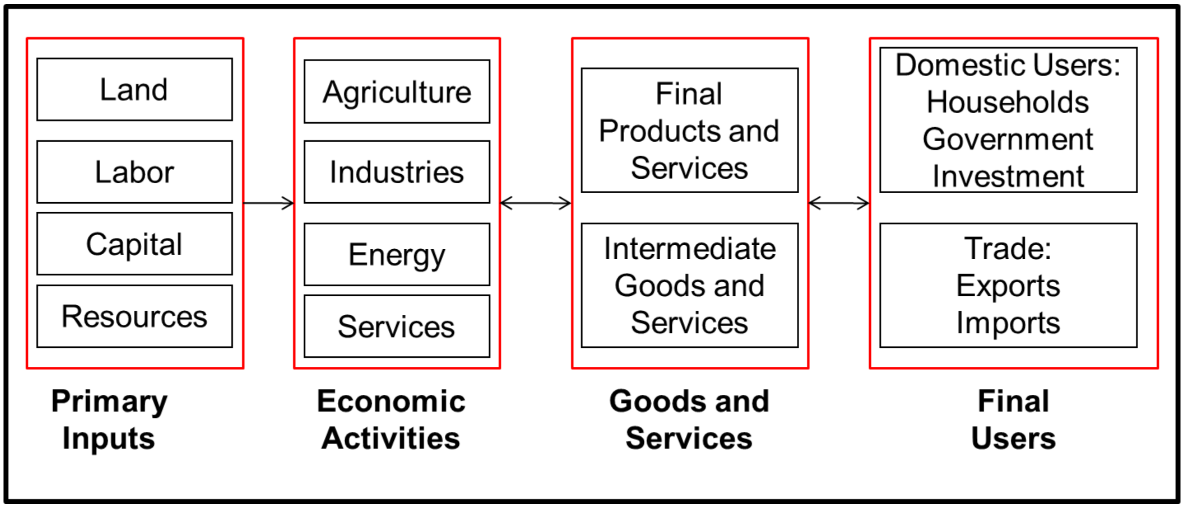

Figure A2. Major components of stylized simple one region CGE model

GTAP databases and the GTAP Center

The standard GTAP model operates based on the standard GTAP database. This data base has been frequently updated over time. The first GTAP database was published in 1993, representing the global economy in 1990 including 15 regions and 37 economic sectors. The two latest versions of this database (versions 10a and 11) have been released in 2019 and 2023. The GTAP database version 10a divides the whole world into 141 regions, represents 65 economic sectors, and contains benchmark databases for reference years of 2004, 2007, 2011, and 2014 (Aguiar et al., 2019). The GTAP database version 11 provides benchmark data bases for 2004, 2007, 2011, 2014 and 2017, divides the global economy into 160 regions, and represents 65 economic sectors (Aguiar et al., 2022). Table A1 shows the list of economic sectors presented in GTAP database versions 10a and 11. A GTAP data base usually includes an Input-Output table (or Social Accounting Matrix (SAM)) for each region containing, bilateral trade data for all tradable goods and services, tariff and trade barriers, emissions data (including CO_2 and non-CO_2 GHGs, and air pollutant emissions (Chepeliev, 2020)), land use and land cover data, crop production, and agricultural domestic support and export subsidies.

The GTAP databases are prepared by the Center for the Global Trade Analysis Project (GTAP) in the Department of Agricultural Economics at Purdue University. These data bases are well-documented and available to GTAP subscribers across the world. Many models including CGE and non-CGE models rely on or use GTAP databases. The GTAP center is the focal point of a global network of more than 27 thousand researchers, scholars, academic institutions, and policy research entities that are conducting quantitative analysis of a wide range of policy issues related to trade, energy, agriculture, and climate change. The members of this network provide and share various databases, develop modeling ideas and codes, conduct research, and disseminate their research findings. The GTAP center facilitates these activities by providing various databases and modeling tools. In particular, this center assembles databases that support modeling practices around the world for various modeling approaches.

Table A1. Economic sectors in versions 10a and 11 of GTAP data base

Paddy rice	Coal	Wood products	Electrical eqpt.	Communication
Wheat	Oil	Pulp, paper etc.	Other mach. & eqpt.	Financial services
Other cereals	Gas	Refined oil etc.	Other manu.	Insurance
Vegetables & fruits	Other minerals	Pharmaceuticals	Electricity	Real estate
Oil seeds	Red meat	Other chemicals	Gas distribution	Other bus. services
Sugar cane & beet	White meat	Rubber & plastics	Water	Recreation etc.
Plant-based fibers	Vegetable oils	Other mineral prod.	Construction	Public Admin.
Other crops	Dairy products	Ferrous metals	W & R trade	Education
Beef etc.	Processed rice	Other metals	Hotels, rests. etc.	Health
Poultry, pork, etc.	Refined sugar	Metal products	Warehousing etc.	Dwellings
Raw milk	Other food	Mot. vehicles & parts	Land transport	
Wool etc.	Beverages & tobacco	Other trp. eqpt.	Sea transport	
Forestry	Textiles	Electronic eqpt.	Air transport	
Fishing	Clothing			
	Leather products			

As shown in Table A1, the standard GTAP databases do not represent biofuel sectors and their outputs explicitly. Therefore, a standard GTAP model that uses this database cannot trace production, consumption, and trade of biofuels. As described in the next section, the GTAP-BIO model and its database fill this omission.

GTAP-BIO model and its data base

GTAP-BIO is an advanced extension of the standard GTAP model. It has been developed, improved, and used frequently to examine the economic and environmental consequences of energy-trade-economic-environmental policies and actions (Taheripour et al., 2010; Hertel et al., 2010; Taheripour et al., 2011; Beckman et al., 2012; Taheripour and Tyner, 2013; Taheripour and Tyner, 2014; Taheripour et al., 2016a; Brookes et al., 2017; Taheripour and Tyner, 2018; Yao et al., 2018; Taheripour et al., 2022; Busch et al., 2022). Taheripour et al. (2017a) described the background of this model and Taheripour et al. (2017b) developed the latest version of this model.

Unlike the standard GTAP model, this advanced model is augmented to trace production, consumption, and trade of biofuels and their co-products/by-products. Therefore, in addition to the standard commodities and services, this model handles production and consumption of biofuels including conventional biofuels such as corn ethanol, wheat ethanol, sugarcane ethanol, by-products of ethanol production (e.g., Distiller's Dried Grains with Solubles (DDGS)) and biodiesel produced from different types of feedstocks such as vegetable oils, tallow, animal fats and used cooking oils. Some versions of this model represent advanced cellulosic biofuels and or SAF produced from agricultural feedstocks as well (Zhao et al., 2021). GTAP-BIO disaggregates oil crops, vegetable oils, and meals into several categories including soybeans, rapeseed (or canola), palm oil fruit, other oil seeds, soy oil, rapeseed (canola) oil, palm oil, other oils and fats, soy meal, rapeseed (canola) meal, palm kernel meal, and other meals. This model considers a blending sector that blends biofuels with conventional petroleum products to be used across different transportation activities. Figure A3 demonstrates the main components of this model and illustrates how biofuels are included the GTAP-BIO modeling framework.

As described in the SI of Taheripour et al. (2019), the left panel of this figure displays the main inputs of this model including: 1) Benchmark data consists of regional Input-Output tables (Social Accounting Matrices (SAMs)), economic parameters, and tax/subsidy rates; 2) International trade data; 3) Land cover, harvested area, crop production, at Agro-Ecological Zone (AEZ) level; 4) Emission data by sources and region; 5) Changes in government policy (e.g. changes in taxes, tariffs, subsidies or changes in biofuel policy); and 6) Changes in technology (e.g. changes in total factor productivity and advances in crop production).

The middle panel of Figure A3 shows that the GTAP-BIO model takes into account the links between: 1) Forestry, livestock, and crop industries as the main land using sectors; 2) Food, feed, and biofuels as the user of livestock and crop products; 3) Energy sectors as the main sources for energy products that interact with other activities in particular with crop and livestock products; and 4) all other industries and services which interact among themselves and also with crop, livestock, food, feed and biofuel sectors. As depicted in this panel, production activities generate intermediate demands for goods and services and demands for primary inputs including labor, land, capital and resources (see the bottom of the middle panel of Figure A3). The producers in each region use these inputs and provide goods and services to be consumed domestically or traded with other regions.

As shown in the right panel of Figure A3, the GTAP-BIO model provides a wide range of simulation results including: 1) Changes in production, consumption, and trade of all goods and services (e.g., crops and livestock) and their prices/costs; 2) Induced Land Use (ILUC) changes; 3) Changes in emissions associated with production and consumption of good and services by source; and 4) Changes in economic well-being (welfare).

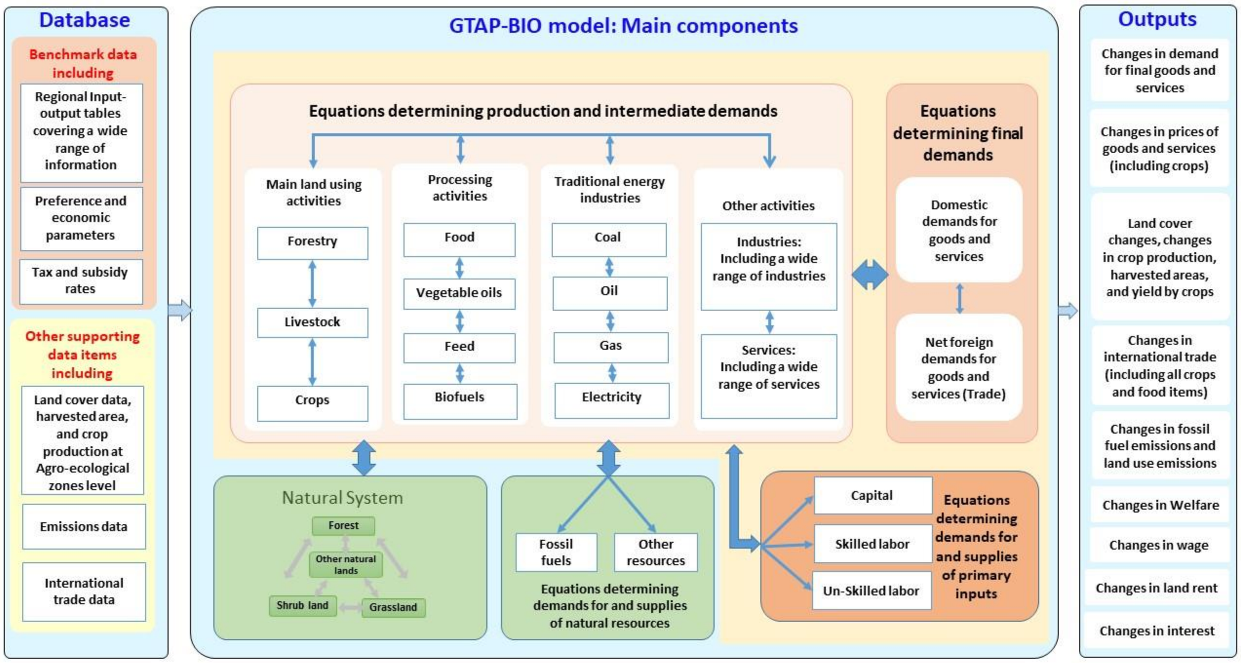

Figure A3. Schematic of GTAP-BIO Model (prepared based on Taheripour et al. 2019)

Following the original GTAP land use and land cover data base (Ramankutty et al., 2005), the GTAP-BIO model divides each geographical regions into up to 18 AEZs which represent different combinations of 6 moisture regions including arid, dry semi-arid, moist semi-arid, sub-humid, humid, and year around humid conditions and 3 climate zones of tropical, temperate, and boreal. Figure A4 shows the global map of these AEZs.

The GTAP-BIO databases closely follow the GTAP-AEZ data bases (for details see Baldos and Corong, 2022). In these data bases land cover categories (forest, pasture, and cropland), harvested areas of crops, and crop outputs are presented at the AEZ level. While the GTAP databases represent managed and unmanaged lands, only managed lands participate in economic activities. In assessing land use changes, GTAP-BIO considers land conversions among accessible managed lands. Managed, accessible forest in this model includes managed forest and unmanaged forest which are easily accessible. Therefore, forest lands that are not easily accessible are excluded from land conversion. The GTAP-BIO allows marginal land (cropland pasture) and unused land to return to crop production, as well.

The latest GTAP-BIO modeling structure allows intensification in crop production due to yield enhancement and improvements in harvest frequency. For each crop, yield is conventionally defined as output per unit of harvested area. Unlike yield, harvest frequency is not defined for each crop. It is a general index that shows the ratio of harvested area over available cropland. A harvest frequency of less than one shows that a portion of the available cropland is not utilized and remains unused or idled. On the other hand, a harvest frequency of larger than one reflects that a portion of the existing cropland has been used more than one time in a crop year (multiple cropping).

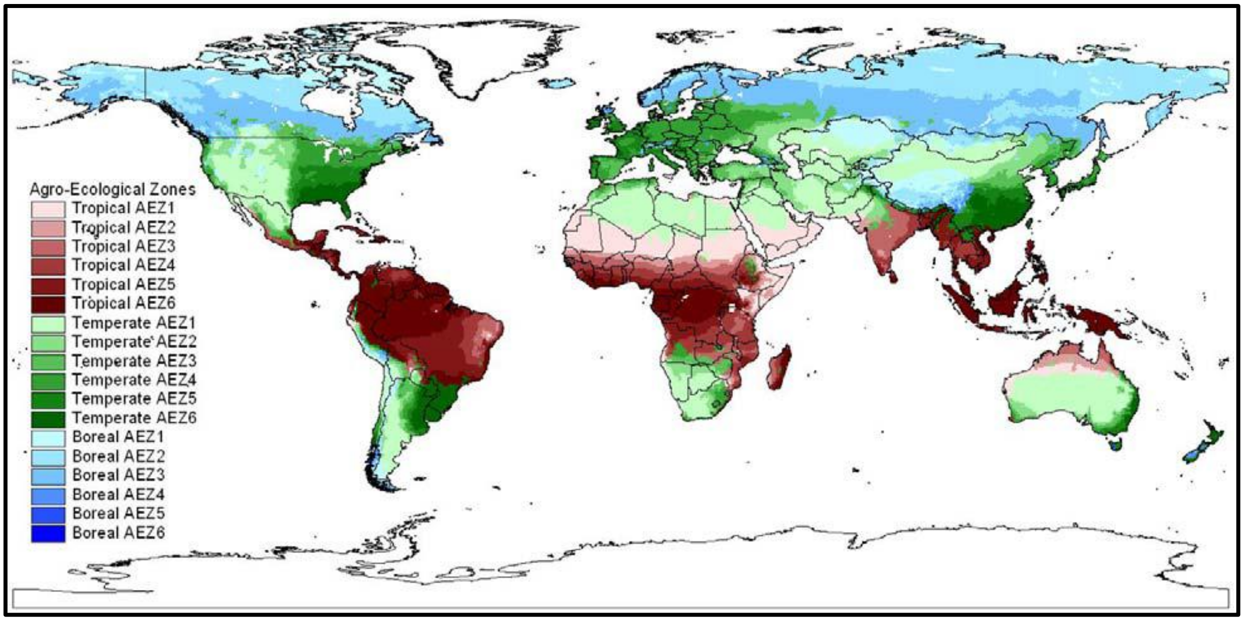

Figure A4. Global map of the 18 AEZs (Ramankutty et al. (2005)

The GTAP-BIO model and its databases usually divides the whole world into 19 countries/regions. Figure A5 presents these regions.

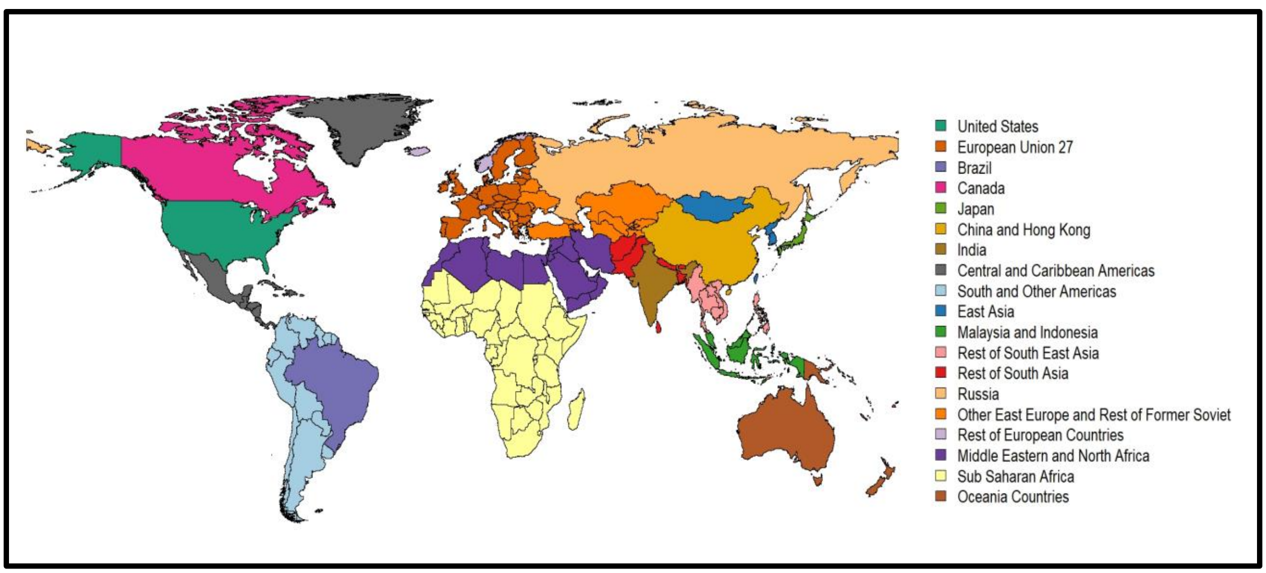

Figure A5. GTAP-BIO aggregated geographical regions

Since the GTAP standard database does not explicitly represent biofuel activities, a benchmark data base has been developed for this model. The first version of this database was developed by Taheripour et al. (2008) with introducing ethanol produced from grains and sugarcane and biodiesel produced from vegetable oils into the GTAP data base version 6 with the reference year of 2001. In that year, except Brazil, only a few countries were producing limited amounts of biofuels. Then, Taheripour and Tyner (2011) introduced grain ethanol, sugarcane ethanol and biodiesel produced from vegetable oils into the GTAP database version 7 with the reference year of 2004. Given the impacts of biofuel industries on the livestock and feed industries, the new GTAP-BIO data base distinguished between the food and feed industries as well. Two hypothetical advanced cellulosic biofuels (corn stover ethanol and miscanthus ethanol) were also introduced in this database.

The next version of the GTAP-BIO data base was developed using the version 9 of the GTAP standard data base for the reference year of 2011 including more data refinements to better represent interactions between crop sectors, livestock industries, and biofuel sectors as described by Taheripour et al. (2016b). The new data base considered more splits of economic activities including: 1) split of oilseeds to soybeans, rapeseed (canola), palm fruit, and other oilseeds; 2) split of vegetable oils to soy oil, rapeseed (canola) oil, palm oil and other vegetable oils and fats; 3) split of outputs of the vegetable oil sectors into meals and oils; 4) split of coarse grains into sorghum and other coarse grains; 5) distinguishing between food and feed products and industries; 6) introducing a new sector to blend biofuels with conventional petroleum products; 7) introducing marginal land (known as cropland pasture) into the rest of crops to allow return of this type of land to crop production as frequently occurs in real world; and 8) including cellulosic ethanol pathways.

Note that in 2011 many countries were producing the first generation of biofuels including grain ethanol (corn or wheat ethanol), ethanol produced from sugar crops, and biodiesel produced from soy oil, rapeseed oil, palm oil, and other types of vegetable oils and fats. These biofuels were introduced in the 2011 GTAP-BIO database. In addition, several hypothetical advanced cellulosic biofuels were also introduced in this database.

The latest version of the GTAP-BIO database represents the reference year of 2014 and it has been developed using the standard GTAP database version 10a. To develop this database several changes were made in the standard GTAP data base as presented in Figure A6. First, the standard GTAP database has been modified to closely follow the FAO production and price data for agricultural activities. Then the database has been further modified to represent the GTAP power generation sectors. Then following the approach outlined by Taheripour et al. (2016b) biofuels sectors along with other required new sectors were introduced in the database. Finally, the land use and land cover data and crop production were introduced in the database. Note that unlike the 2011 data base which only represents area of cropland pasture for the US, Brazil, and Canada, the 2014 data base represents this type of marginal land for all 19 regions included in this data base.

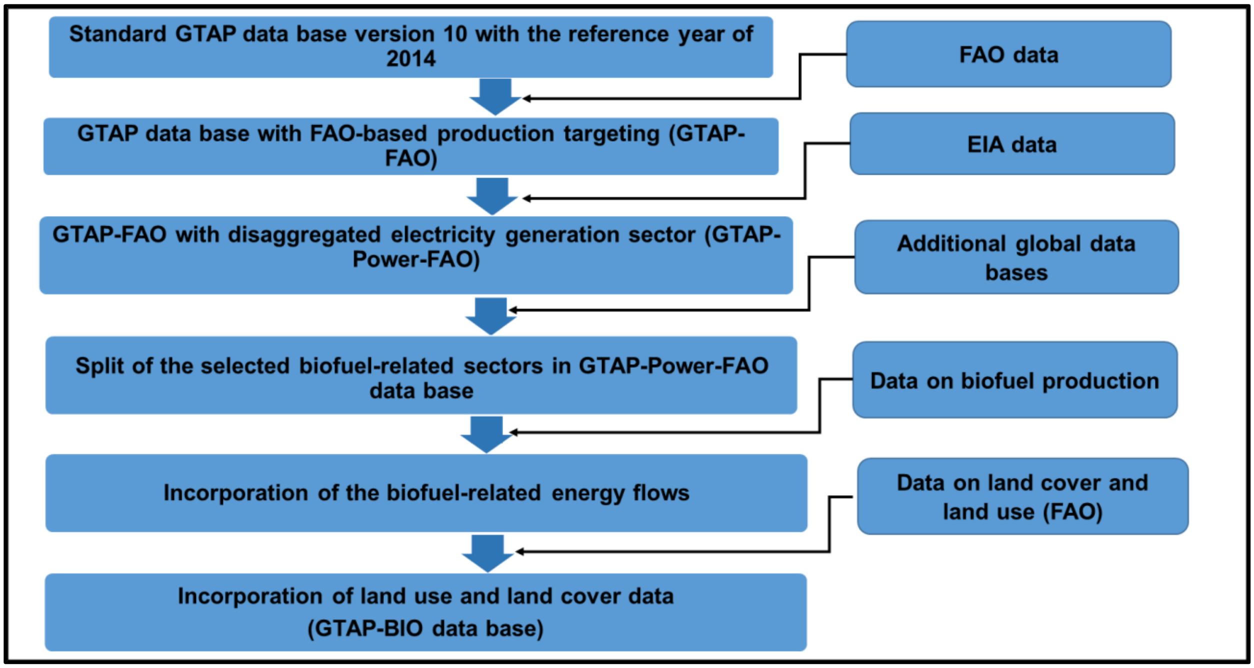

Figure A6. Collected data and implemented steps in developing the 2014 GTAP database

The new 2014 GTAP-BIO data base has been used in a recent research activity to assess the impacts of expansions in US biofuels (corn ethanol and soy biodiesel) on the global GHG emissions (EPA 2023). This database was used in GTAP-BIO simulations for 40BSAF-GREET 2024.

To achieve the goals of the current research, following Zhao et al. (2021) and according to the ICAO (2019) CORSIA life cycle analyses, four SAF pathways have been added to the 2014 GTAP-BIO data base. The included SAF pathways are: alcohol-to-jet with US corn ethanol (corn ATJ-E), alcohol-to-jet with Brazil sugarcane ethanol (sugarcane ATJ-E), US soy oil HEFA; and US rapeseed (canola) oil HEFA. This version of GTAP-BIO was used in this current study.

Selected key results

While the simulation results of each pathway represent the effects of that pathway on a wide range of variables, this work concentrates on a few key selected outcomes. The ILUC results, crops production results by region, and livestock production results by region, are provided in three Excel files (titled "GTAP-BIO Modeling Results for 40B SAF Pathways _ Land Use Changes", "GTAP-BIO Modeling Results for 40B SAF Pathways _ Changes in Crop Production", and "GTAP-BIO Modeling Results for 40B SAF Pathways _ Changes in Livestock Production"). These Excel data files are available at the Argonne R&D GREET website together with this Appendix.

In addition, to the detailed results mentioned above, a few key important impacts are briefly discussed in what follows.

- **Price impacts**; The results show that the price impacts vary across the examined SAF pathway and by region and sector. However, in general the price impacts for crops and livestock products items are relatively small, usually less than 1%. However, the price impacts are larger for US rapeseed (3.5%) and Brazil sugarcane (2.8%). Producing SAFs (by 1 or 0.5 billion gallons for the pathways) leads to small reductions in the prices of fossil fuels and petroleum products at the global scale, smaller than -0.1%.

- **Trade effects:** Trade effects for each pathway are usually small with some exceptions. The US corn ETJ declines the US corn exports by 0.8%. The US soy oil HEFA declines the US soy exports by 0.7%. The US rapeseed HEFA increases the US rapeseed imports by 28%. Note that the supply of US rapeseed is limited and a relatively a big portion of feedstock for rapeseed oil HEFA will be imported from Canada. The Brazilian sugarcane ETJ pathway has no impact on the trade of sugarcane. However, producing sugarcane ETJ has a negative impact (by -1.8%) on the exports of soybeans from Brazil to other countries.

- **Feedstock sources:** The required feedstock for each SAF pathway will come from either more production of the corresponding crop or savings in its other uses. These savings are relatively small compared to their current consumption levels at the global level.

Acknowledgement

This effort was supported by Argonne National Laboratory.

References

Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R., and van der Mensbrugghe, D. (2019) The GTAP Data Base: Version 10. *Journal of Global Economic Analysis,* Vol. 4, No. 1.

Aguiar, A., Chepeliev, M., Corong, E. & van der Mensbrugghe, D. (2022). The GTAP Data Base: Version 11. *Journal of Global Economic Analysis, 7(2)*, 1-37.

Baldos U. and E. Coring (2020) Development of GTAP 10 Land Use and Land Cover Data Base for years 2004, 2007, 2011, 2014. GTAP Research Memorandum No. 36.

Beckman T., Hertel W., Taheripour F., and Tyner W. (2012). Structural change in the biofuels era, *European Review of Agricultural Economics,* 39(1): 137–156.

Brookes G., Taheripour F., and Tyner W.E. (2017). The contribution of glyphosate to agriculture and potential impact of restrictions on use at the global level, *GM Crops & Food*, 8, 4, pp. 216-228.

Busch, J., Amarjargal O., Taheripour, F., Austin, K., Siregar, Ri. N., Koenig, K., & Hertel, T. W. (2022). Effects of demand-side restrictions on high-deforestation palm oil in Europe on deforestation and emissions in Indonesia, *Environmental Research Letters*, *17*(1).

Chepeliev, M. (2020) Development of the Non-CO_2 GHG Emissions Database for the 617 GTAP 10A Database. GTAP Research Memorandum No. 32. 618

Corong, E. L., Hertel, T. W., McDougall, R., Tsigas, M. E., & Van Der Mensbrugghe, D. (2017) The standard GTAP model, version 7. Journal of Global Economic Analysis, 2(1), 1-119.

EPA (2023) Model Comparison Exercise: Technical Document, Transportation and Climate Division Office of Transportation and Air Quality.

Hertel T. (1997) Global Trade Analysis: Modeling and Applications. Cambridge university press.

Hertel T., Marshall B. Burke, David B. Lobell, (2010) The poverty implications of climate-induced crop yield changes by 2030, *Global Environmental Change*, Volume 20, Issue 4, 2010, Pages 577-585.

ICAO (2019) CORSIA methodology for calculating actual life cycle emissions values.

Ramankutty N., Hertel T., Lee H.L. (2005) Global Land Use and Land Cover Data for Integrated Assessment Modeling, Center for Global Trade Analysis, Purdue University, Resource # 1635

Taheripour F., Birur D., Hertel T., Tyner W. (2008). "Introducing Liquid Biofuels into the GTAP Database," GTAP Research Memorandum No. 11, GTAP, 2007.

Taheripour, F. and Tyner, W.E. (2011) Introducing First and Second Generation Biofuels into GTAP Data Base version 7 in *GTAP*. Research Memorandum No 21, Purdue University.

Taheripour F., Hertel T., Tyner W., Beckman J., and Birur D. (2010). "Biofuels and their by-products: Global economic and environmental implications," *Biomass & Bioenergy*, 34(3): 278-289.0

Taheripour F., Hertel T., and Tyner W. (2011). Implications of biofuels mandates for the global livestock industry: A computable general equilibrium analysis, *Agricultural Economics*, 42(3): 325–342.

Taheripour, F. and Tyner, E.E. (2013) Biofuels and Land Use Change: Applying Recent Evidence to Model Estimates. *Applied Sciences*, 3: p. 14-38.

Taheripour, F. and Tyner, W.E. (2014) Corn oil biofuel land use change emission impacts: Sharing emission savings between ethanol and biodiesel Biofuels. *Biofuels*, 5(4): p. 353-364.

Taheripour, F., Mahaffey, H., and Tyner, W.E. (2016a) Evaluation of Economic, Land Use, and Land Use Emission Impacts of Substituting Non-GMO Crops for GMO in the United States. *AgBioForum*, 19(2): p. 156-172.

Taheripour F., Peña-Lévano L., and Tyner W. (2016b). “Introducing First and Second Generation Biofuels into GTAP Data Base version 9”, GTAP Research Memorandum No. 29, GTAP.

Taheripour, F., Cui, H., and Tyner, W.E. (2017a) An Exploration of Agricultural Land use Change at the Intensive and Extensive Margins: Implications for Biofuels Induced Land Use Change, in Qin, Z. Mishra, U. and Hastings, A. (eds), Bioenergy and Land Use Change, American Geophysical Union (Wiley).

Taheripour, F., Zhao X., and Tyner, W.E. (2017b) The Impact of Considering Land Intensification and Updated Data on Biofuels Land Use Change and Emissions Estimates. *Biotechnology for Biofuels*, 10 (191): p. 1-16.

Taheripour, F. and Tyner, W.E. (2018) Impacts of Possible Chinese Protection on US Soybeans and Other Agricultural Commodities. *Choices*, Quarter 2.

Taheripour, F., Hertel, T. W., and Ramankutty, N. (2019). Market-mediated responses confound policies to limit deforestation from oil palm expansion in Malaysia and Indonesia. *Proceedings of the National Academy of Sciences*, *116*(38), 19193–19199.

Taheripour F., Baumes H., and Tyner W. (2022). Economic impacts of the U.S. Renewable Fuel Standard: An *ex-post* evaluation, *Frontiers in Energy Research*, Vol 10 (749738).

Yao G., Hertel T., and Taheripour F. (2018). “Economic drivers of telecoupling and terrestrial carbon fluxes in the global soybean complex,” *Global Environmental Change, 5: 190–200*

Zhao X. Taheripour F., Malina R., Staples M.D., Tyner W.E (2021). “Estimating induced land use change emissions for sustainable aviation biofuel pathways,” *Science of the Total Environment 779 (2021) 146238*.

APPENDIX B: EMISSION PROFILES OF CROP PRODUCTION, LIVESTOCK GROWTH, AND RICE CULTIVATION

(Contribution to Addressing Greenhouse Gas Emissions of Indirect Effects Induced by Sustainable Aviation Fuel Production)
Prepared by ICF under contract to the USDA Office of the Chief Economist

April 2024

This appendix documents the approaches used by ICF to develop emission profiles of crop production, livestock growth, and rice paddies for GTAP regions and categories of crops and livestock. Methodologies in the appendix are divided into three sections:

1. Emissions from crop production, estimated globally and domestically
2. Emissions from livestock production, estimated globally and domestically
3. Methane emissions from rice paddies, estimated globally and domestically

The results of these approaches are presented in Sections 3.2, 3.3, and 3.4 of the technical report.

Section 1: Emissions from Crop Production

This section covers the methodologies that ICF used for this analysis to develop greenhouse gas (GHG) emission factors for crop production. These methodologies include:

- An assessment of the list of GTAP crops for inclusion in the emissions analysis—focusing on those that represent the most important crops grown globally by acreage and production level and where data are available,
- The overall approach to estimating emissions from crop production, including how the emission sources from crop production were estimated, and
- The process used to convert emission factors into GTAP production units.

Crop List Winnowing

GTAP includes over 160 crops across the 10 GTAP crop sectors as modeled in 196 different regions or countries. As shown in Table B1, for the six GTAP crop sectors that contain only one crop, crop-specific GHG values were developed. For the four remaining categories that contain multiple crops,[3] ICF conducted a winnowing process to include "major" crops in each category, meaning those that represent the largest percentages of acreage and production globally and domestically. As insufficient data were available to model all the minor crops, a regionally

[3] These sectors include Sugar Crops, Other Grains, Other Oilseeds and Other Agricultural Crops.

specific weighted average of the data from major crops was used as proxy to estimate the GHG emissions associated with the more minor crops.

To establish which crops in each of four GTAP crop categories represented major crops, ICF compiled the acreage and production levels of all crops in each category both globally and by region. ICF then isolated the set of crops that represented over 60 percent of the crops grown in each crop category globally by acreage and by production level and at least 50 percent of the crops grown in each region by acreage and production for all but three regions.[4]

Specifically, total area harvested in 2014[5] for each crop and country was downloaded from FAOSTAT's Crops and Livestock Products domain (FAOSTAT 2023a). FAOSTAT crops and countries were then mapped to GTAP sectors and regions. For each sector, the total area harvested was disaggregated by each crop type to identify which crops constituted the largest share of area and to ensure that at least 50 percent of production in each region or country was represented. Crops that consisted of only a small share of land area were eliminated from the list of crops. This analysis resulted in a total of 29 crops included for further GHG analysis. Table B1 presents the final list of crops included in the emissions analysis.

Table B1. Crops Selected for International Emissions Estimates

GTAP Crop Category	Crops Included in International Emissions Analysis
OthAgri	Beans, dry; Cassava; Chick peas; Cocoa, beans; Coffee, green; Cucumbers and Gherkins; Grapes; Lentils; Peas, dry; Rubber, natural; Seed cotton; Sweet Potatoes, Yams
Oth_CrGr	Barley; Millet; Sorghum
Oth_oilseed	Coconuts; Groundnuts, with shell; Olives; Sunflower seed
Corn	Corn
Palm	Palm
Rapeseed	Rapeseed
Paddy rice	Paddy rice
Soybeans	Soybeans
Sugar_Crop	Sugar beet; Sugarcane
Wheat	Wheat

This list of crops was further modified for U.S. domestic crop production as many of the chosen crops are not produced in the United States in significant quantities, if at all.

4 When looking at the combined percentage of crops included for the four multi-crop categories, all regions had over 50 percent of production represented by acreage and/or production except for *China and Hong Kong, East Asia*, and *Japan*. Our analysis indicated that given the large number of different crops grown in these three regions it was not possible to reach 50 percent production levels for the categories without adding at least 20 additional crops.

5 Year 2014 domestic and international crop yields were used to be compatible with GTAP activity data, which is based on 2014 production.

Table B2 presents the final list of 13 crops evaluated for domestic emission analysis.

Table B2. Crops Selected for Domestic Emissions Estimates

GTAP Crop Category	Crop Included in Domestic Emissions Analysis
OthAgri	Grapes; Potatoes; Seed cotton
Oth_CrGr	Sorghum
Oth_oilseed	Groundnuts, with shell; Sunflower seed
Corn	Corn
Rapeseed	Rapeseed
Paddy Rice	Paddy Rice
Soybeans	Soybeans
Sugar_Crop	Sugar beet; Sugarcane
Wheat	Wheat

Estimating Emission Factors

Domestic and international emission factors (in GHG emissions per unit of crop produced) for crop production inputs were estimated for the following sources: upstream and on-farm energy use, upstream fertilizer and pesticides use, crop residue, and N-fertilizer application. International and domestic emission factors were estimated separately to reflect the higher granularity of data available in the United States. Table B3 lists the crop production emission sources included.

Table B3. Crop Production Emission Sources Included in the Analysis

Emission Source	Applicable Land Area
Upstream and on farm energy use emissions	Domestic and international[a]
Upstream emissions from insecticides, pesticides and herbicides	Domestic and international[a]
Upstream emissions from nitrogen, phosphate and potassium fertilizer	Domestic and international
On-farm emissions from N fertilizer and crop residue	Domestic and international

[a] International on farm energy use and pesticide application rates are based on national use and are not crop specific.

Note that a subset of crop production emissions sources and sinks that are relevant to cropland and grassland were not included in this analysis, due to either limited data availability, their limited impact on overall emissions, or a combination of both. Table B4 provides a brief description of these sources and the justifications for their exclusion.

Table B4. Crop Production Emission Sources and Sinks Excluded from the Analysis

Emission Source	Applicable Land Area	Justification for Exclusion
Emissions from soil application of manure	Domestic and international	Limited data on manure application available.
On-farm fuel and energy use for silage	Domestic	Limited number of acres and uncertainty associated with which crops are included.
Carbon sequestration in agricultural soils (cropland remaining cropland)[6]	Domestic and international	Limited data available.
Carbon sequestration in pastureland (grassland remaining grassland)[7]	Domestic and international	Limited data available.
Emissions from agricultural residue burning	Domestic and international	Limited data available.
Direct emissions from pesticide application	Domestic and international	Source considered to be insignificant.
Lime application	Domestic and international	Limited data available.

The following sections describe the data sources and estimation methods used to develop both domestic and international emission profiles for each of the crop production emission sources included for the set of crops included for each GTAP country and region. All emission factors were estimated to be both crop- and country-specific.

1. Domestic Upstream and On-Farm Energy Emissions

Information on farm fuel use for corn, soybean, sorghum, rice, and sugarcane was obtained from the Feedstock Carbon Intensity Calculator (FD-CIC) of Argonne National Laboratory (ANL), updated in 2023 (ANL 2023a). On-farm fuel use included fuel usage, emission factors of upstream fuel production, and combustion emission factors for diesel, gasoline, liquified petroleum gas (LPG), electricity, and natural gas. Fuel use inputs are provided on a volume-per-acre basis. The emissions factors are in grams of carbon dioxide per British thermal unit (gCO_2/Btu), grams of methane per Btu (gCH_4/Btu), and grams of nitrous oxide per Btu (gN_2O/Btu). Lower heating value information from ANL's R&D GREET model (ANL 2023b) was used to calculate CO_2, CH_4, and N_2O emissions on a grams per acre (g/acre) of crop basis.

For energy use values not available in GREET, research was conducted to identify data sources providing the most recently available energy use values for each crop. The most recent energy use rates were found in literature for grapes, rapeseed, sunflower seed, and wheat (Hefler and Kissinger 2023; Pimentel et al. 2008; Helgeson and Schaffner 1983; U.C. Cooperative Extension 1994). Note that some references are older as more recent studies on energy use rates for these

6 Note this category refers to any changes in soil carbon due to the production of crops or horticultural plants. It does not include changes in soil carbon due to land use change. Domestic SOC changes from crop production were included in RFS2, international SOC changes from crop production were not.

7 Note this category refers to any changes in soil carbon in pasturelands. It does not include changes in soil carbon due to land use change. Domestic SOC changes from pastureland were included in RFS2, international SOC changes from pastureland were not.

specific crops were not identified. Units were converted to match the corresponding Btu/acre standard energy unit. For on-farm energy values not located from the literature search, similar values for crops with data from GREET were used to proxy a ratio of energy use values for the remaining crops. For example, only total energy use was found for rapeseed and sunflower seed; thus, energy use ratios from other crops in GREET were used to proxy the fuel use rates across the five categories of diesel, gasoline, LPG, electricity, and natural gas. For groundnuts, potato, seed cotton, and sugar beets, data were obtained by using graphing software to read plots in Field to Market (2021) reports. Final fuel use rates estimated in Btu/acre units were converted to units of liters per hectare (L/hectare), kilowatt hours per hectare (kWh/hectare), and gallons per acre (gal/acre).

2. Domestic Upstream Fertilizer and Pesticide Production Emissions and Application Rates

This emissions analysis only includes synthetic fertilizers and pesticides. Emissions from organic fertilizers (e.g., manure applied to agricultural soils) were omitted from this analysis as no global data set exists for the amount and type of manure applied to agricultural soils.

2.1. For crops with emission factors, fertilizer, and pesticide application rates in the FD-CIC

For corn, soybean, sorghum, rice, and sugarcane, fertilizer and pesticide application rates and emission factors were obtained from the FD-CIC (ANL 2023a). Fertilizer and pesticide application rates available in the FD-CIC model included insecticides, herbicides, and nitrogen, phosphorous and potassium fertilizer application rates all on a kg/acre basis for corn, rice, sorghum, soybeans, and sugarcane. Fungicides are not currently included in the FD-CIC model. Emissions factors for nitrogen, phosphorous, and potassium fertilizers are provided separately in the FD-CIC for production and transportation emission factors for pesticides are provided for both transportation and production. Emission factors are in grams carbon dioxide per gram (gCO_2/g) product, grams methane per gram (gCH_4/g) product, and grams nitrous oxide per gram (gN_2O/g) product.

2.2. For crops not included in the FD-CIC

Method for Fertilizer Application Rate

Data for domestic fertilizer application rates for crops not available in the FD-CIC (i.e., cotton, grapes, groundnuts, potato, rapeseed, sugar beets, sunflower seed, and wheat) were compiled from literature and published databases (USDA ERS 2023; NASS Montana 2000; NASS 2024a). For grapes and wheat, weighted average application rates were calculated based on production acres from NASS for the three types of grapes (table, wine, and raisin) and three types of wheat (spring, durum, and winter) (NASS 2024a). For rapeseed, fertilizer application rates were sourced from the international fertilizer application rates calculation described in the International Fertilizer and Pesticide Application Rates section of this Appendix (Ludemann et al. 2022).

Method for Herbicide and Insecticide Application Rate

Data for domestic pesticide application rates for crops not available in FD-CIC were compiled from literature and converted to match the appropriate FD-CIC units (USDA ERS 2023; Pimentel et al. 2008; NASS Montana 2000; NASS 2024a). For grapes and wheat, weighted application rates were calculated based on production acres from NASS as described above for fertilizer application rates above. For sugar beets, a ratio of area applied with a specific pesticide type (insecticide or fungicide) was calculated against total application area to proxy the application rate. Since glyphosate was the predominant herbicide active ingredient applied to sugar beets (accounting for approximately 99 percent), its application rate was used to represent the rate of all herbicide application to sugar beets (EPA 2020).

Method for Fungicide Application Rate and Emission Factors

Data for domestic fungicide application rates and emissions from fungicide production and transportation are not currently available in the FD-CIC model. Therefore, a literature review was conducted to identify current fungicide application rates for the 13 domestic crops being modeled. For corn, grapes, groundnuts, potato, rice, and soybeans, fungicide application rates were obtained from the USDA NASS Quick Stats database (NASS 2024a), with grapes being calculated with a weighted average as described above. Rapeseed, sorghum, sugarcane, and sunflower seed are not typically produced using fungicides, and thus were not included in calculations of fungicide use emissions. Seed cotton and wheat had fungicide application rates obtained from ARMS Survey Data (USDA ERS 2023) while the fungicide rate for sugar beets was calculated from total acreage of pesticides applied.

Upstream emissions from fungicides were proxied to herbicides and insecticides, scaled based on the average manufacturing energy intensities reported by FAO (Karl et al. 2022).

2.3. Method for Generating Emissions

Emissions were generated by multiplying the fertilizer or pesticide application rate per acre by the appropriate upstream production emission factor per kg of fertilizer or pesticide used to generate the final value for upstream emissions per acre.

3. Domestic Crop Residue Emissions and On-Farm Nitrogen Fertilizer Use Emissions

Direct and indirect nitrous oxide emissions from crop residue retention were estimated following 2019 IPCC Tier 1 methodology (IPCC 2019) and using 2021 yield data from FAOSTAT's Crops and Livestock Products domain (FAOSTAT 2023a). The United States was assumed to be a dry climate based on IPCC's guidance for climate classifications. It should be noted that some crops did not have defined emission factors within IPCC guidelines. For these crops, proxies were assigned based on professional judgment to the most suitable values based on crop N-content, above/below ground biomass ratios and harvesting methods. In some cases (e.g., for tree crops), it was assumed that given the plant biology of the crop and/or crop production method, crop residue emissions were not generated. See Table B5 for the list of proxied crops and crops where emissions from crop residue are assumed not to occur.

Table B5. Proxies for Domestic Crop Residue Emissions Estimates

Modeled Crop	Proxy for IPCC Default Values	Proxy for Above-Ground Residue
Rapeseed	Generic value	Root crops, other
Seed cotton	Generic value	Root crops, other
Sunflower seed	Generic value	Root crops, other
Grapes	*Does not result in crop residue*	

Nitrous oxide emissions from N-fertilizer application were also estimated following 2019 IPCC Tier 1 methodologies (IPCC 2019). For both direct and indirect emissions, emission factors are distinguished between rice and non-rice crops and by IPCC climate classification. These emission per kg values were multiplied by the nitrogen fertilizer application rates, generated in the Domestic Upstream Fertilizer and Pesticide Use Emissions section above, to produce indirect and direction nitrous oxide emissions per acre.

4. International Upstream and On-Farm Energy Emissions

Implied emission factors for international on-farm energy use were derived from 2021 FAOSTAT data (FAOSTAT 2023b). FAOSTAT's Emissions from Energy Use in Agriculture domain presents total annual direct emissions from on-farm energy for the entire country for five energy types including electricity, petroleum products, natural gas, coal, and heat. This emissions number is not specific to a crop type and includes only farm-gate emissions. Total emissions were converted to a per-acre emission factor by dividing the total annual area harvested from the FAOSTAT Crops and Livestock Products domain for each country (FAOSTAT 2023a). Note that this baseline for production acres is different than that used for upstream emissions from pesticide application as the analysis assumes that energy consumption is required for areas of both crop and livestock production.

Upstream emission factors for manufacture and transport by energy source were provided by Argonne National Lab in CO2e/TJ for different countries and global regions (ANL 2024). These emission factors were combined with total on-farm energy use from FAOSTAT's Emissions from Energy Use domain (FAOSTAT 2023b) and divided by total area harvested to derive upstream emissions per acre for each country.

5. International Upstream Pesticides and Fertilizer Emissions

Emission factors (represented as kg CO_2e/kg) for fertilizer manufacture were estimated using regional, product-specific values from the International Fertiliser Society, IFS (Hoxha and Christensen 2019) and Brentrup et al. 2018. Fertilizer product manufacturing amounts from FAOSTAT Fertilizer by Product domain (FAOSTAT 2023d) were combined with these product emission factors to develop a weighted-average manufacturing emission factor by nutrient for each region.

To account for international trade of fertilizers, export data from FAOSTAT's Fertilizers by Nutrient domain (FAOSTAT 2023c) was averaged to assess how much a country contributes to global trade of each fertilizer nutrient by its percent contribution. This percentage was then multiplied by an emission factor for each country and summed to develop a single weighted average emission factor for all imported fertilizer products. A country's final emission factor was then apportioned between the emission factor for imported products and the country's regional manufacturing factor based on the percentage of product made in country versus imported. Because fertilizer pricing and trade is highly variable year to year, a five-year average was used in all cases where FAOSTAT data were used in the analysis.

Upstream (manufacturing and transportation) pesticide and fertilizer transportation emission factors were extracted from the FD-CIC (ANL 2023a). Because the FD-CIC does not report fungicide use, upstream emissions from fungicides are proxied to herbicides and insecticides, scaled based on the average manufacturing energy intensities reported by FAO (Karl et al. 2022).

6. International Fertilizer and Pesticide Application Rates

6.1. Method for Fertilizer Application Rate

Data for international fertilizer application rates was drawn primarily from Ludemann et al. 2022. The raw data from this report contains country-specific crop areas from the International Fertiliser Society (IFS) and FAO (in hectares) (FAOSTAT 2023a) and the amount of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) fertilizers applied in metric tons.

Country- and crop-specific fertilizer application rates were calculated in terms of kilograms per acre for nitrogen, phosphorous and potassium fertilizers. Acreage for each crop in each country was first calculated by converting the number of hectares of a crop to acres. Hectare data from IFS were used as the default for this conversion. In instances where IFS data were unavailable, FAO hectare data were used. Second, the tonnage of fertilizer applied was converted from metric tons to kilograms. Then the amount of applied fertilizer in kilograms for each crop type was divided by the acreage for that crop type to calculate the fertilizer application rates.

Application rates in each country for each crop type were calculated for each of the three fertilizers. In cases where crop- and country-specific fertilizer application rates were not available, a proxy from the available data were generated using GTAP regional or global averages.

6.2. Method for Pesticide Application Rate

Data for international pesticide application rates was drawn primarily from FAOSTAT's Pesticides Use (FAOSTAT 2023e) and Crops and Livestock Products domain (FAOSTAT 2023a). FAOSTAT includes data on the harvested area of crops in each country (in hectares) and the total of different pesticides applied (in metric tons of active ingredient) for agricultural use in 2021. FAOSTAT does not provide pesticide use by crop type.

Pesticide application rates were calculated in terms of kilograms of active ingredient (AI) per acre for each of the following pesticide types: fungicides and bactericides, herbicides, and insecticides. First, the harvested area in each country was calculated by summing the harvested area for all crop types reported for that country in FAOSTAT. The harvested area was then converted from hectares to acres. Second, the tonnage of pesticide applied was converted from metric tons into kilograms for each of the pesticide types. Then the amount of each pesticide type was divided by the total harvested area to calculate the pesticide application rates for each country. This process does not give crop specific values, but rather gives an average pesticide application rate per acre of harvested crop.

6.3. Method for Generating Emissions

Upstream emissions were generated by multiplying the fertilizer or pesticide application rate per acre by the appropriate upstream emission factor per kg of fertilizer or pesticide used to generate upstream emissions per acre. No emissions were estimated for the application of pesticides as these emissions are insignificant.

7. International Crop Residue and Fertilizer N_2O Emissions

Direct and indirect nitrous oxide emissions from crop residue retention for each crop and country were estimated following IPCC 2019 Tier 1 methodology (IPCC 2019) using 2021 yield data from FAOSTAT's Crops and Livestock Products Domain (FAOSTAT 2023a). Each country was assigned a wet or dry climate based on IPCC's guidance for climate classifications. It should be noted that some crops did not have defined emission factors within IPCC guidelines. For these crops, proxies were assigned based on professional judgment to the most suitable values based on crop N-content, above/below ground biomass ratios and harvesting methods. In some cases, it was assumed that given the plant biology of the crop and/or crop production method, crop residue emissions were not generated (such as tree crops). See Table B6 for the list of proxied crops and crops where emissions from crop are assumed not to occur.

Table B6. Proxies for International Crop Residue Emissions Estimates

Modeled Crop	Proxy for IPCC Default Values	Proxy for Above-Ground Residue
Cucumbers and gherkins	Generic value	Potato
Oil palm fruit	Generic value	Root crops, other
Rapeseed	Generic value	Root crops, other
Seed cotton	Generic value	Root crops, other
Sugar beet	Generic value	Root crops, other
Sugarcane	Perennial Grasses	Perennial Grasses
Sunflower seed	Generic value	Root crops, other
Cocoa, beans	*Does not result in crop residue*	
Coconuts	*Does not result in crop residue*	
Coffee, green	*Does not result in crop residue*	
Grapes	*Does not result in crop residue*	
Olives	*Does not result in crop residue*	
Rubber, natural	*Does not result in crop residue*	

Nitrous oxide emissions from N-fertilizer application were also estimated following 2019 IPCC Tier 1 methodologies (IPCC 2019). For both direct and indirect emissions, emission factors are distinguished between rice and non-rice crops and by IPCC climate classification. These emission per kg values are multiplied by the nitrogen fertilizer application rates generated in "International Fertilizer and Pesticide Application Rates" above, to produce indirect and direct nitrous oxide emissions per acre.

Converting to GTAP Units

GTAP crop activity data is presented as a change in MT of 2014[5] production for the sector and region. The previously described emissions per acre factors were converted to GTAP units using 2014 country and crop-specific yield and production data. For international crop production, these values were sourced from FAOSTAT's Crops and Livestock Products domain (FAOSTAT 2023a). Domestic crop yields and total production were sourced from survey data in the USDA-NASS QuickStats Database (NASS 2024a).

Country- and crop-specific emission factors were then converted to GTAP regions and sectors by multiplying by a percent share as a conversion factor. The percent share represents the contribution of the crop and country production to the total GTAP regional and sector production. These scaled emission factors were then summed by GTAP region and crop sector to produce a final emissions per MT of production.

To demonstrate the process used to convert to GTAP units, an example calculation for sugar crop production in Mala_Indo (Malaysia & Indonesia) is shown below. This process was repeated for each of the 10 GTAP crop sectors in each of the 19 GTAP regions as needed.

$$
\begin{aligned}
&(emissions/production)_{sugar\_crops,Mala\_Indo} \\
&\quad = \frac{(emissions/acre)_{sugar\ cane,Mala}}{(\frac{production}{acre})_{sugar\ cane,Mala}} \times \frac{production_{sugar\ cane,Mala}}{production_{sugar\_crops,Mala\_Indo}} \\
&\quad + \frac{(emissions/acre)_{sugar\ beets,Mala}}{(\frac{production}{acre})_{sugar\ beets,Mala}} \times \frac{production_{sugar\ beets,Mala}}{production_{sugar\_crops,Mala\_Indo}} \\
&\quad + \frac{(emissions/acre)_{sugar\ cane,Indo}}{(\frac{production}{acre})_{sugar\ cane,Indo}} \times \frac{production_{sugar\ cane,Indo}}{production_{sugar\_crops,Mala\_Indo}} \\
&\quad + \frac{(emissions/acre)_{sugar\ beets,Indo}}{(\frac{production}{acre})_{sugar\ beets,Indo}} \times \frac{production_{sugar\ beets,Indo}}{production_{sugar\_crops,Mala\_Indo}}
\end{aligned}
$$

Section 2: Emissions from Livestock Production

This section covers the methodologies ICF used to develop GHG emission factors for livestock production. These methodologies include:

- An assessment of the list of GTAP livestock species for inclusion in the emissions analysis—focusing on those that represent the most important species globally by emissions share and production level and where data are available,

- The overall approach to estimating emission factors per GTAP sector from livestock production, including how the livestock emission sources were estimated, and

- The approach for mapping GTAP sectors to FAOSTAT livestock production data for major livestock species that contribute most of the global livestock GHG emissions,

- The process used to convert the modelled emission data for the GTAP sectors into GTAP production units.

The following describes the data sources and necessary data processing to develop emission profiles of livestock production both domestically and internationally for each GTAP country and region.

Livestock Species Winnowing

GTAP aggregates livestock into three distinct sectors: Non-ruminants, Ruminants, and Dairy Cattle. As seen in the GTAP sector description of Table B7, the Non-ruminants and Ruminants sectors both contain an extensive assortment of animals and live animal products. To estimate emission factors for these sectors, livestock types only include those with one or more of the largest share of global emissions or the largest share of global production value. Therefore, camels, horses, mules, asses, and buffalo which have a limited share of global emissions and no available price data, were excluded from this analysis. See Table 6 for the livestock types included in the international and domestic production analysis.

Table B7. Global GTAP Sectors, Sector Descriptions and Livestock Types Included in Sectors

GTAP Livestock Sector	GTAP Sector Description	Livestock Types
Non-ruminants	Other Animal Products (oap): swine; poultry; other live animals; eggs of hens or other birds in shell, fresh; reproductive materials of animals; natural honey; snails, fresh, chilled, frozen, dried, salted or in brine, except sea snails; edible products of animal origin n.e.c.; hides, skins and furskins, raw; insect waxes and spermaceti, whether or not refined or coloured	• Poultry • Turkeys • Swine
Dairy cattle	Raw milk (rmk)	• Dairy cattle
Other ruminants	Cattle* (ctl): bovine animals, live, other ruminants, horses and other equines, bovine semen	• Non-dairy cattle • Goats • Sheep

Note: Cattle (ctl) was classified in GTAP modelling as “ruminants” to include ruminant animals including beef cattle, sheep and goats. Dairy cattle are already included in the GTAP category, Raw milk (rmk), despite that they are also ruminants. Reference: https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp

Estimating Emission Factors

This section describes the data sources and data processing used to develop emission factors for domestic and international livestock production. Emissions sources include CH_4 from enteric fermentation, CH_4 from manure management, direct and indirect N_2O from manure management, and direct and indirect N_2O from manure deposited onto pasture, range, and paddock by grazing livestock. N_2O from manure deposited onto pasture by grazing livestock was only estimated for international livestock and was not included in domestic estimates due to data limitations. See B8 provides additional details on the livestock emission sources included. As described above in the cropland section, manure application to croplands is not included in this analysis.

Table B8. Livestock Emission Sources Included in the Analysis

Emission Source	Applicable Geographic Location
Methane from enteric fermentation	Domestic and international
Methane and direct and indirect nitrous oxide emissions from manure management	Domestic and international
Direct and indirect nitrous oxide emissions from manure deposited onto pasture by grazing livestock	International

1. Domestic Livestock Emissions

Implied emission per head factors were developed for each livestock type by dividing 2021 absolute emissions from EPA's U.S. GHG Inventory (EPA 2023) for each livestock type by the 2021 specific livestock population. Emissions reported in EPA's U.S. GHG Inventory are reported by gas and separated into enteric fermentation and manure management emissions.

2. International Livestock Emissions

IPCC (2019) and IPCC (2006) default animal activity data, emission factors and Tier 1 methods were used to develop per-head emission factors for each livestock type and GTAP country or region. Box 1 and Box 2 present the full methods used to estimate emissions per head for each livestock type, for CH_4 and N_2O emissions, respectively, based on the IPCC 2019 and 2006 guidance. Productivity classes for GTAP countries and regions were estimated based on World Bank country economic classification for the dominant economic classification for a group of countries in a region (World Bank Group 2023). For example, productivity level classification for a given country or region was based on whether the country was a low-, lower-middle, upper-middle, or high-income country, and expert knowledge of how productive the dominant livestock systems typically are in that country or region. The dominant climate zone for each of the countries was assigned by selecting the primary IPCC climate zone where the majority of livestock production occurs. As all regions have livestock production systems that occur in *more than one* climate zone, this assumption introduces the most uncertainty in the per- head emission factors.

Box 1: International Livestock Emission Factor Method: CH_4 Emissions

CH_4 from Enteric Fermentation

The 2019 IPCC Refinement provides emission factors by region for cattle (Table 10.11, Volume 4, Chapter 10) and other livestock types (IPCC 2019, Table 10.10) in kg CH_4 head^{-1} year^{-1}. The emission factors have been updated since the previous analysis, which used emission factors published in the 2006 IPCC guidelines. Because these Tier 1 emission factors were already provided per head of livestock per region, no further calculations were needed to develop these emission factors.

CH_4 from Manure Management

Daily default volatile solid (VS) excretion rates per 1000 kg animal mass per livestock type per region (IPCC 2019, Table 10.13a) were multiplied by default live weights (typical animal mass, TAM) per livestock type per region (IPCC 2019, Table 10A.5), divided by 1000kg animal mass to get the VS per kg of animal mass, and multiplied by 365 days in the year to determine annual VS excretion per head of livestock type per region (IPCC 2019, Equation 10.22A).

$$VS_{annual} = VS_{daily} \times \left(\frac{TAM_{livestock,\ prod.,\ region}}{1000}\right) \times 365\ days$$

The annual VS excretion rate was multiplied by the IPCC default CH_4 emission factor specific to livestock type, productivity level, and climate zone (IPCC 2019, Table 10.14), multiplied by the proportion (%) of manure managed (IPCC 2019, Table 10A.6) in each of nine manure management systems (IPCC 2019, Table 10.18). The sum of emissions from all manure management systems provides an annual CH_4 emission factor by livestock type, weighted by and reflecting the default proportions of manure managed in each manure management system.

$$Manure\ CH4\ EF_{annual} = VS_{annual} \times Methane\ CH4\ EF_{livestock,\ prod.,\ clim.} \times AWMS\%$$

The output is a Tier 1 emission factor for each of the relevant IPCC livestock types in kg CH_4 head^{-1} year^{-1}. The output could only be considered Tier 2 when country-specific data on the proportions manure each livestock type that is managed in each manure management system or system specific information on the other variables was known.

Limitations of Method

This method assumes that all animals are the typical animal mass, which is not the case for growing or gestating livestock. Additionally, this method does not account for dietary variability, which affects CH_4 emission generation processes from excreta.

Box 2: International Livestock Emission Factor Method: N_2O Emissions

Direct N_2O from Manure Management

Daily default nitrogen excretion (N_{ex}) rates per 1000 kg animal mass per livestock type per region per productivity class (IPCC 2019, Table 10.19) were multiplied by default lives weights (TAM) per livestock type per region (IPCC 2019, Table 10A.5), divided by 1000kg animal mass to get the N_{ex} per kg animal mass, and multiplied by 365 days in the year to determine annual N_{ex} rates per head of livestock type per region.

$$N_{excreta\ annual} = N_{rate\ daily} \times \left(\frac{TAM_{livestock,\ prod.,\ region}}{1000}\right) \times 365\ days$$

The annual N_{ex} was multiplied by the proportion (%) of manure managed (IPCC 2019, Table 10A.6) in each of nine manure management systems (IPCC 2019, Table 10.18), multiplied by the direct N_2O emission factor (EF_3 in kg N_2O-N per kg nitrogen excreted^{-1}) for each manure management system (IPCC 2019, Table 10.21), and converted from N_2O-N emissions to N_2O emissions using the conversion factor 44/28. N_2O from manure deposited onto pasture range and paddock (PRP) was multiplied by specific emission factors (kg N_2O-N per kg N deposited) for PRP (IPCC 2019, Table 11.1) depending on livestock group (CPP = cattle [dairy, non-dairy and buffalo], poultry and pigs/swine, and SO = sheep and other animals) and climate zone (wet, dry or average), and converted from N_2O-N emissions to N_2O emissions using the conversion factor 44/28.

The sum of emissions from all manure management systems provides an annual direct N_2O emission factor by livestock type, weighted by and reflecting the default proportions of manure managed in each manure management system.

$$Manure\ N2O\ EF_{direct} = N_{excreta} \times AWMS\ \% \times EF_3 \times \frac{44}{28}$$

The output is a Tier 1 emission factor for each of the relevant IPCC livestock types in kg N_2O head^{-1} year^{-1}. The output could only be considered Tier 2 when country specific data on the proportions manure each livestock type that is managed in each manure management system or system specific information on the other variables was known.

Indirect N_2O from Manure Management

Indirect N_2O emissions occur via volatilization and leaching from manure management. The annual N_{ex} was multiplied by the proportion (%) of manure managed (IPCC 2019, Table 10A.6) in each of nine manure management systems (IPCC 2019, Table 10.18), multiplied by the fraction of managed manure that is volatilized from the manure management system, by livestock type to obtain the amount of manure nitrogen that is lost due to volatilization in kg N year^{-1}.

$$N_{volatilization\ annual} = N_{excreta} \times AWMS\ \% \times Frac_{gasMS}$$

The annual N_{ex} was multiplied by the proportion (%) of manure managed (IPCC 2019, Table 10A.6) in each of the nine manure management systems (IPCC 2019, Table 10.18), multiplied by the fraction of managed manure that is leached from the manure management system, by livestock type to obtain the amount of manure nitrogen that is lost due to leaching in kg N year^{-1}.

$$N_{leaching\ annual} = N_{excreta} \times AWMS\ \% \times Frac_{LeachMS}$$

Box 2: International Livestock Emission Factor Method: N_2O Emissions (continued)

The amount of N volatilized annually was multiplied by the direct N_2O emission factor (EF_4 in kg N_2O–N per kg NH_3–N + NOx–N volatilized^{-1}) for each manure management system (IPCC 2019, Table 11.3) and converted from N_2O-N emissions to N_2O emissions using the conversion factor 44/28. The sum of emissions from all manure management systems provides an annual indirect N_2O emission factor from volatilization by livestock type, weighted by and reflecting the default proportions of manure managed in each manure management system.

$$Manure\ N2O\ EF_{indirect\ volatilization} = N_{volatilization\ annual} \times EF_4 \times \frac{44}{28}$$

The amount of N volatilized annually was multiplied by the indirect N_2O emission factor for leaching (EF_5 in kg N_2O–N per kg N leaching/runoff^{-1}) for each manure management system (IPCC 2019, Table 11.3) and converted from N_2O-N emissions to N_2O emissions using the conversion factor 44/28. The sum of emissions from all manure management systems provides an annual indirect N_2O emission factor from volatilization by livestock type, weighted by and reflecting the default proportions of manure managed in each manure management system.

$$Manure\ N2O\ EF_{indirect\ leaching} = N_{leaching\ annual} \times EF_5 \times \frac{44}{28}$$

The output is Tier 1 emission factors for indirect N_2O emissions from volatilization and leaching for each of the relevant IPCC livestock types in kg N_2O head^{-1} year^{-1}. The output could only be considered Tier 2 when country- specific data on the proportions manure each livestock type that is managed in each manure management system or system- specific information on the other variables was known.

Converting to GTAP-BIO Production Units

GTAP livestock activity outputs are presented as a change in 2014 USD value for the livestock sector by GTAP country or region. The USD prices for 2014 were used for all types of livestock across *all* international GTAP counties and regions and due to the lack of country-specific price data for all livestock types across all global regions.

Emission-per-head values by livestock type were converted to emissions per 2014 dollar by sector using population data from FAOSTAT Crops and Livestock Products domain for international livestock FAOSTAT (2023a), and EPA's U.S. GHG Inventory 1990–2021 (EPA 2023) for domestic livestock, IPCC default liveweight data (IPCC 2019) for international and domestic livestock, and domestic price data from various sources for international and domestic livestock. Animal population data, reported by country from FAOSTAT were aggregated to GTAP regions by taking the sum of country populations by animal.

To begin the process to produce emissions with GTAP dollar output units, absolute GHG emissions per species were calculated by multiplying emissions per head by the 2014 animal population. Absolute emissions per species were then summed for each animal in the livestock sector to produce absolute emissions for each GTAP sector. See the example calculation for non-ruminants (oap) below.

$$Emissions_{oap} = population_{swine} \times (emissions/head)_{swine} + population_{poultry} \times (emissions/head)_{poultry} + population_{turkey} \times (emissions/head)_{turkey}$$

Total sector value was calculated by multiplying population and country or regional specific IPCC typical animal mass (TAM) by price per head for each animal and summing across the GTAP sector. See the example calculation for non-ruminants (oap) below.

$$Value_{oap} = population_{swine} \times (price/kg)_{swine} \times (TAM)_{swine} + population_{poultry} \times (price/kg)_{poultry} \times (TAM)_{poultry} + population_{turkey} \times (price/kg)_{turkey} \times (TAM)_{turkey}$$

ICF was unable to find a single source that contained domestic price data for all livestock categories of interest. Additionally, pricing data were published in different units (e.g., per head or per hundredweight (CWT)). Therefore, price data were compiled from multiple sources and converted to consistent price per kg units using North American typical animal masses from IPCC (2019). See B9 for more details.

Table B9. 2014 USD Price Data for All Livestock Types for Estimating Domestic and International Livestock Emissions per USD

Primary IPCC Category	Liveweight[a] (kg), IPCC	Price Input Data	Price Input Data Unit	Source	Price ($/kg liveweight, USD)
Dairy Cattle	650	$1830.00	$/Head	NASS	$2.82
Non Dairy Cattle (Beef)	407	$152.83	$/cwt[b]	USDA Baseline	$3.37
Chickens – Broiler	1.4	$0.64	$/pound	USDA Baseline	$1.41
Chickens – Layers	1.4	$1.44	$/Head	NASS	$1.03
Turkey	6.8	$0.73	$/pound	USDA Baseline	$1.61
Swine - Breeding	184	$77.10	$/cwt	USDA Baseline	$1.70
Swine - Finishing	61	$77.10	$/cwt	USDA Baseline	$1.70
Sheep	40	$115.00	$/Head	NASS	$2.88
Goats	41	$105.00	$/Head	NASS	$2.56

[a] Animal liveweight values in this table represent default IPCC 2019 typical animal mass (TAM) data, variable by region, for North America.

[b] Abbreviation for hundredweight, which is 100 lbs.

Absolute emissions were then divided by total sector value to produce final emissions/$ for each sector and region. See the example calculation for non-ruminants (oap) below.

$$\frac{Kg\ CO_2e}{USD} = \frac{Emissions_{oap}}{Value_{oap}}$$

Section 3: Methane Emissions from Rice Paddy Production

This section covers the methodologies ICF used to develop methane emission factors for rice paddy production. These methodologies include:

- The overall approach to estimating emissions from crop production, including how the emission sources from crop production were estimated, and
- The process used to convert emission factors to GTAP production units.

The following sections described the data sources and data processing used to develop emission profiles of rice paddy methane emissions both domestically and internationally for each GTAP country and region.

Estimating Emission Factors

This section describes the data sources and data processing used to develop emission factors for domestic and international rice cultivation.

1. Domestic Rice Production Methane Emissions

Methane emission factors from rice cultivation (including ratoon rice) were calculated using 2021 emission estimates by state and state-level data on harvested rice area from EPA's U.S. GHG Inventory 1990–2021 (EPA 2023), where emissions were proxied up to 2021 using the state-level data reported in the inventory through 2015. Total emission estimates for each state were then divided by the total acreage and converted from hectares to acres to obtain per acre units. Factors were then aggregated to the regional level. States with rice production were mapped to U.S. regions to enable comparison of the results with those presented by U.S. region in EPA's RFS2 RIA (EPA 2010).

The resulting factors were then converted to per metric tons of production units using a 2014 rice yield estimate (in pounds per acre) from NASS (NASS 2024a) and converted from pounds to metric tons. The CH_4 emission estimates in EPA's GHG Inventory include impacts from both primary and ratooned rice crops.

Nitrous oxide emissions from synthetic fertilizer applied to rice paddies were estimated as part of the crop production estimates described in an above section in this documentation.

2. International Rice Production Methane Emissions

Implied emission factors were developed for rice methane emissions following Tier 1 IPCC methodology (IPCC 2019). The analysis used regional baseline emission factors and default scaling factors for water regimes during the cultivation period relative to continuously flooded fields from Chapter 5 of IPCC (2019). As a centralized updated resource for country water regime distributions and season length was not identified, this information was sourced from the EPA's RFS2 RIA (EPA 2010), which used data from the International Rice Research Institute (IRRI) updated in 2008 as well as the IPCC default water regime distributions by country (IPCC 1996).

Where information on a country's water regime was not available in either source or readily available in literature, estimates were proxied using neighboring country data. For international water regime by country and days cropped per country, the analysis assumed that the RFS2 data are still reliable. Days cropped per year were also sourced from RFS2 data, supplemented by USDA-FAS Rice Explorer (FAS 2024) and the FAO Crop Calendar (FAO 2024). Where information on a country's days cropped per year was not available in these sources, it was proxied to a nearby country. The analysis assumed no rice production in countries without rice production reported in the FAOSTAT Crops and Livestock Products domain (FAOSTAT 2023a) for 2014. Insufficient country-level data were available on organic amendment application and thus the analysis conservatively assumed no organic amendment application. Country regional baseline emissions (EFc) are based on IPCC regional assignments. For countries not included in the list of regions, the default rest of world value was used.

Converting to GTAP Units

Domestic emission factors were converted to per metric tons of production units using a 2014 rice yield estimate (in pounds per acre) from NASS (NASS 2024a) converted from pounds to metric tons.

For international emission factors, country-specific methane emission factors were converted to per metric tons of production units using country-specific 2014 rice yields from the FAOSTAT Crops and Livestock Products domain (FAOSTAT 2023a). Estimates were developed by country and aggregated to GTAP regions using the percent of regional production, as described in the Crop Production section of this documentation, Converting to GTAP units.

Acknowledgements

ICF conducted this work under contract with the U.S. Department of Agriculture's Office of the Chief Economist and, in particular, appreciates the support and guidance of William Hohenstein, Jeffrey O'Hara, and Tony Radich in that office. The ICF Team also thanks Michael Wang, Hao Cai, and Saurajyoti Kar of Argonne National Laboratory for engaging ICF in this effort and for their collaboration. Several ICF staff contributed to this analysis and ICF acknowledges: Kirsten Jaglo, Deanna Lizas, Jason Jones, Kelly Summers, Hazelle Tomlin, Georgia Kerkezis, and Annie Roberts for providing strategic direction and leading the methodology and emission factor development; and Ryan McNamara, Jessica Lyons, Andrew Ford, Roushda Khan, Angus Dillon, Sophie Johnson, Grace Deye, and Manlin Jia for their support in the emission factor development.

References

Aguiar, A., Chepeliev, M., Corong, E., and van der Mensbrugghe, D. (2022). The GTAP Data Base: Version 11. Journal of Global Economic Analysis, 7(2), 1-37. https://www.jgea.org/ojs/index.php/jgea/article/view/181.

ANL (2023a). FD-CIC 2023, Feedstock Carbon Intensity Calculator. Argonne National Laboratory. https://greet.anl.gov/tool_fd_cic.

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

ANL (2024). Upstream energy emission factors for the year 2020. Argonne National Laboratory. Provided over email to ICF on 23 February 2024.

EPA (2010). Renewable Fuel Standard (RFS) Regulatory Impact Analysis. U.S. Environmental Protection Agency. EPA Docket: EPA-HQ-OAR-2005-0161-0947.2.

EPA (2020). Glyphosate National and State Summary Use and Usage Matrix. https://www3.epa.gov/pesticides/nas/glyphosate/appendix-1-4.pdf.

EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430-R-23-002. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

FAO (2024). Crop Calendar. Food and Agriculture Organization of the United Nations. https://cropcalendar.apps.fao.org/#/home.

FAOSTAT (2023a). Crops and Livestock Products Domain. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/QCL.

FAOSTAT (2023b). Emissions from Energy Use in Agriculture. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/GN.

FAOSTAT (2023c). Fertilizers by Nutrient. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/RFN.

FAOSTAT (2023d). Fertilizers by Product. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/RFB.

FAOSTAT (2023e). Pesticides Use. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/RP.

FAOSTAT (2023f). Emissions from Livestock Domain. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/GLE.

FAS (2024). Rice Explorer. Foreign Agriculture Service. U.S. Department of Agriculture. https://ipad.fas.usda.gov/cropexplorer/cropview/commodityView.aspx?cropid=0422110&sel_year=2024&startrow=1.

Field to Market: The Alliance for Sustainable Agriculture (2021). Environmental Outcomes from On-Farm Agricultural Production in the United States (Fourth Edition). https://fieldtomarket.org/media/2021/12/Field-to-Market_2021-National-Indicators-Report_FINAL.pdf.

Hefler, Y.T., and Kissinger, M. (2023). Grape Wine Cultivation Carbon Footprint: Embracing a Life Cycle Approach across Climatic Zones. Agriculture. https://doi.org/10.3390/agriculture13020303.

Helgeson, D.L., and Schaffner, L.W. (1983). The Economics of On-Farm Processing of Sunflower Oil. Journal of the American Oil Chemists' Society. https://doi.org/10.1007/BF02666586.

Hoxha, A., and Christensen, B. (2019). The Carbon Footprint of Fertiliser Production: Regional Reference Values Prague, Czech Republic. https://www.fertilizerseurope.com/wp-content/uploads/2020/01/The-carbon-footprint-of-fertilizer-production_Regional-reference-values.pdf.

IPCC (1996). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual. Volume 3, Chapter 4: Agriculture, pages 53-75.

IPCC (2014). Fifth Assessment Report. https://www.ipcc.ch/assessment-report/ar5/.

IPCC (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

Karl, K., Flammini, A., and Tubiello, F.N. (2022). Methods for estimating greenhouse gas emissions from food systems. Part IV: Pesticides manufacturing. FAO Statistics Working Paper Series, No. 22-32. Rome, FAO. https://doi.org/10.4060/cc3583en.

Ludemann, C. I., Gruere, A., Heffer, P., and Dobermann, A. (2022). Global data on fertilizer use by crop and by country. Sci Data 9, 501. https://doi.org/10.1038/s41597-022-01592-z.

NASS (2022). USDA/NASS QuickStats Ad-hoc Query Tool. https://quickstats.nass.usda.gov/.

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

NASS (2024b). NASS Quick Stats, Statistics Price Data. National Agricultural Service, U.S. Department of Agriculture. https://quickstats.nass.usda.gov/#FF82C78B-DBFA-3A37-8B5D-CBAE950B020F.

NASS Montana Agricultural Statistics Service (2000). Sugar Beets Chemical Usage 2000. https://www.nass.usda.gov/Statistics_by_State/Montana/Publications/Special_Interest_Reports/MT_Sugarbeet_Chem_Use_2000.pdf.

Pimentel, et al. (2008). Biofuel Impacts on World Food Supply: Use of Fossil Fuel, Land and Water Resources. Energies. https://doi.org/10.3390/en1010041.

U.C. Cooperative Extension (1994). 1994 Yolo County Wheat Cost and Return Study (Dryland, No-Till Conditions). https://coststudyfiles.ucdavis.edu/uploads/cs_public/8e/3e/8e3e1278-d09b-4d55-8ae9-62f6fb6a9966/94wheatyolonotill.pdf.

U.S. Livestock Population Data (2023). U.S. Inventory reports Table A-157: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

USDA (2016). Agricultural Baseline Projection Tables, Feb 1, 2016, U.S. Livestock Projections to 2025, Table 18 Beef long-term Projections, Table 19 Pork long-term Projections, Table 20 Young chicken long-term Projections, and Table 21 Turkey long-term projections. https://usda.library.cornell.edu/concern/publications/qn59q396v?locale=en&page=2#release-items.

USDA (2018). Tillage Intensity and Conservation Cropping in the United States. U.S. Department of Agriculture. https://www.ers.usda.gov/webdocs/publications/90201/eib-197.pdf.

USDA ERS (2023). ARMS Survey Data. USDA Economic Research Service. https://data.ers.usda.gov/reports.aspx?ID=17883.

USDA (2024). Agricultural Marketing Service, Livestock, Poultry and Grain Market News, HG234. https://www.ams.usda.gov/mnreports/ams_3452.pdf.

Vendig, I., Guzman, A., De La Cerda, G., Esquivel, K., Mayer, A. C., Ponisio, L., & Bowles, T. M. (2023). Quantifying direct yield benefits of soil carbon increases from cover cropping. Nature Sustainability, 1-10. https://www.nature.com/articles/s41893-023-01131-7.

World Bank Group (2023). World Bank Country and Lending Groups. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

APPENDIX C: GTAP-BIO MODELING RESULTS AND GHG EMISSIONS OF INDIRECT EFFECTS FOR SAF PATHWAYS

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This appendix presents GTAP simulation results and emission results that were used to develop the figures in Section 3 of the Technical Report.

Section 1. GTAP-BIO Modeling Results

Following the methodology described in Appendix A, the Purdue team completed the GTAP-BIO modeling and summarized the results for land use changes over 30 years, annual changes in crop production, and annual changes in livestock production for the four SAF pathways. GTAP-BIO results are presented in three Excel files (titled “GTAP-BIO Modeling Results for 40B SAF Pathways _ Land Use Changes”, “GTAP-BIO Modeling Results for 40B SAF Pathways _ Changes in Crop Production”, and “GTAP-BIO Modeling Results for 40B SAF Pathways _ Changes in Livestock Production”). These Excel data files are available at the GREET website together with this Appendix.

Section 2. Emissions Results

Following the methodology developed by the ICF team and described in Appendix B, the Argonne team summarized the GHG emissions for crop production, methane emissions from rice paddy fields, and methane emissions of livestock production across regions in Table C1, Table C3, and Table C5, respectively. Activity changes projected by GTAP-BIO for crops and livestock production per fuel pathway are tabulated in Tables C7 and C8 respectively. Emission Intensities calculated from the emission profiles and activity changes for crop production, methane emissions from rice paddy fields, and methane emissions of livestock production are presented in Table C2, Table C4, and Table C6, respectively. Finally, Tables C9 and C10 summarize the indirect effects from crop production and livestock change for each fuel pathway.

Table C1. Emissions for other crops aggregated to GTAB-BIO categories, in kg CO_2e/MT, as per IPCC GWP AR5 methodology (estimated by ICF as presented in Figure 2 of the Technical Report)

Regions	Corn	Oth_ CrGr[1]	Oth_Oil seeds[2]	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	338.5	255.9	97.3	386.9	311.2	138.9	338.5	509.3	143.1	707.3
Canada	174.2	294.2	460.6	221.3	0.0	0.0	657.4	279.9	45.5	385.8
Central & Caribn America	991.4	337.3	226.7	951.1	396.5	266.0	0.0	421.8	141.1	1,905.4
China	1,039.5	411.6	456.8	371.5	724.4	142.4	2,087.4	1,409.4	320.0	1,288.2
East Asia	2,444.7	5,878.9	2,879.0	758.5	2,461.3	0.0	2,035.6	9,304.3	292.4	795.8
European Union 27	234.0	321.2	498.8	135.2	267.4	0.0	647.9	349.0	88.9	394.6
India	1,149.9	1,919.0	847.6	1,074.4	874.2	0.0	2,181.2	2,619.6	94.3	937.7
Japan	3,299.5	2,371.7	2,502.7	353.3	1,039.4	0.0	6,210.6	3,975.8	262.4	2,291.3
Malaysia and Indonesia	411.0	0.0	47.8	248.9	244.3	214.1	0.0	469.6	180.5	0.0
Middle Eastern and North Africa	479.3	688.5	749.4	214.8	490.9	0.0	758.6	641.7	76.3	734.5
Oceania Countries	352.1	224.8	233.5	170.8	87.4	0.0	766.0	96.4	62.0	263.9
Other E. Eur & Rest of Soviet Union	189.2	264.4	407.0	109.4	254.3	0.0	627.7	285.0	65.9	485.9
Rest of European Countries	155.7	301.0	615.9	100.5	0.0	0.0	867.9	564.4	100.4	445.2
Rest of South Asia	502.1	681.6	85.4	391.3	380.0	0.0	1,355.2	835.9	90.8	532.0
Rest of SE Asia	556.8	551.3	177.8	149.9	481.6	184.3	0.0	1,019.3	120.2	501.6
Russia	218.8	285.1	456.5	65.5	192.7	0.0	883.8	340.8	72.1	215.9
South and Other Americas	257.0	181.8	174.9	188.8	293.7	204.7	674.1	156.0	82.1	344.8
Sub Saharan Africa	279.8	298.3	263.5	74.8	141.5	94.8	353.3	242.8	95.4	210.1
United States	172.5	31.1	312.1	122.5	278.7	NA	232.9	113.9	48.9	256.0

[1] May include Barley, Sorghum, and Millet.

[2] May include groundnuts with shell, sunflower seed, coconuts, and olives.

Table C2. GHG emissions for non-feedstock crops by region, crop categories, and pathways (g CO_2e/MJ of SAF, as presented in Figure 3 of the Technical Report)

Table C2.a: For the Canola HEFA pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy _Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	0.07	0.00	0.00	0.12	0.00	0.01	0.00	-0.13	-0.12	0.06
Canada	-0.08	-0.16	-0.06	-0.33	0.00	0.00	0.00	-0.24	0.00	-1.04
Central and Caribb. America	0.00	0.00	0.01	0.11	0.00	0.06	0.00	0.01	-0.01	0.07
China	0.11	0.01	0.01	0.28	-0.02	0.00	0.04	-0.01	-0.01	0.10
East Asia	0.04	0.00	0.00	0.02	-0.01	0.00	0.00	-0.06	0.00	0.01
Euro. Union 27	-0.01	-0.10	-0.01	-0.15	0.00	0.00	4.34	-0.03	-0.01	-0.38
India	0.06	0.00	0.10	0.36	0.00	0.00	0.02	-0.14	0.00	0.20
Japan	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.03
Malaysia and Indones.	0.00	0.00	0.00	0.00	-0.01	0.69	0.00	0.00	0.00	0.00
Middle Eastern and North Africa	0.03	0.01	0.02	0.05	-0.01	0.00	-0.02	0.00	0.00	0.25
Oceania	0.00	0.00	0.02	-0.02	0.00	0.00	0.32	0.00	0.00	-0.04
Other East Euro & Rest of Former Soviet Union	0.01	-0.01	0.03	-0.01	0.00	0.00	0.35	-0.03	0.00	0.12
Rest of Europe	0.00	0.00	0.01	0.01	0.00	0.00	-0.01	0.00	0.00	0.07
Rest of South Asia	0.01	0.00	0.00	0.03	0.00	0.00	0.02	0.00	0.00	0.03
Rest of SE Asia	0.03	0.00	0.01	0.03	-0.03	0.05	0.00	0.00	-0.01	0.00
Russia	0.01	-0.01	0.02	0.00	0.00	0.00	0.10	-0.01	0.00	0.11
South and Other America	0.04	0.01	0.00	0.04	0.00	-0.01	0.12	-0.04	0.00	0.06
Sub Saharan Africa	0.03	-0.01	0.02	0.07	0.00	0.02	0.00	0.00	0.00	0.02
United States	0.05	0.00	-0.05	-0.05	-0.01		0.00	-0.38	-0.01	0.13

Table C2.b. For the Corn ATJ-ethanol pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	0.22	0.00	0.00	-0.01	0.01	0.00	0.00	1.01	-0.40	0.07
Canada	0.01	0.01	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.22
Central and Caribbean Americas	0.51	0.00	0.00	0.24	0.01	0.00	0.00	0.00	-0.02	0.06
China	0.41	0.01	0.02	0.47	-0.04	0.00	0.09	0.17	0.00	0.20
East Asia	0.20	0.00	0.00	0.05	-0.03	0.00	0.00	0.06	0.00	0.01
EU 27	0.07	0.01	0.04	0.05	0.00	0.00	0.03	0.02	0.01	0.30
India	0.09	0.03	0.08	0.57	0.02	0.00	0.03	0.15	0.00	0.19
Japan	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.02	0.00	0.06
Malaysia and Indones.	0.03	0.00	0.00	0.05	0.00	0.05	0.00	0.00	0.00	0.00
Middle Eastern & North Africa	0.04	0.00	0.04	0.07	0.00	0.00	0.00	0.00	0.01	0.22
Oceania	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Other East Euro. & Rest of Former Soviet Union	0.10	0.00	0.02	0.01	0.00	0.00	0.00	0.01	0.00	0.14
Rest of Euro.	0.00	0.00	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.03
Rest of South Asia	0.01	0.00	0.00	0.05	0.00	0.00	0.01	0.00	0.00	0.02
Rest of SE Asia	0.11	0.00	0.01	0.06	-0.04	0.00	0.00	0.00	-0.01	0.00
Russia	0.02	-0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.11
South and Other America	0.12	0.00	0.00	0.03	0.01	-0.01	0.00	0.07	-0.01	0.09
Sub Saharan Africa	0.05	0.00	0.02	0.09	0.00	0.00	0.00	0.00	0.00	0.02
United States	0.00	-0.02	-0.05	-0.48	-0.07		-0.01	-0.60	-0.03	-0.73

Table C2.c. For the Soybean HEFA pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	-0.01	-0.01	0.00	-0.07	0.00	0.02	0.00	0.75	-0.16	0.02
Canada	0.03	-0.01	-0.02	0.02	0.00	0.00	-0.28	0.05	0.00	0.16
Central and Caribbean America	0.13	-0.01	0.00	0.08	0.00	0.04	0.00	0.01	-0.01	0.03
China	0.16	0.00	-0.01	0.23	-0.03	0.00	0.01	0.01	-0.01	0.07
East Asia	0.08	0.00	0.00	0.02	-0.02	0.00	0.00	-0.09	0.00	0.01
European Union 27	0.07	-0.07	0.07	0.01	0.00	0.00	0.04	-0.02	0.00	0.11
India	0.10	-0.05	0.14	0.10	-0.02	0.00	0.14	-0.13	-0.01	0.07
Japan	0.00	0.00	0.00	0.01	0.00	0.00	0.00	-0.01	0.00	0.02
Malaysia & Indonesia	-0.01	0.00	0.00	-0.04	-0.03	1.48	0.00	0.00	0.00	0.00
Middle Eastern and North Africa	0.01	0.00	0.03	0.03	0.00	0.00	-0.01	-0.01	0.00	0.09
Oceania	0.00	0.00	-0.01	0.00	0.00	0.00	-0.02	0.00	0.00	0.02
Other East Europe and Rest of Former Soviet Union	0.02	-0.01	0.08	0.00	0.00	0.00	-0.02	-0.02	0.00	0.03
Rest of Europe	0.00	0.00	-0.02	0.00	0.00	0.00	-0.03	0.00	0.00	0.02
Rest of South Asia	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00
Rest of SE Asia	0.04	0.00	0.02	0.01	-0.06	0.12	0.00	-0.02	-0.01	0.00
Russia	0.01	-0.01	0.05	0.00	0.00	0.00	-0.01	-0.01	0.00	0.05
South and Other Americas	0.05	0.00	-0.02	0.01	0.00	-0.04	0.00	0.07	-0.01	0.04
Sub Saharan Africa	0.02	-0.01	0.00	0.04	0.00	0.03	0.00	-0.01	0.00	0.01
United States	0.07	-0.01	-0.23	-0.25	-0.05		-0.06	0.00	-0.01	-0.31

Table C2.d. For Sugarcane ATJ-ethanol pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	-1.57	-0.04	-0.02	-2.16	-0.08	0.00	0.00	-4.03	0.00	-0.54
Canada	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.06	0.00	0.04
Central and Caribbean Americas	0.03	0.00	0.00	0.24	0.01	0.00	0.00	0.00	0.01	0.03
China	-0.02	0.00	0.07	0.39	-0.05	0.00	0.21	0.31	0.00	-0.02
East Asia	0.03	0.00	0.00	0.03	-0.02	0.00	0.00	0.09	0.00	0.01
European Union 27	0.02	0.00	0.06	0.09	0.00	0.00	0.06	0.03	0.01	-0.10
India	0.14	0.02	0.12	0.46	0.03	0.00	0.06	0.22	0.06	0.12
Japan	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.02
Malaysia and Indonesia	0.03	0.00	0.00	0.05	0.00	0.09	0.00	0.00	0.01	0.00
Middle Eastern and North Africa	0.00	0.00	0.06	0.08	0.00	0.00	0.00	0.00	0.01	0.12
Oceania Countries	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01
Other East Europe and Rest of Former Soviet Union	0.04	0.00	0.04	0.01	0.00	0.00	0.01	0.03	0.00	0.02
Rest of European Countries	0.00	0.00	0.03	0.01	0.00	0.00	0.02	0.00	0.00	0.01
Rest of South Asia	0.00	0.00	0.00	0.05	0.00	0.00	0.01	0.00	0.02	0.00
Rest of South East Asia	0.06	0.00	0.04	0.05	-0.05	0.01	0.00	0.00	0.01	0.00
Russia	0.01	0.00	0.05	0.00	0.00	0.00	0.01	0.01	0.00	0.05
South and Other Americas	0.03	0.00	0.00	0.00	0.01	0.00	0.00	0.18	0.00	0.04
Sub Saharan Africa	0.03	-0.01	0.03	0.10	0.00	0.00	0.00	0.01	0.01	0.01
United States	-0.12	0.00	0.00	-0.03	0.01		0.00	0.40	0.00	-0.05

Table C3. Methane emissions for rice paddy fields, in kg CO_2e/MT, as per IPCC GWP AR5 methodology (estimated by ICF, as presented in Figure 4 of the Technical Report)

Regions	Paddy_Rice
Brazil	381.4
Canada	NA
Central and Caribbean Americas	361.7
China	587.2
East Asia	682.5
European Union 27	1,184.7
India	1,368.6
Japan	829.5
Malaysia and Indonesia	1,427.4
Middle Eastern and North Africa	420.9
Oceania Countries	484.0
Other East Europe and Rest of Former Soviet Union	2,044.5
Rest of European Countries	NA
Rest of South Asia	725.5
Rest of South East Asia	1,711.4
Russia	1,639.8
South and Other Americas	702.5
Sub Saharan Africa	1,079.6
United States	1,316.6

Table C4. Emission Intensities for rice paddy fields by region and pathways, in g CO_2e/MJ of SAF (as presented in Figure 5 of the Technical Report)

Regions	Canola HEFA	Corn ATJ-ethanol	Soybean HEFA	Sugarcane ATJ-ethanol
Brazil	0.00	0.01	0.00	-0.10
Canada				
Central and Caribbean Americas	0.00	0.01	0.00	0.01
China	-0.02	-0.03	-0.03	-0.04
East Asia	0.00	-0.01	-0.01	-0.01
European Union 27	-0.01	0.01	0.00	0.01
India	0.00	0.04	-0.02	0.05
Japan	0.00	0.00	0.00	0.00
Malaysia and Indonesia	-0.08	-0.01	-0.19	-0.03
Middle Eastern and North Africa	0.00	0.00	0.00	0.00
Oceania Countries	0.00	0.00	0.00	0.00
Other East Europe and Rest of Former Soviet Union	0.00	0.01	0.00	0.00
Rest of European Countries				
Rest of South Asia	-0.01	0.01	-0.01	0.01
Rest of South East Asia	-0.11	-0.15	-0.21	-0.16
Russia	0.00	0.02	0.01	0.01
South and Other Americas	0.00	0.01	0.01	0.03
Sub Saharan Africa	0.00	0.01	0.00	0.01
United States	-0.06	-0.34	-0.22	0.04

Table C5. Methane emissions for livestock aggregated to GTAP-BIO categories, in kg CO_2e/USD, 2014 USD, as per IPCC GWP AR5 methodology (estimated by ICF as presented in Figure 6 of the Technical Report)

Regions	Dairy_Farms	Ruminant	NonRuminant
Brazil	2.5	1.6	1.3
Canada	3.6	1.5	1.9
Central and Caribbean Americas	2.0	1.8	1.7
China	2.2	2.2	1.4
East Asia	2.5	2.0	1.6
European Union 27	3.2	1.5	1.8
India	3.7	2.0	1.8
Japan	2.7	1.4	2.3
Malaysia and Indonesia	2.9	1.9	1.1
Middle Eastern and North Africa	2.5	2.0	0.4
Oceania Countries	2.3	1.8	3.5
Other East Europe and Rest of Former Soviet Union	2.1	2.2	1.2
Rest of European Countries	2.8	1.6	0.3
Rest of South Asia	3.5	2.3	0.9
Rest of South East Asia	2.8	1.9	1.7
Russia	2.0	1.9	1.1
South and Other Americas	2.1	1.6	0.4
Sub Saharan Africa	2.9	2.2	1.6
United States	2.6	1.4	2.6

Table C6. Emission Intensities for livestock by region and pathways, in kg CO_2e/USD, 2014 USD, as per IPCC GWP AR5 methodology (as presented in Figure 7 of the Technical Report)

Regions	Canola HEFA	Corn ATJ-ethanol	Soybean HEFA	Sugarcane ATJ-ethanol
Brazil	0.03	-0.08	-0.15	-1.81
Canada	-0.10	0.12	0.00	0.05
Central and Caribbean Americas	-0.13	-0.06	-0.25	-0.03
China	-0.01	-0.05	-0.27	-0.11
East Asia	-0.01	-0.08	-0.03	-0.05
European Union 27	-0.27	0.18	-0.18	0.14
India	0.02	-0.03	0.07	-0.04
Japan	-0.06	-0.03	-0.14	-0.01
Malaysia and Indonesia	-0.02	-0.01	-0.05	-0.02
Middle Eastern and North Africa	-0.03	-0.04	-0.03	0.01
Oceania Countries	0.00	0.15	-0.20	0.15
Other East Europe and Rest of Former Soviet Union	-0.01	0.01	-0.08	0.02
Rest of European Countries	0.00	0.01	-0.01	0.00
Rest of South Asia	-0.03	-0.02	-0.03	-0.02
Rest of South East Asia	-0.03	-0.06	-0.07	-0.09
Russia	-0.05	-0.03	-0.06	-0.02
South and Other Americas	-0.06	-0.11	-0.07	-0.01
Sub Saharan Africa	-0.08	-0.02	-0.18	0.05
United States	0.92	-1.80	2.84	-0.21

Table C7. Activity change in crops as estimated by GTAP-BIO, in metric ton

Table C7.a. For the Canola HEFA pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	13,360.0	-118.8	2,161.5	19,264.0	773.0	4,502.9	465.4	-15,744.0	-51,584.0	5,308.5
Canada	-29,129.0	-32,868.0	-8,071.0	-91,913.0	0.0	0.0	409,326.0	-51,986.5	-1,463.6	-166,606.0
Central and Caribbean Americas	194.0	-117.0	4,019.5	7,400.0	133.8	12,926.5	11.9	762.3	-3,088.0	2,144.8
China and Hong Kong	6,304.0	964.0	922.0	46,464.0	-2,096.0	265.9	1,069.0	-230.0	-1,144.0	4,792.0
East Asia	960.3	30.4	-2.6	1,850.0	-339.0	0.0	146.6	-367.7	67.6	560.1
European Union 27	-1,360.0	-20,096.0	-1,237.0	-68,288.0	-367.6	0.0	413,464.0	-4,561.9	-8,800.0	-58,832.0
India	3,174.0	-42.0	7,306.0	20,448.0	16.0	0.0	454.5	-3,266.0	-3,136.0	13,184.0
Japan	0.0	76.9	28.1	1,836.0	-143.0	0.0	-5.1	194.6	274.5	837.4
Malaysia and Indonesia	70.0	0.0	-1,088.0	-64.0	-3,632.0	199,600.0	0.0	-59.8	-790.0	0.0
Middle Eastern and North Africa	4,486.0	1,070.0	1,639.0	15,760.0	-647.0	0.0	-1,343.6	-114.8	552.0	21,000.0
Oceania Countries	5.6	-1,226.0	6,105.8	-6,164.0	-30.3	5,449.3	26,038.3	271.7	-2,258.0	-8,730.0
Other East Europe and Rest of Former Soviet Union	3,904.0	-1,326.0	4,831.0	-3,240.0	-49.1	0.0	34,678.3	-5,564.0	-494.0	15,852.0
Rest of European Countries	1,618.0	592.0	508.5	3,888.0	327.6	0.0	-1,024.8	-1.0	390.0	10,266.0
Rest of South Asia	762.0	-22.1	1,830.0	5,404.0	-664.0	0.0	811.0	33.5	-1,192.0	3,876.0
Rest of South East Asia	3,400.0	-14.5	3,636.0	11,552.0	-3,872.0	16,604.0	0.0	-238.9	-4,448.0	143.7
Russia	1,756.0	-1,802.0	3,277.0	-1,668.0	32.3	0.0	6,982.6	-1,227.5	-304.0	32,428.0
South and Other Americas	9,004.0	2,996.0	-1,459.5	11,800.0	-392.0	-2,430.0	10,588.0	-14,688.0	-3,544.0	9,894.0
Sub Saharan Africa	6,560.0	-1,356.0	3,558.0	59,648.0	-162.0	10,274.0	39.3	-985.5	-1,512.0	5,597.0
United States	18,240.0	-393.0	-9,537.5	-26,376.0	-2,787.0	0.0	200,490.8	-208,280.0	-6,776.0	31,096.0

Table C7.b. For the Corn ATJ-ethanol pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	79,432.0	-942.5	-1,467.0	-4,528.0	3,707.0	170.4	-46.3	244,688.0	-342,144.0	12,212.5
Canada	6,771.0	5,632.0	-187.8	915.0	0.4	0.0	3,980.0	11,382.5	-36.6	70,698.0
Central and Caribbean Americas	63,164.0	655.0	10.0	30,888.0	3,417.5	1,357.5	0.6	432.8	-18,784.0	3,930.0
China and Hong Kong	49,120.0	3,903.0	5,644.0	154,944.0	-6,576.0	66.8	5,577.0	15,081.0	-520.0	19,080.0
East Asia	10,226.8	31.4	-32.0	8,380.0	-1,622.0	0.0	19.8	737.3	335.3	2,170.7
European Union 27	37,128.0	3,184.0	8,793.0	41,680.0	1,071.6	0.0	5,132.0	5,658.8	13,512.0	92,904.0
India	10,166.0	1,816.0	11,202.0	65,056.0	3,504.0	0.0	1,869.5	7,289.0	2,144.0	24,592.0
Japan	-1.0	82.4	11.1	9,900.0	-402.0	0.0	0.4	583.5	1,805.5	3,343.6
Malaysia and Indonesia	10,180.0	0.0	5,196.0	25,356.0	-1,096.0	27,904.0	0.0	822.7	-1,478.0	0.1
Middle Eastern and North Africa	10,447.0	36.0	6,156.0	38,336.0	-172.0	0.0	406.3	-81.4	13,964.0	37,224.0
Oceania Countries	1,273.4	9,024.0	-1,154.5	2,272.0	226.6	-1,066.8	-794.3	-0.9	-1,312.0	20,572.0
Other East Europe and Rest of Former Soviet Union	64,260.0	-1,918.0	5,185.0	8,344.0	752.8	0.0	-70.5	5,271.0	1,594.0	34,360.0
Rest of European Countries	1,771.5	1,732.0	3,973.0	8,452.0	4,258.5	0.0	809.0	3.5	1,544.0	9,290.0
Rest of South Asia	2,616.0	-25.4	1,459.5	17,128.0	976.0	0.0	751.2	102.2	688.0	4,880.0
Rest of South East Asia	23,486.0	92.2	9,084.0	49,456.0	-10,880.0	-639.0	0.0	-153.1	-14,576.0	528.9
Russia	12,235.0	-3,180.0	7,218.0	788.0	1,279.3	0.0	665.3	1,152.8	3,744.0	61,172.0
South and Other Americas	59,740.0	-1,091.0	1,890.0	16,512.0	2,615.0	-4,832.0	160.5	53,864.0	-12,680.0	32,098.0
Sub Saharan Africa	24,112.0	-1,288.0	9,960.0	154,176.0	1,202.0	534.0	132.5	1,439.0	-3,424.0	11,748.0
United States	9,290,240.0	-62,653.0	-21,041.3	-484,248.0	-31,426.0	0.0	-7,351.3	-653,424.0	-75,752.0	-350,996.0

Table C7.c. For the Soybean HEFA pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	-2,328.0	-1,443.0	2,737.8	-11,392.0	113.0	7,626.1	29.9	90,952.0	-67,776.0	1,533.0
Canada	10,001.0	-2,208.0	-3,221.9	5,022.0	0.1	0.0	-26,225.0	10,652.5	37.2	25,924.0
Central and Caribbean Americas	8,006.0	-1,494.0	-931.3	5,240.0	738.5	8,179.0	-2.8	1,568.1	-4,944.0	927.8
China and Hong Kong	9,504.0	272.0	-1,182.0	37,568.0	-2,672.0	668.1	321.0	297.0	-2,376.0	3,528.0
East Asia	1,933.5	-14.6	52.4	1,434.0	-492.0	0.0	-9.1	-593.9	79.9	434.2
European Union 27	17,680.0	-13,320.0	9,055.0	4,592.0	227.5	0.0	3,888.0	-4,104.4	2,936.0	17,760.0
India	5,530.0	-1,556.0	10,512.0	5,792.0	-1,072.0	0.0	3,927.5	-2,995.0	-5,248.0	4,304.0
Japan	-0.1	-10.4	13.8	2,004.0	-153.0	0.0	-0.3	-84.1	384.5	561.4
Malaysia and Indonesia	-1,808.0	0.0	-3,532.0	-10,584.0	-8,240.0	427,344.0	0.0	97.6	-1,318.0	0.0
Middle Eastern and North Africa	1,882.0	-366.0	2,447.0	8,272.0	-135.0	0.0	-619.9	-923.4	2,848.0	7,296.0
Oceania Countries	194.2	915.0	-2,384.8	1,010.0	86.4	11,767.5	-1,425.5	-15.0	-2,574.0	3,706.0
Other East Europe and Rest of Former Soviet Union	7,744.0	-2,394.0	12,494.0	-664.0	132.9	0.0	-1,753.3	-4,573.0	230.0	3,364.0
Rest of European Countries	424.0	-790.0	-1,557.5	2,240.0	929.2	0.0	-2,246.3	-1.3	466.0	2,836.0
Rest of South Asia	238.0	-19.4	2,604.0	2,380.0	-544.0	0.0	434.9	-13.0	-568.0	-28.0
Rest of South East Asia	4,530.0	-158.4	7,704.0	5,392.0	-7,584.0	38,580.0	0.0	-1,072.9	-6,320.0	107.0
Russia	1,961.0	-2,482.0	6,214.0	176.0	290.1	0.0	-865.4	-2,628.5	1,000.0	13,160.0
South and Other Americas	12,040.0	-1,457.0	-8,210.5	3,368.0	786.0	-12,775.0	-136.0	28,624.0	-4,400.0	7,047.0
Sub Saharan Africa	3,712.0	-1,456.0	-200.0	29,600.0	54.0	19,398.0	-223.6	-2,591.0	-1,112.0	2,267.0
United States	24,224.0	-20,429.0	-45,618.0	-125,352.0	-10,248.0	0.0	-17,106.0	672,704.0	-16,216.0	-75,168.0

Table C7:d. For Sugarcane ATJ-ethanol pathway

Regions	Corn	Oth_ CrGr	Oth_Oil seeds	OthAgri	Paddy_ Rice	Palm_f	Canola	Soybeans	Sugar_ Crop	Wheat
Brazil	-745,848.0	-22,252.0	-35,579.8	-894,640.0	-43,291.0	-3,880.8	-912.3	-1,268,456.0	66,024,896.0	-123,086.5
Canada	1,225.0	521.0	628.4	-2,557.0	0.2	0.0	10,456.0	36,028.5	-106.7	18,226.0
Central and Caribbean Americas	4,286.0	-82.0	1,013.3	39,880.0	2,395.3	3,004.0	0.8	432.1	6,896.0	2,342.8
China and Hong Kong	-3,712.0	1,422.0	24,296.0	170,368.0	-10,688.0	382.8	16,261.0	35,472.0	2,312.0	-2,608.0
East Asia	2,039.0	29.7	262.8	6,586.0	-1,193.0	0.0	39.3	1,622.2	254.6	1,048.2
European Union 27	14,232.0	-1,896.0	18,943.0	101,504.0	680.3	0.0	15,700.0	15,365.4	18,344.0	-40,304.0
India	18,944.0	2,070.0	22,082.0	68,992.0	5,568.0	0.0	4,618.0	13,253.0	110,144.0	20,112.0
Japan	-0.3	76.9	24.3	10,952.0	-286.0	0.0	1.4	864.0	1,085.0	1,197.8
Malaysia and Indonesia	11,472.0	0.0	9,116.0	30,456.0	-2,992.0	68,352.0	0.0	680.1	7,230.0	0.0
Middle Eastern and North Africa	-657.0	296.0	13,893.0	61,104.0	-1,441.0	0.0	896.8	-157.7	27,936.0	26,336.0
Oceania Countries	696.6	3,252.0	438.5	5,098.0	249.5	840.3	2,119.8	47.4	2,226.0	5,136.0
Other East Europe and Rest of Former Soviet Union	30,088.0	-1,940.0	14,691.0	20,784.0	163.3	0.0	2,734.8	18,272.5	3,408.0	6,212.0
Rest of European Countries	1,599.0	1,976.0	7,372.5	16,372.0	1,417.3	0.0	3,179.3	17.2	865.0	4,068.0
Rest of South Asia	851.0	-40.9	3,138.0	21,380.0	1,280.0	0.0	1,003.5	152.1	37,384.0	-88.0
Rest of South East Asia	15,928.0	27.9	33,290.0	51,424.0	-15,168.0	5,476.0	0.0	-368.6	9,024.0	355.0
Russia	9,368.0	-844.0	16,188.0	8,996.0	507.6	0.0	1,857.3	3,254.3	10,174.0	37,692.0
South and Other Americas	19,340.0	-3,424.0	4,232.5	-1,104.0	7,391.0	-3,209.0	193.0	184,136.0	-1,800.0	16,420.0
Sub Saharan Africa	16,456.0	-3,176.0	19,292.0	207,168.0	1,538.0	2,658.0	240.6	3,420.5	9,872.0	9,102.0
United States	-108,768.0	-14,261.0	209.3	-45,376.0	5,330.0	0.0	-962.3	566,304.0	-14,976.0	-34,252.0

Table C8. Activity change in livestock as estimated by GTAP-BIO, in Million USD, 2014 USD, for the different biofuel pathways.

Table C8.a. For the Canola HEFA pathway

Regions	Dairy_Farms	NonRuminant	Ruminant
Brazil	0.02	-0.65	1.51
Canada	0.58	2.90	-8.93
Central and Caribbean Americas	-0.32	-3.10	-1.30
China and Hong Kong	-0.13	-2.63	1.43
East Asia	0.06	-0.22	-0.12
European Union 27	-3.47	-2.44	-0.61
India	-0.23	0.22	0.79
Japan	-0.01	-1.42	-0.10
Malaysia and Indonesia	-0.04	-0.02	-0.54
Middle Eastern and North Africa	-0.43	-1.28	-0.23
Oceania Countries	2.71	-0.75	-2.08
Other East Europe and Rest of Former Soviet Union	0.54	-0.78	-0.49
Rest of European Countries	0.00	-0.06	0.05
Rest of South Asia	-0.34	-0.08	-0.31
Rest of South East Asia	-0.04	-0.78	-0.19
Russia	-0.72	-0.20	-0.70
South and Other Americas	-0.37	-0.35	-1.71
Sub Saharan Africa	-0.49	-0.71	-1.04
United States	1.06	13.95	13.11

Table C8.b. For the Corn ATJ-ethanol pathway

Regions	Dairy_Farms	NonRuminant	Ruminant
Brazil	-0.70	-0.08	-4.91
Canada	-0.42	3.62	5.84
Central and Caribbean Americas	-0.48	-1.65	-2.27
China and Hong Kong	-1.01	1.63	-2.58
East Asia	-0.02	-2.33	-3.04
European Union 27	0.09	4.62	9.05
India	-1.93	0.17	1.67
Japan	-0.44	0.22	-1.82
Malaysia and Indonesia	-0.07	0.15	-0.68
Middle Eastern and North Africa	-0.90	-1.61	-0.92
Oceania Countries	1.25	0.56	7.52
Other East Europe and Rest of Former Soviet Union	0.98	-0.54	-0.07
Rest of European Countries	0.12	-0.01	0.23
Rest of South Asia	-0.33	0.04	-0.52
Rest of South East Asia	-0.15	-2.20	-1.73
Russia	-1.70	0.16	-0.06
South and Other Americas	-1.34	0.14	-6.55
Sub Saharan Africa	-1.10	-0.24	0.32
United States	-18.15	-41.66	-49.48

Table C8.c. For the Soybean HEFA pathway

Regions	Dairy_Farms	NonRuminant	Ruminant
Brazil	-0.06	-5.95	-0.72
Canada	-0.11	-1.51	2.15
Central and Caribbean Americas	-0.58	-5.27	-2.87
China and Hong Kong	-0.12	-9.01	-1.91
East Asia	-0.12	-0.50	-0.30
European Union 27	-2.17	-2.01	-0.28
India	0.44	0.42	0.83
Japan	-0.08	-2.41	-1.85
Malaysia and Indonesia	-0.09	-0.38	-1.40
Middle Eastern and North Africa	-0.54	-1.40	-0.05
Oceania Countries	-0.53	-1.61	-3.04
Other East Europe and Rest of Former Soviet Union	-0.49	-1.44	-1.06
Rest of European Countries	-0.09	-0.11	-0.11
Rest of South Asia	-0.26	-0.16	-0.33
Rest of South East Asia	-0.12	-1.97	-0.39
Russia	-0.33	-0.40	-1.41
South and Other Americas	-0.72	-1.17	-1.68
Sub Saharan Africa	-0.61	-1.28	-3.22
United States	10.13	46.69	20.61

Table C8.d. For the Sugarcane ATJ-ethanol pathway

Regions	Dairy_Farms	NonRuminant	Ruminant
Brazil	-25.35	-53.18	-97.88
Canada	-0.24	2.49	2.36
Central and Caribbean Americas	-0.08	-1.10	-1.33
China and Hong Kong	-1.64	-6.51	-2.00
East Asia	-0.10	-2.27	-2.26
European Union 27	-1.66	1.58	16.60
India	-3.37	0.07	2.55
Japan	-0.41	1.10	-1.85
Malaysia and Indonesia	-0.11	-0.27	-0.97
Middle Eastern and North Africa	-1.12	-1.60	2.91
Oceania Countries	2.17	0.38	10.07
Other East Europe and Rest of Former Soviet Union	1.09	-0.81	1.11
Rest of European Countries	0.08	-0.14	0.34
Rest of South Asia	-0.70	-0.04	-0.26
Rest of South East Asia	-0.36	-5.27	-2.12
Russia	-1.97	1.14	-0.08
South and Other Americas	-2.34	-0.30	2.27
Sub Saharan Africa	-1.96	-0.60	6.57
United States	-4.15	-6.93	-3.69

Table C9. Summary of unadjusted indirect effects for other crop production and rice methane emissions, in g CO_2e/MJ, based on the SAF conversion rates considered in GTAP-BIO simulations and as per IPCC GWP AR5 methodology

	US Corn ATJ-ethanol (1 B gallons)	US Soybean HEFA (0.5 B gallons)	US Canola HEFA (0.5 B gallons)	Brazilian Sugarcane ATJ-ethanol (1 B gallons)
Rice Methane	-0.4	-0.7	-0.3	-0.2
Other Crop Production	5.2	2.9	5.5	-3.8

Table C10. Summary of unadjusted indirect effects for livestock production, in g CO_2e/MJ, based on the SAF conversion rates considered in GTAP-BIO simulations and as per IPCC GWP AR5 methodology

	US Corn ATJ-ethanol (1 B gallons)	US Soybean HEFA (0.5 B gallons)	US Canola HEFA (0.5 B gallons)	Brazilian Sugarcane ATJ-ethanol (1 B gallons)
Livestock Production	-2.0	1.1	0.1	-2.0

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