Review of lifecycle GHG calculations for corn ethanol and corn stover ethanol in the CA-GREET2.0 model

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The authors reviewed farming nutrient emission rates and the emission rates of chemicals used in corn ethanol production in the CA-GREET 2.0 model. We have a number of comments, which are detailed in this document.

The table below summarizes the emission impacts of our comments.

Summary of suggested numerical corrections to the CARB values

Corrections	Corn dry mill pathway [gCO_2/MJ]	Corn wet mill pathway [gCO_2/MJ]	Corn stover pathway [gCO_2/MJ]
1.1. Current fertilizer rates	-0.67	-0.66	
1.2. CO_2 emissions from limestone	-0.83 ~ -2.18	-0.82 ~ -2.14	
1.3. Nutrient contents in fertilizers	-0.06	-0.06	-0.05
1.5. Soil N_2O emissions from corn stover in corn ethanol	-0.21	-0.21	
1.6. Supplement nutrients in corn stover ethanol			-7.98
2.2. Lifecycle GHG emissions of sulfuric acid	-0.47	-0.46	-0.92
2.3. Cellulase enzyme loading in corn stover ethanol			-1.32 ~ -1.79
2.4. Marginal electricity in corn stover ethanol			-8.07
Total	-2.24 ~ -3.59	-2.22 ~ -3.57	-26.4~ -26.9

Our comments are presented in the next two sections. The first section details comments on agricultural chemicals, and the second section deals with chemicals used in corn ethanol plants.

1. Feedstock production (corn grain and corn stover)

1.1. Fertilizer rates in corn grain production

The fertilizer application rates per bushel of corn in the CA-GREET2.0 model (in cells: Inputs!F281:F283) do not reflect the current corn culture practices in the US. The CA-GREET2.0

supporting document provides a reference[1] for the fertilizer application rates given in the CA-GREET2.0 model. These values are probably based on available data up to 2005. Unfortunately, the timeframe for the fertilizer application rates was not clearly stated in the reference so we are unable to determine how these California values were generated. Furthermore, newer fertilizer application rates for corn culture practices in 2010 are available and should be used in preference to any earlier values. Thus in this report we have used USDA statistics[2] to estimate the US average 2010 fertilizer application rates per bushel of corn—the most recent time period available. These USDA data are summarized in Table 1. The fertilizer rates in the NASS (USDA study) are slightly lower than those in the CA-GREET2.0 model due to higher corn yields. The NASS fertilizer application rates are 4 – 20% less than the rates in the CA-GREET2.0 model.

Table 1 Fertilizer application rate per bushel of corn produced [2]

	NASS¶	CA-GREET2.0 (in cells: Inputs!F281:F283)
N (gram per bushel)	400.84	415.33
P_2O_5 (gram per bushel)	138.42	147.77
K_2O (gram per bushel)	143.36	172.11

Fertilizer consumption to produce corn silage is excluded from these data.

Using the current fertilizer application rates per bushel of corn from the NASS data summarized in Table 1 reduces the GHG of corn ethanol by 0.67 (0.66) g/MJ in the dry (wet) mill pathway. The detailed calculations are as follows:

[1] Wang, Michael Q., Jeongwoo Han, Zia Haq, Wallace E. Tyner, May Wu, and Amgad Elgowainy. "Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes." Biomass and Bioenergy 35, no. 5 (2011): 1885-1896

[2] National Agricultural Statistics Service. http://www.nass.usda.gov/

The calculations are done in the CA-GREET2.0 spreadsheet model. Replace the fertilizer rates in the CA-GREET2.0 model (in cells: Inputs!F281:F283) by the NASS values in Table 1. Results are summarized in Table 2.

Table 2 Calculations for fertilizer application rates

	Rates from NASS	CA-GREET2.0
GHG associated with fertilizers [gram/MJ] (EtOH!D429)	14.28	14.81
N_2O emissions [gram/MJ] (EtOH!E429)	14.93	15.32
GHG credit of co-products [gram/MJ] (EtOH!G429)	13.21	13.47
GHG of corn ethanol [gram/MJ] (EtOH!Y429)	76.11	76.78

The USDA/NASS statistics[2] also show that fertilizer application rates per bushel (i.e., N, P_2O_5, K_2O applied per bushel of corn produced) have been steadily declining with time. (See Figure 1) Even though total amount of fertilizer applied nationally has increased, the application rate per bushel has actually declined due to higher corn yields. Assuming the trends summarized in Figure 1 have continued, even less total fertilizer use per bushel of corn produced is projected after 2010.

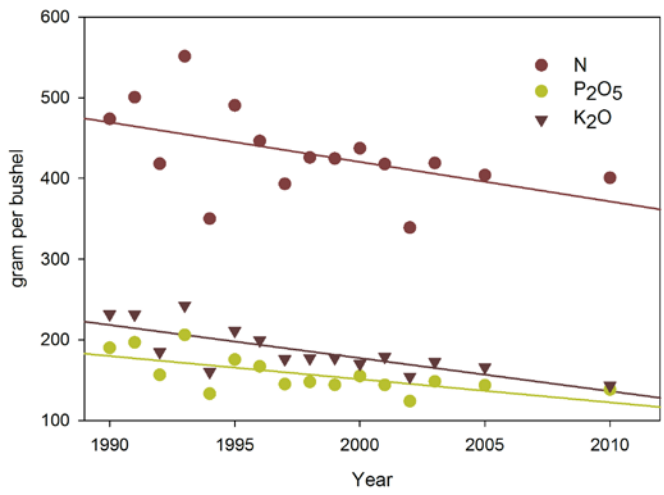

Figure 1 Fertilizer application rates in the US [data source: NASS[2]]

1.2. CO_2 emissions from limestone

Limestone ($CaCO_3$) is the primary agricultural lime used in the US in 2011[3], accounting for about 93% of the total lime applied. The rest is dolomite ($MgCa(CO_3)_2$). The CA-GREET2.0 model incorrectly assumes that 100% of the carbon in limestone that is applied to soil is released to the air as carbon dioxide and fails to account for various soil, water and atmospheric processes that are very relevant. In contrast, a USDA report[4] based on actual, physical processes occurring in soil, water and the atmosphere finds that two-thirds of the carbon in limestone remains in long-term carbon sinks and only one-third of the carbon in limestone is actually released as carbon dioxide.

[3] United States Environmental Protection Agency (2013) U.S. greenhouse gas inventory report: Inventory of U.S. greenhouse gas emissions and sinks: 1990-2011. United States Environmental Protection Agency, Washington, DC.
[4] USDA (2014) Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory. , Washington, DC.

For example, dissolved CO_2 resulting from root and microbial respiration exists in equilibrium in soil water with H_2CO_3. This slightly acidic H_2CO_3 reacts with limestone[5] as described below in Equations (1) and (2).

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (1)$$

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- \quad (2)$$

Dissolved HCO_3^- is stable and is transported to the ocean by rivers and streams. In the ocean, this carbon is sequestered for time periods of decades to centuries[4].

In a separate study, West and McBride[6] also estimate the carbon dioxide emission factors for limestone applied by accounting for leaching and transport by rivers to the ocean. The carbon dioxide emission factors for limestone applied to agricultural land given in their study are 0.059 kg C/kg limestone applied for limestone and 0.064 kg C/kg dolomite applied for dolomite. These are the emission values currently used in the U.S. National GHG Inventory[3]. However, they do not include the entire range of biophysical processes covered by the USDA report[4].

CA-GREET2.0 should use the most comprehensive, scientifically-valid calculations available to estimate the GHG emissions of agricultural lime application. We believe those are the values given by the USDA report[4]. The carbon dioxide emission factors for agricultural limestone applied are summarized in Table 3 below.

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[5] Hamilton, Stephen K., et al. "Evidence for carbon sequestration by agricultural liming." Global Biogeochemical Cycles 21: 1 - 12 (2007).

[6] West TO, McBride AC (2005) The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions. Agr Ecosyst Environ 108:145–154

Table 3 Carbon dioxide emission factors for agricultural limestone application

	Carbon dioxide emission from Limestone [kg CO_2/kg]
CA-GREET2.0	0.44
USDA[4]	-0.15
GREET2014[7] & West and McBride[6]	0.216

Using the carbon dioxide emission factors from the USDA process-based report[4] and the GREET2014 model[7] reduces the GHG of corn ethanol by 0.83 and 2.18 (0.82 and 2.14) g/MJ in the dry (wet) mill pathway, respectively. The detailed calculations are as follows:

Replace the carbon dioxide emission factors in the CA-GREET2.0 model (in cells: EtOH!F380, 44/100) by the factors in Table 3. Results are summarized in Table 4.

Table 4 Calculations for lime application

	Factor from USDA report[4]	Factor from GREET2014[7]	CA-GREET2.0
CO_2 from $CaCO_3$ use [gram/bushel] (EtOH!F380)	-169	249	506
GHG associated with fertilizers [gram/MJ] (EtOH!D429)	11.81	13.66	14.81
GHG credit of co-products [gram/MJ] (EtOH!G429)	12.66	13.16	13.47
GHG of corn ethanol [gram/MJ] (EtOH!Y429)	74.60	75.94	76.78

[7] Argonne National Laboratory (2014) Greenhouse gases, regulated emissions, and energy use in transportation (GREET) computer model 2014.

1.3. Nutrient contents in N and P_2O_5 fertilizers

The CA-GREET2.0 model assumes that N fertilizer consists of ammonia, urea, ammonium nitrate, urea-ammonium nitrate solution, mono-ammonium phosphate, and di-ammonium phosphate, and P fertilizer consists of mono-ammonium phosphate, and di-ammonium phosphate as summarized in Table 5. However, the nutrient contents in some of these fertilizers are not given correctly in the CA-GREET2.0 model. The nitrogen content in di-ammonium phosphates is 18%[8], not 16% as given in the CA-GREET2.0 model. The P_2O_5 contents in mono- and di-ammonium phosphates are 48 -61% (the most common value is 52%) and 46%[8], respectively.

Table 5 Fraction and nutrient content of N and P_2O_5 fertilizers in CA-GREET2.0 [basis: N for N fertilizer, P_2O_5 for P fertilizer]

N fertilizer	Ammonia	Urea	Ammonium Nitrate	Urea-Ammonium Nitrate Solution	Mono-ammonium Phosphate	Di-ammonium Phosphate
Fraction	0.31	0.23	0.04	0.32	0.04	0.06
N content (%)	82.4%	46.7%	35.0%	-	11.0%	16.0% (Ag_Inputs!AC74)
P_2O_5 fertilizer					Mono-ammonium Phosphate	Di-ammonium Phosphate
Fraction					0.5	0.5
P_2O_5 content (%)					48.0% (Ag_Inputs!AE74)	48.0% (Ag_Inputs!AF74)

[8] Penn State Extension, Nitrogen Fertilizers. http://extension.psu.edu/agronomy-guide/cm/tables/table-1-2-11

Using the correct nutrient contents reduces the GHG of corn ethanol by 0.06 (0.06) g/MJ in the dry (wet) mill pathway and reduces the GHG of corn stover ethanol by 0.05 g/MJ. The detailed calculations are as follows:

Replace the nutrient content in the CA-GREET2.0 model (in cells: Ag_Inputs!AC74, Ag_Inputs!AE74, Ag_Inputs!AF74) by the corrected values (18% for Ag_Inputs!AC74; 52% for Ag_Inputs!AE74; 46% for Ag_Inputs!AF74). Results are summarized in Table 6.

Table 6 Calculations for nutrient content

	Corrected values	CA-GREET2.0
Corn ethanol in the dry mill pathway		
GHG associated with fertilizers [gram/MJ] (EtOH!D429)	14.72	14.81
N_2O emissions [gram/MJ] (EtOH!E429)	15.32	15.32
GHG credit of co-products [gram/MJ] (EtOH!G429)	13.44	13.47
GHG of corn ethanol [gram/MJ] (EtOH!Y429)	76.72	76.78
Corn stover ethanol		
GHG associated with fertilizers¶ [gram/MJ]	10.06	10.11
GHG of corn stover ethanol§ [gram/MJ]	14.63	14.68

¶ Sum of GHG from cells EtOH!CJ371:EtOH!CN379 divided by ethanol yield (EtOH!G141) and converted to MJ
§ Sum of cells EtOH!AG412:AH412

1.4. Emissions of N and P_2O_5 fertilizers

Mono- and di-ammonium phosphate fertilizers contain both N and P_2O_5 nutrients. Therefore, the CA-GREET2.0 model probably uses allocation factors to assign emissions to either N or P_2O_5. However, there is no background information given in the CA-GREET2.0 model to describe and define how these putative allocation factors were chosen. The choice of allocation factors should be transparent and readily available through the CA-GREET2.0 model.

The amounts of N and P_2O_5 fertilizers applied based on the fractions of each fertilizer used in agriculture and their respective nutrient contents as given by CA-GREET2.0 are not equal to those of N and P_2O_5 fertilizers used in corn grain production as seen in Table 7. Emissions of N and P_2O_5 fertilizers (in cells: EtOH!D365:E379) are associated with using 439.8 g of N fertilizer and 284.2 g of P_2O_5 fertilizer, not 415.33 g of N fertilizer and 147.77 g of P_2O_5 fertilizer. Therefore, emissions of N and P_2O_5 fertilizers (in cells: EtOH!D365:E379) do not represent emissions associated with the actual amounts of N (415.33 gram/bushel) and P_2O_5 (147.77 gram/bushel) used in corn grain production and should be recalculated to be consistent with current actual corn grain production practice.

Table 7 Quantities of N and P_2O_5 fertilizers in CA-GREET2.0 [basis: N for N fertilizer, P_2O_5 for P_2O_5 fertilizer]

	N fertilizer		P_2O_5 fertilizer	
	Nutrient [gram/bushel]			
	N	P_2O_5	N	P_2O_5
Ammonia	124.3			
Urea	92.2			
Ammonium Nitrate	16.0			
Urea-Ammonium Nitrate Solution	128.3			
Mono-ammonium Phosphate	16.0	70.0	15.9	69.2
Di-ammonium Phosphate	24.1	72.2	23.1	69.2
Sum	400.8	142.1	38.9	138.4
Total N	400.8 + 38.9 = 439.8			
Total P_2O_5	142.1 + 138.4 =284.2			

1.5. Soil N_2O emissions from corn stover due to corn ethanol production

The CA-GREET2.0 model uses the emission factor (1.325%) for N_2O according to the IPCC guidelines[9], which include direct and indirect N_2O emissions. The CA-GREET2.0 model applies this emission factor to both inorganic fertilizer and corn stover. However, the IPCC guideline[9]

[9] Intergovernmental Panel on Climate Change (2006) 2006 IPCC guidelines for national greenhouse gas inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

does not include volatile nitrogen loss from crop residues. This volatile nitrogen is lost to the air and is thus not available for soil microbes to convert it to N_2O. Thus, the N_2O emission factor for corn stover should be reduced to 1.225%. The data surrounding this correction to the CA-GREET2.0 calculations are summarized in Table 8. Box 1 below quotes the relevant procedures for calculating indirect N_2O emissions as given in the IPCC guideline[9].

Table 8 Emission factor

	IPCC[9]	CA-GREET2.0
Fertilizer		
Direct N_2O from fertilizer	0.01	0.01
Indirect N_2O from volatized N from fertilizer	0.001 (=0.1*0.01)	0.001 (=0.1*0.01)
Indirect N_2O from leached N from fertilizer	0.00225 (=0.3*0.075)	0.00225 (=0.3*0.075)
Emission factor for fertilizer	0.01325	0.01325
Crop residues		
Direct N_2O from crop residues	0.01	0.01
Indirect N_2O from volatized N from crop residues	-	0.001 (=0.1*0.01)
Indirect N_2O from leached N from crop residues	0.00225 (=0.3*0.075)	0.00225 (=0.3*0.075)
Emission factor for crop residues	0.01225	0.01325

Box 1. Indirect N_2O calculations (quoted from the IPCC guideline[9])

Volatilization, N_2O(ATD)

N_2O FROM ATMOSPHERIC DEPOSITION OF N VOLATILISED FROM MANAGED SOILS (TIER 1)

$N_2O(ATD)-N = [(FSN \bullet FracGASF) + ((FON + FPRP) \bullet FracGASM)] \bullet EF4$

Where:

N_2O(ATD)–N = annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O–N yr^{-1}

FSN = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1}

FracGASF = fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx, kg N volatilized (kg of N applied) $^{-1}$

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

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

FracGASM = fraction of applied organic N fertilizer materials (FON) and of urine and dung N deposited by grazing animals (FPRP) that volatilizes as NH_3 and NOx, kg N volatilized (kg of N applied or deposited) $^{-1}$)

EF4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces,

[kg N– N_2O (kg NH_3–N + NOx–N volatilized) $^{-1}$]

This correction reduces the GHG of corn ethanol by 0.21 (0.21) g/MJ in the dry (wet) mill pathway. The detailed calculations are as follows:

Replace the emission factor for corn stover in the CA-GREET2.0 model (in cells: EtOH!D382) by the IPCC emission factor given in Table 8 above. Results are summarized in Table 9.

Table 9 Calculations for nutrient content

	IPCC value	CA-GREET2.0
Corn ethanol in the dry mill pathway		
N2O from nitrogen fertilizer, and above and below ground biomass [gram/bushel] (EtOH!D382)	11.374	11.596
N_2O emissions [gram/MJ] (EtOH!E429)	15.03	15.32
GHG credit of co-products [gram/MJ] (EtOH!G429)	13.39	13.47
GHG of corn ethanol [gram/MJ] (EtOH!Y429)	76.56	76.78

1.6. Supplemental nutrients in corn stover ethanol production

In the CA-GREET2.0 model, supplemental nutrients (i.e., N, P_2O_5, K_2O) are added in the subsequent growing season to replace nutrients that are assumed to be lost when corn stover is collected to produce corn ethanol. The amount of the supplement nutrients required is assumed to be exactly equal to the nutrient content of the corn stover removed. However, the supplemental nutrients required depend on actual crop management practices used in the

subsequent growing season. According to USDA statistics[10], only 33% of cornfields function as cornfields ("corn on corn") in the subsequent growing season, while about 48% of cornfields are used to grow soybeans in the subsequent growing season. Approximately 2.4% of cornfields are converted to developed land, open water or left fallow in the subsequent growing season. This information is summarized in Figure 2.

Supplemental N nutrients in the following growing season are therefore not necessary for croplands used to produce soybeans even though the nitrogen content in corn stover was removed. Furthermore, supplemental nutrients are not necessary for lands converted to developed land, open water or left fallow. Therefore, supplemental N nutrients are needed in only 49% (=100% - 48% (soybean) - 2.4% (fallow, etc.)) of corn-producing croplands next year, and the supplemental P and K nutrients are needed in only 98 % (100% – 2.4% (fallow, etc.)) of croplands from cornfields next year. By accounting properly for the actual use of corn land in the subsequent growing season, the GHG of corn stover ethanol is reduced by 7.98 g/MJ. The detailed calculations are as follows:

Multiply the fertilizer used in the CA-GREET2.0 model (in cells: EtOH!H20:H22) by 0.49 for N, and 0.98 for P_2O_5 and K_2O, respectively. Results are summarized in Table 10 below.

[10] USDA, CropScape - Cropland Data Layer. http://nassgeodata.gmu.edu/CropScape/

Table 10 Calculations for supplemental nutrients required for continuous corn

	Corrected values	CA-GREET2.0
GHG associated with fertilizers¶ [gram/MJ]	6.01	10.11
N2O from nitrogen fertilizerΓ [gram/MJ]	-3.87	0
GHG of corn stover ethanol§ [gram/MJ]	6.71	14.68

¶ Sum of GHG from cells EtOH!CJ371:CN379 divided by ethanol yield (EtOH!G141) and converted to MJ
Γ cells EtOH!CJ382 converted to MJ
§ Sum of cells EtOH!AG412:AH412

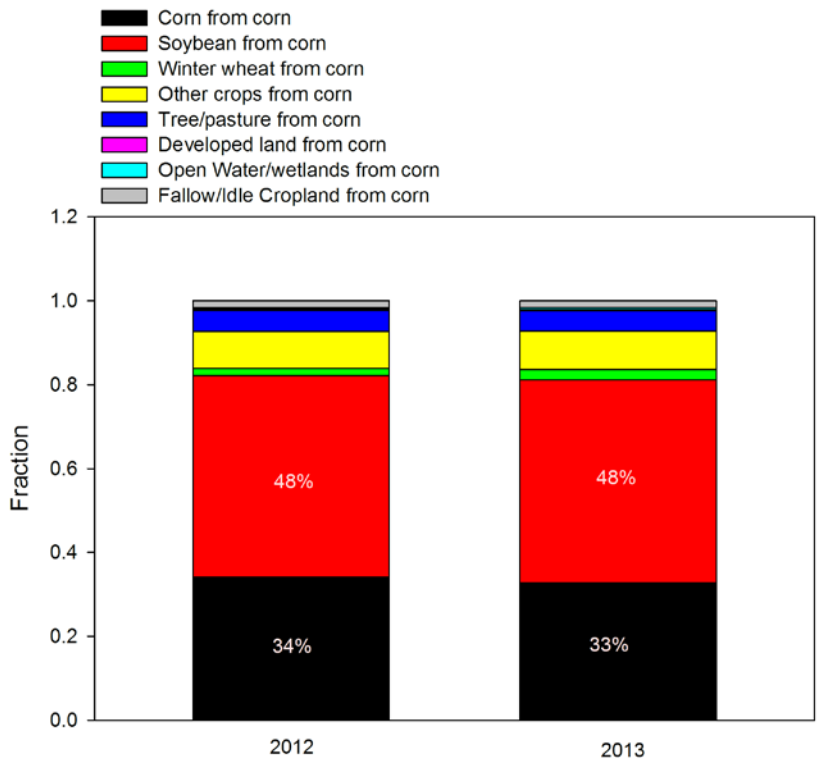

Figure 2 Land use changes in corn cultivation [data source: USDA[10]]

2. Ethanol production (dry mill and cellulosic biorefinery)

2.1. CO_2 emissions from urea displaced by DDGS

Enzymes from bacteria in cattle rumen, specifically urease, break down urea to CO_2 and ammonia, and CO_2 is released. Displacing urea by DDGS avoids those CO_2 emissions. However, the CA-GREET2.0 does not include a credit for CO_2 emissions from urea displaced by DDGS. Even though this value is very small, it should be included in the model for completeness.

2.2. Lifecycle GHG emissions of sulfuric acid in corn stover ethanol

About 250 grams of sulfuric acid (EtOH!CR361) are used to produce one gallon of corn stover ethanol. A plant producing sulfuric acid generally exports thermal energy (steam) and electricity, and therefore its net energy use is negative[11, 12]. However, the CA-GREET2.0 model does not include the correct energy credits for the exported energy in calculating lifecycle emissions of sulfuric acid. Assuming that 2.1 MMBTU per ton of sulfuric acid[11] is exported from a sulfuric acid plant, the GHG of corn ethanol is reduced by 0.47 (0.46) g/MJ in the dry (wet) mill pathway, and the GHG of corn stover ethanol is reduced by 0.92 g/MJ. The detailed calculations are as follows:

Add an energy credit (2.1 MMBTU/ton) in the cell Ag_Inputs!R26 in the CA-GREET2.0 model. Results are summarized in Table 11. In the CA-GREET2.0 model, sulfuric acid is used to manufacture the phosphorus-containing fertilizers.

The lifecycle GHG of sulfuric acid also affects lifecycle GHG of mono- and di-ammonium phosphates. Correcting the lifecycle GHG of sulfuric acid also changes the GHG of corn ethanol.

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[11] USDOE, Energy and Environmental Profile of the U.S. Chemical Industry, 2000.
[12] National Renewable Energy Laboratory. U.S. Life Cycle Inventory Database.

Table 11 Calculations for sulfuric acid

	Corrected values	CA-GREET2.0
Corn ethanol in the dry mill pathway		
GHG associated with fertilizers [gram/MJ] (EtOH!D429)	14.16	14.81
GHG credit of co-products [gram/MJ] (EtOH!G429)	13.29	13.47
GHG of corn ethanol [gram/MJ] (EtOH!Y429)	76.30	76.78
Corn stover ethanol		
GHG associated with fertilizers¶ [gram/MJ]	9.73	10.11
GHG of biorefineryΓ [gram/MJ]	13.65	14.19
GHG of corn stover ethanol§ [gram/MJ]	13.76	14.68

¶ Sum of GHG from cells EtOH!CJ371:CN379 divided by ethanol yield (EtOH!G141) and converted to MJ
Γ Sum of GHG from cells EtOH!CR371:CR380
§ Sum of cells EtOH!AG412:AH412

2.3. Cellulase enzyme loading in corn stover ethanol

Recent authoritative studies[13, 14] show that current cellulase enzyme loadings range from 17.5 - 19.9 mg per g of cellulose for dilute acid pretreatment of corn stover followed by enzymatic hydrolysis and fermentation of the sugars to ethanol. This enzyme application rate is equivalent to about 72 – 83 g enzyme per gallon of ethanol. However, the enzyme loading used the CA-GREET2.0 model (cells EtOH!CR359) is 113.4 g per gallon of ethanol, which is higher than the current enzyme technologies actually require. Applying current enzyme technologies as summarized in the 2011 National Renewable Energy Laboratory study reduces emissions by 1.32 – 1.79 g/MJ. The detailed calculations are as follows:

Replace the enzyme loading rate in the CA-GREET2.0 model (cells EtOH!CR359) by new enzyme loading values. Results are summarized in Table 12.

Table 12 Calculations for enzyme loading

	Current technologies		CA-GREET2.0
Enzyme loading [g per gallon]	72	83	113.4
Ethanol yield [gallon/dry ton]	70	79	80
GHG of biorefineryΓ [gram/MJ]	12.39	12.87	14.19
GHG of corn stover ethanol§ [gram/MJ]	12.89	13.37	14.68

Γ Sum of GHG from cells EtOH!CR371:CR380
§ Sum of cells EtOH!AG412:AH412

[13] Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, Schoen P et al. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: Dilute-acid pretreatment and enzymatic hydrolysis of corn stover. Colorado: National Renewable Energy Laboratory; 2011.
[14] da Costa Sousa L, Jin M, Uppugundla M, Bokade V, Humpula JF, Gunawan C, Foston MB et al. Extractive AFEX™ (E-AFEX™) pretreatment: a unified approach for resolving bottlenecks to efficient cellulosic bioethanol production. New Orleans, LA: 34th Symposium on Biotechnology for Fuels and Chemicals; 2012.

2.4. Marginal electricity in corn stover ethanol

The CA-GREET2.0 model assumes that excess electricity from a cellulosic biorefinery displaces US average electricity demand. However, it is more reasonable to assume that excess electricity would displace marginal electricity, not US average electricity, which consists of electricity from many different energy sources (i.e., fossil fuel, nuclear, renewable energy sources, and hydro). Excess electricity from a cellulosic biorefinery will likely displace electricity from a coal or natural gas-fired power plant, not electricity from nuclear power plant. A nuclear power plant must keep its electricity production level constant at all times. In contrast, marginal electricity is electricity from a power plant which can be brought on line quickly so that the power plant can respond to changing demand for electricity. Nuclear plants and hydroelectric stations are thus ruled out as suppliers of marginal electricity—they can only satisfy base load electricity demand. Electricity from renewable energy sources such as wind and solar are also excluded as sources of marginal electricity because of renewable energy certificates.

Therefore, the marginal electricity replaced by excess electricity from a cellulosic biorefinery would be marginal electricity derived from burning fossil fuels (i.e., coal, petroleum, natural gas). The fuel mix used for marginal electricity production is 64% coal, 34% natural gas and 2% petroleum. These percentages are based on electricity fuel mixes given in the CA-GREET2.0 model. When marginal electricity generated from these fossil fuels is displaced by excess electricity from a cellulosic biorefinery, the GHG of corn stover ethanol is reduced by 8.07 g/MJ. The detailed calculations are as follows:

Create new sheet for marginal electricity in the CA-GREET2.0 model. The new sheet is named "marginal elec". Replace the electricity fuel mixes in the cells (marginal elec!C56:C72) by marginal fuel mixes - coal (64%), natural gas (34%), petroleum (2%), others (0). Replace emissions associated with electricity (EtOH!CS371:CS379) by emissions of marginal electricity. Results are summarized in Table 13.

Table 13 Calculations for marginal electricity

	Marginal electricity	CA-GREET2.0
GHG creditΓ [gram/MJ]	-27.54	-19.47
GHG of corn stover ethanol§ [gram/MJ]	6.62	14.68

Γ GHG from cells EtOH!CS371:CS379 and converted to MJ
§ Sum of cells EtOH!AG412:AH412