**Supplementary material for**

Comparison of biofuel life-cycle GHG emissions assessment tools: the case studies of ethanol produced from sugarcane, corn, and wheat

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**Versions of the models used:**

GREET 2016

GHGenius 4.03 (2013)

BioGrace 1-4d (updated 2016)

VSB 2015

**Table 1S**. Agricultural and industrial inputs for sugarcane ethanol production

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | GREETa | GHGeniusb | BioGracec | VSBd |
| **Inputs per tonne of sugarcane** |  |  |  |  |
| N fertilizer (kg) | 0.80 | 1.08 | 0.91 | 1.23 |
| P2O5 fertilizer (kg) | 0.30 | 0.58 | 0.41 | 0.14 |
| K2O fertilizer (kg) | 1.00 | 1.47 | 1.08 | 1.31 |
| Limestone (kg) | 5.20 | 11.65e | 5.34 | 5.00 |
| Pesticides, herbicides, insecticides (g) | 47.5 | 5.1 | 29.1 | 16.7 |
| Seedlings (kg) | - | 30.3 | 29.1 | 44.1 |
| Diesel (machinery operation) (L) | 1.1 | 2.9 | 0.8 | 1.9 |
|  |  |  |  |  |
| **Inputs per L of ethanol** |  |  |  |  |
| Sulfuric acid (g) | - | 7.40 | 16.06 | 4.94 |
| Lime (g) | 10.85 | 11.00 | 17.97 | 7.48 |
| Cyclohexane (g) | - | - | 1.06 | 0.71 |
| Phosphoric acid (g) | - | - | - | 2.70 |
| Inorganic chemicals (g) | - | - | - | 0.044  |
| Zeolites (g) | - | - | - | 0.047  |

aSeabra et al. [1] apud Wang et al.[2];

bBased on average values from three studies [1,3,4], except for diesel use;

cBased on Macedo et al. [3]; a factor of +40% is applied to industrial inputs for BioGrace to encourage voluntary contribution from the private sector;

dBased on experts’ recommendations and literature;

eThe amount of limestone considered within GHGenius is an average value calculated based on Seabra et al. [1] with 450 kg CaO ha-1, Macedo et al. [3] with 366 kg CaO ha-1 and Macedo et al. [4] with 1,900 kgCaO ha-1, resulting in a much larger value than those assumed for the other models.

**Table 2S**. Main agricultural and industrial inputs for corn ethanol production

|  |  |  |  |
| --- | --- | --- | --- |
|  | GREETa | GHGenius | BioGraceb |
| **Inputs per tonne of corn** |  |  |  |
| N fertilizer (kg) | 16.7 | 17.2 | 13.3 |
| N in animal manure (kg) | - | 1.9 | - |
| P2O5 fertilizer (kg) | 5.7 | 5.0 | 8.9 |
| K2O fertilizer (kg) | 6.0 | 6.9 | 6.6 |
| Limestone (kg) | 45.3 | - | 412.0 |
| Pesticides, herbicides, insecticides (g) | 277.8 | 312.3 | 618.0 |
| Seeds (kg) | - | 2.32 | - |
| Diesel (machinery operation) (L) | 4.2 | 4.8 | 26.3 |
| Natural gas (L) | 2.1 | 8,706 | - |
| LPG (L) | 1.7 | 4.8 | - |
| Electricity (MJ) | 17.4 | - | - |
|  |  |  |  |
| **Inputs per L of ethanol** |  |  |  |
| Electricity (MJ) | 0.7 | 0.9 | -8.0 |
| Natural gas (MJ) | 6.1 | 7.9 | 27.1 |
| Coal (MJ) | 0.53 | 1.8 | - |
| Alpha-amylase (g) | 0.657 | - | - |
| Glucoamylase (g) | 1.41 | - | - |
| Ammonia (g) | 4.67 | 21.6 | - |
| Enzymes (g) | - | 5.0 | - |
| Sodium hydroxide (g) | 5.85 | 5.8 | - |
| Sulfuric acid (g) | 4.67 | 10.9 | - |
| Calcium oxide (g) | 2.8 | - | - |
| Yeast (g) | 0.71 | 3.5 | - |

aGREET considers three types of corn mills existent in the U.S. for the production of ethanol: dry mill without corn oil extraction (17.72%); dry mill with corn oil extraction (70.88%); and wet mill (11.40%) [5].

bA factor of +40% is applied to industrial inputs for BioGrace to encourage voluntary contribution from the private sector; Electricity coproduced with required steam is accounted as a credit to the product system.

**Table 3S**. Main agricultural and industrial inputs for wheat ethanol production

|  |  |  |
| --- | --- | --- |
|  | GHGenius | BioGracea |
| **Inputs per tonne of wheat** |  |  |
| N fertilizer (kg) | 18.0 | 21.0 |
| P2O5 fertilizer (kg) | 10.3 | 4.2 |
| K2O fertilizer (kg) | 0.83 | 3.1 |
| Sulphur fertilizer (kg) | 0.22 | - |
| Pesticides, herbicides, insecticides (g) | 316.1 | 448.3 |
| Seeds (kg) | 43.8 | 23.0 |
| Diesel (machinery operation) (L) | 8.5 | 19.8 |
|  |  |  |
| **Inputs per L of ethanol** |  |  |
| Electricity (MJ) | 10.8 | -5.6 |
| Natural gas (MJ) | 13.4 | 20.2 |
| Ammonia (g) | 13.9 | - |
| Enzymes (g) | 5.5 | - |
| Sodium hydroxide (g) | 1.6 | - |
| Sulfuric acid (g) | 4.9 | - |
| Yeast (g) | 4.0 | - |

aA factor of +40% is applied to industrial inputs for BioGrace to encourage voluntary contribution from the private sector. Industrial inputs considering a configuration with steam production from a natural gas CHP system.

**Table 4S.** Agricultural and processing yields assumed by the LCA models investigated in this study

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | GREET | GHGenius | BioGrace | VSB |
| **Sugarcane** |  |  |  |  |
| Agricultural yield (tonne/ha) | 86.7 | 85.3 | 68.7 | 80.0 |
| Ethanol yield (L/tonne of cane) | 81.0 | 80.0 | 87.0 | 85.2 |
| Surplus electricity (kWh/tonne of cane) | 75.0 | 10.7 | - | 26.1 |
|  |  |  |  |  |
| **Corn** |  |  |  |  |
| Agricultural yield (tonne/ha) | 10.5 | 11.1 | 3.88 | - |
| Ethanol yield (L/tonne of corn) | 426.3 | 405.0 | 448.2 | - |
| DDGSa (kg/tonne of corn) | 274.5 | 288.8 | 495.5 | - |
|  |  |  |  |  |
| **Wheat** |  |  |  |  |
| Agricultural yield (tonne/ha) | - | 2.80 | 5.21 | - |
| Ethanol yield (L/tonne of wheat) | - | 428.0 | 436.4 | - |
| DDGSa (kg/tonne of wheat) | - | 376.4 | 349.2 | - |

aDistiller's dried grains with solubles

**Table 5S**. Industrial inputs for corn ethanol production considered by the GREET model (per L of ethanol)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Unit | Dry mill w/o corn oil extraction | Dry mill with corn oil extraction | Wet mill |
| Alpha amylase | g | 0.66 | 0.66 | 0.71 |
| Gluco amylase | g | 1.43 | 1.42 | 1.53 |
| Yeast | g | 0.72 | 0.72 | 0.77 |
| Sulfuric acid | g | 1.23 | 1.22 | 1.31 |
| Ammonia | g | 4.71 | 4.67 | 5.03 |
| Sodium hydroxide | g | 5.91 | 5.86 | 6.31 |
| Calcium oxide | g | 2.82 | 2.79 | 3.01 |
| Natural gas | MJ | 6.24 | 6.12 | 9.56 |
| Electricity | MJ | 0.71 | 0.70 | 0.00 |
| Coal | MJ | 0.54 | 0.53 | 3.62 |

|  |  |  |  |
| --- | --- | --- | --- |
| Stage | Sugarcane | Corn | Wheat |
| GREET | GHGenius | BioGrace | VSB | GREET | GHGenius | BioGrace | GHGenius | BioGrace |
| Farming | 12.2 | 27.1 | 13.6 | 14.7 | 29.4 | 35.6 | 20.1 | 38.5 | 23.3 |
|  N2O emissions (fertilizers and residues) | 3.0 | 10.8 | 3.3 | 7.9 | 16.2 | 20.2 | 4.3 | 21.0 | 7.8 |
|  NPK fertilizer manufacture | 1.7 | 4.9 | 3.3 | 2.1 | 6.8 | 8.8 | 6.2 | 12.7 | 9.4 |
|  Limestone | 1.3 | 4.9 | 0.4 | 0.9 | 1.1 | 0.0 | 3.6 | 0.0 | 0.0 |
|  Straw burning | 0.9 | 0.0 | 4.9 | 1.0 | - | - | - | - | - |
|  Energy and fuel | 4.3 | 7.8 | 1.3 | 2.2 | 3.8 | 6.6 | 5.5 | 4.8 | 4.8 |
|  Other inputs | 1.1 | 0.7 | 0.4 | 0.6 | 1.5 | 0.0 | 0.5 | 0.0 | 1.3 |
|  |  |  |  |  |  |  |  |  |  |
| Feedstock transportation | 1.1 | 2.3 | 1.0 | 1.1 | 1.9 | 1.6 | 0.3 | 1.8 | 0.4 |
|  |  |  |  |  |  |  |  |  |  |
| Ethanol production | 2.3 | 5.8 | 0.9 | 0.7 | 37.8 | 37.3 | 21.5 | 48.8 | 19.3 |
|  Lime | 0.7 | 0.2 | 0.7 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
|  Bagasse combustion | 0.0 | 5.1 | 0.0 | 0.0 | - | - | - | - | - |
|  Natural gas | 0.0 | 0.0 | 0.0 | 0.0 | 19.7 | 21.8 | 21.5 | 38.3 | 18.9 |
|  Electricity | 0.0 | 0.0 | 0.0 | 0.0 | 4.6 | 5.9 | 0.0 | 8.2 | 0.0 |
|  Coal | 0.0 | 0.0 | 0.0 | 0.0 | 4.2 | 6.5 | 0.0 | 0.0 | 0.0 |
|  Other inputs | 1.6 | 0.5 | 0.2 | 0.3 | 9.3 | 3.5 | 0.0 | 2.3 | 0.4 |
|  |  |  |  |  |  |  |  |  |  |
| Ethanol shipping | 7.2 | 8.1 | 4.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
|  |  |  |  |  |  |  |  |  |  |
| Ethanol ground transportation | 1.0 | 2.6 | 3.1 | 1.0 | 1.2 | 1.6 | 1.5 | 1.6 | 1.5 |
|  |  |  |  |  |  |  |  |  |  |
| Use | 0.2 | 2.2 | - | 0.1 | 0.2 | 2.1 | - | 2.1 | - |
|  |  |  |  |  |  |  |  |  |  |
| Co-product credit | - | -4.3 | - | - | -12.8 | -16.7 | - | -24.5 | - |
|  |  |  |  |  |  |  |  |  |  |
| Net impact | 24.0 | 45.1 | 23.0 | 16.1 | 57.7 | 61.9 | 43.4 | 68.3 | 44.5 |

**Table 6S.** Allocated greenhouse gases emissions impacts per stage for the models investigated (in grams of CO2eq per MJ of ethanol)

**Table 7S**. Methods and parameters for dealing with co-products in the different models

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | GREET | GHGenius | BioGrace | VSB |
| Default method for treatment of coproducts | SubstitutionaEnergyb | Substitutionc | Energyd | Economice |
| Partitioning/credit |  |  |  |  |
|  Sugarcane |  |  |  |  |
|  Ethanol | 95.0% | 100% | 100% | 96.5% |
|  Electricity | 5.0% | -4.3 g CO2eq MJ-1 | - | 3.5%  |
|  Corn |  |  |  |  |
|  Ethanol | 100% | 100% | 54.6% | - |
|  DDGSh | -12.8 g CO2eq MJ-1 | -16.7 g CO2eq MJ-1 | 45.4% | - |
|  Wheat |  |  |  |  |
|  Ethanol | - | 100% | 59.5% | - |
|  DDGSf | - | -24.5 g CO2eq MJ-1 | 40.5% | - |

aSubstitution method in the GREET model is utilized for corn and wheat coproducts; whereas energy allocation is applied to surplus electricity generated in sugarcane ethanol production; surplus electricity of 75.0 kWh tonne of sugarcane-1 in 2015 is considered for sugarcane ethanol production; three types of mills are considered for the production of corn ethanol in the U.S.: dry mills with and without corn oil extraction representing 70.9% and 17.7%, respectively, and wet mills representing 11.4% of total mills; in addition to ethanol, dry mills produce DDGS that displace 78.12% corn, 30.72% soybean meal and 2.27% urea; whereas wet mills produce corn gluten meal (CGM) displacing 152.90% corn and 2.33% urea, corn gluten feed (CGF) displacing 100% corn and 1.52% urea, and corn oil displacing 100% soy oil;

bEnergy content of ethanol (LHV) = 21.3 MJ L-1;

cSubstitution method in GHGenius considers a credit equivalent to surplus electricity produced (10.7 kWh tonne of sugarcane-1) for sugarcane; credit equivalent to the DDGS produced (0.29 kg DDGS kg corn-1 and 0.38 kg DDGS kg wheat-1) displacing 0.78 kg corn kg DDGS-1 and 0.31 kg soybean meal kg DDGS-1 for corn and 0.45 kg wheat kg DDGS-1 and 0.55 kg soybean meal kg DDGS-1 for wheat; in addition to avoided CH4 emissions (3.74 g CH4 kg DDGS-1 equivalent to 2.8 g CO2eq MJ-1 of corn ethanol and 4.0 g CO2eq MJ of wheat ethanol-1);

dEnergy content of ethanol (LHV) = 26.8 MJ kg-1; energy content of dry DDGS = 16.0 MJ kg-1;

eEthanol price = 1.56 R$ L-1 (0.49 US$ L-1); electricity price = 182.5 R$ MWh-1 (57.03 US$ MWh-1), assuming US$ 1.00 = R$ 3.20;

fDistiller's dried grains with solubles.

**References**

[1] Seabra JEA, Macedo IC, Chum HL, Faroni CE, Sarto CA. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. Biofuels, Bioprod Biorefining 2011;5:519–32. doi:10.1002/bbb.289.

[2] Wang L, Quiceno R, Price C, Malpas R, Woods J. Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward. Renew Sustain Energy Rev 2014;40:571–82. doi:10.1016/j.rser.2014.07.212.

[3] Macedo, IC, Leal MRLV, da Silva J. Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil (in Portuguese) 2004.

[4] Macedo IC, Seabra JEA, Silva JEAR. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. Biomass and Bioenergy 2008;32:582–95. doi:10.1016/j.biombioe.2007.12.006.

[5] Wang M, Wu M, Huo H. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. Environ Res Lett 2007;2:024001. doi:10.1088/1748-9326/2/2/024001.