Updated Sugarcane and Switchgrass Parameters in the GREET Model

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Background

The feedstock from which a biofuel derives can have a significant effect on its life-cycle energy consumption and emissions of greenhouse gases (GHG). The aim of this document is to describe our approach to developing GREET parameters for key facets of sugarcane and switchgrass feedstocks that affect their life-cycle air emissions and energy consumption from the field (including the upstream energy to manufacture agricultural inputs such as fertilizer) to the conversion facility gate in the case of switchgrass. For sugarcane ethanol, we also revise aspects of the fuel's life cycle pertaining to the conversion facility including ethanol yield and embodied energy in the sugarcane mill buildings and equipment. A summary of data sources for corn stover and forest residue are provided elsewhere (Han et al. 2011). Note that although this document discusses switchgrass in the context of ethanol production, this crop could also be a feed to a process that directly produces hydrocarbon fuels, such as fast pyrolysis.

Sugarcane

GREET 1.8d uses sugarcane data from the 2002/2003 harvesting season. New data for more recent seasons are available and a number of life cycle analyses (LCA) of sugarcane ethanol have been published recently (Seabra et al. 2011, Macedo et al. 2008, Luo et al. 2009) that present new information. In the following sections, we discuss the development of sugarcane parameters for the new GREET release.

Agricultural Inputs

In this section, we consider agricultural inputs (fertilizers, agrochemicals) to sugarcane farming. Seabra et al. (2011) present a sugarcane ethanol LCA using the latest data available from the Centro de Tecnolgia Canavieira (CTC). These data include the amount of fertilizer that is applied to sugarcane fields. Table 1 records these values and compares them to the fertilizer application rates published in other studies. The final column of Table 1 contains the values adopted in the new GREET release.

The values used in GREET 1.8d derive from Macedo et al. (2004), which used CTC data from 2002. That reference presents data for fertilizer application both with and without application of fermentation residues (filter cake mud and stillage) to the soil. GREET 1.8d used the values that accounted for application of fermentation residues. Macedo et al. (2008) exclude residue application in the fertilizer application values they report. Seabra et al. (2011) report total application, accounting for conventional fertilizer replacement with residues. The new GREET release adopts this approach but does not assign credits for displaced impacts of conventional fertilizer production to sugarcane ethanol.

Table 1. Fertilizer, herbicide, and insecticide application rates for sugarcane production

Fertilizer or Agrochemical (g/metric ton cane)	Seabra et al. (2011)[a]	Macedo (2008)[b]	Macedo (2004)[c]	GREET 1.8d[d]	New GREET release
N	777	765	1,042.2	1,091.7	800
P_2O_5	249	431	539.9	120.8	300
K_2O	980	1096	1,746.7	193.6	1,000
$CaCO_3$	5,183			5,337.7	5,200
Herbicide	44	25.3		26.9	45
Insecticide	3	1.84		2.21	2.5

[a] From CTC data for 2008/2009 growing season
[b] From CTC data for 2005/2006
[c] Fertilizer data with no residue application for 6 year cycle of 1:4:1 planting : ratoon : reforming, and assuming no stillage application
[d] From Macedo et al. (2004) assuming residue application

In GREET 1.8d, corn and sugarcane have identical shares of three nitrogen-containing fertilizers, ammonia (70.7%), urea (21.1%), and ammonium nitrate (8.2%). Seabra et al. (2011), however, report the nitrogen fertilizer shares for sugarcane production as 14%, 49%, and 37% for ammonia, urea, and ammonium nitrate, respectively. In the new GREET release, nitrogen fertilizer shares for sugarcane production are those from Seabra et al. (2011).

Another revision from GREET 1.8d is the recalculation of the life-cycle energy consumption and air emissions associated with manufacturing fertilizers and agricultural chemicals in Brazil rather than in the United States. Brazil has significant capacity to manufacture these products domestically (FAO 2004) and it is unlikely that farmers purchase fertilizers and agrochemicals manufactured outside the country. The new GREET release uses the Brazilian electric grid mix, which relies heavily on hydroelectric power and therefore has lower air emissions than the more carbon-intensive U.S. grid, to calculate total energy consumed and emissions associated with electricity consumption during agricultural input production. With the exception of $CaCO_3$, as discussed below, point-of-manufacture energy consumption for each chemical derives from U.S. and European data and remains unchanged from GREET 1.8d. The new GREET release continues to use U.S. values for fossil fuel production (residual oil, diesel, natural gas) and transport distances from factory to field for fertilizers and agrochemicals.

Finally, the energy consumption of $CaCO_3$ production in Brazil was revised based on data from seven Brazilian agricultural limestone production facilities (Seabra 2011) as shown in Table 2. GREET 1.8d used values equivalent to those for K_2O production in the U.S.

Table 2. Energy inputs to $CaCO_3$ manufacturing in Brazil

Parameter (mmBtu/ton)	GREET1.8d	New GREET release
Natural gas consumption	1.053	0
Electricity consumption	1.638	0.022
Diesel fuel consumption	1.209	0.08

Harvest

Traditionally sugarcane farmers burned the cane in the field prior to manually cutting and collecting it. Air emissions from the burning, however, have been a concern and the federal and state governments have instituted regulations to scale back burning, with burning completely banned in 2030 (Macedo et al. 2011).

Brazilian sugarcane farms have phased out crop burning more swiftly than the law requires. Seabra et al. (2011) report that 65% of sugarcane was burned prior to harvest in the 2008/09 season. GREET 1.8.d assumed that sugarcane farmers burn 80% of sugarcane prior to harvesting in 2010. To reflect this accelerated adoption of mechanized harvest in place of traditional burn and manual gathering techniques, the new GREET release incorporates values of 65% and 20% of cane burned in the field in 2010 and 2015, respectively. This is a conservative estimate; the actual rate of burning may fall much faster due a protocol put forth by the industry organization UNICA proposing complete elimination by 2017 (UNICA 2009).

Similarly, mechanical harvest is becoming more prevalent, and this may affect the energy consumption of farming sugarcane. Seabra et al. (2011) report 48% mechanical harvesting, compared with the 35% considered in GREET. However, the impact of this change may or may not be significant, due to the existing use of machinery even in manual harvesting methods (Wang 2005). In the new GREET release, the production energy of sugarcane has been increased based on newly available data. Seabra et al. (2011) provide the total volume of diesel fuel consumed in sugarcane production, including fuel consumed during transport to processing facilities, as 29 gal/acre. These authors' analysis assumes a transport distance of 13 miles and a transportation energy efficiency of 131 tonne miles/gal (by truck). For two-way truck travel, the energy consumption is 0.10 gal/tonne. The yield per acre is 14 metric tons. Diesel fuel consumption for feedstock production is then 92,942 Btu/tonne cane. Macedo et al. (2008) provide the fuel consumption for the following agricultural operations in the 2005/2006 growing season: planting the cane, managing the ratoon (the new cane growing from stubble left behind after harvest), harvesting, and operating loaders and tractor haulers. The total diesel fuel these activities consumed was 96,051 Btu/tonne cane. In the new GREET release, we use the average of these two values, or 95,000 Btu/tonne cane. This value is significantly larger than the feedstock production energy in GREET1.8d, 41,952 Btu/tonne. The increase in fuel consumption may be due to increased mechanization of harvest as farmers reduce burning in compliance with law.

GREET allows a user to analyze life cycle impacts of sugarcane ethanol with and without energy embedded in farming equipment. The values in GREET 1.8d derive from Macedo et al. (2004). Macedo et al. published new LCA results in 2008, but their estimates for farm equipment embedded energy did not change. Accordingly, we did not modify this value in the new GREET release.

Finally, the new GREET release adopts a dry straw yield of 0.14 dry tonne straw/dry tonne cane (UNICA 2009).

Conversion of Sugarcane to Ethanol

Seabra et al. (2011) report total fossil energy consumption during sugarcane conversion to ethanol as 305 Btu/gal. The value for this parameter in GREET 1.8d (251 Btu/gal) has been updated to a value of 300 Btu/gal to reflect Seabra et al.'s result. Seabra et al. (2011) report that current technology recovers 90% of sugar in the cane. Further yield increases through 2020 will likely come from enhancements in cane quality rather than technology improvements, so GREET uses 300 Btu/gal through this year. GREET assumes that all fossil fuel consumed during sugarcane conversion is lubricant (residual) oil.

GREET allows users to decide whether to include the embedded energy in buildings and equipment at sugarcane mills in model calculations. The GREET 1.8d values for these parameters were from Macedo et al. (2004). Since that publication Macedo and co-authors adjusted embodied energy coefficients and mill scale. Consequently, these authors updated sugar mill construction values in their 2008 publication to be 758 Btu/gal and 20 Btu/gal for constructing the buildings and equipment at a sugarcane mill, respectively. These values, now adopted in the new GREET release, are significantly lower than those in Macedo et al. (2004).

Bagasse

Over the past decade, the combustion of bagasse to generate electricity has risen quickly. Combustion technology continues to develop, with new high-pressure boilers coming on-line and plans to utilize sugarcane trash poised to provide great increases in the power generated. The current value for electricity export, 0.96 kWh per gallon ethanol or 23 kWh per wet tonne cane, is reasonably accurate for the current industry (UNICA 2009). UNICA (2009) reports that the amount of electricity sugarcane mills have contracted with power distribution companies to provide in 2012 is 65 kWh per ton of cane. The association predicts that in the future excess power generation values will exceed 100 kWh per ton of cane. Macedo et al. (2008) predict 135 kWh/wet tonne cane by 2020, assuming full implementation of high-pressure boilers and recovery and utilization of 40% of sugarcane trash and 100% of bagasse. The new GREET release therefore includes a time scale for electricity export to the grid for sugarcane mills as depicted in Table 3. In GREET, the exported electricity is modeled as being generated from the marginal electricity supply, assumed to be 100% natural gas. This approach aligns with that of Seabra et al. (2011). Additionally, these authors note that as field residue is added to the electricity mix, increasing electricity exported from sugar mills, it may become necessary to reconsider applying the displacement co-product allocation methodology to electricity that sugar mills export.

Table 3. Time series for electricity co-produced with sugarcane ethanol

Year	Electricity Export (kWh/gal ethanol)	kWh/tonne cane
Prior to 2010	0.96	23
2010	1.0	25
2015	3.1	75
2020	4.2	100

Land-use Change (LUC)

At present, GREET does not include LUC GHG emissions for sugarcane.

Switchgrass

Switchgrass is a tall perennial grass that has great potential as a biofuel feedstock in a wide variety of climates (Guretzky et al. 2011). Scientific understanding of switchgrass agronomy and biology continues to evolve with new studies joining the literature frequently. In the following sections, we discuss the development of switchgrass parameters for the new GREET release.

Production

Switchgrass has a two- or three-year establishment period after planting (Parrish and Fike 2005). Sustainable yields are approximately 15 Mg/ha (Parrish and Fike 2005) although field studies report yields as high as 20 Mg/ha (Smeets et al. 2009). In the United States, Guretzky et al. (2011) report a yield range between 10.4 to 15.5 Mg/ha. Yields and nutrient requirements are undoubtedly location-dependent. For example, Guretzky et al. (2011) report that switchgrass response to nitrogen fertilizer may be less pronounced in northern locations than in southern locations. Further, switchgrass management practices are still evolving. For these reasons, adopting a single value for fertilizer application rates is difficult.

Table 4 outlines fertilizer and herbicide input rates that three recent studies report. We consider only data for a single harvest each year, based on information in the literature that this approach is preferred over biennial harvesting for harvest of switchgrass for biomass production (Parrish and Fike 2005). Guretzky et al. (2011) examined the impacts of harvest system and N fertilizer rates on biomass yield and nutrient composition of switchgrass at sites in the southern Great Plains. These authors reported biomass yield as a function of N application rate. As Figure 1 illustrates, above 8,000 g N/dry ton, the switchgrass yield does not increase and may even decline. We include averages of the results for a once-per-year harvest taken after seed set and after frost for a fertilization rate (8,337 g N/dry ton) that produced a yield of 14.7 Mg/ha. Bai et al. (2010) conducted a life cycle analysis of switchgrass-derived ethanol and modified agricultural input data from Bullard and Metcalfe (2001) such that fertilizer is applied in every year, not just in the establishment year. Parrish and Fike (2005) published a comprehensive review of switchgrass agronomy for biofuel production and reported N application rates at six sites in the United States and Canada that had one harvest per year. These rates (g/ha) were converted to mass of nitrogen applied per mass switchgrass harvested assuming a yield of 15 Mg/ha.

Table 4. Agricultural input rates for switchgrass production

Input (g/dry ton)	Guretzky et al. (2011)	Bai et al. (2010)	Parrish and Fike (2005)	Adopted for GREET
N	8,000[a]	7,700[a]	6,300	7,300
P	50[b]	150[c]		100
K	200[d]	300[e]		200
Lime		11,500		0
Herbicides		900		28

a. As ammonium nitrate
b. As CaH_2PO_4
c. As P_2O_5
d. As KCl
e. As K_2O

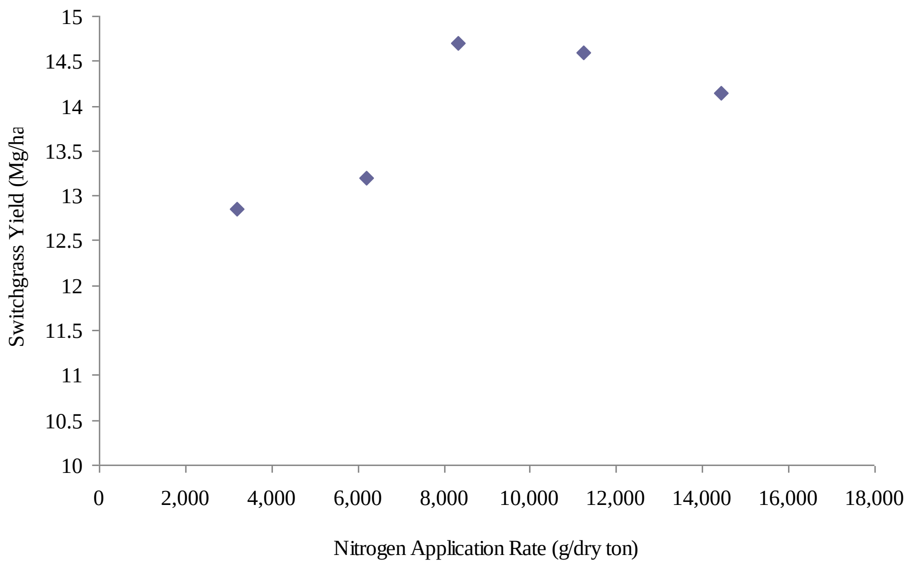

Figure 1. Switchgrass yield (Mg/ha) response to nitrogen application rate (g/dry ton) (Guretzky et al. 2011)

The nitrogen fertilizer application rate adopted for use in GREET is the average of the three studies' values for this parameter. The previous version of GREET included a value of 10,635 g N/dry ton and reducing this value is consistent with evidence that nitrogen is often overapplied on switchgrass stands (McLaughlin and Kszos 2005). Both Guretzky et al. (2011) and Bai et al. (2010) indicated that the identity of the N fertilizer was ammonium nitrate. As more data becomes available on N fertilization of switchgrass, GREET may be revised to reflect different N fertilizer shares. (Default shares of N fertilizer are 70.7%, 21.1%, and 8.2% for ammonia, urea, and ammonium nitrate, respectively.)

For P_2O_5 and K_2O, we average Bai et al. (2010) and Guretzky et al.'s (2011) data, which seem consistent with literature reports that switchgrass is P and K thrifty and would not require much of these fertilizers (Parrish and Fike 2005). Insufficient data were available to alter GREET 1.8d's values for herbicide application rate. Similarly, uncertainty surrounding benefits and application rates of lime applications (Parrish and Fike 2005) preclude selection of a value for $CaCO_3$ application at this point. As no consensus has been reached concerning optimal fertilization rates for switchgrass (Parrish and Fike 2005, Guretzky et al. 2011), we will continue to monitor the literature on this topic and update GREET in subsequent releases.

Harvesting

Hess et al. (2009) provide a detailed investigation of the techniques and energy consumption during switchgrass harvesting. Table 5 outlines each of the steps during switchgrass harvest and the corresponding energy consumption. The total of these steps, 123,700 Btu/dry ton replaces a higher value in GREET 1.8d, 217,320 Btu/dry ton. Further processing of the feedstock to a format appropriate for feeding to a conversion process by grinding, for example, is included in the conversion step energy consumption (e.g., Han et al. 2011).

Table 5. Energy use during switchgrass harvest (Hess et al. 2009)

Process	Energy use (Btu/dry ton)
Condition and windrow	36,100
Baling	69,600
Roadside/Loading	18,000
Total	123,700

LUC

GREET's companion tool, CCLUB, is being updated to include LUC associated with the use of switchgrass as a biofuel feedstock.

Life cycle results with updated parameters

Figure **2** displays life-cycle GHG emissions for corn ethanol, switchgrass-derived ethanol, and sugarcane ethanol produced under two scenarios. The corn ethanol scenario included in Figure **2** is for a natural gas-fired, dry mill plant with dry distillers' grains solubles (DDGS) as a co-product. One sugarcane ethanol scenario does not account for energy embodied in sugarcane infrastructure (farming equipment, mill buildings and equipment) but includes electricity the sugar mill exports to the grid. The second includes infrastructure in the simulation and shows an increase of 13% in life-cycle GHG emissions. Regardless of scenario, sugarcane ethanol displays significantly lower life-cycle GHG emissions than corn ethanol. GREET modeling of the sugarcane ethanol life cycle, however, does not include GHG emissions from LUC, whereas the calculation of corn ethanol life-cycle GHG emissions does include LUC emissions (15,013 grams CO_2e/mmBtu). In the case of switchgrass-derived ethanol, reducing harvest energy and nitrogen application rates, as compared to GREET 1.8d, decreased the life-cycle GHG emissions of switchgrass-derived ethanol. This fuel now exhibits a small net reduction in CO_2e emissions during its life cycle.

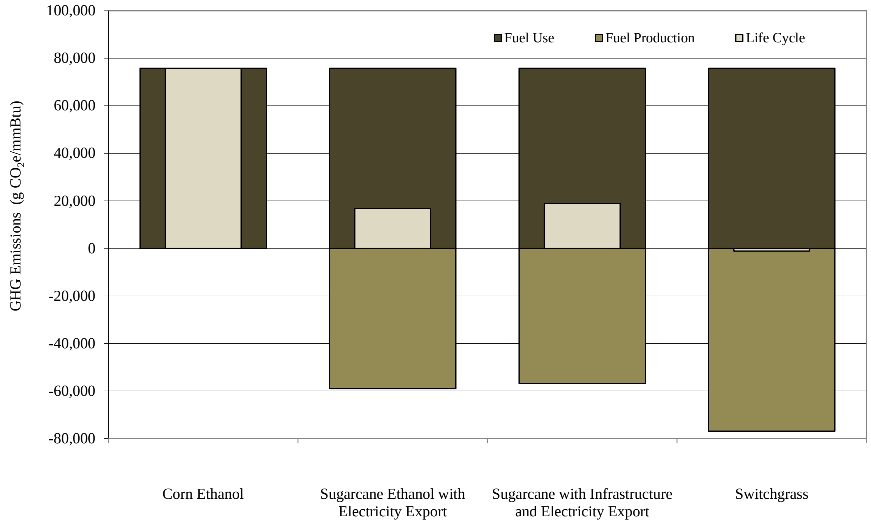

Figure 2. Life Cycle GHG emissions of corn ethanol, sugarcane, and switchgrass-derived ethanol

A similar pattern is observed in Figure 3, which displays fossil energy consumption of corn, sugarcane, and switchgrass-derived ethanol. (Corn ethanol life cycle results are for a natural gas-fired dry mill producing WGDS as a co-product.) Switchgrass-derived ethanol exhibits a net reduction in fossil fuel use.

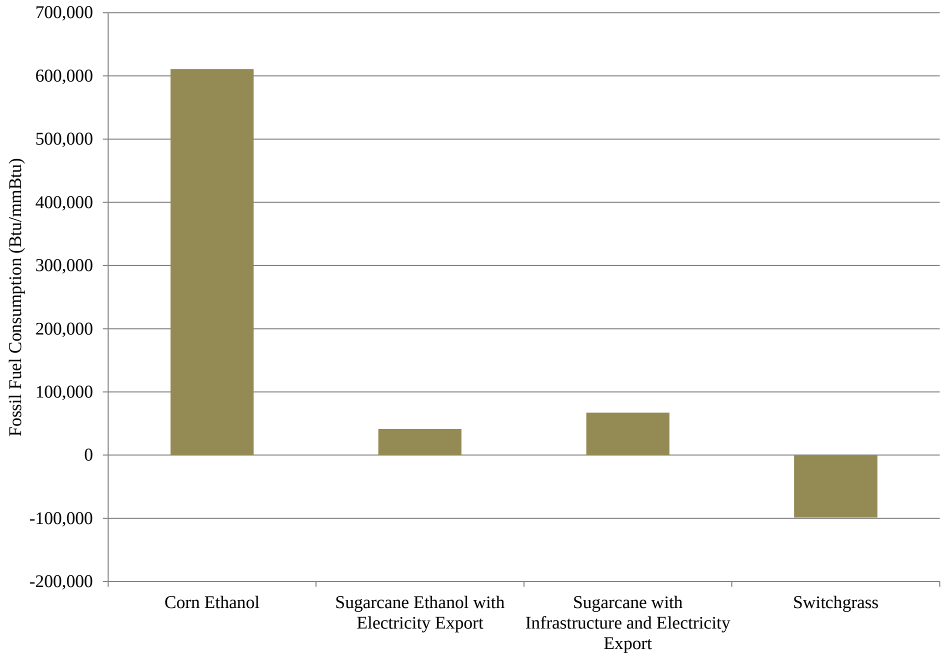

Figure 3. Life-cycle fossil fuel consumption of corn, sugarcane, and switchgrass-derived ethanol

Figure 4 displays GHG emissions during each stage of sugarcane and switchgrass ethanol's life cycle for scenarios that include co-production of electricity but exclude infrastructure impacts. In the case of sugarcane ethanol, biomass burning in the field is the largest contributor to life-cycle GHG emissions, followed by feedstock harvesting. As discussed earlier, Brazilian law will prohibit sugarcane harvest by burning in 2030, dropping these emissions to zero. N_2O emissions from fertilizer use is the largest GHG emissions contributor for cellulosic ethanol. Figure 5 details the contribution of various components of sugarcane and switchgrass-derived ethanol's life cycle to total energy consumption. In both cases, fertilizer consumes no more than 5% of the life-cycle energy. This result indicates that although fertilizer rates are uncertain, especially in the case of switchgrass, they have minimal impact on life cycle energy consumption.

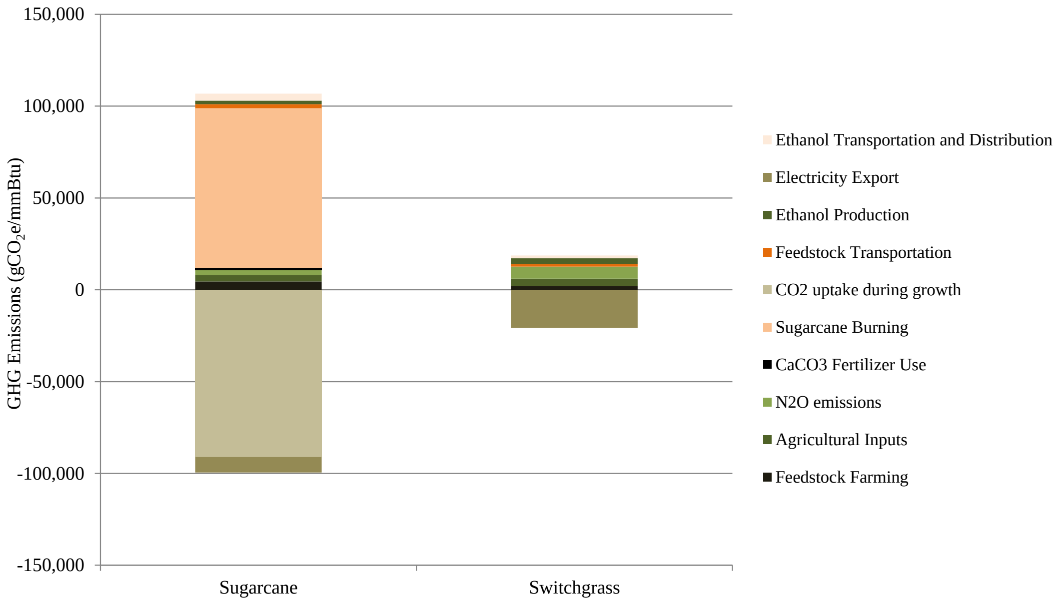

Figure 4. Contributions of sugarcane and switchgrass-derived ethanol life cycle stages to GHG emissions with electricity export and without infrastructure ($gCO_2e/mmBtu$)

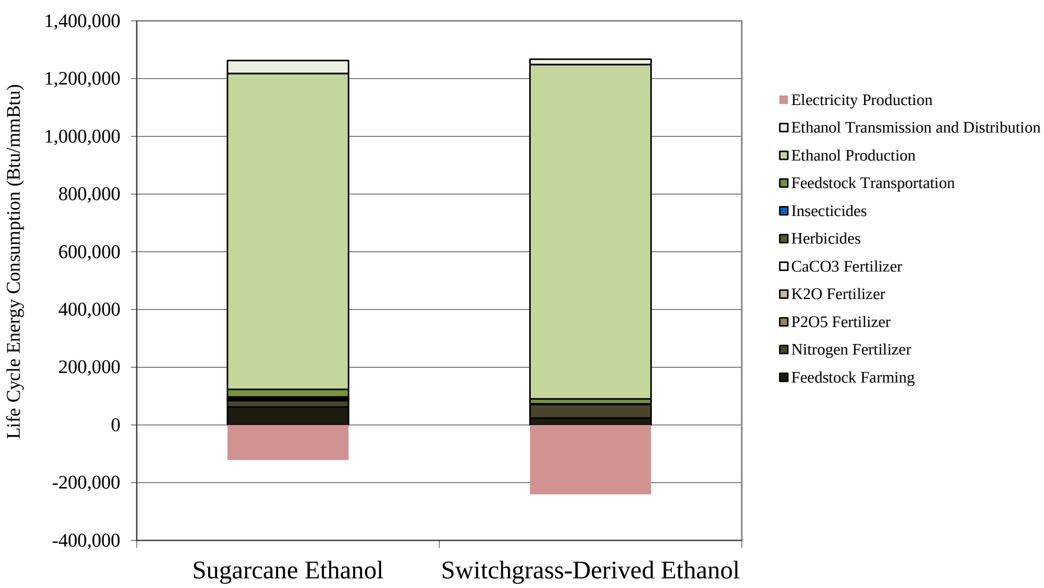

Figure 5. Contributions of sugarcane ethanol life cycle stages to total energy consumption (Btu/mmBtu)

Outstanding Issues

Generally, Argonne will track advances and changes in production and conversion technologies for the two feedstocks considered in this report, sugarcane and switchgrass. Below, we discuss specific elements of these feedstocks' life cycles that may merit further investigation.

Farming

Sugarcane farming is evolving as burning phases out and mechanization increases. Argonne will update the parameters in GREET that reflect field conditions as new data becomes available from CTC or other sources. Switchgrass harvesting as a biofuel feedstock is in its early stages and more information will become available as experience grows with appropriate fertilization rates and harvesting techniques.

Land-use Change

As mentioned earlier, the CCLUB companion tool that estimates LUC emissions will be updated to include switchgrass.

Spatial Factors

Especially in the case of switchgrass, many aspects of a feedstock's production are dependent on local factors such as weather and soil type. Although GREET is not currently configured to specifically consider location-dependent factors, users can enter user-defined values for farming quantities such as fertilizer application rates and harvesting energy consumption to develop location-specific results.

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