ANL/ESD/12-5 Rev. 6

Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB)

Users' Manual and Technical Documentation

Energy Systems Division

ANL/ESD/12-5 Rev. 6

Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB)

Users' Manual and Technical Documentation

prepared by
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Version Notes

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Acronyms

AEZ	Agro-ecological Zone
ARMS	Agricultural Resource Management Survey
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use and Land Management Change from Biofuels Production (Formerly, Carbon Calculator for Land Use Change from Biofuels Production)
CDL	Cropland Data Layers
CH_4	Methane
CT	Conventional Tillage
EF	Emission Factor
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Technologies model (Formerly, Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model)
GTAP	Global Trade Analysis Project model
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle Analysis
LMC	Land Management Change
LUC	Land Use Change
NASS	National Agricultural Statistics Service
NLCD	National Land Cover Datasets
N_2O	Nitrous oxides
NT	No Till
RT	Reduced Tillage
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
U.S.	United States
USDA	U.S. Department of Agriculture

1. Introduction

The Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) has been developed as an integral part of Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) model (Wang et al., 2020a, 2020b) to analyze greenhouse gas (GHG) emissions from land use change (LUC) and land management change (LMC) in the context of overall biofuel life-cycle analysis (LCA).

CCLUB relies on i) biofuel production scenarios, ii) LUC and LMC scenarios, and iii) emission factors (EF) to generate GHG emissions of LUC and LMC for biofuel production in gram carbon dioxide equivalent (CO_2e) per MJ of fuel produced. Figure 1 outlines the calculations and data sources within CCLUB that are described in this document and Table 1 identifies where these data are stored and used within CCLUB, which is built in Microsoft Excel.

Biofuel production scenarios include four ethanol pathways (corn grain ethanol and cellulosic ethanol from corn stover, *Miscanthus*, and switchgrass) and one soy biodiesel pathway. In response to the scenarios, Global Trade Analysis Project (GTAP), a computable general equilibrium economic model, estimates the conterminous United States (or domestic) and international area of land that transits from one of four land use types (i.e., forest, grassland, cropland pasture, and feedstock lands) to another at the agro-ecological zone (AEZ) level (Section 2).

Then the area changed due to land transition is multiplied by corresponding EFs (CO_2e emitted per unit area), which are aggregated/disaggregated from different spatial coverages, to estimate LUC GHG emissions for biofuel production scenarios. While both domestic and international EFs are derived from an empirical database resolved at the biome or U.S. state-equivalent level, CCLUB utilizes feedstock- and county-level domestic belowground (or soil) carbon EFs generated with a process-based simulation model (i.e., a parameterized CENTURY) described in Section 3. Aboveground carbon content data for forest ecosystems are sourced from the Carbon Online Estimator (COLE), which provides domestic forest carbon characteristics. COLE data are included in CCLUB at the county level (Section 4). International carbon EFs are calculated either from the Winrock or the Woods Hole datasets (Section 5).

Section 6 elaborates the calculation of domestic soil carbon EFs associated with LMC scenarios, which include conservation farming options practiced when corn stover is harvested as cellulosic ethanol feedstock. Section 7 includes domestic and international nitrous oxide (N_2O) and methane (CH_4) emissions, which are derived from Intergovernmental Panel on Climate Change (IPCC), associated with LUC. Temporal issues associated with modeling LUC emissions are discussed in Section 8 and a step-by-step guide to using CCLUB and obtaining results is provided in Section 9. Finally, outstanding issues are detailed in Section 10.

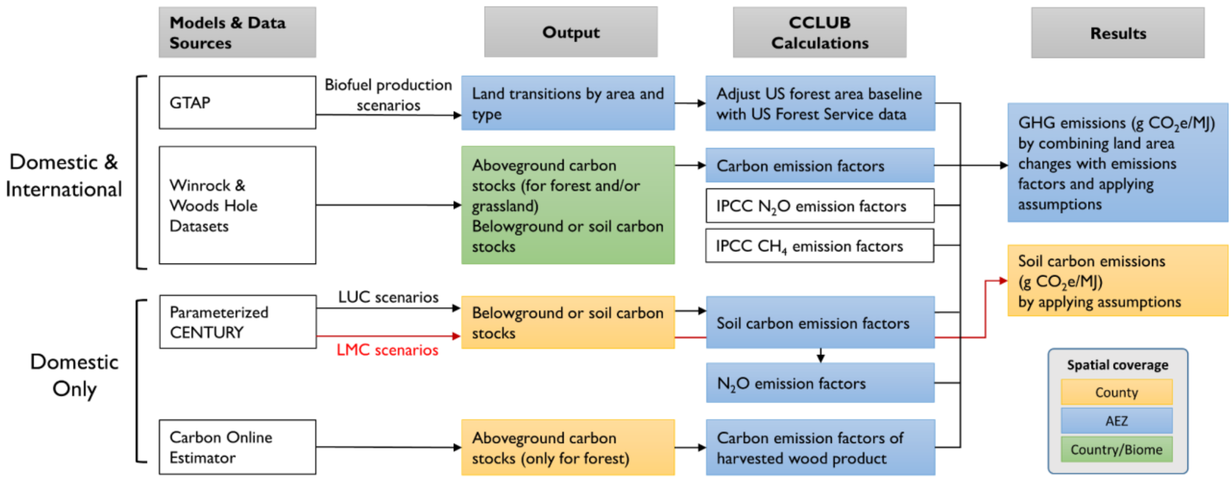

Figure 1 Schematic of Data Sources and Calculations in CCLUB.

Table 1 Overview of CCLUB Worksheets.

Worksheet	Description
Overview	Information on CCLUB-related documentation
Scenario & Results	Enables selection of data sources, key assumptions, and biofuel production scenarios and displays results. Two worksheets are included for LUC and LMC scenarios
Modeling	Computes carbon, N_2O, and CH_4 emissions from LUC
Domestic C-Factors	Derives carbon and N_2O emission factors for domestic LUC
International C-Factors	Derives carbon, N_2O, and CH_4 emission factors for international LUC
GTAP Data	Lists and summarizes GTAP source data
C-Database	Contains soil carbon emission factors from a parameterized CENTURY and forest aboveground carbon data from COLE at county level for domestic LUC and LMC
Forest Land Area	Computes forest correction factor for shrubland transitions
International Conversion	Source data for international land conversions
International Reversion	Source data for international land reversions
Saved Results	LUC and LMC results to be used in GREET

2. Global Trade Analysis Project Data

CCLUB includes GTAP results from nine biofuel scenarios for ethanol and soy biodiesel production pathways (Table 2). Each scenario reflects a shock to the economy in response to an increase in demand for a particular biofuel. The first four scenarios were modeled in 2011 (Taheripour and Tyner, 2011). The fifth scenario (case H) was modeled in 2013 (Taheripour and Tyner, 2013). The sixth and seventh scenarios were derived from California Air Resources Board (CARB), while the last two scenarios were from recent GTAP simulations released in 2017 (Chen et al. 2018) for more details on soy biodiesel simulations).

Table 2 Biofuel Production Scenarios Modeled in CCLUB.

Case	Case Description	Billion Gallons (BG)	Reference
A	An increase in corn ethanol production from its 2004 level (3.41 BG) to 15 BG	11.59	Taheripour and Tyner (2011)
E*	An increase in ethanol from corn stover (i.e., AdvfE-Stover) by 9 BG, on top of 15 BG corn ethanol	9	
F*	An increase in ethanol from *Miscanthus* (i.e., AdvfE-Misc) by 7 BG, on top of 15 BG corn ethanol	7	
G*	An increase in ethanol from switchgrass (i.e., AdvfE-Swit) by 7 BG, on top of 15 BG corn ethanol	7	
H	An increase in corn ethanol production from its 2004 level (3.41 BG) to 15 BG with GTAP recalibrated land transformation parameters	11.59	Taheripour and Tyner (2013)
S1	Increase in soy biodiesel production by 0.812 BG (CARB case 8)	0.812	Chen et al. (2018); Taheripour et al. (2017)
S2	Increase in soy biodiesel production by 0.812 BG (CARB average proxy)	0.812	
S3	Increase in soy biodiesel production by 0.8 BG (GTAP 2004)	0.8	
S4	Increase in soy biodiesel production by 0.5 BG (GTAP 2011)	0.5	

* The cellulosic ethanol scenarios (stover, *Miscanthus*, switchgrass) are modeled in GTAP as incremental production volumes on top of corn ethanol production.

The 2013 case H scenario shocked the production of corn ethanol by the same volume as the 2011 case A scenario. These two modeling exercises, however, differ in the treatment of two key aspects of the GTAP model. First, in 2011, GTAP included one land transformation elasticity for the globe. Land transformation elasticity is a parameter that reflects the ease of land transition from one state to another; a low value indicates limited land transitions. Taheripour and Tyner (2013) used two United Nations Food and Agriculture Organization land cover datasets to develop region-specific land transformation elasticities that were used in developing the 2013 GTAP results provided in CCLUB. One dataset allows determination of changes in agricultural land area. Based on this dataset, the authors categorized GTAP regions (Section 4) as having a low, medium, or high land transition elasticity. Taheripour and Tyner (2013) used the second dataset to characterize changes among crop types within harvested areas. They used it to develop land transformation elasticities among crops. The United States was characterized as having low rates of land transformation overall, but high transformation elasticity among crops. Taheripour and Tyner (2013) found that the United States moved a sizeable amount of agricultural land to produce corn and oilseed crops without significant expansion in overall agricultural land.

The second change in GTAP between the 2011 and 2013 modeling exercises is the treatment of the costs of converting pasture and forest to cropland. In 2011, the cost of conversion of both of these land types to cropland was identical. Taheripour and Tyner (2013) modified the land nesting structure in GTAP to reflect the greater cost of converting forest to cropland than converting pastures that is generally observed in the real world. This change essentially makes it more costly to convert forest to cropland than in the 2011 GTAP version. It should be noted that the 2011 case A scenario is set as a default since it is consistent with the GTAP version that CARB is using.

In 2017, four GTAP-based LUC results became available for soy biodiesel production in the United States. Depending on the case, the LUC matrices vary by GTAP versions and biofuel shocks. In particular, cases S1 and S2 represent LUC results used by CARB. The former refers to the case 8 (of 30 cases) used by CARB, while the latter aims to proxy LUC for the 30-case average by using averaged GTAP parameters (Chen et al. 2018). In these two cases, GTAP used 2004 database, and did not consider land intensification (e.g., multiple cropping and/or returning unused cropland to crop production). In cases labeled “GTAP 2004” and “GTAP 2011”, however, GTAP applied land intensification in both, and used the 2004 and 2011 database, respectively (Chen et al. 2018).GTAP permits three land types to be tapped for biofuel production: forest, grassland, and feedstock lands. The latter is agricultural land that has been converted to agriculture dominated by the production of biofuel feedstocks. In a differently nested category, the model also accesses a fourth land type: cropland pasture. Figure 2 illustrates the land transitions considered in CCLUB.

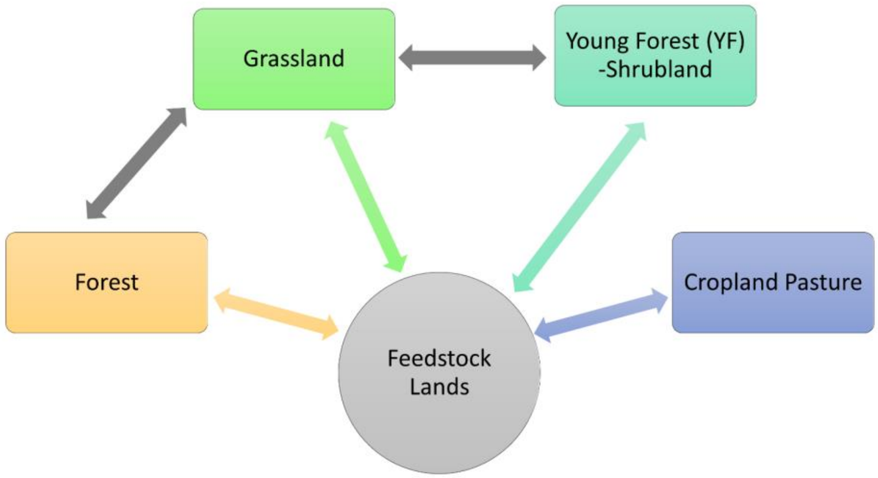

Figure 2 Land Transitions Modeled in CCLUB.

In 2010 as Argonne National Laboratory worked to develop EFs for cases A-G (Table 2), along with collaborators at the University of Illinois at Chicago we compared the GTAP land database with both the National Land Cover Datasets (NLCD), which are part of the U.S. Department of Agriculture (USDA)-National Agricultural Statistics Service (NASS) Cropland Data Layers (CDL), and the U.S. Forest Service's Forest Inventory data. We aimed to align forest area in the United States in our analysis with this database because we used Forest Service data to develop EFs for aboveground and belowground carbon in addition to values for foregone sequestration. We therefore needed to reconcile forest area in the NLCD with forest area in GTAP.

The NLCD for 2006 put forest area at 207 million hectares (ha) for the conterminous United States. Including woody wetlands would bring this number up to 240 million ha, which is similar to 254 million ha forest area from the U.S. Forest Service's Forest Inventory Data Online (FIDO) database. Adding forested area in Alaska, the total forest area rises to 285 million ha. However, the GTAP database includes a significantly higher value (370 million ha) for total forested land than these other data sources (Table 3).

Table 3 GTAP vs. CDL Forest Area Comparison.

AEZ	CDL Forest Area	GTAP Forest Area	CDL Accessible Forest Area (CDL_a)	GTAP Accessible Forest Area ($GTAP_a$)	Proration Factor ($CDL_a/GTAP_a$)
			ha		**unitless**
7	47,405,654	8,565,128	4,916,174	3,855,223	1.28
8	17,272,038	16,811,112	3,249,339	7,568,672	0.43
9	10,321,261	10,603,159	4,877,404	4,774,257	1.02
10	57,660,896	68,714,584	38,053,673	51,625,425	0.74
11	49,317,712	56,696,608	41,537,500	41,732,227	1.00
12	48,740,427	69,617,736	41,543,291	53,074,258	0.78
13	10,325,263	17,098,376	2,860,066	7,697,724	0.37
14	24,624,059	61,735,484	10,557,947	27,793,441	0.38
15	18,497,217	55,407,136	9,066,574	24,948,026	0.36
16	780,733	5,180,770	361,713	2,332,297	0.16
Total	284,945,260	370,430,093	157,023,681	225,401,549	0.70

Of the total forest area in both the CDL and GTAP data, some is inaccessible for biofuel production (national and state forest) and the remainder is accessible. Purdue provided the total split between accessible and inaccessible forest land in GTAP with accessible forest land accounting for 225 million ha of the 370 million total forest ha. Our analysis indicated that the GTAP database uses the methodology by Sohngen and Tennity (2004) to derive accessible versus inaccessible land ratios by AEZ and applies these ratios to the GTAP forest areas by AEZ. The reproduced GTAP accessible forest land by AEZ is shown in Table 3. A map in Figure 3 shows the distribution of AEZs in the United States. In our CDL analysis, subtracting state and national forest areas from the CDL total forest area data yielded 157 million ha of accessible forest. Across most (but not all) AEZs, this is substantially less accessible forest land than GTAP predicts.

Based on the differences in the amount of accessible forest lands estimated by GTAP and the CDL analysis, we assume that some of the GTAP accessible forest land is shrubland rather than mature forest land. To address this issue and to be consistent with U.S. Forest Service data, we added young forest-shrubland (YF-Shrub) as a fifth land type. Shrubland is defined in the NLCD Classification as "areas characterized by natural or semi-natural woody vegetation with aerial stems, generally less than 6 meters tall." To determine the amount of land classified as YF-Shrub, we applied a proration factor to the accessible forest land GTAP predicted to be converted. The proration factor is calculated at the AEZ level as the ratio of accessible forest land in the CDL database to accessible forest land in the GTAP database (Table 3). For example, if in a certain scenario GTAP predicted the conversion of 10,000 ha of forest to feedstock lands in AEZ 14, applying the proration factor results in CCLUB modeling 3,800 ha and 6,200 ha of forest and YF-Shrub lands being converted, respectively. In two AEZs, the proration factor exceeds one. In that case, our approach increases the amount of mature forest that is converted and effectively decreases the amount of YF-Shrub that converts to feedstock production land.

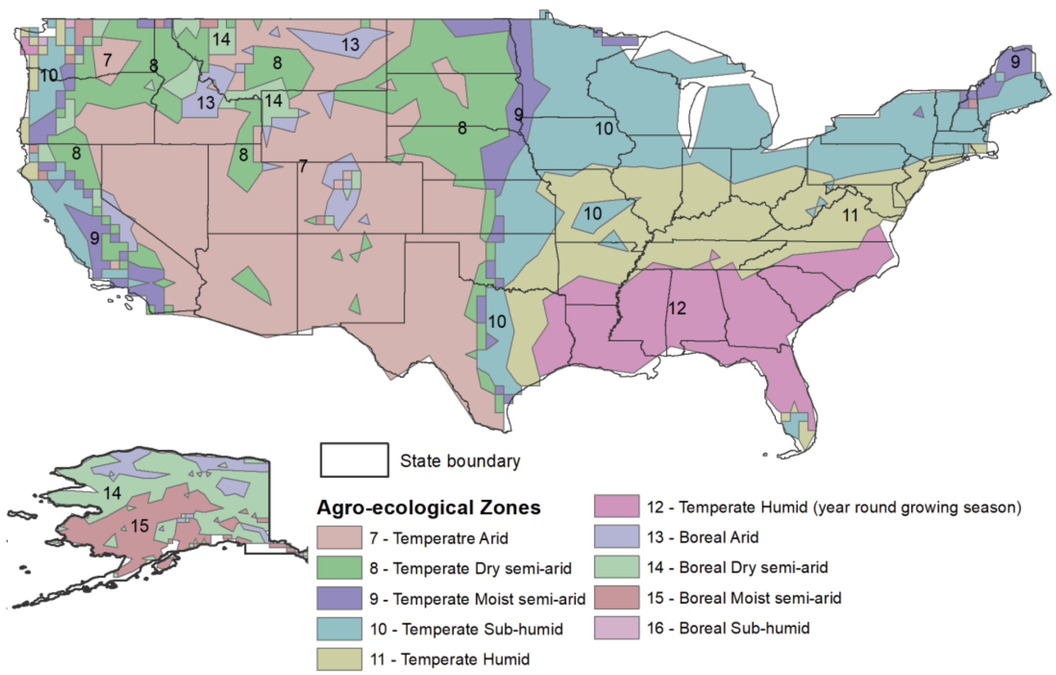

Figure 3 Distribution of AEZs in the Conterminous United States.

Converting YF-Shrub lands will have a lower carbon penalty than converting mature, carbon-rich forests. We therefore modified mature forest carbon emission factors to reflect this difference. The modified forest emissions factor for YF-Shrub is based on the relative height of forest stands in each state compared to shrubland. The relative tree heights for each state were derived from Pflugmacher et al. (2008) and Simard et al. (2011).

3. Domestic Belowground or Soil Carbon Data for the Conterminous United States

Spatially explicit soil carbon EFs are calculated from SOC stock change simulated by using a parameterized CENTURY (formerly, a surrogate model for CENTURY's SOC sub-model) developed as an inverse modeling tool (Kwon and Hudson, 2010). CENTURY (Parton et al. 1987) is well-developed for cropland, grassland, and forest and can simulate land transitions incorporated in the GTAP modeling framework. Recently, Kwon et al. (2017) further evaluated the accuracy and precision of the model for estimating SOC sequestration under rainfed corn-based cropping systems in the United States.

The parameterized CENTURY includes mass balance and decomposition kinetics equations for the three primary soil organic matter (SOM) pools – active, slow, and passive SOM – described by CENTURY v4 and DayCENT v4.5 (the daily time-step version of CENTURY, Del Grosso et al. 2001). Important differences from CENTURY are that it is coded and solved within a non-linear regression model (PROC MODEL) of SAS (SAS Institute Inc., 2014) and decoupled from models of plant growth, nutrient cycling, and hydrologic processes described within CENTURY and associated variants. Use of the parameterized CENTURY provides the advantages of transparency and relative simplicity while allowing users to easily modify time-dependent CENTURY inputs (Kwon et al. 2017). Important inputs to the model include i) aboveground and belowground crop/plant carbon inputs that are empirically calculated using observed crop yields, agronomic indices (i.e., harvest index and root-to-shoot ratio), and crop carbon and nitrogen composition; and ii) SOM decay rate adjustments that reflect the influence of climatological, physical (e.g., tillage or other field operations), and input factors (e.g., fertilizer addition or residues returned).

Overall, SOC modeling work in CCLUB has been built from Kwon et al. (2013) and expanded by Qin et al. (2016) to estimate domestic soil carbon EFs associated with LUC scenarios at either the state or county level (Figure 4). The LUC scenarios include four historical land use types (i.e., cropland, grassland, forest, and cropland pasture) and five current land use types with different biofuel crops (i.e., corn, switchgrass, *Miscanthus*, poplar, and willow). For corn grain and stover, various management practices were introduced to indicate possible combinations of tillage practices – conventional tillage (CT), reduced tillage (RT), no till (NT) – and stover residue harvest rates (either 0% or 30%). The 30% harvest rate was determined to avoid increasing soil erosion or diminishing soil fertility (Johnson et al. 2006; Nelson, 2002; Simon et al. 2010; Wilhelm et al. 2004). For the other four biofuel feedstock crops (switchgrass, *Miscanthus*, poplar, and willow trees), only no till practice and 90% harvest level that can avoid soil depletion were included.

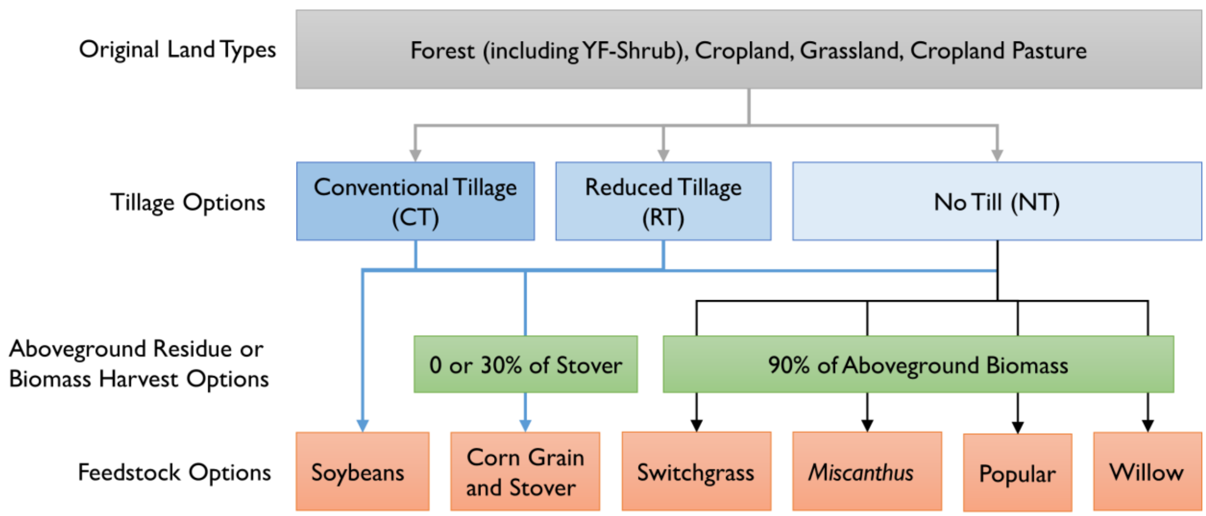

Figure 4 LUC Scenarios Modeled in CCLUB.

For each LUC scenario, the SOC dynamics are modeled with spatially referenced data describing land use types, crop yield, and soil and climate conditions at the county level. The land use history was constructed for model spin-up by dividing the entire simulation into three periods, pristine (prior to 1881), pre-modern (1881–1950), and modern (1951–2010) agricultural periods (Appendix A). Pristine land use was either native grassland or forest. The LUC period from 2011 to 2040 was designated as biofuel crop establishment. The number of counties under each LUC scenario varies, because the historical land use (e.g., forest) may not be available in certain areas. Historical crop yields (i.e., corn, wheat, and soybean) were based on USDA-NASS statistical data (Kwon et al. 2013). The reference yields in 2011 for switchgrass, *Miscanthus*, poplar, and willow were obtained from the PRISM-EM modeled results (Eaton et al. 2013). For the LUC period (2011–2040), biomass yield was either held constant or assumed to increase. For corn, the constant yield case was set to the 20-year yield averages from 1991 to 2010; the yield increase case was projected using historical yield records from 1951 to 2010 (Kwon et al. 2013). For PRISM-EM yields, the reference yield and a 1% annual increase were used for yield constant and yield increase cases, respectively. The 1% annual increase is more conservative than the recent update from the Billion-Ton Study (Perlack et al. 2011), which considered annual yield increases of either 2, 3, or 4%.

Soil texture data were extracted from the Harmonized World Soil Database (Fischer et al. 2008). Climate data (e.g., temperature, precipitation) were derived from monthly averages of the National Oceanic and Atmospheric Administration climate data (1981–2010) and organized at the county level (Arguez et al. 2012).

The SOC, from both 0-30 and 0-100 cm soils, was modeled at the county level with a monthly time step. In total, 80 model runs (40 LUCs × 2 yield scenarios) were conducted to simulate dynamic SOC for each county (over 2000 counties per LUC scenario). For each county in a given model run, the SOC sequestration rate was described as the annual change in SOC over the modeled period following LUC, which was calculated as the difference between final SOC (in 2040) and initial SOC (in 2011) divided by the duration of the modeled time period (i.e., 30 years). A positive sequestration rate indicates net soil carbon gain while a negative value indicates soil carbon loss. The soil carbon EF demonstrates the carbon emissions from soil to air; it is simply the opposite of the corresponding SOC sequestration rate.

All SOC modeling includes the effects of erosion. The average soil loss or erosion rates (Mg soil/ha/yr) for croplands and pasture/hay/grasslands were obtained from the National Resources Inventory erosion estimates (USDA, 2009), which are based upon the Universal Soil Loss Equation and Wind Erosion Equation (for wind erosion), by averaging periodic erosion estimates from 1982, 1987, 1992, 1997, 2002, and 2007. For forest and land used for either switchgrass or *Miscanthus*, we assumed zero soil erosion rates. Under a no-erosion scenario, we assumed zero soil erosion rates for the cropland and pasture/hay/grassland as well.

It is important to note that the SOM decay coefficients in CENTURY for corn production were adjusted from default values because several studies have shown that CENTURY soil decay coefficients need to be adjusted upward to properly estimate SOC levels under row-cropped systems (Leite et al. 2004; Matthews and Pilbeam, 2005). Dunn et al. (2013) reported the influence of using the calibrated value of this parameter and the inclusion of erosion in SOC modeling on LUC GHG emissions.

Finally, county-level SOC changes are grouped by AEZs and then averaged to calculate the soil carbon EFs for a given scenario in that AEZ. For the calculation, the county-level average harvested areas for corn over five years (2006–2010) is used as the weighting factor.

Recently, CCLUB included an additional option for tillage practice – U.S. Average tillage – to estimate the soil carbon EFs at the U.S. national level. This option calculates the weighted average of SOC changes based on the share of corn-planted area using different types of tillage. Our baseline uses the U.S. Average tillage that assumes 34% residue left on the soil surface (USDA, 2015) and CCLUB's assumptions about the amount of residue associated with NT, RT, and CT practices (Table 4). The latter differs from USDA's Agricultural Resource Management Survey (ARMS), which reports the share of corn-planted area and the amount of residue left on the soil surface after planting for four tillage types (no till, mulch till, reduced, or conventional tillage) (USDA, 2015). We have assumed that our CT and NT are comparable to USDA's CT and NT while our RT combines USDA's reduced tillage and mulch till (Liu et al, 2020).

Table 4 Comparison of Tillage Systems in USDA's ARMS and CCLUB.

Tillage type	**USDA-ARMS***		**CCLUB**		
	Residue remaining after planting (%)	Share of corn-planted area (%)	Practices	Residue remaining after planting (%)	Share of corn-planted area (%)
CT	8	25	Moldboard plow, fertilize, disk, cultivate, plant, cultivate	3	25
RT	22	23	Fertilize, cultivate, plant, cultivate	31	51
Mulch till	41	28			
NT	65	24	Fertilize, plant, spray	64	24
U.S. Average	*34*	*100*		*34*	*100*

* The ARMS data are derived from tailored report of corn residue management practices from 2010.

Alternatively, CCLUB can be parameterized with domestic EFs taken either from the Winrock dataset (Harris et al. 2009) developed for U.S. Environmental Protection Agency's Renewable

Fuel Standard (RFS) or from the Woods Hole dataset (Houghton, 2012) that was provided to the CARB and GTAP to support land use modeling efforts. Importantly, the Winrock-derived EFs are provided at the state level for all land use conversions while Woods Hole EFs reflect biome-level (e.g., temperate evergreen forest) emissions from forest and grassland conversion to feedstock lands.

4. Domestic Aboveground Carbon Data for the Conterminous United States

Forest-to-feedstock land conversion results in foregone carbon sequestration due to non-soil carbon losses from forest ecosystems. We assessed such foregone carbon sequestration based on COLE data (Van Deusen and Heath, 2010), which include net annual tree biomass growth rate and carbon density of the five different non-soil components — aboveground live and dead tree, understory, forest floor, and coarse woody debris. Note that the emissions/sequestration effects from root biomass are accounted for in soil carbon EFs estimated by the parameterized CENTURY (Section 3).

The carbon in some harvested wood is assumed not be emitted but contained within harvested wood products (HWP) in productive uses such as buildings. Based on Heath et al. (1996), we determined that 60% of the combined aboveground live and dead tree carbon can be removed from the forest as HWP. Of this HWP, 35% (21% out of 60%) is stored in wood products while another 35% is converted into useful energy (both considered harvested wood product offsets). The carbon in the remaining HWP categories is assumed to be released to the atmosphere as is carbon in the waste wood, resulting in a 58% of aboveground live and dead tree carbon (Figure 5).

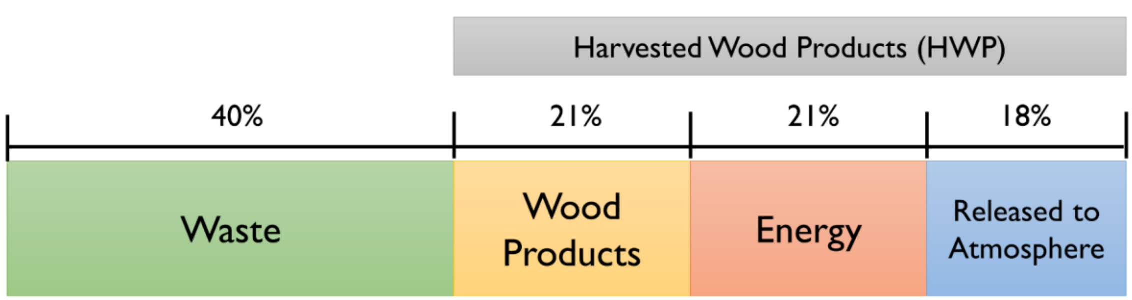

Figure 5 Fate of Aboveground Live and Dead Tree Carbon.

For the emissions assessments based on the Woods Hole dataset, the amount of aboveground live and dead tree carbon emitted to the atmosphere is 75%. CCLUB users can adjust this estimate in the sections of the Domestic C-Factors worksheet (in the column titled "C Released During Conversion"). Unlike the Woods Hole dataset, the Winrock dataset does not consider carbon sequestered in HWP (Harris et al. 2009).

Since GTAP adopts AEZ boundaries to summarize its results, aboveground carbon EFs calculated are also aggregated/disaggregated to this scale.

5. International Carbon Emission Factors

The CCLUB's international carbon EFs are primarily calculated from the Winrock dataset (Harris et al. 2009), which has been developed using recent land cover products derived from satellite imagery and other data sources (Table 5) to provide country-level or smaller administrative-level EFs.

Table 5 Data Sources and Key Methodology Points for Winrock Dataset

Land Type	Forest	Grassland	Cropland Pasture*
Data source	Figure 3 in (Harris et al.,2009) shows a world map color-coded to indicate the data source for each region.	Data for Brazilian grasslands based on a number of data sources. For all other countries, estimates based on Table 6.4 of the IPCC Agriculture, Forestry, and Other Land Use Guidelines (Eggleston et al. 2006)	Calculated as the average of forest, shrubland, grassland, and cropland carbon stocks.
Key methodology points	Includes CH_4 and N_2O emissions from forests cleared by burning. No carbon is assumed to be sequestered in harvested wood products. Foregone sequestration is included based on several literature reports.	Outside of Brazil, ratios of savanna and shrubland areas were calculated from grasslands based on the ratios of areas of these land types from the Brazilian dataset.	Follows International Geosphere-Biosphere Programme (IGBP) land cover definitions.

* CCLUB assigns emission factors the "Mixed" category from Winrock, which consists of a crop and vegetation mosaic, to international cropland pasture areas undergoing LUC as predicted by GTAP.

Since CCLUB considers EFs over a 30-year period for both domestic and international LUC, we derived such from the Winrock's EFs developed for three different periods following the land transition (Eq. 1).

$$EF_{30} = EF_1 + 19 \times EF_{2-19} + 10 \times EF_{20-30} \qquad [1]$$

where

EF_{30} = GHG emissions 30 years during the transition [Mg CO_2e/ha]

EF_1 = GHG emissions in the first year after the transition [Mg CO_2e/ha]

EF_{2-19} = GHG emissions in years 2 through 19 after the transition [Mg CO_2e/ha]

EF_{20-30} = GHG emissions in years 20 through 30 after the transition [Mg CO_2e/ha]

With the exception of reversion to forests, reversion EFs are estimated as the inverse of the Winlock's EFs. We assumed that all biomass carbon is restored in the first year after reversion while soil carbon on abandoned cropland would be sequestrated over the next 20 years to reach pre-conversion values. In the case of croplands that revert to forests, biomass accumulates annually over the 30-year reversion period. To be conservative, Winrock assumed that the newly growing trees accumulate carbon at the foregone sequestration rate. In reality, these young trees would incorporate carbon at a faster rate than the trees in more established forests that may have been cleared for feedstock production. Further details on these calculations are available in Harris et al. (2009).

In CCLUB, international LUC EFs associated with either conversion or reversion are aggregated into the categories in which GTAP results are reported by either using a land area-weighted average or arithmetic mean of country-level EFs (Table 6). In addition, CCLUB provides a second option to calculate international EFs using the Woods Hole dataset.

Table 6 Aggregation of Countries in Winrock Dataset to GTAP Regions

Region	GTAP Code	Countries Included
United States*	U.S.	United States†

European Union	EU 27	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
Brazil	Brazil	Brazil†
Canada	Canada	Canada†
Japan	Japan	Japan
China	CHIHKG	China†
India	India	India†
Central America	C_C_Amer	Belize, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico†, Nicaragua
South America	S_o_Amer	Argentina†, Bolivia, Chile, Colombia, Paraguay†, Peru, Uruguay, Venezuela
East Asia	E_Asia	Mongolia, North Korea, South Korea, Taiwan
Malaysia and Indonesia	Mala_Indo	Indonesia†, Malaysia†
Rest of Southeast Asia	R_SE_Asia	Philippines†, Singapore, Thailand†, Vietnam†
Rest of South Asia	R_S_Asia	Bangladesh, Cambodia, Pakistan, Sri Lanka
Russia	Russia	Russia†
Other Eastern Europe and Rest of Former Soviet Union	Oth_CEE_CIS	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Croatia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkey, Turkmenistan, Uzbekistan
Middle East and North Africa	MEAS_NAfr	Afghanistan, Algeria, Egypt, Ethiopia, Iran†, Iraq, Israel, Liberia, Libya, Morocco, Oman, Saudi Arabia, Tunisia
Sub Saharan Africa	S_S_AFR	Angola, Botswana, Cameroon, Central African Republic, Democratic Republic of the Congo, Ghana, Guinea, Kenya, Madagascar, Malawi, Mozambique, Namibia, Nepal, Nigeria†, Senegal, Somalia, South Africa†, Tanzania, Togo, Uganda, Zambia, Zimbabwe

* Winrock data for the United States are used in CCLUB only if the user selects that dataset for the domestic emissions modeling scenario.

† Subregions of the country were included in the average.

6. Domestic Belowground or Soil Carbon Emissions from Land Management Change

Unlike the concept of LUC, the potential impacts of LMC on soil carbon EFs during feedstock production for biofuels have not been widely included in biofuel LCA (Qin et al. 2018). Since 2015, CCLUB has adopted SOC modeling where several options of LMC such as cover crop adoption and manure application and varying levels of tillage are considered to simulate spatially explicit soil carbon EFs in the United States (Figure 6) (Qin et al., 2015, 2018).

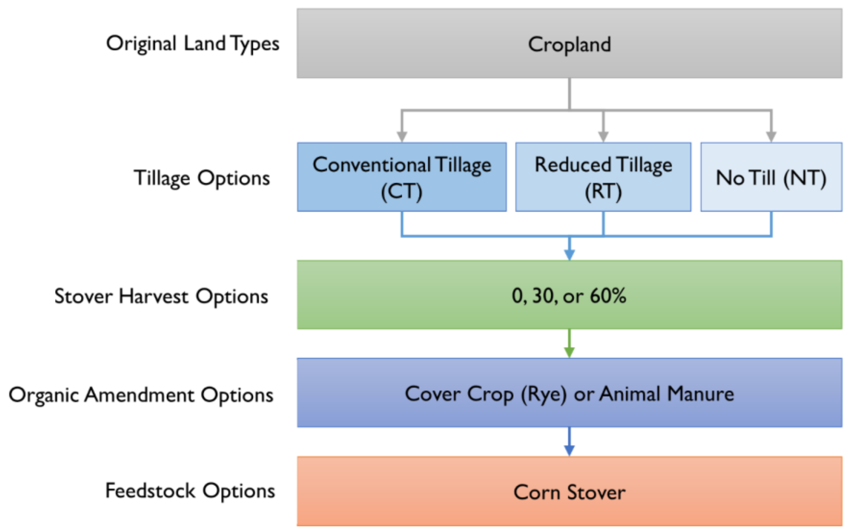

Figure 6 LMC Scenarios Modeled in CCLUB.

Table 7 Impacts of LMC Soil Carbon EFs Updates on Corn Stover Ethanol Life-Cycle GHG

Approach to Calculate a U.S. National Emission Factor*		**Integrated Corn/Stover Ethanol (Associated with Corn Stover Ethanol)**	
		Cover cropping	Manure application
		g CO_2e/MJ†	
CCLUB 2019	Arithmetic average	38.9	35.3
CCLUB 2020	Area-weighted average	42.7	36.1
	+ New SOC baselines using corn-planted areas treated with animal manure	43.5	36.9

* Based on the yield increase case with a 30% of corn stover harvest rate and U.S. average tillage.

† Calculated using energy allocation approach where the burden of all inputs for corn production is split between the grain and stover ethanol based on the energy content of the biomass (Qin et al. 2018).

In the 2020 version of CCLUB, we updated the current LMC-driven soil carbon EFs with two modifications. First, instead of using an arithmetic average of county-level EFs as the U.S. national EF, we adopted a weighted average based upon county-level corn harvested areas over the period of 2006 to 2010, which is consistent with the calculation of LUC EFs. Second, we refined a new baseline for SOC stock levels by considering a share of corn-planted areas typically treated with animal manure to enhance soil fertility. This change was made to reflect the fact that SOC sequestration is often higher with animal manure application than without it, and thus the old baseline SOC stock levels might be underestimated. We estimated this share to be 15% based on a weighted average of state-level percentage of corn-planted areas treated with manure (USDA, 2015). These modifications affected soil carbon EFs and relevant corn stover ethanol life cycle GHG emissions (Table 7).

7. Domestic and International Methane and Nitrous Oxide Emissions

CCLUB estimates CH_4 and N_2O emissions (Mg CO_2e/ha) from domestic and international LUC at the AEZ level using the approach recommended by Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al. 2006). CH_4 emissions are considered for countries where biomass burning is often used to clear lands for cultivation. Similarly, N_2O emissions from biomass burning are accounted for in CCLUB. In addition, N_2O emitted when SOM is directly and indirectly lost due to LUC and leaching/runoff are considered (Figure 7). Other sources of N_2O emissions — synthetic nitrogen fertilizer and agricultural residues — are accounted for through attribution to the feedstock carbon intensity in GREET rather than CCLUB (Liu et al. 2020).

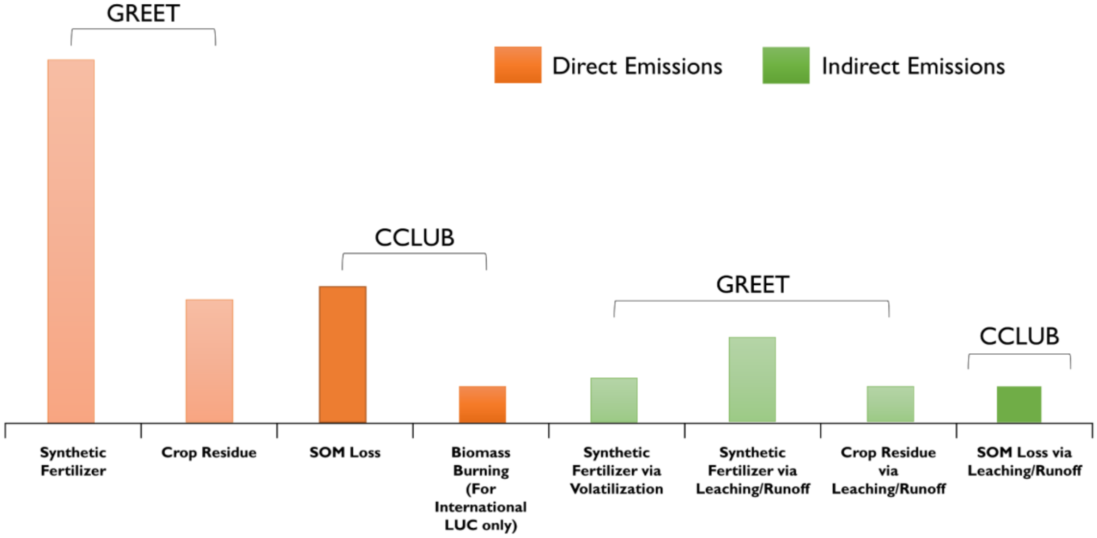

Figure 7 Direct and Indirect N_2O Emissions from Different Nitrogen Sources in CCLUB and GREET.

Because biomass burning is uncommon in the United States (Harris et al. 2009), such N_2O emissions for international LUC are calculated only by using the Winrock dataset or the Woods Hole dataset coupled with IPCC EFs. In the latter approach, the default carbon contents of wood and herbaceous grass (0.5 and 0.47 g C/g dry matter, respectively) are used to calculate biomass production from existing national biomass carbon stocks (Eggleston et al. 2006). To choose IPCC N_2O EFs for biomass burning, the major vegetation category (e.g., tropical, temperate, and boreal) are classified based on dominant GTAP AEZ-level forest or grassland LUC area (see "Conversion Factors" in CCLUB).

N_2O emissions due to direct SOM loss are derived from multiplying soil C EFs by C to N ratio of SOM (default value: 15). The emissions from indirect SOM loss are estimated using IPCC N_2O EFs. The calculation of N_2O emissions for peat conversions in Southeast Asia employs the N_2O EF of 1.5 Mg CO_2e/ha/yr for peatlands managed for extraction.

To be consistent with GREET, the global warming potential values relative to CO_2 are derived from the IPCC fifth assessment report, which estimates CH_4 and N_2O as 28 and 265, respectively (Stocker et al. 2013).

8. Temporal Issues in Modeling Land Use Change Emissions

CCLUB's assessment of carbon emissions from LUC depends on two critical time horizons: the duration of biofuels production and the emissions amortization period. Assumptions regarding the duration of biofuels production impact foregone sequestration from annual biomass growth and the associated soil carbon adjustments. Since the dataset on soil carbon adjustments from the parametrized CENTURY and the Winrock dataset are based on 30-year equilibrium values, the production duration should not differ significantly from that value. We assume that a relatively small variation of ±5 years may not introduce significant errors. The emissions amortization period refers to the duration over which a biofuels policy is analyzed.

9. Using CCLUB

In this section, we explain the contents of the eight sheets that make up CCLUB. We describe them in order of calculation flow rather than the left-to-right progression of sheets.

9.1. Overview Worksheet

It contains author information, a list of worksheets and their descriptions, and references related to late updates.

9.2. Scenario and Results Worksheets

It includes the scenario and results generated from either LUC or LMC. Below we show an example of how to use the LUC worksheet. The use of the LMC worksheet is similar.

The *LUC Scenario & Results* sheet contains user inputs and a results section. Users select input values in the rose-colored cells. All options are visible in the yellow cells in each section. The first user input (Input 1) is the feedstock-to-fuel pathway. The user can choose from among the biofuel production scenarios in Table 2 of this document, which include options for corn and cellulosic ethanol feedstock (corn stover, switchgrass, or *Miscanthus*), and soy biodiesel.

The second user input is the scenario selection for domestic carbon emissions scenarios (Input 2a). The data underpinning these scenarios is described in sections 3 and 4. If users opt to include domestic soil carbon EFs from SOC modeling, it is necessary to select whether to use modeling results that take into account yield increases (Input 2b) and select a soil depth (30 or 100 cm) as Input 2d. The LMC options (Section 7) allow the user to assess the influence of tillage practice on the results for corn and corn stover pathways (Input 2c) and to identify which method to use for domestic N_2O emissions estimates (Input 2e). For Input 3a, users can select either Winrock or Woods Hole datasets for international LUC emissions (Input 3a) including both carbon (Section 5) and CH_4 and N_2O emissions (Section 7). In particular, if Winrock is selected, users can navigate to Input 3b to determine the percentage of palm expansion on peat forest (Southeast Asia), with "0%" assuming no expansion on peat forest and "22%" being the latest updates (Qin and Kwon, 2018).

Users can select an HWP scenario for Input 4, either using the assumptions of Heath et al. (1996) or assuming all forest aboveground carbon is emitted when forests are converted to biofuel feedstock production.

In Input 5, users can indicate whether to include biomass burning for initial land clearing in international LUC. Answer "No" indicates no burning for all countries, and "Yes" for burning in all international countries only when "CENTURY SOC" or "Woods Hole" is selected in Input 2e.

If Input 2e selects "Winrock," then "Yes" indicates burning in countries in which biomass burning is a common practice based on Winrock estimates (Harrison et al. 1996).

In developing CCLUB, we modified GTAP data for area of converted forest as described in Section 2. Input 6 allows users to adopt adjustments to converted forest lands by selecting "Yes" or to use raw GTAP data by selecting "No." Input 7 allows users to choose an approach for spatial average in both domestic (Section 3) and international LUC factors (Section 5).

Users can alter the foregone carbon sequestration period by adjusting Input 8. Users are cautioned, however, that the modeling runs that produced domestic soil C values and Winrock emission factors are based on 30-year time horizons. Choosing values outside that time window may produce inaccurate results.

Finally, users can alter the amortization period in Input 9. See Section 6 for a discussion of how amortization influences results.

Once all inputs are selected, the user can click the "Run Simulation" button and view results within CCLUB as described in the following paragraph. If the user also clicks on "Copy to GREET," inputs and results will be transferred to GREET and incorporated into overall biofuel life cycle analysis. The user will have an active GREET spreadsheet after clicking this button.

No input or adjustments are required on other sheets to see the results, which vary based on the user selection in the Inputs section. Emissions are divided into land types of forest, grassland, cropland-pasture, and young forest-shrub. Note that Woods Hole dataset does not include the latter two land types. Just to the right of the main results table, results are tabulated for all dataset options within CCLUB. In this section, the emissions are divided into domestic and international emissions, each of which are broken out as follows by land type (carbon emissions as an example):

- Domestic or International Emissions (Mg C): Total carbon emissions for the selected scenario by land type.
- Domestic or International Emissions (Mg CO_2e): The total carbon emissions are converted to CO_2e (3.67 g CO_2e/g C).
- Domestic or International Annualized Emissions (Mg CO_2e/yr): The total CO_2e emissions are divided by the amortization period specified in Input 7.

- Domestic or International Annualized Emissions (g CO_2e/gal): The annualized emissions are divided by the annual fuel production volume.
- Domestic or International Annualized Emissions (g CO_2e/MJ): The volume-based emissions are converted to a unit energy basis with the lower heating value of ethanol (80.53 MJ/gal) or biodiesel (126.13 MJ/gal).

The red-highlighted box in the results section contains the total carbon, N_2O & CH_4 or total GHG emissions associated with the selected scenario in units of g CO_2e/MJ.

9.3. Modeling Worksheet

At the top of this sheet, conventions used in calculations are defined. Carbon emission and sequestration factors are defined as positive and negative, respectively. Converted land areas are treated as negative, whereas reverted lands are defined as positive. The color coding of the spreadsheet is also defined. Soil and non-soil emissions factors are highlighted in red and blue, respectively. The annual growth of forests is highlighted in green. Land areas imported from other tabs are colored gray.

The first data section A1 in the sheet contains domestic EFs for both CO_2 and N_2O based on data from the parameterized CENTURY modeling effort described in Section 3. The results are grouped as follows. First, EFs for conversion and reversions of forests, grasslands, YF-shrublands, and cropland-pasture lands (as Figure 2 depicts) are calculated as the sum of aboveground carbon, soil carbon, and foregone sequestration from annual growth. Note that the soil carbon EFs for the corn ethanol, stover ethanol, and soy biodiesel scenarios are dependent on the selected tillage scenario (CT, RT, and NT). Second, these EFs are matched to the selected biofuels scenario and multiplied by the corresponding GTAP LUC projection for each transition. It is in this sheet that the forest proration factor is applied.

Domestic emissions calculated with Woods Hole and Winrock datasets are also displayed in this sheet in Sections A.2 and A.3. The international components of the Woods Hole and Winrock dataset described above are used to assess international emissions for the selected biofuel production scenarios in Sections B1 and B2.

All carbon emissions are included in subsection *a* while N_2O emission are in subsection *b*.

9.4. Domestic C-Factors Worksheet

This worksheet displays the domestic EFs based on the parametrized CENTURY/COLE, Winrock and Woods Hole datasets. This sheet uses color coding to guide the user's eye. Soil and non-soil carbon stock changes are red- and blue-highlighted, respectively. Annual growth values are green-highlighted.

The first table contains soil carbon stock changes by AEZ as modeled with the parameterized CENTURY and described in Section 3. Separate tables are provided for each scenario option in Input 2.

The second table contains non-soil carbon by AEZ, developed as explained in Section 4. Note that only aboveground carbon emissions impacts of forest conversion are considered because belowground carbon stock changes (from soil and tree roots) are considered in SOC modeling. In this table, the YF-Shrub correction factor described in Section 2 is also calculated.

The third table contains data from COLE for total net tree growth. The values stated in Mg carbon per hectare per year are calculated from the carbon contained in the new tree growth using a forest carbon factor of 50%, which is consistent with the IPCC Good Practice Guidance for Land Use, Land Use Change, and Forestry.

Section B and Section C of this sheet contains the Woods Hole and Winrock domestic EFs, respectively.

9.5. International C-Factors Worksheet

This sheet has the same color scheme as the Domestic C-Factors sheet. It calculates International EFs from the Winrock and Woods Hole datasets, which are described in Section 5.

9.6. GTAP Data Worksheet

This worksheet contains three sections. The bottom section with a heading of "GTAP Source Data Tables" contains the raw GTAP data, generated as described in Section 2. The data are grouped by scenario. The section above the raw data, titled "Land Use Summary by Region and AEZ," selects the LUC data from the appropriate scenario. The top section, "Land Use Summary by Region," contains the total LUC by land type and country/region. These values are multiplied by the appropriate EFs to generate LUC emissions results.

9.7. C-Database Worksheet

In this worksheet, soil C stock changes under any LUC and LMC scenario simulated from the parameterized CENTURY are included for the U.S. counties where corn harvested area is reported. County-level COLE data for forest aboveground carbon are also included in this worksheet to the right of county-level soil C data. The county-level EFs are aggregated to the AEZ level in the table at the top of the worksheet for use in the Domestic C-Factors worksheet.

Note that soil carbon stock change results are reported in a unit of Mg C/ha/yr over a 30-year simulation period. If these are positive, it means that a positive soil carbon sequestration or negative soil carbon emission occurs. If negative, vice versa.

9.8. Forest Land Area Worksheet

Section A of this sheet contains state-level land use data from CDL analysis mapped to the AEZ level using the matrix displayed in Section B. Forest proration factor calculations are shown in Section C of the sheet. Section 2 of this document discusses these calculations.

9.9. International Conversion and Reversion

Section 5 describes details behind these factors.

9.10. Saved Results

It reports carbon and GHG (CH_4 and N_2O) emissions associated with LUC in a unit of g CO_2e/gal biofuel and carbon emissions associated with LMC for corn stover ethanol in a unit of g CO_2e/dry ton biomass or MJ biofuel. These can be copied and pasted into GREET for overall biofuel LCA calculations.

10. Outstanding Issues

Critiques have been raised regarding the LUC emissions estimated in CCLUB particularly for land conversion from cropland pasture to corn in the United States and for the forest-on-peat to palm transition in Southeast Asia (mainly Indonesia and Malaysia) (Malins et al. 2020; Searle, 2018).

The first issue is related to the fact that in CCLUB, changes of cropland pasture to continuous corn result in SOC gains in the United States. Especially, Malins et al. (2020) pointed out that the CCLUB's EFs stand in marked contrast to all other sets of EFs for GTAP, which assume carbon loss from cropland pasture conversion. Although Malins et al. (2020) characterized cropland pasture as closer characteristics of pasturelands, CCLUB has focused more on the frequency of switches between cropland and pasture phases that influences SOC levels. From a carbon accounting perspective in CCLUB, we are interested in how land has been chronologically transitioned in reality between these two land use categories. In our approach regarding the movement of land on the margin of conversion, we follow closely the understanding developed by Claassen et al. (2011) who pointed to the main drivers for land conversions which are consistent with the GTAP approach: "Given the availability of grassland with land quality characteristics that place it on the margin with cultivated cropland, changes in the relative profitability of cropland and grassland may prompt producers to convert land from one use to the other (Tyner et al. 2010)." We also investigated this to some extent in Emery et al. (2017) and further elaborated our approach in Taheripour et al. (under review).

The second is CCLUB's *palm-on-peat factor* to calculate area changed due to forest-on-peat to palm conversion. The *palm-on-peat factor* is defined as the ratio of predicted future new palm-on-peat to new palm on all lands and has largely relied on historical palm plantation pattern. As a result, it varies among different studies and has evolved with up-to-date data. However, Searle (2018) criticized a lower ratio adopted in CCLUB (0.22) than that in AEZ-EF model (0.33), which is the primary LUC EF model used by CARB. The author further argued that CARB's LUC soil carbon EF for forest-on-peat to palm conversion (95 Mg CO_2e/ha/yr) is more reliable than CCLUB's EF (73 Mg CO_2e/ha/yr) (Chen et al. 2018). To respond to the critiques, we have elaborated our modeling approaches and provided further CCLUB update of soil carbon EF to 55 Mg CO_2e/ha/yr based on IPCC EF (Qin and Kwon, 2018).

Along with engaging in discussion that has fostered improvements in LUC and LMC emission modeling, we have improved the modeling framework embedded in CCLUB and provided reliable information to the scientific community in estimating LUC and LMC emissions. In particular, we have developed a database of regional variations in land uses and management practices and their impacts on SOC changes for biofuel feedstock production by conducting a meta-analysis of published literature and/or open source database (Kwon et al. 2017; Qin et al. 2016b; Xu et al. 2019). The results and findings obtained from the new databases continue to be employed for updating/evaluating CCLUB's SOC modeling.

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Appendix A: Tabular Summary of Land Conversions

Scenario	Pristine	Early Agriculture (1880–1950)	Modern Agriculture (1951–2010)	LUC or LMC Period (2011–2040)		
				Crop	**Tillage**	**Aboveground Residue or Biomass Harvest (%)**
1	Grassland	Cropland	Cropland	Corn	CT	0
2				Corn	CT	30
3				Corn	RT	0
4				Corn	RT	30
5				Corn	NT	0
6				Corn	NT	30
7				Switchgrass	NT	90
8				*Miscanthus*	NT	90
9				Poplar	NT	90
10				Willow	NT	90
11	Grassland	Grassland	Grassland	Corn	CT	0
12				Corn	CT	30
13				Corn	RT	0
14				Corn	RT	30
15				Corn	NT	0
16				Corn	NT	30
17				Switchgrass	NT	90
18				*Miscanthus*	NT	90
19				Poplar	NT	90
20				Willow	NT	90
21	Forest	Forest	Forest	Corn	CT	0
22				Corn	CT	30
23				Corn	RT	0
24				Corn	RT	30
25				Corn	NT	0
26				Corn	NT	30
27				Switchgrass	NT	90
28				*Miscanthus*	NT	90
29				Poplar	NT	90
30				Willow	NT	90
31	Grassland	Cropland		Corn	CT	0
32			Grassland (1951-1975)-Cropland (1976-2010)	Corn	CT	30
33				Corn	RT	0
34				Corn	RT	30
35				Corn	NT	0
36				Corn	NT	30
37				Switchgrass	NT	90
38				*Miscanthus*	NT	90
39				Poplar	NT	90
40				Willow	NT	90

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