Supplemental Information – Life Cycle Inventories Used in the Study

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S1. Corn Wet Milling and Refining Inventories

S1.1 About the Inventory

Grouping was used for the portions of the corn milling and refining process that were sufficiently similar, as defined by examination of the process structures and data provided and confirmed by comparing their LCIA and uncertainty analysis resulting in acceptable coefficients of variation. Only the refining stage was found to be intractable. Thus, starch milling, steam generation and cogeneration were grouped (cogeneration with and without coal, boiler steam with and without coal, starch milling using cogeneration with and without coal; and starch milling with boiler steam with and without coal). Corn input to Starch Milling used the aggregated corn supplied to participating CRA producers.

Separate anonymized processes were created for each site's refining, on a per pound of starch processed basis, which utilizes the appropriate grouped subprocesses. This approach also reduced the combined corn sweeteners LCIA uncertainty to a range from which meaningful interpretation of the results was possible and defensible, while simultaneously meeting confidentiality and anti-trust compliance needs. The results presented in this study are all based on this final hybrid approach. However, due to confidentiality needs, the starch refining inventory below is aggregated across the industry and unallocated.

Some notes specific to the inventory are below.

1. For starch milling, facilities were sorted into CHP or boiler and with or without coal.
2. Where possible, inputs and outputs have been assigned to specific products. Where this has not been possible, the input/output has been assigned to starch milling as every product is derived from this stage.
3. In most facilities, water use is not tracked by process/product directly, and in many cases the system is open, and storm water collected without monitoring, so that closing the water loop is not possible. Instead, we have used the available process data together with engineering models from the literature. The corn wet milling processes utilizes large quantities of steam, generated onsite in boilers largely from returning condensate. Steam production at mills is most often accompanied by electricity production (8 of 13 facilities, covering 70% of grind).

4. Water consumption in the steam and/or cogeneration processes was calculated based on total steam production following Walker, et al. 2013. For steam/power, water consumption is reflected by the quantity of water used to make up for water exiting the steam system. This compensates for blowdown losses, deaerator losses, losses from leaks, venting, etc., and water taken from the steam cycle for use in the process.
For the purposes of this study, water originating in the utilities section of facilities ultimately used in starch milling or sweeteners production is treated as entering the system in those processes rather than included in the heat and power production module. Utilities water consumption thus includes 8% (range from > 5% to as high as 10%) for blowdown, 0.5% for deaeration, and 3% for leaks and venting losses; base uncertainty includes the range from 3% to 16% of steam flow.

S1.2 Inventories

These tables contain the aggregated and normalized inventory data for starch milling, refining, heat or heat and electricity production, and coproduct drying based on data provided by each participating site, uncertainty and data quality notations as supplied by the participating facilities, and augmented with publicly reported data.

Table S-1: Life Cycle Inventory for Corn Wet Milling to Starch per Bushel of Corn by Technology Grouping and Weighted Average. Industry level impacts reported in the study were modeled using the four technology types weighted by their share of annual grind (not shown).

Inputs & Outputs for Starch Milling	Unit (per bu)	Annual Weighted Average	Cogen - Non-coal	Cogen - with Coal	Boilers only - Non-Coal	Boilers only - with coal	Data Quality & Uncertainty Parameters
PRODUCTS							
Starch	lb dm	32.46	32.85591	32.58805	31.69970	32.68404	Using “not starch” Lognormal 1.03
Germ	lb dm	3.24	3.50944	3.22832	2.98041	3.43452	Normal 0.28
Corn gluten meal (CGM) (wet)	lb dm	1.78	2.07529	1.67316	1.86792	1.82976	Normal 0.29
Corn gluten feed (CGF) (wet)	lb dm	9.40	12.67	9.50	7.51	8.34	Lognormal 1.23
Corn gluten feed (wet), for dry feed	*lb dm*	*5.89*	*3.71412*	*7.81792*	*0.39372*	*8.24197*	
Corn gluten feed (wet), for wet feed	*lb dm*	*3.50*	*8.95688*	*1.68444*	*7.11691*	*0.09383*	
Steepwater not incorporated into feed	lb dm	0.01525	0.00105	0.01422	0.03572	-	By difference
INPUTS							
Corn grain	bu	1.00	1.00	1.00	1.00	1.00	Normal 0.1
Moisture content	%	15.8%	15.7%	15.8%	15.8%	16.0%	
Sourcing - Specific sourcing and transport for facilities not shown to preserve anonymity							
Energies and Fuels for primary milling (excludes LSW evaporation)							
Steam	BTU	2,271	2,943	2,445	1,881	1,220	Lognormal 1.63
Electricity	kWh	1.47	1.41	1.48	1.71	1.07	Lognormal 1.33
Share of electricity from grid		*44%*	*52.54%*	*13.83%*	*100%*	*100%*	
Gas (NG & biogas) primary milling (steeps & clams, no LSW evap)	scf	1.31	1.33	1.58	0.51	1.27	Lognormal 2.38
biogas share		4%	5.30%	1.42%	11.24%	0.00%	

Inputs & Outputs for Starch Milling	Unit (per bu)	Annual Weighted Average	Cogen - Non-coal	Cogen - with Coal	Boilers only - Non-Coal	Boilers only - with coal	Data Quality &Uncertainty Parameters
Chemical Inputs							
SO_2	lb	1.63E-02	4.00E-02	1.66E-02	-	1.64E-02	Normal 0.032
S	lb	1.75E-02	-	2.59E-02	1.35E-02	-	Normal 0.18
Soda ash, dense	lb	7.32E-03	2.61E-02	-	2.05E-02	-	Normal 0.024
Filter Aid (Diatomaceous Earth)	lb	4.10E-04	3.21E-03	-	-	-	Normal 0.002
NaOH	lb	2.91E-02	4.40E-03	2.47E-02	2.75E-02	8.73E-02	Normal 0.032
$NaHSO_3$	lb	2.37E-02	8.44E-03	-	7.72E-02	7.32E-02	Normal 0.064
NaCl	lb	3.39E-05	-	1.02E-05	1.44E-04	-	Normal 0.062
HCl	lb	2.34E-03	-	-	1.20E-02	-	Normal 0.011
H_2SO_4	lb	1.46E-02	-	1.49E-02	3.01E-02	2.26E-03	Normal 0.04
Chelant	lb	7.71E-05	6.05E-04	-	-	-	Undefined
Cooling Tower Chemicals (NaOCl, polymer, anti-scalent)	lb	3.79E-05	2.97E-04	-	-	-	Undefined
IP Enzyme	lb	3.59E-06	-	-	1.85E-05	-	Undefined
Transport Distance for Chemical Inputs	mi	50	50	50	50	50	{4,3,1,1,3} Lognormal 1.62
Water Inputs -- Representative only -- Insufficient Data Quality							
Estimated Effective Water Use (includes process water from other processes)	total, gal	9.96E+00	1.02E+01	9.51E+00	9.83E+00	1.24E+01	
WASTES, EFFLUENTS & EMISSIONS							
Outputs to Solid Waste Treatment							
Municipal Landfill	lb	1.337E+00	3.29E-01	3.79E-02	6.51E+00	6.74E-02	{2,3,1,1,3} Lognormal 1.22
Hazardous landfill	lb	1.38E-06	-	-	5.68E-07	1.22E-05	{4,4,1,1,2} Lognormal 1.25
Incineration Facility	lb	1.43E-05	-	1.22E-05	3.16E-05	1.12E-05	{4,4,1,1,2} Lognormal 1.25
Hazardous incineration	lb	8.47E-05	2.39E-06	7.36E-05	2.12E-04	9.49E-06	{4,4,1,1,2} Lognormal 1.25
On-site water treatment facility	lb	3.85E-02	3.02E-01	-	-	-	{4,4,1,1,2} Lognormal 1.25
Hazardous waste water treatment	lb	6.24E-09	-	-	3.21E-08	-	{4,4,1,1,2} Lognormal 1.25
Recycle/Reclaim	lb	1.29E-02	1.06E-04	-	-	1.24E-01	{4,4,1,1,2} Lognormal 1.25
Hazardous Recycle/Reclaim	lb	1.66E-06	-	-	-	1.60E-05	{4,4,1,1,2} Lognormal 1.25
Composting	lb	1.38E+01	-	-	7.07E+01	1.96E-01	{4,4,1,1,2} Lognormal 1.25
Wastewater Treatment							
On-site water treatment facility							
Wastewater	gal	5.19E+00	3.21E+00	6.53E+00	5.32E+00	-	{4,3,1,1,3} Lognormal 1.62
COD loading	lb	1.12E-02	6.79E-02	-	1.32E-02	-	{4,3,1,1,3} Lognormal 1.62
BOD loading	lb	5.86E-02	-	1.02E-01	1.33E-13	-	{4,3,1,1,3} Lognormal 1.62
Off-site water treatment facility							
Wastewater offsite (POTW)	gal	4.84E+00	5.23E+00	4.97E+00	6.54E-01	1.15E+01	{4,3,1,1,3} Lognormal 1.62
Waste treatment load (TOC), lb	lb	1.37E-02	1.35E-02	8.30E-03	6.41E-04	6.81E-02	{4,3,1,1,3} Lognormal 1.62
Any Direct Discharges - Releases to Water and Land							
Direct discharge to water/Releases to Water in model year							
Acids	lb	4.38E-09	3.44E-08	-	-	-	Uniform (0, 8.4E-08)
Ammonia	lb	2.67E-06	1.26E-06	-	1.29E-05	-	Uniform (0, 9.7E-5)
Dissolved solids	lb	3.13E-03	-	-	-	3.02E-02	Uniform (0, 0.08)
Suspended solids	lb	7.68E-05	-	-	-	7.40E-04	Uniform (0, 0.002)
BOD	lb	1.47E-03	-	-	-	1.41E-02	Uniform (0, 0.038)

Inputs & Outputs for Starch Milling	Unit (per bu)	Annual Weighted Average	Cogen - Non-coal	Cogen - with Coal	Boilers only - Non-Coal	Boilers only - with coal	Data Quality & Uncertainty Parameters
Iron	lb	5.59E-06	-	-	1.33E-06	5.14E-05	Uniform (0, 1.4E-04)
Lead	lb	7.36E-09	-	-	3.78E-08	-	Uniform (0, 2.9E-07)
Zinc	lb	2.30E-07	-	-	1.18E-06	-	Uniform (0, 8.9E-06)
Nitrates	lb	8.68E-08	6.80E-07	-	-	-	Uniform (0, 1.4E-04)
Total Residual Chlorine	lb	3.73E-06	-	6.50E-06	-	-	Uniform (0, 5.4E-05)
Direct discharge to land/Releases to Land (Emissions to site) in model year							
Oils	gal	1.68E-07	-	-	8.65E-07	-	Uniform (0,1.6E-06)
Sodium Chloride	lb	7.49E-08	-	-	3.85E-07	-	Uniform (0, 7E-07)
Chlorine	gal	1.05E-08	-	-	5.38E-08	-	Uniform (0, 9.8E-08)
Ferric Chloride	lb	1.20E-07	-	-	6.15E-07	-	Uniform (0, 1.1E-06)
Ethylene Glycol (antifreeze)	gal	1.12E-08	-	-	5.77E-08	-	Uniform (0, 1.05E-07)
Sodium Hypochlorite	lb	6.42E-07	-	1.12E-06	-	-	Uniform (0, 4.0E-06)
Emissions to air (including coproduct-specific)							
PM10	lb	1.39E-04	-	8.58E-05	4.64E-04	-	{2,2,1,1,1} Lognormal 1.51
PM2.5	lb	2.78E-03	4.59E-03	1.30E-03	5.94E-03	2.77E-03	{2,2,1,1,1} Lognormal 1.51
CO	lb	8.10E-04	2.06E-03	4.28E-04	8.96E-04	1.23E-03	{2,2,1,1,1} Lognormal 1.51
NO2	lb	1.46E-03	2.64E-03	1.82E-04	4.24E-03	1.84E-03	{2,2,1,1,1} Lognormal 1.51
SO2	lb	6.38E-04	8.23E-04	7.72E-05	2.10E-03	7.65E-04	{2,2,1,1,1} Lognormal 1.51
VOC	lb	2.59E-03	4.60E-03	1.90E-03	2.19E-03	4.63E-03	{2,2,1,1,1} Lognormal 1.51
Acetaldehyde	lb	4.63E-03	8.33E-03	2.98E-03	5.01E-03	8.53E-03	{2,2,1,1,1} Lognormal 1.51
Acrolein	lb	8.61E-05	3.96E-04	1.16E-06	-	3.36E-04	{2,2,1,1,1} Lognormal 1.51
Methanol	lb	6.44E-07	-	-	-	6.21E-06	{2,2,1,1,1} Lognormal 1.51
NH3	lb	9.27E-06	4.97E-05	-	-	2.83E-05	{2,2,1,1,1} Lognormal 1.51
Formaldehyde	lb	8.31E-06	3.30E-05	-	-	3.95E-05	{2,2,1,1,1} Lognormal 1.51
Ethylene Glycol	lb	7.50E-06	5.56E-05	-	-	3.89E-06	{2,2,1,1,1} Lognormal 1.51
Hg	lb	1.93E-06	2.01E-09	-	9.02E-06	1.70E-06	{2,2,1,1,1} Lognormal 1.51
Pb	lb	3.11E-06	3.87E-09	-	1.60E-05	2.93E-09	{2,2,1,1,1} Lognormal 1.51
H2SO4	lb	6.92E-10	-	-	5.49E-10	5.64E-09	{2,2,1,1,1} Lognormal 1.51
HCl	lb	7.95E-07	-	-	-	7.66E-06	{2,2,1,1,1} Lognormal 1.51
Dioxin and Dioxin-like Compounds	lb	9.70E-09	-	-	-	9.35E-08	{2,2,1,1,1} Lognormal 1.51
Corn Dust	lb	4.65E-16	-	-	-	4.48E-15	{2,2,1,1,1} Lognormal 1.51
HF	lb	5.93E-03	-	-	3.05E-02	-	{2,2,1,1,1} Lognormal 1.51

Table S-2: Aggregated, Representative Life Cycle Inventory for Milled Starch to HFCS55, HFCS42 and DE95-100. Refining was modeled using anonymized site models; this inventory reflects the simple production weighted inventory across all participating sites and is not reflective of any site modeled. Impacts for this inventory will differ from those calculated as a production weighted average of the confidential disaggregated refining inventories. Uncertainty parameters for each site used standard deviation if it was provided, or a data quality index (pedigree matrix) based on characteristics of the data as provided (generally 1,2,1,1,3).

Inputs & Outputs for Starch Refining	Units	Quantity
PRODUCTS		
HFCS42	lb dm product	*0.1883*
HFCS55	lb dm product	*0.7493*
DE95/97/99	lb dm product	*0.1610*
INPUTS		
Dry Starch	lb	1.00
Energies and Fuels		
Steam	BTU	905
Electricity	kWh	0.064
Share of electricity from grid	%	65%
Natural Gas	scf	5.49E-02
Biogas	m^3	1.18E-04
Chemical Inputs		
HCl	lb	1.72E-02
NaOH	lb	8.51E-03
Soda ash	lb	3.69E-03
Filter Aid/Diatomaceous Earth	lb	1.92E-03
Carbon	lb	1.03E-03
Sulfuric acid	lb	2.30E-04
Ammonia	lb	1.80E-04
Nitrogen	lb	3.68E-05
CaCl	lb	4.46E-05
Very small (<0.001% by mass of any product) amount of other materials including Magnesium and Sodium Salts, Carbide Lime		
Enzymes		
Alpha Amylase	lb	2.71E-04
Gluco Amylase	lb	5.32E-04
Isomerase	lb	3.63E-04
other enzymes	lb	3.80E-05
Transport Distance for Chemical Inputs	mi	50
Water Inputs -- Representative only -- Insufficient Data Quality		
Estimated Water Use (includes process water from other processes)	*gal*	*0.3444*
Approximate Freshwater Share	%	*36%*
WASTES, EFFLUENTS & EMISSIONS		
Outputs to Solid Waste Treatment		
Physical Wastes		
Muni landfill	ton	
Wastewater Treatment		
On-site water treatment facility		
Wastewater offsite (POTW)	gal	0.269

Inputs & Outputs for Starch Refining	Units	Quantity
Waste treatment load (TOC), lb	lb	0.005
Off-site water treatment facility		
Wastewater	gal	0.056
Loading (BOD)	lb	0.001
loading, lb/gal	lb/gal	0.008
Any Direct Discharges - Releases to Water and Land		
Direct discharge to water/Releases to Water in model year		
Discharge to surge well & lake	gal	1.59E-02
Loading (TOC)	lb	8.43E-06
TOC load	lb/gal	1.40E-04
Emissions to air (including coproduct-specific)		
Particulate matter (PM 10)	lb	7.60E-05
Particulate matter (PM 2.5)	lb	7.17E-05
Particulate matter (unspecified)	lb	6.62E-05
Carbon monoxide (CO)	lb	1.94E-05
Nitrogen oxides (NOx)	lb	1.33E-05
Sulfur dioxide (SO2)	lb	9.84E-06
VOCs	lb	2.39E-05
HCl	lb	3.92E-08
Acetaldehyde	lb	7.87E-07
Ethylene Glycol	lb	-
Methanol	lb	1.56E-06
NH3	lb	2.77E-07

Table S-3: Life Cycle Inventory for Heat or Heat and Power Generation for Corn Refineries by Technology Group, 1MMBTU Energy Output. The outputs are in terms of net energy generated (parasitic steam and electricity use have been subtracted from total generation). Combustion emissions were calculated using the associated library unit processes.

Inputs & Outputs for Heat and Power Generation	Unit	Cogen-coal	Cogen non-coal	Boilers-coal	Boilers non-coal	Data Quality & Uncertainty Parameters
OUTPUTS						
Total Energy Output	MMBTU	1.00	1.00	1.00	1.00	
Electricity Produced	kWh	43.11	42.36	-	-	Lognormal 1.66
Steam Produced	MMBTU	0.85	0.86	1.00	1.00	Lognormal 1.08
INPUTS						
Energies and Fuels						
Grid Electricity	kWh	2.03	1.39	4.10	5.62	{4,4,1,1,2} Lognormal 1.24
Coal	lb	112.7	-	56.3	-	Lognormal 2.2
Natural gas	cuft	81.6	1,059	431.7	972.4	Lognormal 3
Biogas	cuft	-	-	-	-	{2,3,1,1,3} Lognormal 1.22
Corn stover	lb	0.025	-	-	-	{2,3,1,1,3} Lognormal 1.22
Wood	lb	3.5	-	-	-	{2,3,1,1,3} Lognormal 1.22
Tires	lb	0.1	-	-	-	{2,3,1,1,3} Lognormal 1.22

Inputs & Outputs for Heat and Power Generation	Unit	Cogen-coal	Cogen non-coal	Boilers-coal	Boilers non-coal	Data Quality & Uncertainty Parameters
Seed Corn	lb	0.1	-	-	-	{2,3,1,1,3} Lognormal 1.22
Chemical Inputs						
NaOH (50%)	lb	0.0	2.2	-	-	{2,3,1,1,3} Lognormal 1.22
Limestone	lb	15.2	-	-	-	{2,3,1,1,3} Lognormal 1.22
HCl (22')	lb	0.0	0.7	-	-	{2,3,1,1,3} Lognormal 1.22
Boiler treatment chemicals (Nalco antiscale)	lb	-	-	0.011	0.004	{2,3,1,1,3} Lognormal 1.22
Water Inputs -- Representative only -- Insufficient Data Quality						
Water	gal	35.5	73.7	106.4	22.3	{4,3,1,1,3} Lognormal 1.62
Share freshwater	%	19%	15%	7%	20%	{4,3,1,1,3} Lognormal 1.62
Share of municipal water	%	81%	85%	93%	80%	By difference
WASTES, EFFLUENTS & EMISSIONS						
Outputs to Solid Waste Treatment						
Municipal Landfill	lb	487.3	-	4.1	-	{2,3,1,1,3} Lognormal 1.22
Hazardous incineration	lb	0.0	-	-	-	{4,4,1,1,2} Lognormal 1.24
Beneficial reuse/Mine and quarry reclamation of fly ash	lb	22,420.6	-	-	-	{4,4,1,1,2} Lognormal 1.24
Beneficial reuse/Ag land application of bed ash	lb	0.2	-	-	-	{4,4,1,1,2} Lognormal 1.24
Wastewater Treatment						
On-site water treatment facility						
Wastewater	gal	1.6	-	-	12.9	{4,3,1,1,3} Lognormal 1.62
Off-site water treatment facility						
Wastewater	gal	1.2	-	4.5	-	{4,3,1,1,3} Lognormal 1.62
Any Direct Discharges - Releases to Water and Land						
Direct discharge to water/Releases to Water in model year						
FW Discharge, TOC load	lb	-	7.3	0.011	-	{4,3,1,1,3} Lognormal 1.62
FW Discharge, volume	gal	-	0.0	21.257	-	{4,3,1,1,3} Lognormal 1.62
Direct discharge to land/Releases to Land in model year						*(coal users only)*
Lead	lb	5.52E-05	-	2.41E-04	-	Lognormal 1.43
Zinc	lb	1.09E-04	-	4.77E-04	-	Lognormal 1.43
Mercury	lb	3.69E-07	-	1.61E-06	-	Lognormal 1.43
Antimony	lb	2.53E-06	-	1.10E-05	-	Lognormal 1.43
Arsenic	lb	3.93E-05	-	1.71E-04	-	Lognormal 1.43
Barium	lb	1.03E-03	-	4.49E-03	-	Lognormal 1.43
Beryllium	lb	2.19E-05	-	9.57E-05	-	Lognormal 1.43
Chromium	lb	2.66E-04	-	1.16E-03	-	Lognormal 1.43
Cobalt	lb	7.26E-05	-	3.17E-04	-	Lognormal 1.43
Copper	lb	2.08E-04	-	9.07E-04	-	Lognormal 1.43
Manganese	lb	2.52E-04	-	1.10E-03	-	Lognormal 1.43
Nickel	lb	1.42E-04	-	6.18E-04	-	Lognormal 1.43
Selenium	lb	8.09E-06	-	3.53E-05	-	Lognormal 1.43
Vanadium	lb	3.10E-04	-	1.35E-03	-	Lognormal 1.43

Table S-4: Life Cycle Inventory for Dry Corn Germ and Corn Gluten Meal

Dry Corn Germ Inventory	Unit, per lb dry germ	Production Weighted Average	Cogen - Non-coal	Cogen - with Coal	Boilers only - Non-Coal	Boilers only - with coal
Output						
Dry Germ (3-4% moisture)	lb dm	1.00	1.00	1.00	1.00	1.00
Inputs						
Wet germ, dry basis	lb dm	1.00	1.00	1.00	1.00	1.00
Steam	BTU	1,370	996	1,507	1,225	1,392
Electricity	kWh	0.0557	0.0580	0.0541	0.0348	0.0984
share of electricity from grid		*44%*	*52.54%*	*13.83%*	*100%*	*100%*
Gas (natural gas, biogas)	scf	0.3461	0.5829	0.1735	0.3921	0.8640
biogas share		4%	5.30%	1.42%	11.24%	0.00%
Coal	lb	0.0003	-	0.0005	-	-
Wood	lb	0.0131	-	0.0234	-	-

Dry Corn Gluten Meal (CGM) Inventory	Unit, per lb dry germ	Production Weighted Average	Cogen - Non-coal	Cogen - with Coal	Boilers only - Non-Coal	Boilers only - with coal
Output						
Dry CGM (3-4% moisture)	lb dm	1.00	1.00	1.00	1.00	1.00
Inputs						
Wet CGM, dry basis	lb dm	273	236.95	309.54	303.64	77.78
Steam	BTU	0.1179	0.0920	0.1354	0.0498	0.1821
Electricity	kWh	1.8387	1.6686	1.7795	2.4347	1.2909
share of electricity from grid	*%*	*44%*	*52.54%*	*13.83%*	*100%*	*100%*
Gas (natural gas, biogas)	scf	0.0257	-	0.0457	-	-
biogas share	*%*	4%	5.30%	1.42%	11.24%	0.00%
Coal	lb	0.0006	-	0.0010	-	-
Wood	lb	0.0257	-	0.0457	-	-

S1.3 Unit Processes

Table S-1: Unit Processes used for the HFCS55 – Heat and Power Generation (parameter values and data quality factors in Table S-3)

Product(s)/Processes	Unit	Quantity Notes
Products		
Boiler Steam - technology family i	BTU	heat production for aggregate technology family i
CHP Steam - technology family i	BTU	heat production for aggregate technology family i
CHP Electricity - technology family i	kWh	electricity production for aggregate technology family i

Product(s)/Processes	Unit	Quantity Notes
Inputs		
_Bituminous coal, for use in industrial boiler/U.S. split from Bituminous coal, combusted in industrial boiler/U.S.	lb	amt_coal reported for aggregate technology family i
_Combustion of Bituminous coal no upstream, combusted in industrial boiler/U.S.	lb	amt_coal reported for aggregate technology family i *FfP_combustion
_Natural gas, for use with combusted in industrial boiler/U.S. U.S.LCI per m3 NG	m^3	amt_natgas reported for aggregate technology family i
_Combustion of Natural gas, combusted in industrial boiler no upstream/U.S. U.S.LCI per m3 NG	m^3	amt_natgas reported for aggregate technology family i *FfP_combustion
Wood chips, wet, measured as dry mass {RoW}| market for | Cut-off, U	lb	amt_wood reported for aggregate technology family i
_Combustion of Wood Chips, extracted from Heat, district or industrial, other than natural gas {MRO, U.S. only} | heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	lb	amt_wood reported for aggregate technology family i *FfP_combustion
_Combustion of Biogas no upstream, extracted from Heat, central or small-scale, other than natural gas {MRO, U.S. only} | heat and power co-generation, biogas, gas engine | Cut-off, U	m^3	amt_biogas reported for aggregate technology family i *FfP_combustion
_Combustion of Proxy Waste Tire, extracted from Waste rubber, unspecified {RoW}| treatment of municipal incineration | Cut-off, U	lb	amt_tire reported for aggregate technology family i *FfP_combustion
Corn stover, production, average, U.S., 2022/kg/RNA	lb	amt_stoverstraw reported for aggregate technology family i
_Combustion of Stover or Straw no upstream, extracted from Heat, district or industrial, other than natural gas {GLO}| heat production, straw, at furnace 300kW | Cut-off, U	lb	amt_stoverstraw reported for aggregate technology family i * FfP_combustion
corn grain, delivered to mill, hfcs average mix, per kg	lb	amt_corngrain reported for aggregate technology family i
_Combustion of AD waste, extracted from Heat, for reuse in municipal waste incineration only {CH}| treatment of digester sludge, municipal incineration with fly ash extraction | Cut-off, U	lb	amt_stoverstraw reported for aggregate technology family i *FfP_combustion
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	lb	0.5*amt_NaOH reported for aggregate technology family i
Hydrochloric acid, without water, in 30% solution state {RoW}| market for | Cut-off, U	lb	0.35*amt_HCl reported for aggregate technology family i
Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | Cut-off, U	lb	amt_limestone reported for aggregate technology family i
__Tap water {MRO}| market for | Cut-off, U	lb	water_use_muni* reported for aggregate technology family i
Water, unspecified natural origin, U.S.	gal	water_use_fresh* reported for aggregate technology family i
Electricity/Heat		
_Electricity, high voltage {MRO, U.S. only} | 2018 EIA NERC production mix | Cut-off, U	kWh	amt_grid_elec for aggregate technology family i
Boiler Steam - non-coal sites	kWh	non-zero only for (technology family i = non-cogeneration without coal), parasitic steam
Boiler Steam - coal-burning sites	BTU	non-zero only for (technology family i=non-cogeneration with coal), parasitic stream
CHP Steam - non-coal sites	BTU	non-zero only for (technology family i = cogeneration without coal), parasitic steam
CHP Steam - coal sites	BTU	non-zero only for (technology family i = cogeneration with coal), parasitic steam
CHP Electricity - non-coal sites	kWh	non-zero only for (technology family i = cogeneration without coal), parasitic electricity
CHP Electricity - coal sites	kWh	non-zero only for (technology family i = cogeneration with coal), parasitic electricity

Product(s)/Processes	Unit	Quantity Notes
CHP Steam - non-coal sites	BTU	non-zero only for (technology family i = cogeneration without coal), parasitic steam
Waste to Treatment		
Wastewater, average {RoW}| market for wastewater, average | Cut-off, U	gal	wwt_muni
Wastewater, average {RoW}| market for wastewater, average | Cut-off, U	m^3	wwt_onsite reported for aggregate technology family i
Hard coal ash {RoW}| treatment of residual material landfill | Cut-off, U	lb	landfill_muni reported for aggregate technology family i
Hazardous waste, for incineration {RoW}| treatment of hazardous waste, hazardous waste incineration | Cut-off, U	lb	incineration_hazardous reported for aggregate technology family i
Final Waste Flows		
Waste returned to mine	lb	quarry_reclamation reported for aggregate technology family i
Emissions to Air		
Calculated using combustion processes		
Emissions to water		
TOC, Total Organic Carbon	lb	amt_direct_discharge for technology family i
Emissions to soil		
Lead	lb	amt_lead reported for aggregate technology family i
Zinc	lb	amt_zinc reported for aggregate technology family i
Mercury	lb	amt_mercury reported for aggregate technology family i
Antimony	lb	amt_antimony reported for aggregate technology family i
Arsenic	lb	amt_arsenic reported for aggregate technology family i
Barium	lb	amt_barium reported for aggregate technology family i
Beryllium	lb	amt_beryllium reported for aggregate technology family i
Chromium	lb	amt_chromium reported for aggregate technology family i
Cobalt	lb	amt_cobalt reported for aggregate technology family i
Copper	lb	amt_copper reported for aggregate technology family i
Manganese	lb	amt_manganese reported for aggregate technology family i
Nickel	lb	amt_nickel reported for aggregate technology family i
Selenium	lb	amt_selenium reported for aggregate technology family i
Vanadium	lb	amt_vanadium reported for aggregate technology family i

Table S-2: Unit Processes used for HFCS55 - Starch Milling (representative parameter values and data quality factors in Table S-1)

Product(s)/Processes	Unit	Quantity Note
Products		
milled starch - (technology family i)	lb	1
starch milling coproducts before drying - boilers coal sites	lb	combined mass_germ+mass_corn_gluten_meal+mass_corn_gluten_feed+mass_other_milling_outputs for aggregate technology family i

Product(s)/Processes	**Unit**	**Quantity Note**
Inputs		
per bu corn grain, delivered to mill, hfcs average mix, per bu	p	1/starch recovered for aggregate technology family i
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	lb	mass_caustic50 for aggregate technology family i + mass_naoh for aggregate technology family i
Soda ash, dense {GLO}| market for | Cut-off, U	lb	mass_soda_ash for aggregate technology family i
Sulfur dioxide, liquid {RoW}| market for | Cut-off, U	lb	mass_SO2 for aggregate technology family i
Sulfur {GLO}| market for | Cut-off, U	lb	mass_S for aggregate technology family i
Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	lb	mass_H2SO4 for aggregate technology family i
Sodium sulfite {RoW}| market for sodium sulfite | Cut-off, U	lb	mass_NAHSO3 for aggregate technology family i
Sodium chloride, brine solution {RoW}| production | Cut-off, U	lb	mass_NaCl_sln for aggregate technology family i
Balanced Salt Solution	lb	mass_bss for aggregate technology family i
Tap water, market for {MRO}	gal	vol_muniwater for aggregate technology family i
Water, unspecified natural origin/m3	gal	vol_freshwater for aggregate technology family i
Diatomite	lb	mass_filteraid for aggregate technology family i
Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	tmi *	mass_chemicals for aggregate technology family i * chemicals_distance
Energy & Fuels		
_Bituminous coal, for use in industrial boiler/U.S. split from Bituminous coal, combusted in industrial boiler/U.S.	lb	amt_coal for aggregate technology family i
_Combustion of Bituminous coal no upstream, combusted in industrial boiler/U.S.	lb	amt_coal for aggregate technology family i
_Natural gas, for use with combusted in industrial boiler/U.S. U.S.LCI per m3 NG	m^3	amt_natgas for aggregate technology family i
_Combustion of Natural gas, combusted in industrial boiler no upstream/U.S. U.S.LCI per m3 NG	m^3	amt_natgas for aggregate technology family i
Biogas {RoW}| treatment of sewage sludge by anaerobic digestion | Cut-off, U	m^3	amt_biogas for aggregate technology family i
_Combustion of Biogas no upstream, extracted from Heat, central or small-scale, other than natural gas {MRO, U.S. only} | heat and power co-generation, biogas, gas engine | Cut-off, U	m^3	amt_biogas for aggregate technology family i
Bundle, energy wood, measured as dry mass {GLO}| market for | Cut-off, U	lb	mass_wood for aggregate technology family i
_Combustion of Wood Chips no upstream, extracted from Heat, district or industrial, other than natural gas {MRO, U.S. only} | heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	lb	mass_wood for aggregate technology family i
_Electricity, high voltage {MRO, U.S. only} | 2018 EIA NERC production mix | Cut-off, U	kWh	amt_gridelec for aggregate technology family i
Boiler Steam - non-coal sites	BTU	non-zero only for (technology family i = non-cogeneration without coal)
Boiler Steam - coal-burning sites	BTU	non-zero only for (technology family i=non- cogeneration with coal)
CHP Steam - non-coal sites	BTU	non-zero only for (technology family i = cogeneration without coal)
CHP Steam - coal sites	BTU	non-zero only for (technology family i = cogeneration with coal)
CHP Electricity - non-coal sites	kWh	non-zero only for (technology family i = cogeneration without coal)
CHP Electricity - coal sites	kWh	non-zero only for (technology family i = cogeneration with coal)
Waste to Treatment		

Product(s)/Processes	Unit	Quantity Note
Limestone residue {RoW}| treatment of inert material landfill | Cut-off, U	lb	landfill_mass for aggregate technology family i
Hazardous waste, for incineration {RoW}| treatment of hazardous waste, hazardous waste incineration | Cut-off, U	lb	haz_incin_mass for aggregate technology family i
Wastewater, unpolluted {RoW}| market for wastewater, unpolluted | Cut-off, U	gal	wwt_muni for aggregate technology family i
Wastewater from maize starch production {GLO}| market for | Cut-off, U	gal	wwt_onsite for aggregate technology family i
Final Waste Flows		
Waste to recycling	lb	Amt_rec for aggregate technology family i
Hazardous waste, recovery	lb	Amt_hazrec for aggregate technology family i
Compost	lb	Amt_Composting for aggregate technology family i
Emissions to Air		
Particulates, < 10 um	lb	Aamt_PM10 for aggregate technology family i
Particulates, < 2.5 um	lb	Aamt_PM25 for aggregate technology family i
Carbon monoxide	lb	Aamt_CO for aggregate technology family i
Nitrogen dioxide	lb	Aamt_NO2 for aggregate technology family i
Sulfur dioxide	lb	Aamt_SO2 for aggregate technology family i
VOC, volatile organic compounds, unspecified origin	lb	Aamt_VOC for aggregate technology family i
Acetaldehyde	lb	Aamt_Acetaldehyde for aggregate technology family i
Acrolein	lb	Aamt_Acrolein for aggregate technology family i
Ammonia	lb	Aamt_NH3 for aggregate technology family i
Methanol	lb	Aamt_Methanol for aggregate technology family i
Formaldehyde	lb	Aamt_Formaldehyde for aggregate technology family i
Ethylene glycol	lb	Aamt_EthyleneGlycol for aggregate technology family i
Mercury	lb	Aamt_Hg for aggregate technology family i
Lead	lb	Aamt_Pb for aggregate technology family i
Hydrogen chloride	lb	Aamt_HCl for aggregate technology family i
Dioxins (unspec.)	lb	Amt_dioxins for aggregate technology family i
Emissions to Water		
Ammonia	lb	Wamt_Ammonia for aggregate technology family i
Iron	lb	Wamt_Iron for aggregate technology family i
Lead	lb	Wamt_Lead for aggregate technology family i
Zinc	lb	Wamt_Zinc for aggregate technology family i
Acids, unspecified	lb	Wamt_Acids for aggregate technology family i
Cyanide compounds	lb	Wamt_Cyanides for aggregate technology family i
Suspended solids, unspecified	lb	Wamt_SuspendedSolids for aggregate technology family i
BOD5, Biological Oxygen Demand	lb	Wamt_BOD for aggregate technology family i
TOC, Total Organic Carbon	lb	Wamt_DissolvedSolids for aggregate technology family i
Oils, unspecified	lb	Wamt_Oils for aggregate technology family i
Phenols, unspecified	lb	Wamt_Phenols for aggregate technology family i
Nitrate compounds	lb	Wamt_NitrateCmpds for aggregate technology family i
Chlorine	lb	Wamt_Chlorine for aggregate technology family i
Sodium chloride	lb	Wamt_NaCl for aggregate technology family i
Emissions to Soil		
Oils, unspecified	lb	Samt_Oils for aggregate technology family i
Sodium hypochlorite	lb	Samt_SodiumHypochlorite for aggregate technology family i
Iron III	lb	Samt_FerricChloride for aggregate technology family i
Chlorine	lb	Samt_Chlorine for aggregate technology family i
Ethylene glycol	lb	Samt_EthyleneGlycol for aggregate technology family i

Table S-3: Unit Process for HFCS55 - Starch Refining (representative parameter values in Table S-2, data quality factors based on site)

Product(s)/Processes	Unit	Quantity Note
Products		
hfcs55 - Site X (technology family i)	lb	mass_hfcs55
hfcs42 - Site X (technology family i)	lb	mass_hfcs42
de9597 - Site X (technology family i)	lb	mass_de9597
other syrups - Site X (technology family i)	lb	mass_csu_other_syrups
Inputs		
milled starch - boilers non-coal sites	lb	non-zero only for (technology family i = non-cogeneration without coal)
milled starch - boilers coal sites	lb	non-zero only for (technology family i=non- cogeneration with coal)
milled starch - cogen non-coal sites	lb	non-zero only for (technology family i = cogeneration without coal)
milled starch - cogen coal sites	lb	non-zero only for (technology family i = cogeneration with coal)
__Tap water {MRO}| market for | Cut-off, U	lb	amt_muniwater for Site X
Water, deionised, from tap water, at user {MRO}| production | Cut-off, U	lb	amt_diwater for Site X
Water, fresh	gal	amt_freshwater for Site X
Diatomite, land	lb	amt_fileraid for Site X
Enzyme, Alpha-amylase, Novozyme Liquozyme/kg/RER	lb	amt_alphaamylasefor Site X
Enzyme, Glucoamylase, Novozyme Spirizyme/kg/RER	lb	amt_glucoamylase for Site X
Enzymes {RoW}| enzymes production | Cut-off, U	lb	amt_isomerase for Site X
Enzymes {GLO}| market for enzymes | Cut-off, U	lb	amt_otherenzymesfor Site X
Hydrochloric acid, Mannheim process (30% HCl), at plant/RER Mass	lb	amt_HClfor Site X
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	lb	amt_NaOHfor Site X
Soda ash, dense {GLO}| market for | Cut-off, U	lb	amt_SodaAshfor Site X
Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	lb	amt_H2SO4 for Site X
Lime, hydrated, loose weight {RoW}| production | Cut-off, U	lb	amt_CarbideLime for Site X
Magnesium sulfate {GLO}| market for | Cut-off, U	lb	amt_MgSO4 for Site X
Magnesium Bisulfite Proxy	lb	amt_MagBiS for Site X
Nitrogen, liquid {RoW}| market for | Cut-off, U	lb	amt_N2 for Site X
Calcium chloride {RoW}| market for calcium chloride | Cut-off, U	lb	amt_CaCl for Site X
Anionic resin {RoW}| market for anionic resin | Cut-off, U	lb	amt_AnionicResin for Site X
Cationic resin {RoW}| market for cationic resin | Cut-off, U	lb	amt_CationicResin for Site X
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	lb	amt_Carbon for Site X
Ammonia, liquid {RoW}| market for | Cut-off, U	lb	amt_Ammonia for Site X
Sodium sulfite {RoW}| market for sodium sulfite | Cut-off, U	lb	amt_MBS for Site X
_Electricity, high voltage {MRO, U.S. only} | 2018 EIA NERC production mix | Cut-off, U	kWh	amt_gridelec for Site X
Boiler Steam - non-coal sites	BTU	non-zero only for (technology family i = non-cogeneration without coal)
Boiler Steam - coal-burning sites	BTU	non-zero only for (technology family i=non- cogeneration with coal)

Product(s)/Processes	Unit	Quantity Note
CHP Steam - non-coal sites	BTU	non-zero only for (technology family i = cogeneration without coal)
CHP Steam - coal sites	BTU	non-zero only for (technology family i = cogeneration with coal)
CHP Electricity - non-coal sites	kWh	non-zero only for (technology family i = cogeneration without coal)
CHP Electricity - coal sites	kWh	non-zero only for (technology family i = cogeneration with coal)
Waste to Treatment		
Wastewater from maize starch production {GLO}| market for | Cut-off, U	gal	wwt_onsite_volfor Site X
Wastewater, unpolluted, from residence {GLO}| market for | Cut-off, U	gal	wwt_muni_vol for Site X
Emissions to air		
Particulates, unspecified	lb	Aamt_Pmunsp for Site X
Particulates, < 10 um	lb	Aamt_PM10 for Site X
Particulates, < 2.5 um	lb	Aamt_PM25 for Site X
Carbon monoxide	lb	Aamt_CO for Site X
Nitrogen dioxide	lb	Aamt_NO2 for Site X
Sulfur dioxide	lb	Aamt_SO2 for Site X
VOC, volatile organic compounds, unspecified origin	lb	Aamt_VOC for Site X
Acetaldehyde	lb	Aamt_Acetaldehyde for Site X for Site X
Ammonia	lb	Aamt_NH3 for Site X
Methanol	lb	Aamt_Methanol for Site X
Formaldehyde	lb	Aamt_Formaldehyde for Site X
Ethylene glycol	lb	Aamt_EthyleneGlycol for Site X
Mercury	lb	Aamt_Hg for Site X
Lead	lb	Aamt_Pb for Site X
Hydrogen chloride	lb	Aamt_HCl for Site X
Benzene, 1,4-dichloro-	lb	Aamt_dichlorobenzene for Site X
Toluene	lb	Aamt_Toluene for Site X
Benzene	lb	Aamt_Benzene for Site X
Nickel	lb	Aamt_Nickels for Site X
Selenium	lb	Aamt_Selenium for Site X
Naphthalene	lb	Aamt_Naphthalene for Site X
Hydrogen cyanide	lb	Aamt_HCNfor Site X
Acrolein	lb	Aamt_Acrolein for Site X
Emissions to Water		
TOC, Total Organic Carbon	lb	amt_TOC_dischargefor Site X

Table S-4: Unit process for Balanced Salt Solution, Based on ThermoFisher 14185

Product(s)/Process	Amount	Unit	Notes & Sources

Product			
Balanced Salt Solution	85.5	kg	
Description: Based on ThermoFisher 14185 - HBSS, 10x, no calcium, no magnesium, no phenol red 85.5g/L. https://www.thermofisher.com/us/en/home/technical-resources/media-formulation.157.html Dextrose from supplier omitted because produced on site			
Materials			
Sodium chloride, powder {GLO}| market for | Cut-off, U	80	kg	
Sodium phosphate {RoW}| market for sodium phosphate | Cut-off, U	0.9	kg	
Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, U	0.432059849	kg	combined with potassium hydroxide to get Potassium Phosphate monobasic (KH2PO4) - 0.6g/L
Potassium hydroxide {GLO}| market for | Cut-off, U	0.247369403	kg	combined with phosphoric acic to get Potassium Phosphate monobasic (KH2PO4) - 0.6g/L
Hydrochloric acid, without water, in 30% solution state {RoW}| market for | Cut-off, U	1.956287281	kg	combined with KOH to get KCl
Potassium hydroxide {GLO}| market for | Cut-off, U	3.010310484	kg	combined with HCl to get KOH
Water, deionised, from tap water, at user {RoW}| production | Cut-off, U	998.953973	kg	1L water less water produced from KOH + H3PO4 -> H2O + KH2PO4 and from HCl + KOH -> H2O + KCl

S2. Corn Production Inventories

S2.1 Relevant Parameters

Table S-1: Physical characteristics of corn

Quantity	Value	Unit	Notes & Sources
Corn, Shelled	56	lb/bu	USDA, ftp://www.ilga.gov/jcar/admincode/008/00800600ZZ9998bR.html
Corn Water Content	0.155	kg/kg	USDA, ftp://www.ilga.gov/jcar/admincode/008/00800600ZZ9998bR.html
N Content Corn	0.0147	kg/kg	(Peplinski et al. 1977)
Nitrogen immobilization	28	-	corn/Midwest Corn (Ortiz-Reyes & Anex 2020)

Table S-2: Management practice and relevant Field Emissions Parameters for Corn

Input parameters	Unit	Value	Uncertainty Information	Notes & Sources
Management				
Rotation	corn/corn/soy			
Fraction Reduced Tillage	%	0.391	[Undefined]	Weighted average of catchment for participating facilities. (Claasen et al. 2018)
Fraction No Tillage	%	0.249	[Undefined]	Weighted average of catchment for participating facilities. (Claasen et al. 2018)

Input parameters	Unit	Value	Uncertainty Information	Notes & Sources
Factors for Calculating IPCC NIR Field Emissions				
T_{base}	years	20	[Undefined]	default time
$SOC_{reference}$	t/ha	59.5	[Normal 3.8]	Table 2.3. IPCC2019R, assuming 50:50 high- and low-activity clay soils, 64%pm5%, 55%pm8%
N_{ag_T}	kg N/kg dm	0.006	[Normal 0.00045]	maize AG 0.006, BG 0.007 pm75% = 2sigma Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL
N_{bg_T}	kg N/kg dm	0.007	[Normal 0.00525]	maize AG 0.006, BG 0.007 pm75% = 2sigma Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL
$R_{\_ag\_T}$	-	1	[Undefined]	maize corn 1, no uncertainty Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL
$RS_{\_T}$	-	0.22	[Normal 0.0572]	Table 11.1A p11.17 Ratio of Above and Belowground biomass IPCC 2019R NIR GL-maize /cane - perennial 0.8 pm 50% = 2sig
$DRY_{\_T}$	-	0.87	[Undefined]	Maize crop dry matter at harvest. default 0.87 Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL
RbgT	-	2.65	[Undefined]	Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL maize
CropDM_IPCC	-	0.89	[Undefined]	
Frac_renew	-	1	[Undefined]	IPCC N2O emissions from managed soils factor. Annual crop = 1; N year crop = 1/N (sc =1/4)

S2.2 Inventory

Table S-1: Life Cycle Inventory for Consumption-weighted Corn Production. Weighted averages for each parameter are calculated as described in the associated Notes & Sources entry. Where possible, state-level data obtained from USDA NASS for the relevant states for 2010-2018 and a temporal average over three years centered around the study year (2017) calculated for each state. The temporal averages for each state were then used to calculate the consumption weighted average.

Inputs & Outputs for Corn Production	Unit	Value	Uncertainty Information	Notes & Sources
Product(s)				
Corn yield	bu/ac	185.3	[Normal 15.8]	USDA NASS
Inputs				
N fertilizer application rate	lb N/ac	150.5	[Lognormal 1.145]	scaled value across all acres from NASS data %ac in state treated * amount per treated acre
P fertilizer application rate	lb/ac	57.7	[Lognormal 1.114]	scaled value across all acres from NASS data %ac in state treated * amount per treated acre
K fertilizer application rate	lb/ac	63.55	[Normal 10.4]	scaled value across all acres from NASS data %ac in state treated * amount per treated acre
S fertilizer application rate	lb/ac	15.56	[Normal 4]	scaled value across all acres from NASS data %ac in state treated * amount per treated acre
Lime application rate	lb/ac	510.0	[Lognormal (3,3,2,3,3,na)1.25]	rescaled from (Gallagher et al. 2016)
Fungicide application rate	lb/ac	0.056	[Triangle 00.07]	scaled value across all acres from NASS data %ac in state treated * amount per treated acre
Herbicide application rate	lb/ac	0.4287	[Triangle 0.40.45]	scaled value across all acres from NASS data %ac in state treated * amount per treated acre
Insecticide application rate	lb/ac	0.058	[Triangle 00.093]	scaled value across all acres from NASS data %ac in state treated * amount per treated acre
Seeding rate	lb/ac	23.23	[Triangle 17.2626.8]	USDA NASS
Diesel Use	gal/ac	11.9	[Triangle 418]	rescaled from (Gallagher et al. 2016)

Gasoline Use	gal/ac	1.88	[Triangle 1.632.29]	IL, IA, NE, MN from state extension crop budgets; others rescaled from (Gallagher et al. 2016)
LPG Use	gal/ac	1.75	[Triangle 1.333.33]	rescaled from (Gallagher et al. 2016)
Natural Gas Use	cuft/ac	26.21	[Triangle 10110]	rescaled from (Gallagher et al. 2016)
Electricity Use	kWh/ac	17.31	[Triangle 3.25108]	rescaled from (Gallagher et al. 2016)
Irrigation Water	gal/ac	108.433	[Lognormal 1.5]	share of irrigated acres at state level. scaled value across all acres from NASS data %ac in state treated * amount per treated acre; USDACV 9% [80.05887288; 182.7]
Emissions to Air, Water and Soil calculated during modeling, average values below				
Calculated in modeling using IPCC NIR				

S2.3 Unit Process(es)

Table S-1: Unit Processes Used for Corn Production. NH_3, N_2O, and CO_2 emissions to air are calculated parameters, values shown are single point values associated with the input quantities in this table only.

Product(s)/Process(es)	Value	Unit	Notes & Sources
Product			
Corn Production at Farm, U.S. HFCS552017 Mix	56	lb	per bushel
Inputs			
Corn Production at Farm, U.S. HFCS552017 Mix	0.125	lb	Seeding
Nitrogen Mix U.S. - effective N-P-K -S 60-0-0-1.4, per kg N	0.72	lb	N fertilizer based on nat'l use. N demand less N supplied by other fertilizers
Phosphates Mix U.S. - effective N-P-K 14.5-49-0, per kg P2O5	0.311	lb	P fertilizer based on nat'l use.
Potash Mix U.S. - effective N-P-K-S 0-0-59.3-1.2, per kg K2O	0.343	lb	K fertilizer based on nat'l use.
Sulfur {GLO}| market for | Cut-off, U	0.0602	lb	Sulfur nutrient after accounting for other sources
Lime {RoW}| market for lime | Cut-off, U	2.75	lb	Liming
Herbicides Mix Corn	0.00231	lb	Herbicides used for corn, U.S., correlated to emissions
Insecticides Mix Corn	0.000313	lb	Insecticides used for corn, U.S., correlated to emissions
Fungicides Mix Corn	0.000302	lb	Fungicides used for corn, U.S., correlated to emissions
Diesel, low-sulfur {GLO}| market group for | Cut-off, U	0.454	lb	Diesel for Use on Farm
_Diesel Combustion In Agricultural Equipment, extracted from ei Sowing {CA-QC} | sowing | Cut-off, U	0.454	lb	Combustion of Diesel on Farm
Petrol, 4% ETBE additive by volume, with ethanol from biomass {GLO}| market for | Cut-off, U	0.0634	lb	Diesel for Use on Farm
_Gasoline Combustion in Agricultural Equipment, extracted from ei Petrol, unleaded, burned in machinery {GLO}| petrol, unleaded, burned in machinery | Cut-off, U	0.0634	lb	Combustion of Diesel on Farm
Natural gas, high pressure {U.S.}| market for | Cut-off, U	0.141	cuft	Diesel for Use on Farm
_Combustion of Natural gas, combusted in industrial boiler no upstream/U.S. U.S.LCI per m3 NG	0.141	cuft	Combustion of Diesel on Farm
Liquefied petroleum gas {RoW}| market for | Cut-off, U	0.0527	lb	Diesel for Use on Farm
_LPG, combusted in industrial boiler, at pulp and paper mill (EXCL.)/l/RNA	0.00944	gal	Combustion of Diesel on Farm
_Electricity, high voltage {MRO, U.S. only} | 2018 EIA NERC production mix | Cut-off, U	0.0934	kWh	Non-irrigation electricity
Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	0.0402	tkm	Transport of agrochemicals
Water, unspecified natural origin, U.S.	0.585	gal	Water for irrigation
Occupation, agriculture	21.8	m^2a	Cropping
Emissions to Air			
Ammonia	*0.13*	lb	NH3 offgassing - Direct emissions from fertilizers, residues and manure (IPCC NIR calculation)
Dinitrogen monoxide	*0.0302*	lb	Direct emissions from fertilizer and manure offgassing (IPCC NIR calculation)

Dinitrogen monoxide	*0.00185*	lb	Indirect emissions from fertilizers, residues and manure - volatilization (IPCC NIR calculation)
Dinitrogen monoxide	*0.00498*	lb	Indirect emissions from fertilizers, residues and manure - leaching and runoff (IPCC NIR calculation)
Carbon dioxide	*0.271*	lb	CO2 from urea in field (IPCC NIR calculation)
Carbon dioxide, land transformation	*1.12*	lb	Emissions from land transformation (IPCC NIR calculation)
Carbon dioxide	*1.21*	lb	CO2 from lime application (IPCC NIR calculation)
Glyphosate	7.87E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Atrazine	6.02E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Acetochlor	4.40E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Metolachlor, (S)	3.24E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Dimethenamid	1.62E-05	lb	Calculated pesticide partitioning. Used for other herbicides
Chlorpyrifos	7.83E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Bifenthrin	1.28E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Tefluthrin	4.38E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Lambda-cyhalothrin	6.26E-06	lb	Calculated pesticide partitioning. Used for other insecticides
Propiconazole	6.65E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Azoxystrobin	4.84E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Pyraclostrobin (prop)	1.42E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Trifloxystrobin	2.72E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Difenoconazole	1.81E-06	lb	Calculated pesticide partitioning. Used for other fungicides
Emissions to Water			
Nitrate, to groundwater	0.873	lb	Leaching based on Ortiz-Reyes & Anex 2020
Phosphate, to ground water	0.218	lb	Runoff based on Ortiz-Reyes & Anex 2018
Glyphosate	6.69E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Atrazine	5.11E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Acetochlor	3.74E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Metolachlor, (S)	2.75E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Dimethenamid	1.38E-05	lb	Calculated pesticide partitioning. Used for other herbicides
Chlorpyrifos	6.65E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Bifenthrin	1.09E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Tefluthrin	3.72E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Lambda-cyhalothrin	5.32E-06	lb	Calculated pesticide partitioning. Used for other insecticides
Propiconazole	5.65E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Azoxystrobin	4.11E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Pyraclostrobin (prop)	1.21E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Trifloxystrobin	2.31E-06	lb	Calculated pesticide partitioning (Margni et al. 2002)
Fungicides, unspecified	1.54E-06	lb	Calculated pesticide partitioning. Used for other fungicides
Emissions to Soil			
Atrazine	0.00046	lb	Calculated pesticide partitioning (Margni et al. 2002)
Glyphosate	0.000602	lb	Calculated pesticide partitioning (Margni et al. 2002)
Acetochlor	0.000336	lb	Calculated pesticide partitioning (Margni et al. 2002)
Metolachlor, (S)	0.000248	lb	Calculated pesticide partitioning (Margni et al. 2002)
Dimethenamid	0.000124	lb	Calculated pesticide partitioning. Used for other herbicides
Chlorpyrifos	5.99E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Bifenthrin	9.82E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Tefluthrin	3.35E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Lambda-cyhalothrin	4.79E-05	lb	Calculated pesticide partitioning. Used for other insecticides
Propiconazole	5.09E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Azoxystrobin	3.70E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Pyraclostrobin (prop)	0.000109	lb	Calculated pesticide partitioning (Margni et al. 2002)
Trifloxystrobin	2.08E-05	lb	Calculated pesticide partitioning (Margni et al. 2002)
Fungicides, unspecified	1.39E-05	lb	Calculated pesticide partitioning. Used for other fungicides

S2.4 Inventories & Unit processes for agrochemical inputs

Table S-1: Unit Processes for Primary Nutrient Mixes U.S., from USDA NASS data

Product(s)/Process(es)	Quantity	Unit	Quantity Uncertainty		
Product(s)					
Nitrogen Mix U.S. - effective N-P-K -S 60-0-0-1.4, per kg N	1	kg			
Materials/fuels					
Urea, as N {GLO}| market for | Cut-off, U	0.513	kg	Uniform	0.5	0.52
Ammonia, liquid {RoW}| market for | Cut-off, U	0.428	kg	Uniform	0.41	0.45
Ammonium sulfate, as N {GLO}| market for | Cut-off, U	0.059	kg	Uniform	0.03	0.09

Product(s)/Process(es)	Quantity	Unit	Quantity Uncertainty
Product(s)			
Phosphates Mix U.S. - effective N-P-K 14.5-49-0, per kg P2O5	1	kg	
Materials/fuels			
Phosphate fertiliser, as P2O5 {RoW}| diammonium phosphate production | Cut-off, U	0.5	kg	Undefined
Phosphate fertiliser, as P2O5 {RoW}| monoammonium phosphate production | Cut-off, U	0.5	kg	Undefined

Product(s)/Process(s)	Quantity	Unit	Quantity Uncertainty		
Product(s)					
Potash Mix U.S. - effective N-P-K-S 0-0-59.3-1.2, per kg K2O	1	kg			
Materials/fuels					
Potassium chloride, as K2O {GLO}| market for | Cut-off, U	0.93	kg	Uniform	0.89	0.96
Potassium sulfate, as K2O {GLO}| market for | Cut-off, U	0.93	kg	Uniform	0.89	0.96

Table S-2: Unit Process for the Herbicide Mix, weighted averages of USDA NASS 2014-2018 data (3-year average)

Product(s)/Process(es)	Quantity	Unit	Quantity Uncertainty			Fit for Purpose Uncertainty if applied		
Product(s)								
Herbicides Mix Corn	1	kg						
Materials/fuels								
Glyphosate {GLO}| market for | Cut-off, U	0.34	kg	Uniform	0.31	0.36	Lognormal	(1,2,1,2,1,na)	1.06
Atrazine {GLO}| market for | Cut-off, U	0.26	kg	Uniform	0.25	0.27	Lognormal	(1,2,1,2,1,na)	1.06
Acetamide-anillide-compound, unspecified {GLO}| market for | Cut-off, U	0.19	kg	Uniform	0.18	0.21	Lognormal	(1,2,1,2,1,na)	1.06
Metolachlor {GLO}| market for | Cut-off, U	0.14	kg	Lognormal	1.07		Lognormal	(1,2,1,2,1,na)	1.06
Pesticide, unspecified {GLO}| market for | Cut-off, U	by difference	kg	by difference			Lognormal	(1,2,1,2,1,na)	1.06

Table S-3: Unit Process for the Insecticide Mixes, weighted averages of USDA NASS 2014-2018 data (3-year average)

Product(s)/Process(es)	Quantity	Unit	Quantity Uncertainty			Fit for Purpose Uncertainty if applied		
Product(s)								
Insecticides Mix Corn	1	kg						
Materials/fuels								
Organophosphorus-compound, unspecified {GLO}| market for | Cut-off, U	0.25	kg	Triangle	0	0.5	Lognormal	(1,2,1,2,1,na)	1.06
Pyrethroid-compound {GLO}| market for | Cut-off, U	0.41	kg	Uniform	0.3	0.47	Lognormal	(1,2,1,2,1,na)	1.06
Pyrethroid-compound {GLO}| market for | Cut-off, U	0.14	kg	Uniform	0.1	0.3	Lognormal	(1,2,1,2,1,na)	1.06
Pesticide, unspecified {GLO}| market for | Cut-off, U	by difference	kg	by difference			Lognormal	(1,2,1,2,1,na)	1.06

Table S-4: Unit Process used to represent the fungicides mixs, weighted averages of USDA NASS 2014-2018 data (3-year average)

Product(s)/Process(es)	Quantity	Unit	Quantity Uncertainty			Fit for Purpose Uncertainty if applied		
Product(s)								
Fungicides Mix Corn	1	kg						
Materials/fuels								
Pesticide, unspecified {GLO}| market for | Cut-off, U	0.47	kg	Uniform	0.35	0.53	Lognormal	(1,2,1,2,1,na)	1.06
Pesticide, unspecified {GLO}| market for | Cut-off, U	0.22	kg	Uniform	0.22	0.23	Lognormal	(1,2,1,2,1,na)	1.06
Pesticide, unspecified {GLO}| market for | Cut-off, U	0.16	kg	Uniform	0.12	0.23	Lognormal	(1,2,1,2,1,na)	1.06
Pesticide, unspecified {GLO}| market for | Cut-off, U	0.09	kg	Uniform	0.04	0.12	Lognormal	(1,2,1,2,1,na)	1.06
Pesticide, unspecified {GLO}| market for | Cut-off, U	by difference	kg	by difference					

S3. Agriculture Field Emissions Calculations

Field emissions other than pesticides were calculated based on the IPCC National Inventory Report (NIR) guidance (IPCC 2006, IPCC 2019), with Tier 2 parameters where possible.

Rather than calculating the field emissions exogenously, the NIR equations (reproduced below the tables) were calculated endogenously during modeling (entered as calculated parameters in the crop production unit processes) using the associated parameters (Table) so field emissions automatically responded to changes in field applications during sensitivity analysis. The NIR equations were.

Parameter values are in Table S-1 and primary equations used are provided below the table.

Table S-1: IPCC NIR Emissions and Land Use Parameters (Tier 1, Tier 2) used in this study.

Parameter Name	Value	Unit	Uncertainty Information			Source Notes
F_lu_cult_trop	0.83	-	Normal	0.04		Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_lu_cult_temp	0.69	-	Normal	0.05		Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_lu_setaside	0.82	-	Normal	0.08		Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_mg_notill	1.1	-	Normal	0.022		Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_mg_redtill	1.05	-	Normal	0.02		Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_mg_fulltill	1	-	Undefined			Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_i_med	1	-	Undefined			Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_i_hinoman	1.11	-	Normal	0.055		Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
F_i_hiwman	1.44	-	Normal	0.094		Table 5.5 Updated - Relative Carbon Stock Change Factors for management activities on cropland; IPCC NIR GL 2019 Refinement
N2O_EF1	0.01	kg N_2O-N/kg N	Uniform	0.001	0.018	Table 11.1, 2019 Refinement
N2O_EF1_sn	0.016	kg N_2O-N/kg N	Uniform	0.013	0.019	direct N2O emissions factor for synthetic N, Tier 2. IPCC Table 11.1 Updated, NIR GL 2019 Refinement. for "wet" climates. Used in Eqn 11.2
N2O_EF1_os	0.006	kg N_2O-N/kg N	Uniform	0.001	0.011	direct N2O emissions factor for other N - biomass residues, organic matter, manures, SOM breakdowns, Tier 2. IPCC Table 11.1 Updated, NIR GL 2019 Refinement. for "wet" climates. Used in Eqn 11.2
N2O_EF4	0.01	kg N_2O-N/kg N volatilized	Uniform	0.002	0.05	Default value for N volatilization and re-deposition Table 11.3 (Updated) Updated, NIR GL 2019. Used in equation 11.9
N2O_EF4_wet	0.014	kg N_2O-N/kg N volatilized	Uniform	0.011	0.017	N volatilization and re-deposition in wet climates Table 11.3 (Updated) Updated, NIR GL 2019 equation 11.9
N2O_EF4_dry	0.005	kg N_2O-N/kg N volatilized	Uniform	0	0.011	N volatilization and re-deposition in dry climates Table 11.3 (Updated) Updated, NIR GL 2019 equation 11.9
N2O_EF5	0.011	kg N_2O-N/kg N runoff	Uniform	0	0.02	Leaching/runoff factor, Table 11.3 (Updated) Updated, NIR GL 2019 used in equation 11.10 kg N2O–N/ (kg NH3–N + NOX–N volatilized)

Parameter Name	Value	Unit	Uncertainty Information			Source Notes
N2O_FracGASF	0.1	kg N volatilized/kg N applied	Uniform	0.03	0.3	For synthetic fertilizer Table 11.3, used in equation 11.11
N2O_FracGASF_Urea	0.15	kg N volatilized/kg N applied	Uniform	0.03	0.43	For synthetic fertilizer Table 11.3, kg N volatilized/kg N applied
N2O_FracGASF_ammonium	0.08	kg N volatilized/kg N applied	Uniform	0.02	0.3	For synthetic fertilizer Table 11.3, kg N volatilized/kg N applied
N2O_FracGASF_nitrate	0.01	kg N volatilized/kg N applied	Uniform	0	0.03	For synthetic fertilizer Table 11.3, kg N volatilized/kg N applied
N2O_FracGASF_ammoniumnitrate	0.05	kg N volatilized/kg N applied	Uniform	0	0.2	For synthetic fertilizer Table 11.3, kg N volatilized/kg N applied
N2O_FracGASF_eff		Calculated based on fertilizer mix				Weighted FracGASF based on synthetic N mix
N2O_FracGASM	0.21	kg N volatilized/kg N applied	Uniform	0	0.31	IPCC Table 11.3 2019 Refinement for MANURE (not used)
N2O_FracLEACHh	0.24	kg N volatilized/kg N applied	Uniform	0.1	0.8	N losses by leaching/runoff in wet climates IPCC Table 11.3, 2019 Refinement
CO2_EF_lime	0.12	tonne CO_2-C/tonne lime	Undefined			tonne CO2-C/tonne lime, IPCCC 2006 Sect 11.3.2 Tier 1 default
CO2_EF_urea	0.2	tonne CO_2-C/tonne urea	Uniform	0.1	0.2	tonne CO2-C/tonne urea, IPCCC 2006 Eqn 11.13 Tier 1 default 0.2, uncertainty -50%
Gef_CO2_biogenic	1515	g/kg dry matter burnt	Normal	177		Table 2.5 Emissions factors (g/kg dry matter burnt) for biomass burning (ag residues) IPCC 2019 Refinement
Gef_CO	92	g/kg dry matter burnt	Normal	84		Table 2.5 Emissions factors (g/kg dry matter burnt) for biomass burning (ag residues) IPCC 2019 Refinement
Gef_N2O	0.07	g/kg dry matter burnt	Undefined			Table 2.5 Emissions factors (g/kg dry matter burnt) for biomass burning (ag residues) IPCC 2019 Refinement
Gef_CH4	2.7	g/kg dry matter burnt	Undefined			Table 2.5 Emissions factors (g/kg dry matter burnt) for biomass burning (ag residues) IPCC 2019 Refinement
Gef_NOx	2.5	g/kg dry matter burnt	Normal	1		Table 2.5 Emissions factors (g/kg dry matter burnt) for biomass burning (ag residues) IPCC 2019 Refinement
T_default	20	Years				Default time occupancy
SOC_ref	59.5	Tonne/ha	Normal	3.8		Soil Organic Carbon reference value. Table 2.3. IPCC2019, assuming 50:50 high- and low-activity clay soils, 64%±5%, 55%±8%. ± is 95%cl as % of mean. (=2SD)
N_ag_T corn	0.006	kg N/kg dm	Normal	0.0145		Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL. maize 0.006±75% / 0.019±75%
N_bg_T	0.014	kg N/kg dm	Normal	0.01505		Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL.
R_ag_T corn	1	kg N/kg dm	Undefined			Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL. corn 1, no uncertainty
RS_T corn	0.22	kg N/kg dm	Normal	0.1		Table 11.1A p11.17 Crop Residue Above and Belowground N and Mass IPCC 2019R NIR GL. Table 11.1A corn 0.22 ± 26%
R_c2c	10	-	Undefined			C:N ratio for cropland remaining cropland,, IPCC 2019R page 11.20
Yield_wheat	86	Ton/ac	Triangle	77	92	From NASS for SOC change with rotation
Frac_renew_annual **Frac_renew_4year**	1 0.25	-	Undefined			IPCC N2O emissions from managed soils factor. Annual crop = 1; N year crop = 1/N (sc =1/4)

Equation 11.2

Direct N₂O Emissions from Managed Soils (Tier 2)

$$N_2O-N = \sum_i (F_{SN}+F_{ON})_i * EF_{1i} + (F_{CR}+F_{SOM}) * EF_1 + N_2O-N_{OS} + N_2O-N_{PRP}$$

$N_2O-N = annual\ direct\ N_2O-N\ emisions\ produced\ from\ managed\ soils, kg\ N_2O-N\ yr^{-1}$

$N_2O-N_{N\ inputs} = annual\ direct\ N_2O-N\ emisions\ produced\ from\ N\ inputs\ to\ managed\ soils, kg\ N_2O-N\ yr^{-1}$

$N_2O-N_{OS} = annual\ direct\ N_2O-N\ emisions\ produced\ managed\ organic\ soils, kg\ N_2O-N\ yr^{-1}$

$N_2O-N_{PRP} = annual\ direct\ N_2O-N\ emisions\ produced\ from\ urine\ and\ dung\ inputs\ to\ grazed\ soils, kg\ N_2O-N\ yr^{-1}$

$F_{SN} = annual\ amount\ of\ synthetic\ fertilizer\ N\ inputs\ to\ soils, kg\ N\ yr^{-1}$

$F_{ON} = annual\ amount\ of\ animal\ manure, compost, sewage\ sludge\ and\ other\ organic\ N\ additions\ applied\ to\ soils, kg\ N\ yr^{-1}$

$F_{CR} = annual\ amount\ of\ N\ in\ crop\ residues\ (above\ ground\ and\ below\ ground) including\ N - fixing\ crops, and\ from\ forage\ or\ pasture, returned\ to\ soils\ annually, kg\ N\ yr^{-1}$

$F_{SOM} = annual\ amount\ of\ N\ in\ minerals\ soils\ that\ is\ mineralized, in\ association\ with\ loss\ of soil\ C\ fom\ soil\ organic\ matter\ as\ a\ result\ of\ changes\ to\ land\ use\ management, kg\ N\ yr^{-1}$

$F_{OS} = annual\ area\ of\ managed\ or\ drained\ organic\ soils, ha\ (Note: the\ subscripts\ CG, F, Temp, Trop, NR\ and\ NP\ refer\ to\ Cropland\ an$

$F_{PRP} = annual\ amount\ of\ urine\ and\ dung\ N\ deposited\ by\ grazing\ animals\ on\ pasture, range\ and\ paddock, kg\ N\ yr^{-1}, (Note: the\ subsc$

$EF_1 = emission\ factor\ for\ N_2O\ emissions\ from\ N\ inputs, kg\ N_2O-N (kg\ N\ input)^{-1}\ (Table\ 11.1)$

$EF_{1FR} = emission\ factor\ for\ N_2O\ emissions\ from\ N\ inputs\ to\ flooded\ rice, kg\ N_2O-N (kg\ N\ input)^{-1}\ (Table\ 11.1)^4$

EF_2 = emission factor for N_2O emissions from drained or managed organic soils, kg N_2O − N(kg N input)$^{-1}$, (See guidance in 2013 *Supplement to the* 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*: Wetl − 5 where further disaggregation by climate and land use is available) (*Note*: *the subscripts CG*, *F*, *Temp*, *Trop*, *NR and NP refer toCr*

$EF_1 = emission\ factor\ for\ N_2O\ emissions\ from\ urine\ and\ dung\ N\ deposited\ on\ pasture, range\ and\ paddock\ by\ grazing\ ani$ $- N(kg\ N\ input)^{-1}$, (*Table* 11.1)(Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respec

Parameter Name	Value	Unit
N2O_EF1	0.01	kg N2O-N / kg N

Equation 11.9

N2O From Atmospheric Deposition of N Volatilize from Managed Soils (Tier 1)

$$N_2O_{(ATD)} - N = [(F_{SN} * Frac_{GASF}) + ((F_{ON} + F_{PRP}) * Frac_{GASM})] * EF_4$$

$N_2O_{(ATD)} - N = annual\ direct\ N_2O - N\ produced\ from\ atmospheric\ deposition\ of\ N\ volatilized\ from\ managed\ soils, kg\ N_2O - N\ yr^{-1}$

$F_{SN} = annual\ amount\ of\ synthetic\ fertilizer\ N\ inputs\ to\ soils, kg\ N\ yr^{-1}$

$Frac_{GASF} = fraction\ of\ synthetic\ fertilizer\ N\ that\ volatilizes\ as\ NH_3\ and\ NO_x, kg\ N\ volatilized\ (kg\ of\ N\ applied)^{-1}\ (Table\ 11.3)$

$F_{ON} = annual\ amount\ of\ animal\ manure, compost, sewage\ sludge\ and\ other\ organic\ N\ additions\ applied\ to\ soils, kg\ N\ yr^{-1}$

$F_{PRP} = annual\ amount\ of\ urine\ and\ dung\ N\ deposited\ by\ grazing\ animals\ on\ pasture, range\ and\ paddock, kg\ N\ yr^{-1},$

$Frac_{GASM} = fraction\ of\ applied\ organic\ N\ fertilizer\ materials\ (F_{ON})and\ of\ urine\ and\ dung\ N\ deposited\ by\ grazig\ animals\ (F_{PRP}), that\ vo$

$EF_4 = emission\ factor\ for\ N_2O\ emissions\ from\ atmospheric\ deposition\ of\ N\ on\ soils\ and\ water\ surfaces, [kg\ N - N_2O(kg\ NH_3 - N + NO_x - N\ volatilized)^{-1}]\ (Table\ 11.3)$

$Conversion\ of\ N_2O_{(ATO)} - N\ emissions\ to\ N_2O\ emissions\ for\ reporting\ purposes\ is\ performed\ by\ using\ the\ following\ equation:$

$$N_2O_{(ATO)} = N_2O_{(ATO)} - N * 44/28$$

Parameter Name	Value	Unit
N2O_EF4	0.01	kg N2O-N / kg N volatilized
N2O_FracGASF	0.1	kg N volatilized / kg N applied
N2O_FracGASM	0.21	kg N volatilized / kg N applied

Equation 11.11

N2O From Atmospheric Deposition of N Volatilize from Managed Soils (Tier 2)

$$N_2O_{(ATD)} - N = \{\sum_i (F_{SN_i} * Frac_{GASF_i}) + [(F_{ON} + F_{PRP}) * Frac_{GASM}]\} * EF_4$$

$N_2O_{(ATD)} - N = annual\ direct\ N_2 - N\ produced\ from\ atmospheric\ deposition\ of\ N\ volatilized\ from\ managed\ soils, kg\ N_2O - N\ yr^{-1}$

$F_{SN_i} = annual\ amount\ of\ synthetic\ fertilizer\ N\ inputs\ to\ soils\ under\ different\ conditions\ i, kg\ N\ yr^{-1}$

$Frac_{GASF} = fraction\ of\ synthetic\ fertilizer\ N\ that\ volatilizes\ as\ NH_3\ and\ NO_x\ under\ different\ conditions\ i\ , kg\ N\ volatilized\ (kg\ of\ N\ app$

Parameter Name	Value	Unit
N2O_FracGASF	0.1	kg N volatilized / kg N applied

Equation 11.11

N_2O From N Leaching/Runoff from Managed Soils in Regions where Leaching/Runoff Occurs (Tier 1)

$$N_2O_{(L)} - N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) * Frac_{LEACH-(H)} * EF_5$$

Equation 11.6

N from Crop Residues and Forage/Pasture Renewal (Tier 1)

$$F_{CR} = \sum_{T} \{[AGR_{(T)} * N_{AG(T)} * (1 - Frac_{Remove(T)} - (Frac_{Burnt(T)} * C_f))] + [BGR_{(T)} * N_{BG(T)}]\}$$

$$N_2O_{(ATD)} = N_2O_{(ATD)} - N * 44/28$$

$$BGR_{(T)} = \left(Crop_{(T)} + AG_{DM(T)}\right) * RS_{(T)} * Area_{(T)} * Frac_{Renew(T)}$$

$F_{CR} = annual\ amount\ of\ N\ in\ crop\ residues\ (above\ ground\ and\ below\ ground) including\ N - fixing\ crops, and\ from\ forage\ or\ pasture, returned\ to\ soils\ annually, kg\ N\ yr^{-1}$

$AGR_{(T)} = annual\ total\ amount\ of\ above\ ground\ crop\ residue\ for\ crop\ T, kg\ d.m.yr^{-1}.$

$N_{AG(T)} = N\ content\ of\ above\ ground\ residues\ for\ crop\ T, kg\ N\ (kg\ d.m.)^{-1}\ (Table\ 11.1a)$

$Frac_{Remove(T)} = fraction\ of\ above\ ground\ residues\ of\ crop\ T\ removed\ annually\ for\ purposes, such\ as\ feed, bedding\ and\ construction, dimens$

$Frac_{Burnt(T)} = fraction\ of\ annual\ harvested\ area\ of\ crop\ T\ burnt, dimensionless$

$C_f = combustion\ factor (dimensionless)\ (refer\ to\ Chaoter\ 2, Table\ 2.6)$

Equation 2.27

Estimation of Greenhouse Gas Emissions from Fire

$$L_{fire} = A * M_B * C_f * G_{ef} * 10^{-3}$$

$L_{fire} = amount\ of\ greenhouse\ gas\ emissions\ from\ fire, tonnes\ of\ each\ GHG\ e.g., CH_4, N_4O, etc.$

$A = area\ burnt, ha$

$C_f = combustion\ factor (dimensionless)\ (refer\ to\ Chaoter\ 2, Table\ 2.6)$

M_B
$= mass\ of\ fuel\ available\ for\ combustion, tonnes\ ha^{-1}. This\ includes\ biomass, ground\ liter\ and\ dead\ wood, When\ Tier\ 1\ methods$
$- use\ change\ (see\ Section\ 2.3.2.2).$

$G_{ef} = emission\ factor, g\ kg^{-1}\ dry\ matter\ burnt (default\ values\ in Table\ 2.5)$

Equation 2.14

Annual Carbon Losses in Biomass Due to Disturbances

$$L_{disturbance} = \{A_{disturbance} * B_W * (1 + R) * CF * fd\}$$

L_{fire}
$= annual\ other\ losses\ of\ carbon, tonnes\ Cyr^{-1}, (Note\ that\ this\ is\ the\ amount\ of\ biomass\ that\ is\ lost\ from\ the\ total\ biomass.$

$transferred\ to\ dead\ organic\ matter\ and\ biomass\ that\ is\ oxidezed, and\ released\ to\ the\ atmosphere\ is\ explained\ in Equations\ 2.15$

$A_{disturbance} = area\ affected\ by\ disturbances, ha\ yr^{-1}$

$B_W = average\ above\ ground\ biomass\ of\ land\ areas\ affected\ by\ disturbances, tonnes\ d.m.\ ha^{-1}$

R
$= ratio\ of\ below\ ground\ biomass\ to\ above\ biomass, in\ tonne\ d.m.\ below\ ground\ biomass, (tonne\ d.m.\ above\ ground\ biomass)^{-1}.$

$CF = carbon\ fraction\ of\ dry\ matter, tonne\ C\ (tonne\ d.m.)^{-1}$

$fd = fraction\ of\ biomass\ lost\ in\ disturbance\ (see\ note\ below)$

Equation 2.25

Annual Change in Organic Carbon Stocks in Mineral Soils

$$\Delta C_{mineral} = \frac{(SOC_0 - SOC_{(O-T)})}{D}$$

$$SOC_{Mineral} = \sum_{c,s,i} (SOC_{0_{c,s,i}} * F_{LU_{c,s,i}} * F_{MG_{c,s,i}} * F_{I_{c,s,i}} * A_{c,s,i})$$

$\Delta C_{mineral} = annual\ change\ in\ organic\ C\ stocks\ in\ mineral\ soils, tonnes\ C\ yr^{-1}$

$SOC_{(0-T)} = mineral\ soil\ organic\ C\ stock\ (SOC_{Mineral})\ at\ the\ beginning\ of\ the\ inventory\ time\ period, tonnes\ C$

$SOC_0 = mineral\ soil\ organic\ C\ stock\ (SOC_{Mineral})\ at\ the\ last\ year\ of\ the\ inventory\ time\ period, tonnes\ C$

$T = number\ of\ years\ over\ a\ single\ inventory\ time\ period, yr$

D
$= time\ dependence\ of\ mineral\ soil\ organic\ C\ stock\ change\ factors, which\ is\ the\ default\ time\ period\ for\ transition\ between\ equ$
$- T\ years).$

$c = represents\ the\ climate\ zones\ included\ in\ the\ inventory$

$s = represents\ the\ soil\ types\ included\ in\ the\ inventory$

$i = represents\ the\ set\ of\ management\ systems\ included\ in\ the\ inventory.$

$SOC_{Mineral} = total\ mineral\ soil\ organic\ C\ stock\ at\ defined\ time, tonnes\ C$

$SOC_{REF_{c,s,i}} = the\ soil\ organic\ C\ stock\ for\ mineral\ soils\ in\ the\ reference\ condition, tonnes\ C\ ha^{-1}\ (Table\ 2.3)$

$$F_{LU_{c,x,i}} = stock\ change\ factor\ for\ mineral\ soil\ organc\ C\ land - use\ systems\ or\ sub - systems\ for\ a\ particular\ land\ use, dimensionless$$

$F_{MG_{c,x,i}} = stock\ change\ factor\ for\ mineral\ soil\ organic\ C\ for\ management\ regime, dimensionless$

$F_{I_{c,x,i}} = stock\ change\ factor\ for\ mineral\ soil\ organic\ C\ for\ the\ input\ of\ organic\ amanedments, dimensionless$

$A_{c,x,i} = land\ area\ of\ the\ stratum\ being\ estimated, ha$

Parameter Name	Value	Unit
SOC_ref	59.5	Tonne / ha