Estimates of the land-use-change carbon intensity of ethanol from switchgrass and corn stover using the GCAM 4.0 model

Prepared for Environmental Working Group
by
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September 22, 2015

1. Introduction

The purpose of this study is to estimate the land-use change (LUC) emissions from increased production of cellulosic ethanol produced from corn stover and switchgrass in the U.S. For this analysis, we used version 4.0 of the Global Change Assessment Model (GCAM 4.0), a global long-term economy, energy, and environment model developed and managed by the Pacific Northwest National Laboratory (PNNL) (Clarke, Lurz et al. 2007; Calvin, Clarke et al. 2011).

The general approach is to create a reference scenario similar to EPA's reference case used in its RFS2 analysis, and estimate the change in emissions resulting from a given change in production of stover ethanol and of switchgrass ethanol. More specifically, we calibrated GCAM to match the RFS2 volumes of domestically produced biofuels in years 2020 and 2025 (*Baseline Scenario*), shown in Table 1.

Table 1. Baseline RFS2 biofuel volumes

Fuel	Volume (10^9 gal/y)	Notes
Corn ethanol	15	In 2020-2050
Cellulosic ethanol	2.92	In 2020-2050
Biodiesel	0.85	In 2020-2050
Fischer-Tropsch biofuels	*see note*	3.87 B gal/y in 2020; 6.52 B gal/y in 2025-2050

To calculate the carbon intensity of switchgrass ethanol, we modeled an increase in cellulosic ethanol production by 2 billion gallons per year in 2025 and beyond, with the incremental production sourced entirely from switchgrass. We refer to this case as the *switchgrass ethanol scenario*.

We adopted a similar approach for stover ethanol, except that the incremental biomass production was sourced from crop and forest residue, with the predominant source being

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corn stover (*stover ethanol scenario*). Table 2 shows the shock volumes in gallons and exajoules (EJ), and the ILUC emissions intensities under two accounting approaches.

Table 2. Summary of results. LUC-only counts only CO_2 from the oxidation of soil and biomass carbon; RFS-style adds to this the (100y) CO_2-equivalent emissions of N_2O and/or CH_4 resulting from changes in rice and livestock production and the production and use of fertilizer.

Fuel	Shock (10^9 gal/y) (EJ/y)	Land-use change only (g CO_2e MJ^{-1})	RFS-style accounting (g CO_2e MJ^{-1})
Corn stover ethanol	2 (0.17)	-2.5	-2.3
Switchgrass ethanol	2 (0.17)	45	52

2. Carbon intensity metrics

To allow comparison of our results with the analyses performed by EPA for the Renewable Fuel Standard (RFS2) regulation, we match as closely as possible the emissions intensity metric used in EPA's analysis and expressed in units of g CO_2e MJ^{-1} biofuel. The denominator represents the change in biofuel production (gallons per year converted to megajoules) used to "shock" the model. For both the baseline and switchgrass scenarios, the change in cellulosic ethanol production was linearly interpolated between 5 year time-steps to produce annual quantities, and then summed over the 30-year period modeled.

The numerator represents the change in CO_2e emissions resulting from the shock. In EPA's RFS2 analysis[2], the numerator included changes in:

a. Global soil and biomass carbon stocks (emissions or sequestration) and other land-use change (LUC) emissions, expressed as CO_2
b. Emissions of methane (CH_4) resulting from changes in global rice and livestock production
c. N_2O emissions related to crop fertilization
d. Changes in on-farm energy use resulting from crop shifting

Unlike EPA, changes in energy use in farm operations are *not* included in GCAM results.

We summed emissions weighted by their 100-year IPCC (AR4) global warming potential (GWP) values (Forster, Ramaswamy et al. 2007), summed, and linearly interpolated results

[2] We note that other jurisdictions define the LUC emissions intensity differently. For the Low-Carbon Fuel Standard, the California Air Resources Board includes only changes in soil and biomass carbon stocks and related land-clearing emissions.

projected for 5-year time-steps to produce annual values.[3] The resulting emissions intensity is expressed in units of g CO_2e MJ^{-1}. We also present results for LUC emissions only.

2.1. Challenges of modeling specific cellulosic biofuel pathways

While corn and cane ethanol are represented in GCAM as distinct feedstock-biorefining-fuel pathways, all cellulosic feedstocks are aggregated into a homogenous “regional biomass”, which serves as the input to various biomass-consuming processes for liquid fuel production as well as for other uses. Figure 1 presents a schematic of the biomass and biofuels sectors in GCAM.

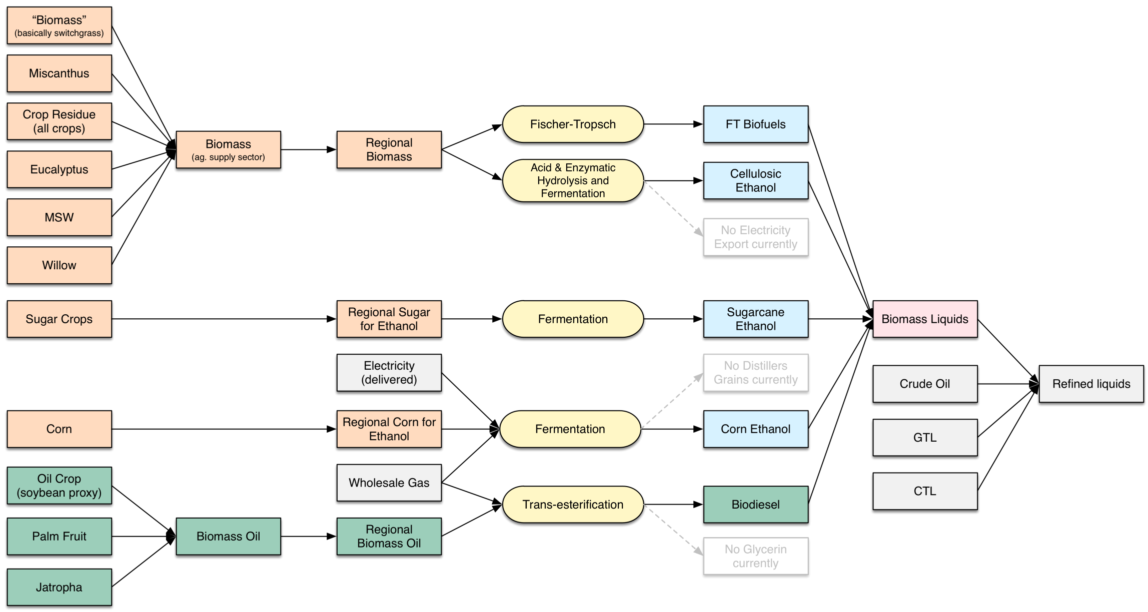
In GCAM, the "regional biomass" market incorporates biomass from crop residue as well as from forestry residue, municipal solid waste (MSW), and purpose-grown energy crops. In addition to use in the production of liquid biofuels, regional biomass is consumed by the electricity sector and is an input to the "delivered biomass" market subsector, which in turn provides inputs to industrial and commercial sector.

Several of the biomass sources (e.g., Miscanthus, Willow, Eucalyptus) occur in only a couple of regions. GCAM does not explicitly model “switchgrass”; however, the generic purpose-grown “biomass” in the U.S. is modeled on switchgrass.

Crop and forestry residues are a “secondary” output in GCAM, which means their availability is determined by the primary product (timber or crops), while the quantity harvested is determined by the market price of regional biomass, constrained by a requirement to leave a fixed amount (kg/ha) unharvested to control erosion. A challenge with modeling corn stover ethanol in GCAM is that it is not possible to create a market for secondary outputs, so we cannot directly constrain corn stover (or any residues) to a desired quantity. Rather, we must adjust the supply curves and/or erosion control parameters to affect which residues are available and in what quantities.

[3] We configured GCAM to report LUC emissions on an annual basis since linear interpolation of annual values at 5-year time-steps cannot correctly reproduce total emissions. All other GHG emissions were interpolated as described.

Figure 1. Schematic of biofuel pathways in GCAM. Although the default model does not include distillers grains, we added these as a second output of the corn ethanol production process.



3. GCAM reference and EWG baseline scenarios

The following tables compare key results for the standard GCAM reference and the EWG baseline scenario. The biofuel volumes in the EWG baseline match the targeted RFS2 volumes with minimal distortion of prices or quantities, as shown in the tables below. The EWG baseline includes the modifications from the GCAM reference assumptions shown in Table 3.

By default, the market for biomass is global in GCAM. We implemented instead a separate U.S. market to prevent knock-on effects in other regions from changes in cellulosic ethanol production in the U.S., so that additional domestically produced biomass feedstock is consumed entirely in the U.S., and all bioenergy produced in the U.S. is based on domestically produced biomass. The rest of the world's regions continue to trade biomass.

To match RFS2 projected production volumes of corn ethanol, cellulosic ethanol, FT biofuels, and biodiesel, we implemented the following changes:

1. Created markets for each of these biofuels and taxed or subsidized the fuel so that production was constrained to the desired level.
2. Allowed introduction of FT biofuels and cellulosic ethanol in 2015. (By default they become available in 2020, making it difficult to ramp up production as desired.
3. To produce a cellulosic ethanol scenario sourced predominantly from corn stover, we restricted the response of other crop residues, forest residues, and MSW, as described in Table 3.

Table 3. Modifications to GCAM reference to produce EWG baseline

GCAM Reference	EWG Baseline	Rationale
Biomass is traded globally.	The U.S. has its own regional biomass market; the rest of the world trades globally.	This minimizes cascade effects of manipulating biomass markets in the U.S..
Distillers grains from corn ethanol production are not represented.	Included DDGS output from corn ethanol conversion process as animal feed. (Further, corn ethanol conversion costs and efficiency factors were adjusted to match EPA assumptions.)	Leaving out DDGS overestimates land-use changes.
FT biofuels and cellulosic ethanol aren't available until 2020.	These fuels become available in 2015.	This is necessary to allow rapid scale-up to the target.
FT biofuel non-energy cost starts at about 1975$2.75 in 2020 and declines somewhat over time.	FT biofuel non-energy-cost is increased to 3.25 before 2030 and to 4.10 from 2030 onward.	This makes the subsidy constraint binding in all years. Otherwise FT biofuels would need a tax in some years and subsidy in others (not possible.)
Residue supply curves allow up to 25% of residue to be harvested at 1975$1.20, 65% at 1975$1.50, and 100% at $10 for all crops and regions*	Changed these to 25% at $1.50 and 50% at $2.00 and (NB: prices remain under $6 in all cases.)	Ensure that residue is sourced predominantly from corn stover.
Forest residue supply curve allows 60% harvesting at $1.20 and 80% at $1.50*	Changed these to 10% at $2.50 and 80% at $4.00.	Reduces response of these residues to changes in biomass demand.
Municipal solid waste*	Reduced the supply elasticity and increased the price of MSW.	Reduces response of MSW to changes in biomass demand.
Corn stover has same supply curve as other residues, in all regions.	Modified U.S. corn stover supply curve to allow: 60% at $2.00, and 85% at $1.45.	Stover supply responds more readily to biofuel feedstock demand.
N/A	Created tax on cellulosic ethanol, and subsidies on FT biofuels, corn ethanol, and biodiesel.	Required to force GCAM to produce these fuels at the desired levels.
About 90% of forest land is "protected", i.e., not available for conversion.	Land protections have been removed.	To ensure that the reference case does not underestimate forest conversion.

* These changes ensure that residue and waste for cellulosic ethanol is sourced predominantly from corn stover in the corn stover ethanol scenario. They were implemented in the baseline although they were needed only for the corn stover ethanol scenario. These changes do not affect the results when modeling switchgrass ethanol scenario, but we include them here so that both fuel shocks are compared to an identical baseline. Note that the percentage harvested shown is the percentage of residue remaining after accounting for the amount required to be left behind for erosion control.

3.1. Fuel production volumes

Table 4 and Table 5 show the volume of liquid fuels produced, in exajoules (EJ = 10^{12} MJ). Comparing the GCAM reference with the EWG baseline, we see that the baseline meets the designated target volumes from 2025 through 2050. The total volume of fuel produced is very similar between the two cases.

Table 4. GCAM Reference: Refined liquid fuel production in the U.S., by technology (EJ)

Technology	2015	2020	2025	2030	2035	2040	2045	2050
FT biofuels	0.00	0.29	0.47	0.66	0.83	1.00	1.14	1.27
biodiesel	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01
cell ethanol	0.00	0.35	0.56	0.78	1.00	1.20	1.37	1.53
coal to liquids	0.00	0.80	2.03	3.02	3.90	4.80	5.61	6.35
corn ethanol	1.48	1.28	1.19	1.13	1.05	1.01	0.95	0.91
gas to liquids	0.00	0.82	2.04	2.97	3.72	4.37	4.84	5.16
oil refining	34.77	33.77	31.87	30.25	28.93	28.23	27.79	27.69
TOTAL	**36.28**	**37.33**	**38.18**	**38.82**	**39.45**	**40.62**	**41.71**	**42.92**

Table 5. EWG Baseline: Refined liquid fuel production in the U.S., by technology (EJ)

Technology	2015	2020	2025	2030	2035	2040	2045	2050
FT biofuels	0.37	0.50	0.85	0.85	0.85	0.85	0.85	0.85
biodiesel	0.04	0.11	0.11	0.11	0.11	0.11	0.11	0.11
cellulosic ethanol	0.00	0.23	0.23	0.23	0.23	0.23	0.23	0.23
coal to liquids	0.00	0.00	1.42	2.61	3.64	4.69	5.61	6.47
corn ethanol	1.00	1.21	1.21	1.21	1.21	1.21	1.21	1.21
gas to liquids	0.00	0.00	1.43	2.56	3.47	4.26	4.83	5.24
oil refining	34.90	35.10	32.92	31.32	30.04	29.39	29.01	28.97
TOTAL	**36.31**	**37.15**	**38.17**	**38.89**	**39.54**	**40.75**	**41.85**	**43.08**

3.2. Purpose-grown biomass production

The quantity of purpose-grown biomass (effectively, switchgrass) in the U.S. is shown in Table 6 (GCAM reference) and Table 7 (EWG baseline). By default, GCAM produces substantial quantities of both FT biofuel and cellulosic ethanol, which require a large quantity of biomass. Since we (i) hold the volumes of FT and cellulosic ethanol to lower levels, (ii) separated the U.S. from the global biomass market, and (iii) made corn stover more readily available, the reduction in fuel demand translates into a reduction in biomass demand.

Table 6. GCAM Reference: Purpose-grown biomass in the U.S. (EJ)

2015	2020	2025	2030	2035	2040	2045	2050
0.00	1.78	3.35	5.24	7.04	7.81	8.33	8.70

Table 7. EWG Baseline: Purpose-grown biomass in the U.S. (EJ)

2015	2020	2025	2030	2035	2040	2045	2050
0.00	1.79	2.93	3.61	4.18	4.58	5.00	5.45

3.3. Select prices

Table 8 and Table 9 show prices of select feedstocks and end products, again, mainly for comparison to show that the EWG baseline does not distort prices very much.

Table 8. GCAM Reference: Select prices in the U.S. by technology (1975$/GJ)

Sector	2015	2020	2025	2030	2035	2040	2045	2050
refined liquids end-use	5.90	5.92	5.91	5.96	6.01	6.06	6.09	6.12
regional biomass	1.98	1.93	1.89	1.85	1.83	1.86	1.89	1.92
regional biomass oil	10.25	9.57	9.37	9.19	9.05	8.91	8.78	8.66
regional corn for ethanol	3.57	3.49	3.45	3.40	3.39	3.38	3.37	3.36
regional oil	3.48	3.57	3.64	3.71	3.78	3.84	3.88	3.90
regional sugar for ethanol	7.40	6.97	6.77	6.61	6.49	6.38	6.28	6.19
traded unconventional oil	3.84	3.70	3.71	3.71	3.71	3.72	3.73	3.74

Table 9. EWG Baseline: Select prices in the U.S. by technology (1975$/GJ)

Sector	2015	2020	2025	2030	2035	2040	2045	2050
refined liquids end-use	5.89	5.99	5.90	5.92	5.96	6.01	6.04	6.06
regional biomass	2.16	1.92	1.86	1.77	1.73	1.74	1.76	1.77
regional biomass oil	9.93	9.70	9.47	9.27	9.12	8.97	8.83	8.70
regional corn for ethanol	3.43	3.42	3.39	3.36	3.35	3.35	3.34	3.33
regional oil	3.51	3.57	3.64	3.72	3.79	3.85	3.88	3.91
regional sugar for ethanol	7.22	6.99	6.77	6.61	6.49	6.38	6.28	6.19
traded unconventional oil	3.69	3.70	3.71	3.71	3.71	3.72	3.73	3.74

3.4. Residue production

Projected residue production is shown in Table 10 (GCAM Reference) and Table 11 (EWG Baseline). By design, the EWG Baseline results in more corn stover production, which inevitably results in somewhat less production of residues from other crops. Since we hold biomass-based fuel volumes constant over time, the total residue production in the EWG baseline varies less than in the GCAM Reference case. Here, we were aiming mainly to avoid large distortions in the production of residues other than corn stover.

Table 10. GCAM Reference: Residue production by crop (EJ)

Crop	2015	2020	2025	2030	2035	2040	2045	2050
Corn	0.87	0.87	0.87	0.89	0.95	1.01	1.06	0.87
FiberCrop	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
MiscCrop	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Forestry	0.47	0.48	0.48	0.49	0.52	0.55	0.59	0.47
OilCrop	0.11	0.11	0.12	0.14	0.16	0.19	0.21	0.11
OtherGrain	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Rice	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.04
Root_Tuber	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
SugarCrop	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Wheat	0.19	0.22	0.25	0.26	0.28	0.31	0.33	0.19
TOTAL	1.80	1.84	1.87	1.92	2.07	2.21	2.35	1.80

Table 11. EWG Baseline: Residue production by crop (EJ)

Crop	2015	2020	2025	2030	2035	2040	2045	2050
Corn	2.60	2.36	2.36	2.31	2.33	2.45	2.57	2.69
FiberCrop	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03
MiscCrop	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Forestry	0.26	0.23	0.22	0.21	0.21	0.22	0.23	0.25
OilCrop	0.09	0.09	0.09	0.09	0.10	0.12	0.14	0.15
OtherGrain	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Rice	0.04	0.03	0.03	0.03	0.02	0.03	0.03	0.03
Root_Tuber	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
SugarCrop	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
Wheat	0.15	0.15	0.17	0.18	0.19	0.20	0.22	0.23
TOTAL	3.26	2.95	2.97	2.91	2.94	3.10	3.26	3.43

4. Point estimate results

In this section, we present *differences* between each of the switchgrass and corn stover ethanol scenarios and the EWG baseline. Note that GCAM reports results in 5-year time-steps, however our calculations were performed on an annual basis, with values between time-step years interpolated linearly.

In the two policy scenarios—switchgrass and corn stover ethanol—we constrained the production volumes of all biofuels other than cellulosic ethanol to the baseline levels. In both scenarios, we increased cellulosic ethanol production by 2 B gal/y in 2025 and beyond. The incremental production is sourced entirely from switchgrass in the switchgrass ethanol scenario, and from crop and forestry residue (predominantly corn stover) in the stover ethanol scenario. Figure 3 shows changes in cellulosic ethanol production in the U.S. in the switchgrass scenario. A similar change was implemented for the stover scenario.

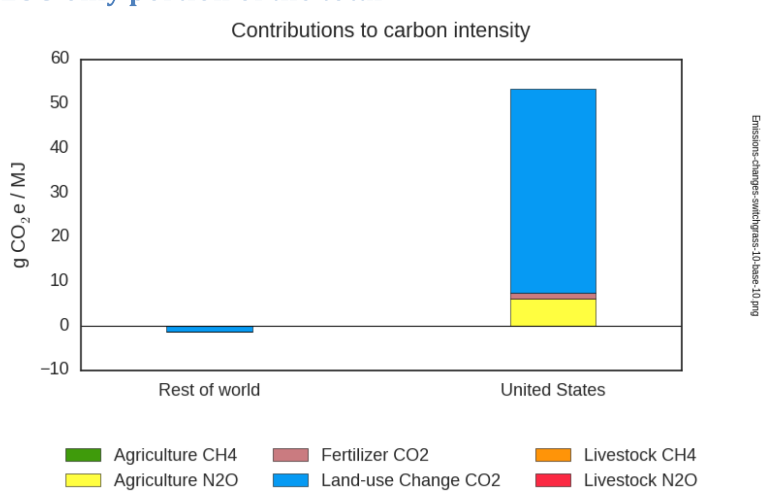
In both the switchgrass and corn stover scenarios, we constrained the total biomass consumed by all other sectors of the U.S. economy to the baseline level to prevent changes in ethanol production from affecting biomass consumption in those sectors. To accomplish this, we read the results from the baseline scenario and created constraints on regional biomass equal to the baseline results plus the quantity of additional biomass required to produced the desired quantity of cellulosic ethanol, based on GCAM's assumed conversion efficiencies, which improve over time.

4.1. Switchgrass ethanol

4.1.1. Carbon intensity

The estimated carbon intensity of switchgrass ethanol considering only land-use change CO_2 emissions (i.e., CO_2 from the oxidation of soil and biomass carbon resulting from land use changes) is **45 g CO_2e MJ^{-1}**. In addition to emissions attributed to changes in land use, GCAM projects increased emissions from the production and use of fertilizer applied to the additional switchgrass. Consistent with the RFS2 Regulatory Impact Analysis, we also count CH_4 and N_2O emissions from changes in livestock and CH_4 from rice production, these quantities are negligible in the final total. Inclusion of these emissions in the "RFS-style" result increases the estimated carbon intensity to **52 g CO_2e MJ^{-1}.** The breakdown by contributing GHG source is depicted in Figure 2.

Figure 2. Estimated carbon intensity of switchgrass ethanol, disaggregated by source. This figure is based on RFS-style accounting. The dark green segments represent the LUC-only portion of the total.



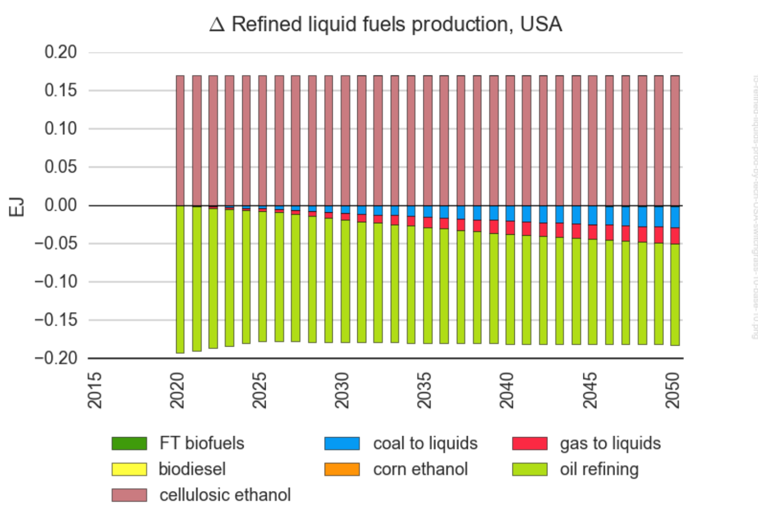
These values are within the range of values estimated by Wise et al. (2015), which varied between about 14 and 70 g CO_2e MJ^{-1} and close to their estimate for switchgrass in AEZ-7, which is about 35 g CO_2e MJ^{-1} (reading from their figure 7, shown here as Figure 10.)

4.1.2. Switchgrass production

We used a subsidy to increase switchgrass production relative to the baseline level by the exact amount necessary to produce the desired quantity of additional cellulosic ethanol, based on GCAM's modeled conversion efficiencies (which improve by about 1.8% per year.)

Figure 4 shows the changes in biomass consumption in the switchgrass scenario. Figure 5 shows the change in total biomass consumption by region, virtually all of which occurs in the U.S., as intended. Figure 6 shows that residue production was barely changed in this scenario. (Note that the scale is much smaller than in the other figures.) These three figures show that virtually all of the increased biomass production is sourced from purpose-grown biomass (i.e., switchgrass) in the U.S., as expected.

Figure 3. Modeled change in cellulosic ethanol production in the U.S. in the switchgrass ethanol scenario relative to the baseline. Production of other biofuels was constrained to baseline levels.



As shown in Figure 3, GCAM projects that producing biofuels in the USA results in a slight decrease in total global liquid fuel production. We note that this result runs counter to many other economic analyses of fossil fuel displacement by biofuels (Smeets, Tabeau et al. 2014). The GCAM outcome is the result of several GCAM assumptions, including:

1. Elasticities of fuel supply and demand with respect to price (expressed in GCAM as share-weights and logit function exponents).
2. Price and availability of GTL and CTL fuels.
3. Treating the global crude oil market as competitive.
4. Little response in transportation (and fuel) demand to changes in fuel cost, because the majority of vehicle cost is the value-of-time to the driver.

Figure 4. Change in total biomass consumption in the Switchgrass Ethanol Scenario relative to the Baseline.

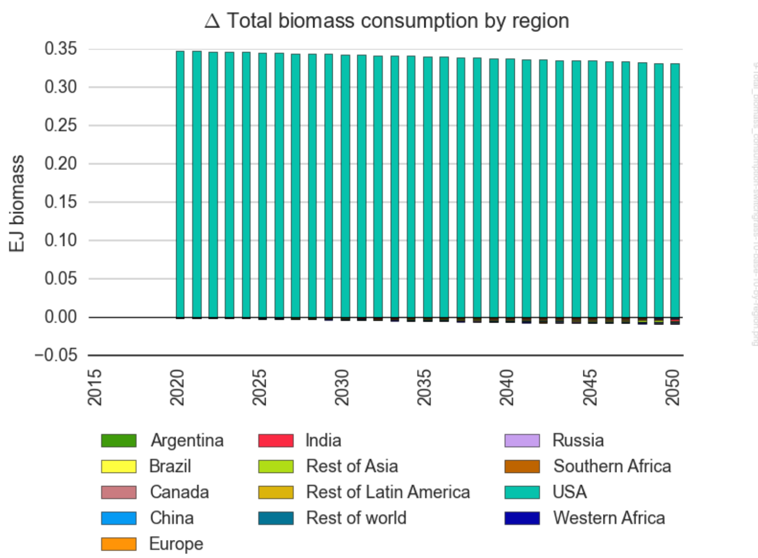


Figure 5. Change in purpose grown biomass production in the switchgrass scenario relative to the Baseline.

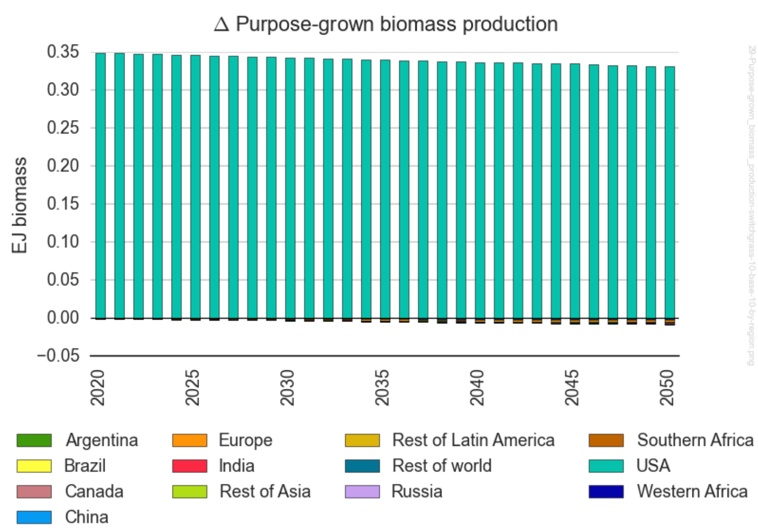


Figure 6. Change in residue biomass production in the switchgrass scenario relative to the baseline. Annualized values for both numerator (biomass) and denominator (biofuel) are summed from 2020-2050. (Note the small scale on the Y-axis, indicating essentially no change.)

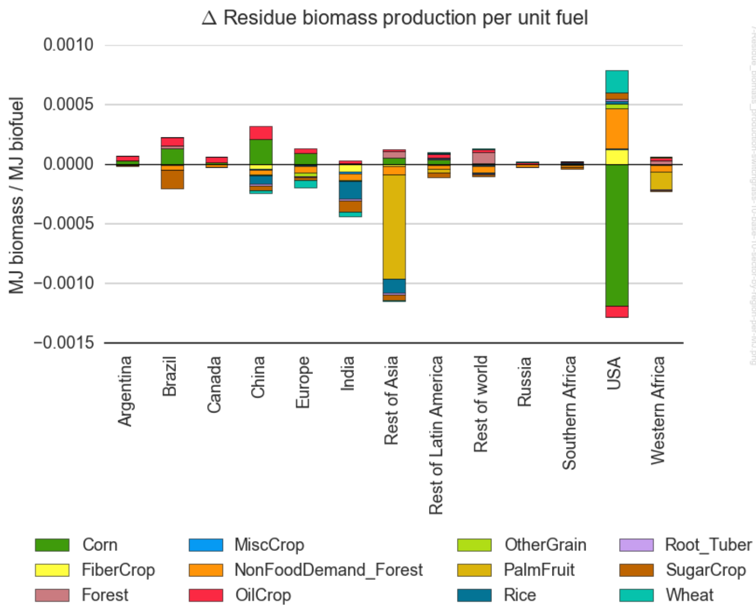


Table 12. Changes in liquid fuel production (EJ) in the U.S. following an increase in cellulosic ethanol production from 0.23 to 0.40 EJ.

Technology	2020	2025	2030	2035	2040	2045	2050
FT biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00
biodiesel	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cellulosic ethanol	0.17	0.17	0.17	0.17	0.17	0.17	0.17
coal to liquids	0.00	0.00	-0.01	-0.01	-0.02	-0.02	-0.03
corn ethanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00
gas to liquids	0.00	0.00	-0.01	-0.01	-0.02	-0.02	-0.02
oil refining	-0.20	-0.17	-0.16	-0.15	-0.15	-0.14	-0.13
TOTAL	**-0.03**	**-0.01**	**-0.01**	**-0.01**	**-0.01**	**-0.01**	**-0.01**

4.1.3. Changes in land allocation and LUC emissions

In the switchgrass ethanol scenario, forestry, grassland, and pastureland were converted to grow switchgrass in the U.S. (Figure 7). As a result, carbon sequestration by the biomass sector increases relative to the baseline scenario, but these are dominated by the reduced sequestration by the forestry and pasture sectors (Figure 8).

Note that when expanding land for agriculture, GCAM distributes the area changes over the prior time-step, thus to properly count all emissions associated with the projected LUC requires counting LUC emissions from 2016-2050 rather than merely from 2020-2050.

(Since the first biofuel shock is in 2020, there should be no LUC emissions prior to that year.)

Figure 7. Change in land allocation by land-use type for the USA and rest of world in 2020, the year of the initial shock.

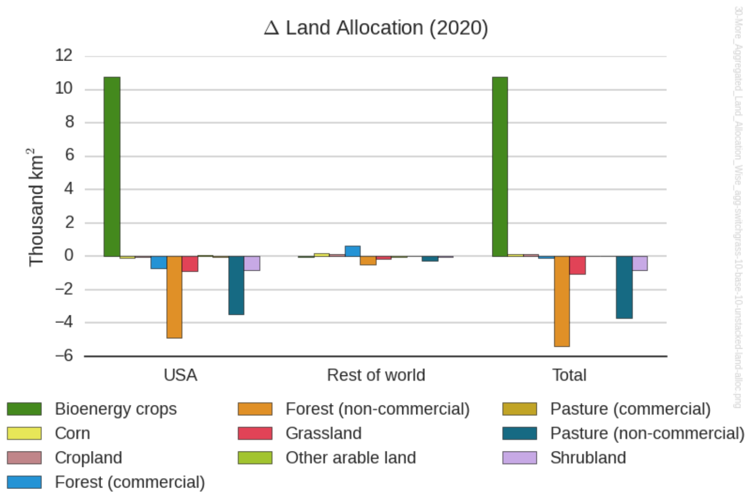
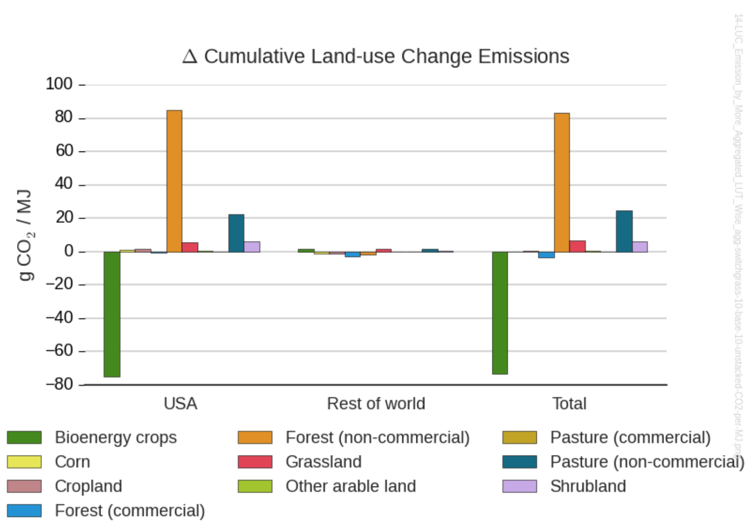


Figure 8. Cumulative LUC emissions intensity (g CO_2e MJ^{-1}) for the USA and rest of world.



4.1.4. Changes in refined fuel production

Figure 9 shows changes in refined liquid production in the U.S. in the switchgrass scenario. The increase in cellulosic ethanol is nearly perfectly compensated by decreases in coal- and gas-to-liquids and conventional oil refining. This nearly 1:1 replacement is based on GCAM's default elasticities of fuel supply and demand and would change under other assumptions. Also, GCAM is quite optimistic about CTL and GTL production, so it counts greater CO_2

reductions than would be the case if more lower-carbon-intensity crude was offset by biofuels.

Carbon accounting for bioenergy in GCAM includes counting the uptake of CO_2 into plant carbon—for bioenergy crops only, not for food crops—and then counting all combustion CO_2 from biofuels. Since there's a nearly perfect replacement of liquid fossil fuels by biofuels in GCAM, the additional plant growth (net of LUC emissions) results in additional sequestration that is not offset by additional combustion: the total CO_2 from liquid fuel combustion is largely unchanged.

Figure 9. Modeled change from baseline refined fuel production in the U.S. in the switchgrass ethanol scenario. Production of other biofuels were constrained to baseline levels and prevented from responding to changes in cellulosic ethanol production.

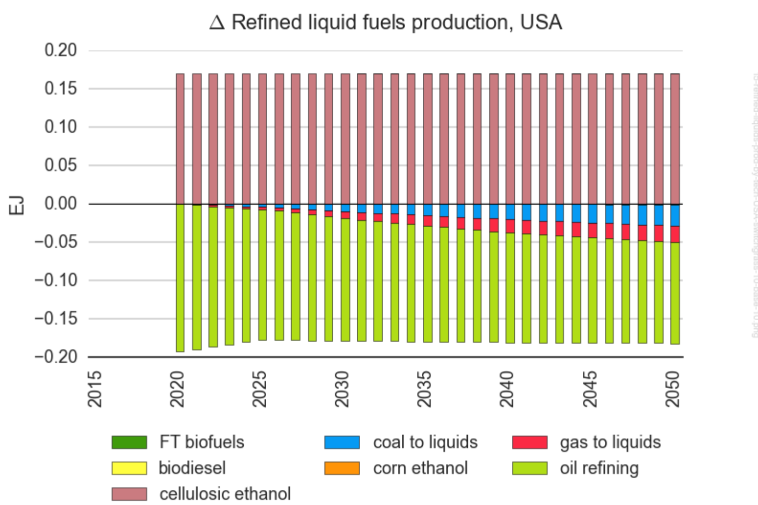
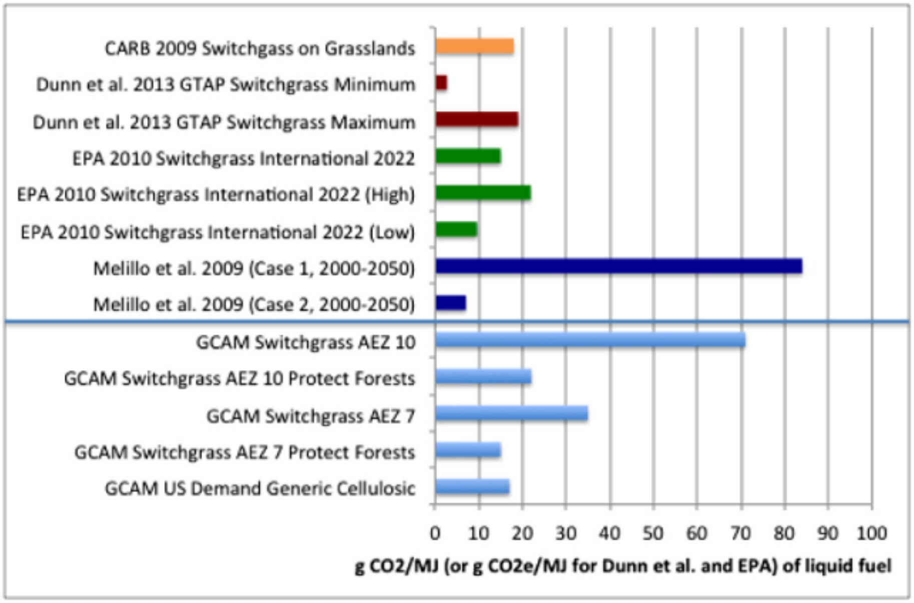


Figure 10. Carbon intensity from GCAM and other studies (taken from Wise, Hodson et al. 2015)

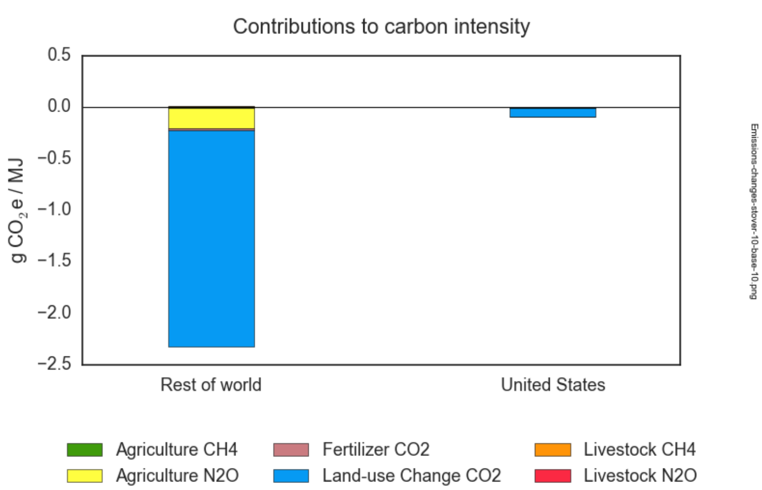


4.2. Corn stover ethanol

4.2.1. Carbon intensity

The carbon intensity of stover ethanol production for an increase from 0.23 to 0.40 EJ per year of cellulosic ethanol production was **-2.2 g CO_2e MJ^{-1}** for LUC-only and **-2.4 g CO_2e MJ^{-1}** for RFS-style CI calculations (Figure 11).

Figure 11. Estimated of carbon intensity of stover ethanol, disaggregated by source. The "RFS-style" CI calculation includes all the emission source categories shown.

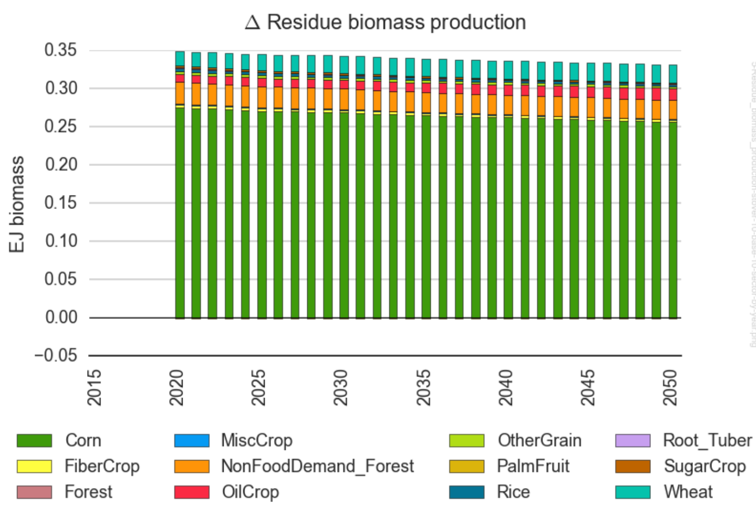


4.2.2. Corn stover production

Although we cannot directly control the quantity or type of residues produced, we were able to force the increased biomass to be sourced from residues, and primarily from corn stover, as depicted in Figure 12. To accomplish this, we constrained U.S. switchgrass production to the baseline level, in addition to the changes described earlier for the baseline.

As seen in Figure 12, approximately 80% of the supply response to increased cellulosic ethanol production is sourced from corn stover, with most of the remainder coming from forestry and wheat residues. Considering that all biomass is fungible in GCAM, this result would be consistent with producing all cellulosic ethanol from corn stover, with 80% of the feedstock coming from additional stover collection (above the baseline), with the remaining 20% diverted from other uses and replaced predominantly by wheat and forestry residue.

Figure 12. Change in residue production in the stover ethanol scenario relative to the baseline.

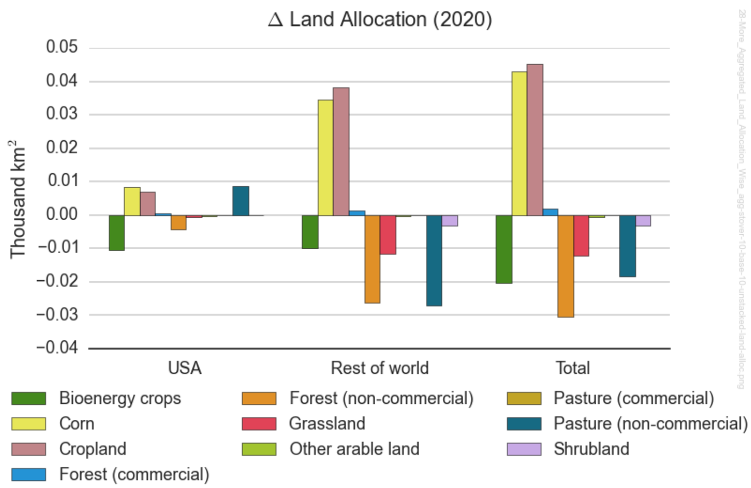


Residue collection removes nutrients that must be replaced or a yield reduction may occur (Nelson, Walsh et al. 2004; Kenney, Blanco-Canqui et al. 2013). A loss of yield would result in some incremental land-use change if total grain output were maintained. GCAM does not presently account for this potential nutrient loss or yield reduction. Since crop yields are unchanged between the baseline and corn stover ethanol scenario, the harvesting of stover in GCAM incurs no land-use change and no increased fertilizer emissions. Including this dynamic would somewhat increase the CI of stover ethanol.

4.2.3. Land allocation

As shown in Figure 13, decreasing corn stover ethanol production results in relatively small changes in land allocation, compared to those projected for switchgrass ethanol.

Figure 13. Change in land allocation in 2020 for corn stover ethanol.



5. Monte Carlo simulation

An estimate of LUC emissions from biofuel production is subject to a broad array of assumptions in a model as complex as GCAM. We ran a Monte Carlo simulation by applying random values drawn from distributions to sets of related values in GCAM's input files.

5.1. Stochastic parameters

5.1.1. Parameter distributions

In the GCAM-MCS framework, a "parameter" is a name associated with a set of input values identified in one of GCAM's input XML files. Distributions are applied to all of the values returned, either individually (i.e., independent) or together as a set (i.e., perfectly correlated). In addition, correlations between 0 and 1 can be defined among sets of parameter values.

Table 13 lists the parameters treated stochastically in this analysis, along with the distributions assigned. The parameters fall broadly into three categories: (i) logit exponents that influence the substitutability between different land cover types in response to a biofuel shock, (ii) the soil and biomass carbon density of various land cover types, and (iii) the income and price elasticity of food crops and meat. Allowing for greater income and price elasticity of food demand has the effect of reducing LUC emissions by virtue of reducing consumption of land-intensive food, particularly meat.

Table 13. Parameter distributions. Draws from the given distributions were multiplied by the GCAM default values to produce values for each trial, except for food crop price elasticity, which is zero by default—in this case, the drawn values were added instead. The "nodes" column indicates the number of distinct numerical values in the XML files that comprise each variable.

Parameter name	Distribution	Definition	Nodes
Forest-logit-exp	Triangle(0.75, 1.0, 1.25)	Managed vs unmanaged forest	283
Crop-logit-exp	Triangle(0.75, 1.0, 1.25)	Substitution among crops	283
Grass-shrub-logit-exp	Triangle(0.75, 1.0, 1.25)	Grass vs shrubland	283
Pasture-logit-exp	Triangle(0.75, 1.0, 1.25)	Managed vs unmanaged pasture	283
Forest-grass-crop-logit-exp	Triangle(0.75, 1.0, 1.25)	Forest vs grassland vs cropland	283
Crop-biomass-c	Triangle(0.7, 1.0, 1.3)	All crops biomass carbon	3636
Crop-soil-c	Triangle(0.7, 1.0, 1.3)	All crops soil carbon	3636
Mgd-forest-biomass-c	Triangle(0.7, 1.0, 1.3)	Managed forest biomass carbon	566
Mgd-forest-soil-c	Triangle(0.7, 1.0, 1.3)	Managed forest soil carbon	566
Unmgd-forest-biomass-c	Triangle(0.7, 1.0, 1.3)	Unmanaged forest biomass carbon	283
Unmgd-forest-soil-c	Triangle(0.7, 1.0, 1.3)	Unmanaged forest soil carbon	283
Other-arable-biomass-c	Triangle(0.7, 1.0, 1.3)	Other arable land biomass carbon	283
Other-arable-soil-c	Triangle(0.7, 1.0, 1.3)	Other arable land soil carbon	283
Shrub-biomass-c	Triangle(0.7, 1.0, 1.3)	Unmanaged shrubland biomass carbon	283
Shrub-soil-c	Triangle(0.7, 1.0, 1.3)	Unmanaged shrubland soil carbon	283
Grass-biomass-c	Triangle(0.7, 1.0, 1.3)	Unmanaged grassland biomass carbon	283
Grass-soil-c	Triangle(0.7, 1.0, 1.3)	Unmanaged grassland soil carbon	283
Mgd-pasture-biomass-c	Triangle(0.7, 1.0, 1.3)	Managed pasture biomass carbon	283
Mgd-pasture-soil-c	Triangle(0.7, 1.0, 1.3)	Managed pasture soil carbon	283
Unmgd-pasture-biomass-c	Triangle(0.7, 1.0, 1.3)	Unmanaged pasture biomass carbon	283
Unmgd-pasture-soil-c	Triangle(0.7, 1.0, 1.3)	Unmanaged pasture soil carbon	283
Crop-productivity	Triangle(0.7, 1.0, 1.3)	Agricultural productivity (yield, %/year)	66,222
Food-crop-price-elast	Triangle(-0.2, 0, 0)*	Price elasticity of food crop demand	558
Meat-price-elast	Triangle(0.8, 1.0, 1.2)	Price elasticity of meat demand	558
Food-crop-income-elast	Triangle(0.8, 1.0, 1.2)	Income elasticity of food crop demand	558
Meat-income-elast	Triangle(0.6, 1.0, 1.4)	Income elasticity of meat demand	558

* Random values were added rather than multiplied since default values are zero everywhere.

5.2. Results

5.2.1. Carbon intensity

The following figures depict the frequency distribution of results from Monte Carlo simulations (MCS) for the two biofuels.

Note that the distributions shown here do not constitute predictions about the mostly likely CI values, nor does the 95% central interval offer bounds on possible CI values. Rather, the MCS results should be treated as a sensitivity analysis of one particular model (GCAM) configured the way described herein, with a particular set of distributions applied to a subjectively chosen set of parameters. The bounds give us a sense of the range of results that can be produced by this model under alternative "reasonable" parameterizations.

Figure 14. Frequency distribution of the carbon intensity of stover ethanol (LUC only)

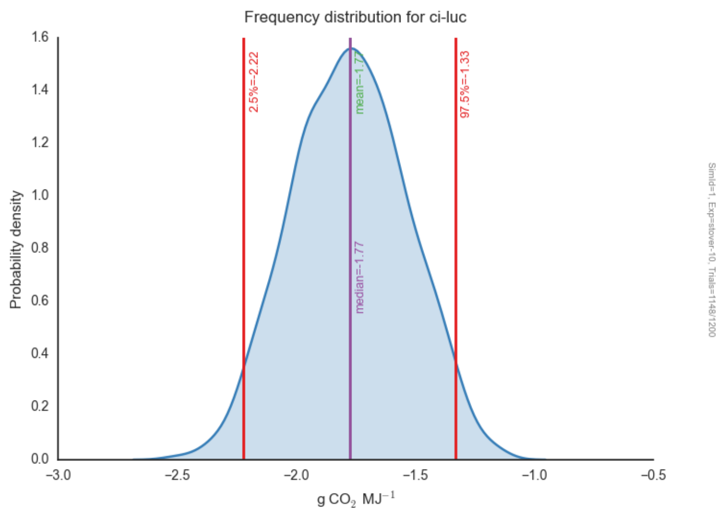


Figure 15. Frequency distribution of the carbon intensity of stover ethanol (RFS-style)

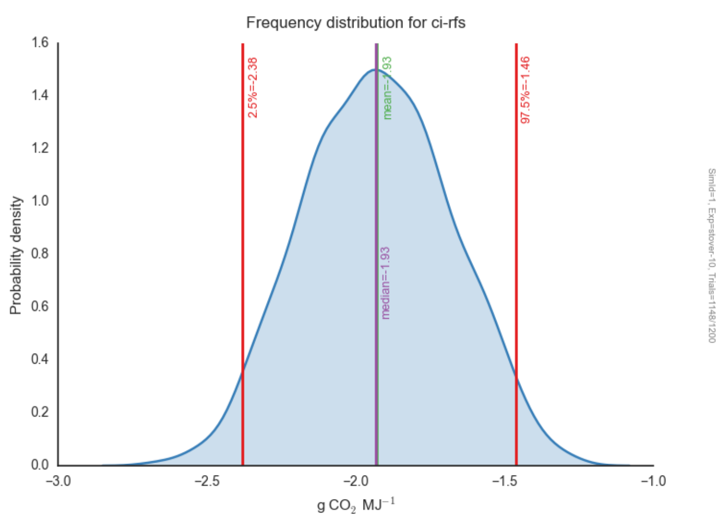


Figure 16. Frequency distribution of the carbon intensity of switchgrass ethanol (LUC only)

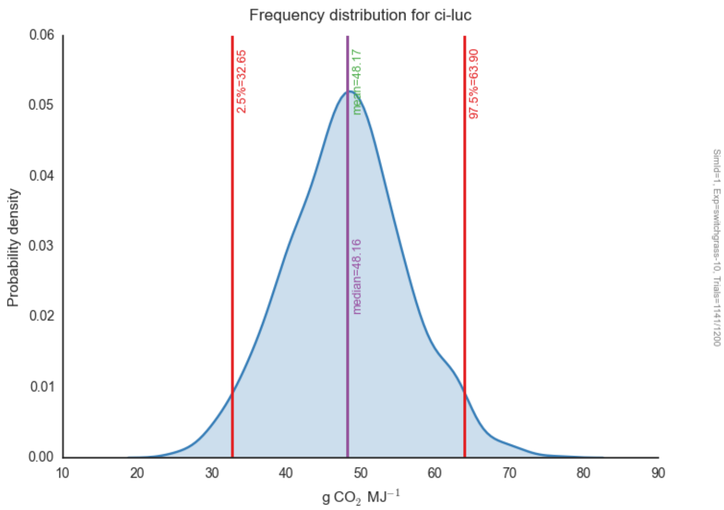


Figure 17. Frequency distribution of the carbon intensity of switchgrass ethanol (RFS-style)

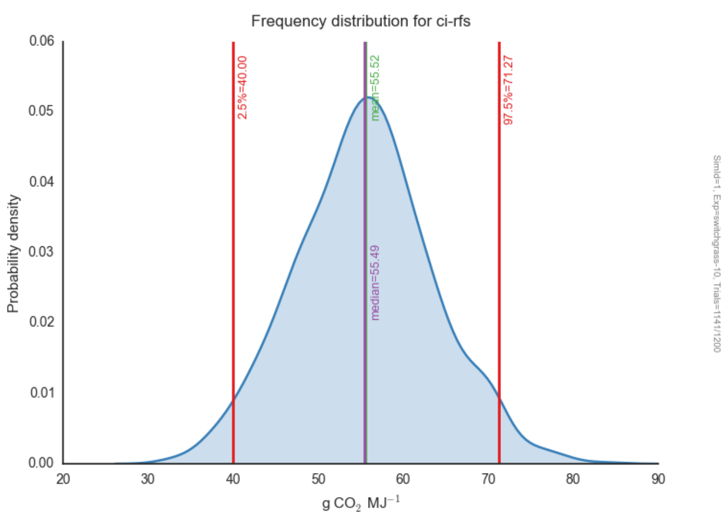
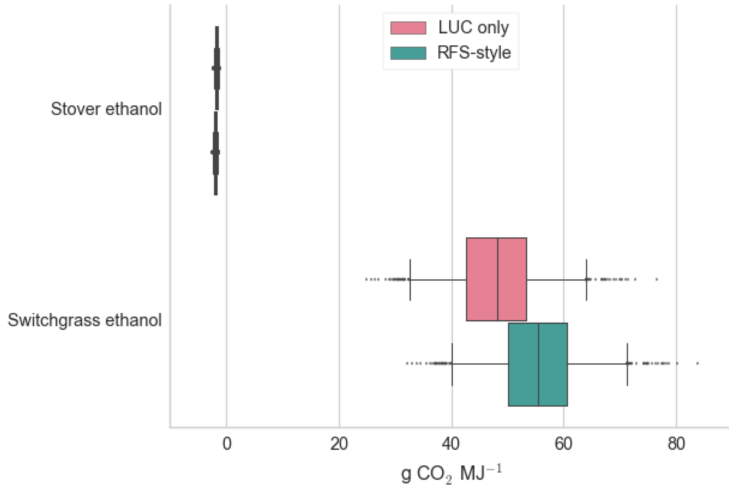


Figure 18. Frequency distribution of the carbon intensity of stover and switchgrass ethanol, LUC-only and RFS-style.



5.2.2. Contribution to variance

The following figures depict the contribution of each parameter that was treated as uncertain in the analysis to a specific model output.

Note that these results should be treated as indicative only: to produce a stable analysis of contribution to variance would require at least 5000 trials, thus for the baseline and two biofuel shocks would require an *additional* 12,000 runs of GCAM.

As shown, key uncertain parameters for stover ethanol include soil and biomass carbon in unmanaged forest and unmanaged pasture; logit exponents controlling ease of substitution among crops and among forest, grassland, and crops. Smaller contributors include crop productivity (changes to yield over time) and soil carbon for crops and grassland. For switchgrass, the same parameters comprise the most important, but the ordering is slightly different. switchgrass ethanol CI shows a small but non-trivial dependence on the elasticity of meat demand to changes in income.

Figure 19. Contribution of uncertain parameters to variance in stover ethanol CI (LUC only).

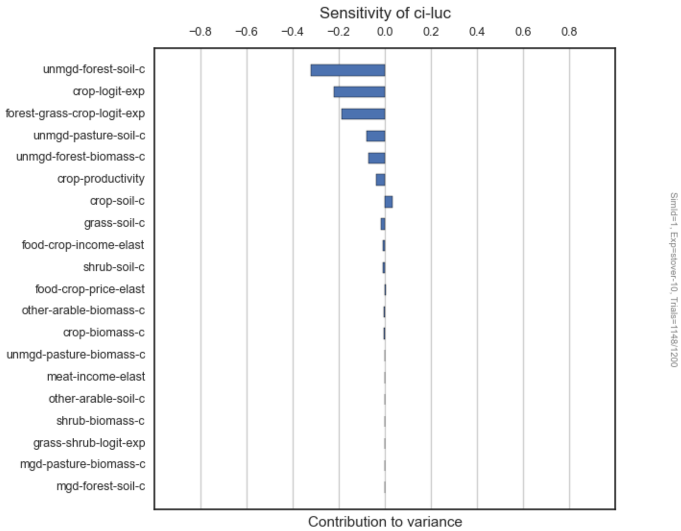


Figure 20. Contribution of uncertain parameters to variance in stover ethanol CI (RFS-style)

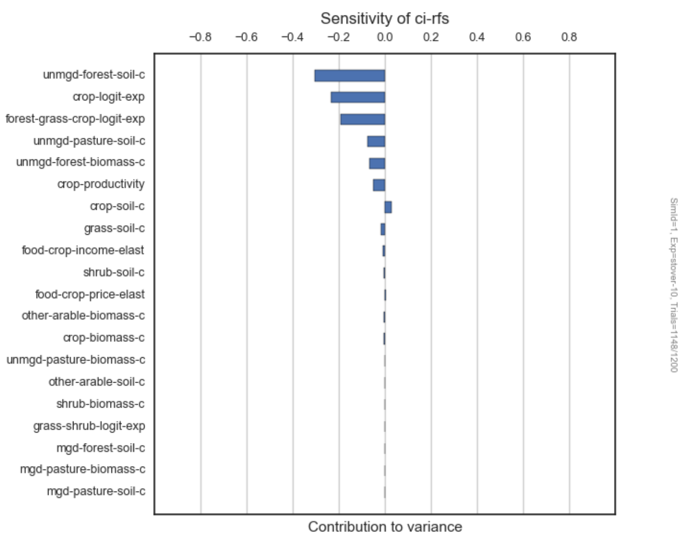


Figure 21. Contribution of uncertain parameters to variance in switchgrass ethanol CI (LUC only).

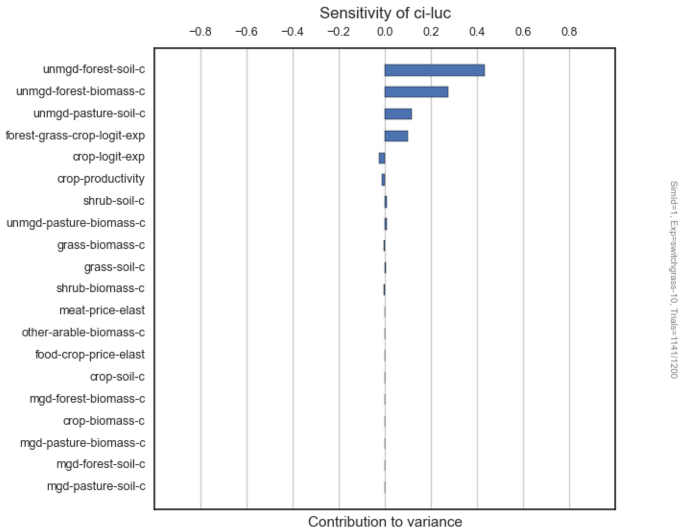
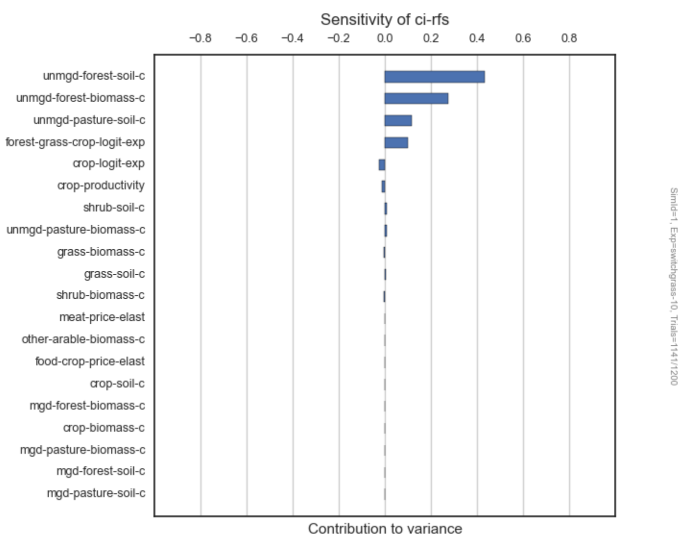


Figure 22. Contribution of uncertain parameters to variance in switchgrass ethanol CI (RFS-style).



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