Agro-ecological Zone Emission Factor (AEZ-EF) Model (v47)

A model of greenhouse gas emissions from land-use change for use with AEZ-based economic models

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1. OVERVIEW

The purpose of the agro-ecological zone emission factor model (AEZ-EF) is to estimate the total CO_2-equivalent emissions from land use changes, e.g., from an analysis of biofuels impacts or policy analyses such as estimating the effect of changes in agricultural productivity on emissions from land use. The model combines matrices of carbon fluxes (Mg CO_2 ha^{-1} y^{-1}) with matrices of changes in land use (ha) according to land-use category as projected by GTAP or similar AEZ-oriented models. As published, AEZ-EF aggregates the carbon flows to the same 19 regions (Table 1) and 18 AEZs (Figure 1) used by GTAP-BIO, the version of GTAP currently used by Purdue University researchers for modeling CO_2 emissions from indirect land-use change (ILUC) (e.g., Tyner, Taheripour et al. 2010). The model, however, is designed to work with an arbitrary number of regions, as described in section 8.3.

The AEZ-EF model contains separate carbon stock estimates (Mg C ha^{-1}) for biomass and soil carbon, indexed by GTAP AEZ and region, or "Region-AEZ" (Gibbs and Yui 2011; Gibbs, Yui et al. 2014). The model combines these carbon stock data with assumptions about carbon loss from soils and biomass, mode of conversion (i.e., whether by fire), quantity and species of carbonaceous and other greenhouse gas (GHG) emissions resulting from conversion, carbon remaining in harvested wood products and char, and foregone sequestration.[4] The model relies heavily on IPCC greenhouse gas inventory methods and default values (IPCC 2006), augmented with more detailed and recent data where available.

The AEZ-EF model was designed for use with a static comparative economic model, i.e., one that starts with a baseline and computes a new equilibrium in one step, rather than as a series of steps over time. Handling a dynamic analysis properly would require tracking the carbon status of land that may be going through a series of conversions and reversions. This could be done if the carbon accounting were performed in the GTAP TABLO code, but this is clearly beyond the scope of the current model and report. A very simple approach to using the AEZ-EF model with a dynamic economic analysis would be to compute the change in land-cover areas by AEZ and region between the starting and ending states and to apply the emission factor model to these changes in the same way it is used for the static model.

1.1 Sinks and sources of greenhouse gas emissions from land use change

Following the IPCC GHG inventory guidelines, the AEZ-EF model includes the following sources / sinks of greenhouse gas emissions:

1. Above-ground live biomass (trunks, branches, foliage)
2. Below-ground live biomass (coarse and fine roots)
3. Dead organic matter (dead wood and litter)
4. Soil organic matter
5. Harvested wood products
6. Non-CO_2 climate-active emissions (e.g., CH_4 and N_2O)
7. Foregone sequestration

[4] A version of this model implemented in the Python language includes estimates of uncertainty in all parameters, thereby enabling quantitative analysis of uncertainty in the AEZ-EF model separately or in conjunction with the GTAP-BIO model.

In this report, we use the following definitions and acronyms:

- Above-ground live biomass (AGLB): trunk, branches, and foliage
- Dead organic matter (DOM): standing and downed dead trees, coarse woody debris, and litter
- Above-ground biomass (AGB): AGLB plus DOM
- Total AGLB: AGLB + understory
- Total AGB: AGB + understory
- Below-ground biomass (BGB): coarse and fine roots
- Soil organic carbon (SOC)
- Total ecosystem biomass (TEB): Total AGB + BGB
- Total ecosystem carbon (TEC): SOC + carbon fraction of TEB

Table 1. Regions used in the GTAP-BIO and AEZ-EF models.

Region ID	Description
USA	United States
EU27	European Union 27
Brazil	Brazil
Canada	Canada
Japan	Japan
ChiHkg	China and Hong Kong
India	India
C_C_Amer	Central and Caribbean Americas
S_O_Amer	South and Other Americas
E_Asia	East Asia
Mala_Indo	Malaysia and Indonesia
R_SE_Asia	Rest of South East Asia
R_S_Asia	Rest of South Asia
Russia	Russia
Oth_CEE_CIS	East Europe and Rest of Former Soviet Union
Oth_Europe	Rest of European Countries
ME_N_Afr	Middle Eastern and North Africa
S_S_Afr	Sub Saharan Africa
Oceania	Oceania

(Source: Tyner, Taheripour et al. 2010)

1.2 Data sources

The AEZ-EF model includes global data that describe carbon stocks in above- and below-ground live biomass and in soils beneath forests and pastures. Forest AGLB is derived from various remote-sensing and ground-based sources, whereas pasture AGLB is gathered from the literature. Soil carbon data are from the Harmonized World Soil Database (HWSD), from which we produced SOC estimates to depths of 30 cm and 100 cm aggregated for each Region-AEZ (Gibbs, Yui et al.

2014). Below-ground biomass carbon for all land cover types is based primarily on root:shoot ratios (Saatchi, Harris et al. 2011), except for the pan-tropics. Peatland, deadwood, and litter carbon stocks are taken from the literature. (Specific sources are described below.)

The AEZ-EF model combines these carbon stock data with assumptions about carbon dynamics that together determine the CO_2-equivalent emissions associated with land-use conversion. These assumptions, described later in this report, include:

- The fraction of soil carbon lost or gained upon conversion
- Sequestration rates (Mg C ha^{-1} y^{-1}) for forests (foregone if converted)
- Growth rates (Mg C ha^{-1} y^{-1}) for forests growing on onetime pasture or cropland
- The fraction of conversion achieved using fire
- The non-CO_2 emissions associated with land clearing using fire
- N_2O emissions associated with the loss of soil organic carbon
- The fraction of forest AGLB that is harvested and remains sequestered in wood products at the end of the analytical horizon (currently 30 years).

2. CARBON STOCK AGGREGATION

The C stock database contains area-weighted averages of above- and below-ground C stocks by land cover class, aggregated to Region-AEZ boundaries (Gibbs, Yui et al. 2014).

The method of aggregation selected affects the emission factors that are generated. Computing area-weighted averages is clearly the simplest approach, and does not require additional data. However, this method provides a good proxy for land selection only if selection is random across each land cover class, or if there is little variance in C stock across each class. A more sophisticated approach (though the data are impoverished and not necessarily more accurate) would weight C stocks by likelihood of conversion, based on suitability, accessibility, evidence from remote sensing analysis, and so on. For example, a simple, first-order approach would be to use relative proximity to roadways as a proxy for likelihood of conversion.[5]

Application of a likelihood-of-conversion criterion produces a preference order for land conversion and converts the C stock database from one of average values to one representing marginal values. Marginal values are generally scale-dependent, i.e., the marginal land source (and thus emissions) will vary as more land is utilized in a region. It would thus be useful to explore the variance in marginal emissions across relevant scales, not only of biofuel demand but of global land demand under different assumptions regarding food production (e.g., in light of crop losses from extreme weather events.)

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[5] A “road-proximity rule” will not be appropriate throughout the tropics. Depending on historical land use, roads may actually reduce the likelihood of clearing in regions with sparse forest cover. It may only be relevant for the heart of the Amazon and Congo basins and the Papua province of Indonesia. But roads and ports are planned in these regions so conditions will be dynamic over the next 5-10 years. Thus we could consider making some rough assumptions to see if there is an impact on the results, but this would not necessarily be an improvement.

2.1 Comparing carbon stocks with those in earlier ILUC modeling

We note that the prior emission factor model used by the California Air Resources Board (CARB) relied on data from the Woods Hole Research Center (WHRC) and aggregated emission factors to slightly different GTAP regional boundaries, based on an estimate of the percentage of land conversion in each region that involved particular ecosystem types. For example, if the newly cropped land in a given region was previously 40% forest and 60% grassland, it was assumed that any addition of cropland projected by GTAP-BIO to occur in that region would be converted 40% from forest and 60% from grassland. Thus, although the regional carbon stock estimates from the AEZ-EF model can be compared with those of the former model, the use of area weighting in the AEZ-EF and historical conversion weightings in the earlier model means these two approaches—by definition—estimate different quantities. However, the final emission factors are commensurable as both models estimate the emissions associated with biofuel-induced LUC, albeit using different methods and data.

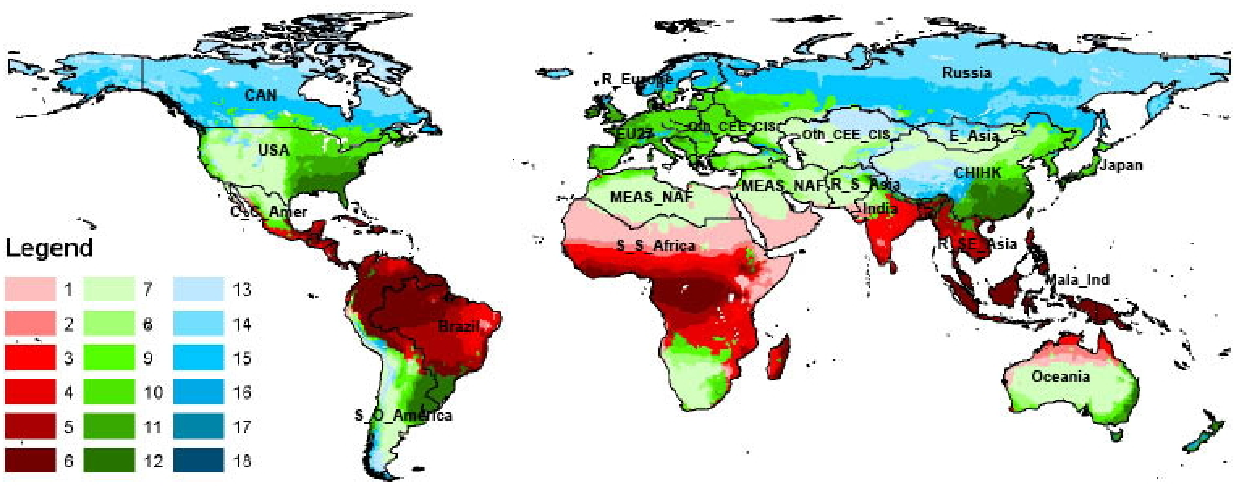

Figure 1. Distribution of agro-ecological zones (AEZs 1-18) and regions used in the GTAP-BIO model. Shades of red, green, and blue represent tropical, temperate, and boreal AEZs, respectively.

2.2 Mapping to GTAP-BIO boundaries and economic uses

GTAP-BIO considers land to be in one of five usage categories:

1. Forestry (accessible, by definition)
2. Livestock pasture
3. Cropland (including the subset cropland-pasture)
4. Unmanaged (non-forest, not in current economic use)
5. Inaccessible (because of a lack of infrastructure or other restrictions)

However, GTAP-BIO considers land competition and conversion only among forestry, pasture and cropland; it excludes land deemed unmanaged and inaccessible (Golub and Hertel

2012). Excluding inaccessible forest from the analysis tends to underestimate the conversion of forest as a result of price changes (Gouel and Hertel 2006).

The carbon data used in AEZ-EF have been aggregated to GTAP-BIO boundaries, but they include both accessible and inaccessible forests, as well as grasslands other than those used for livestock grazing, and thus represent broader resources than those represented in GTAP-BIO. Some of the issues involved in these differing representations are discussed below.

3. BIOMASS CARBON STOCKS

3.1 Forestry

Ideally, the carbon stocks for each Region-AEZ would represent the same land represented by GTAP-BIO, that is, only accessible forests rather than all forests in a given AEZ. However, the data that quantify accessible versus inaccessible forest are not spatially explicit, but are based on FAO national data and percentages in each category (Gibbs, Yui et al. 2014).

We followed the approach taken by WHRC and Winrock to produce average C stocks that combine accessible and inaccessible forests. We also mask out land identified by the GTAP maps as “unmanaged,” since this includes shrublands and grasslands not used for grazing. Forest areas are not based on the GTAP definition because the GTAP forest map does not account for areas cleared by logging or for other non-agricultural purposes (Gibbs, Yui et al. 2014). Thus, we use the GTAP-BIO cropland and pasture boundaries but rely on satellite data for forest boundaries.

3.1.1 Below-ground biomass

Below-ground biomass stocks are generally estimated using root:shoot ratios, which vary by species and region. In CARB’s previous model of ILUC emissions, BGB was included in estimates of biomass carbon from the Woods Hole Research Center (WHRC). The new carbon stock data (Gibbs, Yui et al. 2014) break out above- and below-ground data based largely on IPCC (2006) recommendations. AEZ-EF model explicitly includes estimates of below-ground biomass and the gain or loss thereof for conversions of among forest, pasture, and cropland.

It was not possible to have separate belowground and aboveground biomass layers specific for each dataset because not all databases provide this information separately. The following methods were used to create separate above- and below-ground biomass values:

- For data from Saatchi, Harris et al. (2011), we created a look-up table based on the allometric equation described below to estimate root-to-shoot ratios[6].
- For boreal forests and tropical forests with data from sources other than Saatchi et al. (2011), we used root-to-shoot ratios based on total tree biomass from the widely used

[6] Root-to-shoot ratios relate the belowground biomass quantities to the aboveground biomass. They are routinely used because aboveground biomass in an easier quantity to measure through field plots or remote sensing imagery. The correlations between above and belowground biomass are established through detailed field analysis at a limited number of plots (harvesting, drying and weighing the entire plant to weight the biomass).

IPCC GPG (IPCC 2006)[7], as shown in Table 4. Note that AEZs 1-6 indicate tropical regions, and AEZs 13-18 indicate boreal regions. In some cases, the values were averaged as the translation between AEZs and the IPCC ecological zones were not exact.

- For temperate forests a root-to-shoot ratio of 0.25 was assumed in all cases.

Forest carbon data for Russia (sourced from WHRC) represent total biomass, including AGB, BGB, and understory carbon. We use a default root:shoot ratio of 0.25 to convert the total biomass to AGB and BGB, and for this region, we apply a value of 0 Mg ha^{-1} in the model for understory carbon to avoid double-counting. We recognize that this implicitly assigns a root:shoot ratio of 0.25 to understory biomass, but any error caused by the small difference in this small quantity in a single region is likely of little consequence.

3.1.2 Carbon stored in dead organic matter

Forest biomass carbon estimates (including our own database) include only live tree trunks, branches, and foliage. In addition to live biomass, forests also often contain a substantial quantity of dead organic matter (DOM). For example, according to the US Forest Inventory, 35% of the total forest carbon pool is in live vegetation, 52% in soil, and 14% in dead organic matter, excluding fine woody debris (Woodall, Heath et al. 2008). Elsewhere, these ratios vary across climatic zones.

DOM consists of litter and deadwood. Deadwood includes all non-living tree biomass not included in litter, including standing dead trees, down dead trees, dead roots, and stumps larger than a specific diameter, often 10 cm (Woodall, Heath et al. 2008). Although the IPCC implies that litter refers to the organic layers on the surface of mineral soils, soil science, by contrast, considers litter to be restricted to freshly fallen leaves, and regards decomposing leaves as humus (Takahashi, Ishizuka et al. 2010). The IPCC guidelines assume that dead organic matter stocks are zero for non-forest land-use categories. The Tier 1 IPCC GHG inventory guidelines assume that deadwood and litter carbon stocks are in equilibrium, i.e., that there are no net emissions from this pool. However, the inventory guidelines provide estimates for litter but not for deadwood.

Assuming that deadwood and litter stocks are in equilibrium, conversion of forest to pasture or cropland releases the carbon in these pools and ends the processes that replenish these pools. Since the biomass stock rates and growth rates we use are net of mortality, the CO_2 from combustion of dead wood and litter is a source of additional emissions.

3.1.2.1 Deadwood

The quantity of deadwood in a forest depends on several factors; these include the density of live trees, the age of the forest, temperature, humidity, harvest frequency, self-thinning mortality, time elapsed since the last disturbance, and whether this was fire, which removes dead wood, or an event that introduces deadwood, such as blow-downs, diseases, or pests. Because of these diverse influences, there is no predictive relationship between the stocks of live tree biomass

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[7] Using Table 4.4, references included Mokany et al 2006, Lie et al 2003, and Fittkau and Klinge 1997

carbon and deadwood carbon (Woodall and Westfall 2009). Ratio methods fail spectacularly in cases of low live and high dead biomass. Large-scale disturbances are location-specific, so it is difficult to generalize from these results.

To complicate matters further, deadwood is infrequently measured. What empirical data do exist are based on diameter measurements, from which volume and carbon are estimated (Woodall, Heath et al. 2008). The carbon density of deadwood varies with the state of decay, adding further uncertainty to the magnitude of this carbon pool.

The amount of deadwood in forests is highly variable around the world, and range from 0 to >600 Mg biomass ha^{-1}, but most forests contain 30 to 200 Mg biomass ha^{-1} of deadwood (Richardson, Peltzer et al. 2009). Estimates of coarse woody debris (CWD) – fallen dead trees and large branches – in tropical forests vary widely from 0 to >60 Mg biomass ha^{-1} (Baker, Honorio Coronado et al. 2007). The IPCC defines deadwood as "the carbon in coarse woody debris, dead coarse roots, standing dead trees, and other dead material not included in the litter or soil carbon pools" (IPCC 2006), so CWD is a subset of DOM.

In a study of deadwood in New Zealand's forests, Richardson, Peltzer et al. (2009) found that at a plot scale, there was a weak positive relationship between total live tree biomass and deadwood, and a negative relationship between the percentage of above-ground biomass as deadwood and live tree biomass. However, they conclude:

> At a small scale, in even-aged stands, there should be a negative relationship between live tree biomass and deadwood biomass reflecting the reciprocal oscillation of forest biomass between live and dead pools (Lambert et al., 1980; Allen et al., 1997). However, in this national-scale analysis, live tree and deadwood biomass were weakly positively correlated because plots containing large-sized tree species produced larger pieces of deadwood. This positive relationship between live tree and deadwood biomass was also retained within forest types because our broad forest types all contain a wide range of tree sizes and environments.

In the case of New Zealand, they conclude that the mass of deadwood is approximately 16% of the live tree biomass. For the scale of analysis in GTAP-BIO and the AEZ-EF model, it is reasonable to estimate the size of the deadwood pool based on the pool of above-ground live biomass.

In Japan, Takahashi, Ishizuka et al. (2010) found that deadwood carbon stocks for coniferous plantations with a history of non-commercial thinning showed 17.1 Mg C ha^{-1} and semi-natural broad-leaved forests showed 5.3 Mg C ha^{-1} on average, although these values are based on limited data.

Oswalt, Brandeis et al. (2008) found that on the Caribbean island of St. John, deadwood materials contributed 8.9±0.8 (SE) Mg C ha^{-1}, while litter contributed a mean of 5.8 ± 0.6 Mg C ha^{-1}.

Thus, despite the uncertainties, the amount of DOM in forests is clearly non-negative: excluding it (which is equivalent to assigning a value of zero) would bias C stock estimates. Most of this carbon would be released quickly upon conversion by fire. These C stocks were not accounted for in the original ARB ILUC model or in the EPA/Winrock model.

Estimates of carbon stored in deadwood used in AEZ-EF are derived from Pan et al. (2011). The US, Europe, and Canada are shown separately in the Pan et al. data, and since these correspond to regions used in the GTAP-BIO model, the values are adopted directly. For other areas, the average values from Pan et al. for boreal, temperate, and tropical latitudes are used according to the latitude of the region, as shown in Table 2.

Table 2. Estimates of deadwood by region or latitude (Mg C ha^{-1}).

Region or latitude	Deadwood
USA	10.5
EU27	2.1
Canada	21.8
Boreal	14.3
Temperate	4.2
Tropical	27.5

Source: Pan, Birdsey et al.(2011)

3.1.2.2 Litter

The IPCC gives litter values for two categories of mature forests: broadleaf deciduous and needleleaf evergreen. However, their regional boundaries do not conform exactly to AEZs. To use these values, three methods must be developed:

1. A means to map the IPCC spatial aggregation to AEZs
2. A means to combine the broadleaf deciduous and needleleaf evergreen values into a single value
3. A protocol to adjust the value for mature forests to reflect the forests actually converted

The AEZ-EF model simply averages the values for broadleaf deciduous and needleleaf evergreen forests, and averages the two values (cold and warm) for dry temperate forests and for moist temperate forests. Table 3 lists the IPCC's default values for litter in mature forests. Table 4 lists the values used in AEZ-EF, by AEZ.

Table 3. IPCC default values for litter in mature forests (Mg C ha^{-1}).

Latitude/humidity	Broadleaf deciduous	Needleleaf evergreen	Average
Boreal, dry	25 (10–58)	31 (6–86)	28.0
Boreal, Moist	39 (11–117)	55 (7–123)	47.0
Cold temperate, dry	28 (23–33)[a]	27 (17–42) [a]	27.5
Cold temperate, moist	16 (5–31) [a]	26 (10–48) [a]	21.0
Warm temperate, dry	28.2 (23.4–33.0) [a]	20.3 (17.3–21.1) [a]	24.3
Warm temperate, moist	13 (2–31)a	22 (6–42) [a]	17.5
Subtropical	2.8 (2–3)	4.1	3.5
Tropical	2.1 (1–3)	5.2	3.7
Averages of IPCC categories above			
Temperate, dry			25.9
Temperate, moist			19.3

(Source: IPCC 2006, Table 2.2)
[a] Values in parentheses marked by superscript "a" are the 5th and 95th percentiles from simulations of inventory plots, while those without the superscript indicate the entire range.

Table 4. Litter values used for forests in AEZ-EF model, by AEZ (Mg C ha^{-1}).

AEZ	Description	IPCC Category	Litter
1	Tropical-Arid	Tropical	3.7
2	Tropical-Dry semi-arid	Tropical	3.7
3	Tropical-Moist semi-arid	Tropical	3.7
4	Tropical-Sub-humid	Tropical	3.7
5	Tropical-Humid	Tropical	3.7
6	Tropical-Humid (year round)	Tropical	3.7
7	Temperate-Arid	Temperate, dry	25.9
8	Temperate-Dry semi-arid	Temperate, dry	25.9
9	Temperate-Moist semi-arid	Temperate, dry	25.9
10	Temperate-Sub-humid	Temperate, moist	19.3
11	Temperate-Humid	Temperate, moist	19.3
12	Temperate-Humid (year round)	Temperate, moist	19.3
13	Boreal-Arid	Boreal, dry	28.0
14	Boreal-Dry semi-arid	Boreal, dry	28.0
15	Boreal-Moist semi-arid	Boreal, dry	28.0
16	Boreal-Sub-humid	Boreal, Moist	47.0
17	Boreal-Humid	Boreal, Moist	47.0
18	Boreal-Humid (year round)	Boreal, Moist	47.0

3.1.3 Understory

The forest understory consists of shrubs, herbs, grasses, mosses, lichens, and vines. Carbon stocks in the understory increase as gaps appear in the canopy and decrease as the canopy closes, so these are inversely proportional to forest carbon stock to a degree (Plantinga and Birdsey 1993). Thus, for regrowing forests with low carbon densities, the exclusion of understory biomass would be expected to underestimate carbon stocks and thus emissions. Understory carbon is added separately in AEZ-EF except in the case of Russia, where the biomass stock estimates (from WHRC) already include this pool.

Woodbury et al. (2007) examined carbon sequestration in the US forest sector, and suggested that the minimum understory carbon density is about 0.5% of the tree carbon density found in mature stands where density is high. Woodbury et al. note: "The maximum understory carbon density is predicted to occur when the plot contains no trees greater than 2.54 cm in diameter, and ranges from 1.8 to 4.8 t C ha^{-1}, depending on forest type."

These studies permit us to use the minimum of 0.5% of AGLB or a maximum of 4.8 Mg C ha^{-1}, at least in US forests. Some studies note that understory biomass has a negative exponential relationship to tree biomass, since canopy openings increase understory growth and closed canopies reduce it. Thus any factor multiplied by AGLB is questionable.

Telfer (1972) finds a grand total of 2.5 to 8.9 Mg biomass (or 1.2 to 4.5 Mg C) per ha in Nova Scotia, with mosses comprising a large component.

In their Amazonian rainforest studies, Nascimento et al. (2002) find an average of 1.28 Mg biomass ha^{-1} of stemless plants plus 8.30 Mg biomass ha^{-1} of lianas (woody vines that hang from trees), totaling 9.6 Mg biomass, or about 4.8 Mg C ha^{-1}, in addition to the large and small trees. They conclude that biomass in herbs, epiphytes, and climbing vines are less abundant in the Amazonian rainforest than in many other neotropical forests, and suggest that a value of 4.5 to 5 Mg C ha^{-1} for understory carbon in tropical rainforests would be conservative.

Cummings et al. (2002) find a mean biomass of live "non-tree" components in the Brazilian Amazon of equal to 22 Mg biomass or about 11 Mg C ha^{-1}. This includes palms that they consider "non-tree" species. They calculate a total of 18.5 Mg biomass ha^{-1} of non-tree live biomass (seedlings + palms + vines) in open forest, 17.7 Mg biomass ha^{-1} in dense forest, and about 40 Mg biomass ha^{-1} in ecotone forest (edge forests in contact with savanna and any of the other classes of forest formations).

Table 5 shows the estimates of understory biomass used in AEZ-EF. For boreal forests and temperate forests, we use a value of 3 Mg C ha^{-1}, a round value approximately in the middle of the ranges suggested by Telfer (1972) and Woodbury et al. (2007), respectively. For tropical forests, we use the mean value (11 Mg C ha^{-1}) found by Cummings et al. (2002) for the Brazilian Amazon.

Table 5. Understory carbon values used in AEZ-EF (Mg C ha^{-1}).

Latitude	**Mg C ha^{-1}**
Boreal	3.0
Temperate	3.0
Tropical	11.0

3.1.4 Carbon stored in harvested wood products (HWP)

Some harvested forest carbon remains sequestered in wood products for the full analytic time horizon used in AEZ-EF, 30 years. To estimate the carbon remaining after this period requires estimates of the volume of wood harvested, the fraction that is converted to long-lived products, and the fate of those products over time, as well as the fractions added to landfills and the fractions of the landfill biomass sequestered long term, emitted as CH_4, or combusted for energy generation either as biomass or CH_4.

AEZ-EF uses values derived from a study by Earles, Yeh, and Skog (2012), listed in Table 6, based on the values shown in Figure 2.

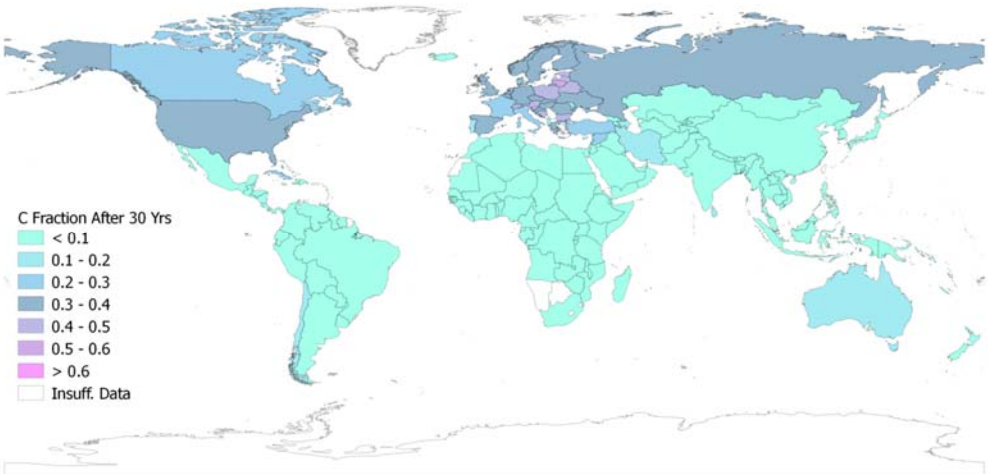

Figure 2. Fraction of AGLB remaining in HWP after 30 years.
Source: Earles, Yeh and Skog (2012)

We note that the fraction of HWP that remains sequestered after 30 years is lower than the fraction originally harvested because some wood is lost in the production of wood products. The model currently uses a single parameter to represent both the reduction in fuel load and long-term sequestered carbon. However, since the wood that is removed but not sequestered is in many cases combusted, we feel that this is an acceptable approximation. We also note that Earles, Yeh, and Skog (2012) do not include landfill emissions of CO_2 or CH_4, nor (obviously) whether the CH_4 is vented or captured for energy production.

3.2 Pasture

Pasture carbon stock values are based on IPCC 2006 GHG Inventory Guidelines, using Tier I defaults for grasslands. Table 7 lists IPCC grassland biomass data (IPCC 2006, Table 6.4); Table 8 shows how these values are mapped to AEZs in the AEZ-EF model.

Table 6. Weighted fraction of AGLB carbon remaining after 30 years.
(weighted by total above ground biomass in each country).

Region	HWP fraction		Region	HWP fraction
Brazil	7%		Oceania	13%
C_C_Amer	5%		Oth_CEE_CIS	30%
Canada	28%		Oth_Europe	34%
ChiHkg	6%		R_S_Asia	3%
E_Asia	6%		R_SE_Asia	3%
EU27	35%		Russia	35%
India	2%		S_O_Amer	5%
Japan	7%		S_S_Afr	2%
Mala_Indo	4%		USA	36%
ME_N_Afr	9%			

Table 7. IPCC grassland biomass data (Mg dry biomass ha^{-1}).

Zone ID	Latitude	Humidity	Peak AGLB	root:shoot	BGB	Total
1	Boreal	Dry & Wet	1.7	4.0	6.8	8.5
2	Temperate	Cold, dry	1.7	2.8	4.76	6.46
3	Temperate	Cold, wet	2.4	4. 0	9.6	12.0
4	Temperate	Warm, dry	1.6	2.8	4.48	6.08
5	Temperate	Warm, wet	2.7	4.0	10.8	13.5
6	Tropical	Dry	2.3	2.8	6.44	8.74
7	Tropical	Moist & wet	6.2	1.6	9.92	16.12
8	Temperate	Dry (avg cold & warm)	1.65	2.8	4.62	6.27
9	Temperate	Wet (avg cold & warm)	2.55	4.0	10.2	12.75

Source: IPCC 2006 GHG Inventory Guidelines, table 6.4. The IPCC indicates a nominal estimate of error of ±75% (two times the standard deviation, as a percentage of the mean) for the total biomass stocks.

Table 8. Grassland biomass data used in AEZ-EF.

AEZ	Latitude	Humidity	Zone ID	AGB	BGB	Total
1	Tropical	Arid	6	2.3	6.44	8.74
2	Tropical	Dry semi-arid	6	2.3	6.44	8.74
3	Tropical	Moist semi-arid	6	2.3	6.44	8.74
4	Tropical	Sub-humid	7	6.2	9.92	16.12
5	Tropical	Humid	7	6.2	9.92	16.12
6	Tropical	Humid (year round)	7	6.2	9.92	16.12
7	Temperate	Arid	8	1.65	4.62	6.27
8	Temperate	Dry semi-arid	8	1.65	4.62	6.27
9	Temperate	Moist semi-arid	8	1.65	4.62	6.27
10	Temperate	Sub-humid	9	2.55	10.2	12.75
11	Temperate	Humid	9	2.55	10.2	12.75
12	Temperate	Humid (year round)	9	2.55	10.2	12.75
13	Boreal	Arid	1	1.7	6.8	8.5
14	Boreal	Dry semi-arid	1	1.7	6.8	8.5
15	Boreal	Moist semi-arid	1	1.7	6.8	8.5
16	Boreal	Sub-humid	1	1.7	6.8	8.5
17	Boreal	Humid	1	1.7	6.8	8.5
18	Boreal	Humid (year round)	1	1.7	6.8	8.5

Source: Based on IPCC grassland data (Mg dry matter ha^{-1}). The column labeled “Zone ID” links this table to IPCC default values in the preceding table.

3.3 Cropland

To estimate the AGB on cropland after conversion from pasture, cropland pasture, or forest, or of cropland prior to reversion to these categories, prior versions of AEZ-EF used an estimate of annual net primary productivity (NPP) of C4 plants[8], estimated using the Terrestrial Ecosystem Model (TEM) by AEZ and by region. These are the same data used in GTAP-BIO to estimate the relative productivity of newly converted cropland.

In the new version of the model, the post-conversion yield for each crop is computed using GTAP-BIO's endogenous projections of production and area harvested, dividing the former by the latter to produce yield by crop (sector), region, and AEZ (Mg biomass ha^{-1}). This approach allows any uncertainties that propagate through GTAP-BIO to its projections of yield (e.g., in response to price changes) to be transmitted to the AEZ-EF model so the two models use identical yield assumption. In addition, yield is now crop- and location- specific.

Table 9. Parameters used to compute total biomass carbon from crop yield.

Crop	Dry fraction	Harvest Index	AGB-C factor	Root:Shoot	Total C Factor
Corn grain	0.87	0.53	0.74	0.18	0.87
Corn Silage	0.26	1.00	0.12	0.18	0.14
Soybean	0.92	0.42	0.99	0.15	1.13
Oats	0.92	0.52	0.80	0.4	1.11
Barley	0.9	0.50	0.81	0.5	1.22
Wheat	0.89	0.39	1.03	0.2	1.23
Sunflower	0.93	0.27	1.55	0.06	1.64
Hay	0.85	1.00	0.38	0.87	0.72
Sorghum grain	0.87	0.44	0.89	0.08	0.96
Sorghum silage	0.26	1.00	0.12	0.18	0.14
Cotton	0.92	0.40	1.04	0.17	1.21
Rice	0.91	0.40	1.02	0.46	1.49
Peanuts	0.91	0.40	1.02	0.07	1.10
Potatoes	0.20	0.50	0.18	0.07	0.19
Sugarbeets	0.15	0.40	0.17	0.43	0.24
Sugarcane	0.3	0.78	0.17	0.18	0.20
Tobacco	0.80	0.60	0.60	0.80	1.08
Rye	0.9	0.50	0.81	1.02	1.64
Beans	0.76	0.46	0.74	0.08	0.80

(Source: West, Brandt, et al. 2010, adjusted as per email exchange with T. West.)

[8] From http://www.biology-online.org/dictionary/C4_plant: A C4 plant is one in which the CO_2 is first fixed into a compound containing four carbon atoms before entering the Calvin cycle of photosynthesis. A C4 plant is better adapted than a C3 plant in an environment with high daytime temperatures, intense sunlight, drought, or nitrogen or CO_2 limitation.

To compute the average amount of biomass held out of the atmosphere over the course of a year, we apply the factors in Table 9, as per West et al. (West, Brandt et al. 2010). A per-crop "crop carbon expansion factor" for each crop is computed as follows:

$$CropCarbonExpansionFactor = \frac{DryFraction * CarbonFraction * (1 + RootShootRatio)}{HarvestIndex}$$

Where *DryFraction* is the portion of the harvested crop that is dry matter, *CarbonFraction* is the constant 0.45 for all crops, *RootShootRatio* is the mass ratio of roots to above-ground biomass, and *harvest index* is the fraction of above-ground biomass removed at harvest. The values used are presented in the table below are based on West, Brandt et al. (2010), with a couple of modifications. The sugarcane dry fraction (originally 0.7) has been changed to 0.3 based on other literature and confirmation of this error via email with the paper's lead author, Tristam West. As per his email, the root:shoot ratio for rye has also been modified. Finally, the harvest index for sugarcane has been changed to 0.78 based on Leal, Galdos, et al. (2013).

Finally, the *CropCarbonExpansionFactor* is multiplied by the harvested yield computed from GTAP to produce a post-simulation estimate of crop biomass carbon stock at the time of harvest. This value is divided by 2 a produce an average amount of carbon held out of the atmosphere over the course of a year.

Oil palm is treated separately from row crops since the tree carbon is cannot be computed from crop yield. In this case, we assigned a constant above-ground carbon value of 34.9 Mg C ha^{-1}, based on an analysis of palm oil produced for the USEPA (Harris 2011), which uses a value of 128 Mg CO_2 ha^{-1} for oil palm.

The crops broken out in the GTAP-BIO model include paddy rice, wheat, sorghum, soybeans, palm, and rapeseed. Additionally, the "Other coarse grains" sector is mostly corn (and treated as though 100% corn); the Sugar Crop sector includes both sugar cane and sugar beets; the Other Oilseeds sector includes all oilseeds other than soybeans, sunflowers; and Other Agriculture includes all other crops.

Table 10. Other parameters used to compute total biomass carbon from crop yield for crops.

Crop	Dry fraction	Harvest Index	AGB-C factor	Root:Shoot	Total C Factor
Rapeseed	0.70	0.35	0.90	0.18	1.06
OthAgri	0.71	0.54	0.59	0.31	0.77
Oth_Oilseeds	0.85	0.35	1.10	0.13	1.25
Sugar_Crops	0.23	0.59	0.17	0.31	0.22

(Various sources described below.)

The version of GTAP-BIO used to develop the model includes the following food sectors: Paddy_Rice, Wheat, Sorghum, Oth_CrGr, Soybeans, Palmf, Rapeseed, Oth_Oilseeds, Sugar_Crop, and OthAgri. The sectors Paddy_rice, Wheat, Sorghum, Oth_CrGr, and Soybeans were mapped to the corresponding rows in Table 9 for Rice, Wheat, Grain Sorghum, Corn, and Soybean, respectively. Values for other crop sectors, shown in Table 10 were developed as follows:

The West et al. (2010) paper doesn't offer data on all the individual crops represented in the current GTAP-BIO model (e.g., it is missing rapeseed), and the model also has three aggregated sectors—Oth_CrGr, Oth_Oilseeds, and Oth_Agri—that must also be converted to C. Values for other crop sectors, shown in Table 10 were developed as follows:

- Rapeseed parameters are taken from the literature: harvest index approximated at 0.35 from (Sultana, Ruhul Amin et al. 2009); dry fraction estimated at 0.90[9]; root:shoot ratio is estimated at 0.18[10].
- Oth_CrGr is treated as 100% corn (since several other grains have been split out already)
- Oth_Oilseeds parameters are averaged from the values for soybean, sunflower, and rapeseed.
- OthAgri parameters are averaged from all crops shown in Table 9 plus rapeseed from Table 10. (The individual parameters in the first three columns were averaged and the final column, total C carbon is computed from these averages.)
- As noted above, oil palm is treated differently since it is a tree from which only the fruit is harvested.

Computing post-simulation changes in crop biomass in this manner has required the addition of TABLO code which can be built into the main GTAP.TAB file, or run as a post-processor. The separate version of the code, (cropcarbon.tab) is presented in section 9.2. This code reads the post-simulation file from GTAP (gtap.upd) to estimate crop biomass for all changes in cropland area.

3.3.1 Cropland-Pasture

The cropland-pasture category is a subcategory of cropland in GTAP-BIO. This land-use category is included in the GTAP 7 database only for the US and Brazil. Cropland-pasture is poorly characterized. According to the USDA[11]:

> **Cropland used only for pasture** generally is considered in the long-term crop rotation, as being tilled, planted in field crops, and then re-seeded to pasture at varying intervals. However, some cropland pasture is marginal for crop uses and may remain in pasture indefinitely. This category also includes land that was used for pasture before crops reach maturity and some land used for pasture that could have been cropped without additional improvement. Cropland pasture and permanent grassland pasture have not always been clearly distinguished in agricultural surveys.

Given the broad range of land that might be considered cropland-pasture, it is challenging to assign carbon stocks to this category. Because management of cropland-pasture ranges from long-term crop rotation to permanent grassland pasture, we do not estimate carbon stocks for cropland pasture; instead we simply assume an emission factor equal to half the pasture-to-cropland emission factor for the same Region-AEZ. This assumption is also supported by IPCC SOC stock change factors for reduced tillage and no-till. These are assumed to produce a 2–15% and 10–22% increase in soil carbon, respectively, compared to full conventional tillage. We

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[9] See http://www.hort.purdue.edu/newcrop/afcm/canola.html and http://www.canolacouncil.org/crop-production/canola-grower's-manual-contents/chapter-11-harvest-management/chapter-11.

[10] http://ec.europa.eu/environment/soil/pdf/som/Chapters7-10.pdf, Table 1.

[11] See http://www.ers.usda.gov/data/majorlanduses/glossary.htm#cropforpasture

assume that cropland-pasture would likely fit into reduced or no-till management, and that conversion to crop production requires tillage.

3.3.2 Conservation Reserve Program

Conservation Reserve Program (CRP) lands include forest and shrub cover in addition to grasslands. Returning CRP land to crop production leads to carbon losses from tillage, foregone soil carbon sequestration, and increased N_2O emissions (Gelfand, Zenone et al. 2011). Gelfand, Zenone et al. estimate that the carbon debt repayment period for converted CRP land under no-till management is 29 to 40 years for corn–soybean and continuous corn crops, respectively, and 89 to 123 years under conventional tillage. In contrast, they project modest, immediate GHG savings from conversion of CRP land to production of cellulosic biofuel feedstocks.

GTAP-BIO does not consider conversion of CRP land, thus the current version of AEZ-EF does not model emissions caused by restoring this land to production.

4. SOIL CARBON STOCKS

The data provided by Gibbs, Yui et al. (2014) include soil carbon stock estimates to both 30 and 100 cm depths by aggregating data from the Harmonized World Soil Database (HWSD) to AEZ and region boundaries, and filtering out areas categorized as wetlands. In addition, lands with carbon stocks greater than 500 Mg C ha^{-1} were filtered out for Malaysia and Indonesia. (The treatment of emissions from peatland conversion is presented in section 6.1.7.)

AEZ-EF uses estimates of soil C change to 30 cm of depth for all transitions, and adds to this estimates of subsoil (30 – 100 cm) for temperate regions, the only regions for which we have found data.

5. LAND COVER TRANSITIONS

The GTAP-BIO model projects net change in each of four managed land-use classes: forestry, pasture, cropland, and cropland-pasture. Since the emissions from land-use change depend on the specific transitions (e.g., forest to pasture, forest to cropland, cropland-pasture to cropland) we must deduce these transitions from the net area changes provided by GTAP-BIO.

5.1 Assumed transitions, given net changes

The AEZ-EF model estimates the CO_2-equivalent emissions released or sequestered when land cover classes are converted. Table 11 shows the eight transitions examined in the AEZ-EF model. An X indicates that a transition may occur.

Table 11. Land use transitions modeled in AEZ-EF.
***X* indicates that a transition is considered.**

		To			
		Cropland	**Pasture**	**Forest**	**Cropland-Pasture**
From	**Cropland**		X	X	X
	Pasture	X		X	
	Forest	X	X		
	Cropland-Pasture	X			

Since GTAP-BIO does not provide for conversion of unmanaged land to or from managed land, all changes are assumed to occur within the pool of the four land-use classes, and the sum of the changes is approximately zero in each Region-AEZ combination. We assume that cropland-pasture is exchanged only with cropland. For the three remaining land use categories—forestry, pasture, and cropland—one land-use class must have a sign opposite the two other classes. (A negative sign indicates a reduction in area of a given class; a positive sign indicates a gain.) In the absence of more detailed information, we assume that the remaining transitions represent either (i) the two land-use classes losing area to the one that gains, or (ii) one losing area to the two gaining.

As an example, consider a case in which a region loses 8,000 ha of pasture and 10,000 ha of cropland-pasture, while gaining 2,000 ha of forestry land and 16,000 of cropland. In this case, assume that 10,000 ha of cropland-pasture were converted to cropland, and that 8,000 ha of pasture are converted to 2,000 ha of forestry land and 6,000 ha of cropland. If, instead, the region were to lose 18,000 ha of forestry land while gaining 2,000 of pasture and 16,000 ha of cropland, we would model 2,000 ha of forest-to-pasture conversion and 16,000 ha of forest-to-cropland conversion.

In this implementation, the round-off errors are sometimes lost in transition. If the sum of the area losses and gains differs from zero, the "extra" may or may not be included. This depends on the nature of the transition.

5.2 Net changes may underestimate emissions

GTAP-BIO reports the net changes in land use between the initial equilibrium and equilibrium reached after a shock is applied. This change may underestimate the climate effects of underlying changes. For example, if 1,000 ha were converted from forest to pasture while another 1,000 ha were simultaneously converted from pasture to forest, the net LUC would be 0 ha. However, since carbon is emitted much more quickly during deforestation than it can be re-sequestered by growing biomass, the total additional CO_2 in the atmosphere can remain elevated for longer than our 30-year time horizon.

5.3 Deforestation versus avoided afforestation

The GTAP-BIO model provides projected increases and decreases in forestry land by AEZ and region. To compute the emissions from these changes, we consider the baseline rates of deforestation and afforestation in each region, and compute a weighted average for emission (or sequestration) given the prevalence of each type of conversion. We take estimates of the fraction of forest conversion attributable to afforestation and deforestation from Pan, Birdsey et al. (2011)

and assign them to the corresponding regions in the model (Table 12). The deforestation fraction is the deforested area divided by the sum of the areas deforested and afforested. The afforestation fraction is simply one minus the deforestation fraction.

The emission factor for forest-to-cropland is the weighted average of the emission factors for deforestation and avoided afforestation. The "sink" factor for cropland-to-forest conversion is the same in magnitude but with the opposite sign. (And forest-to-pasture and pasture-to-forest are analogous.)

Table 12. Fraction of forest change attributable to deforestation, by GTAP-BIO region.

Region	% Deforest.	Description
Brazil	96%	
C_C_Amer	96%	
Canada	94%	
ChiHkg	0%	
E_Asia	12%	Temperate average
EU27	14%	Average Boreal / Temperate
India	55%	
Japan	12%	
Mala_Indo	99%	
ME_N_Afr	83%	
Oceania	66%	Average Australia / NZ
Oth_CEE_CIS	14%	Average Boreal / Temperate
Oth_Europe	14%	Average Boreal / Temperate
R_S_Asia	55%	
R_SE_Asia	55%	
Russia	4.7%	Average Asian / Euro Russia
S_O_Amer	96%	
S_S_Afr	83%	
USA	24%	

(Sources: Pan et al. 2011 for all except Mala_Indo, which was estimated by Jacob Munger, U. Wisconsin, based on data from Tropenbos International. Values were mapped to GTAP-BIO regions by the authors.)

6. EMISSIONS FROM LAND COVER CONVERSION

The AEZ-EF model treats all emissions from land cover conversion as though they occurred instantaneously, much as GTAP does when computing a new economic equilibrium. These up-front emissions from LUC are amortized linearly over 30 years. The choice of amortization period is subjective; legislation in the EU requires using 20 years. An alternative approach would be to track cumulative radiative forcing until some date in the future, accounting for both emissions and atmospheric decay of GHGs (see, e.g., O'Hare, Plevin et al. 2009). Using the latter approach results in greater relative warming from ILUC compared to simple amortization. AEZ-EF uses the simpler amortization approach, which is consistent with regulations in the US.

We follow the IPCC GHG inventory approach to estimate emissions (IPCC 2006). For each Region-AEZ combination, we estimate the following in metric tonnes of carbon or CO_2 per ha:

1. Changes in carbon stocks above- and below-ground, including biomass and soil
2. The portion of above-ground carbon sequestered in harvested wood products
3. CO_2 and CO_2-equivalent non-CO_2 emissions from land cleared by fire
4. N_2O emissions associated with loss of soil organic carbon
5. Carbon emitted as CO_2 through decay processes
6. Foregone sequestration

For each land cover transition sequence, we sum all emissions and sinks to produce an emission factor (EF) in Mg CO_2e ha^{-1}. The emission factor for each Region-AEZ combination is multiplied by the corresponding hectares projected by GTAP-BIO to be gained or lost for each land cover change sequence. The sum of these emissions and sinks is amortized linearly over the analytic horizon and divided by the quantity of additional biofuel modeled in GTAP-BIO to produce an ILUC factor in units of g CO_2e MJ^{-1}.

Section 6.1 describes the basic approach to handling changes in carbon stocks for each land-cover transition category. Section 6.2 discusses carbon sequestration in harvested wood products. Section 6.3 covers emissions from land clearing by fire. Section 6.4 discusses accounting for foregone carbon sequestration when trees are removed. Section 6.5 discusses soil carbon changes and N_2O emissions resulting from the loss of soil organic matter.

6.1 Changes in carbon stocks

Table 13 summarizes the carbon stocks considered for each type of conversion. The carbon accounting details are provided below.

Table 13. Summary of carbon stock changes counted for each land cover transition.

	AGB	BGB	SOC	Foregone sequestration	HWP
Forest to cropland	✓	✓	✓	✓	✓
Forest to pasture	✓	✓		✓	✓
Pasture to cropland	✓	✓	✓		
Cropland to forest	✓	✓	✓		
Cropland to pasture	✓	✓	✓		
Pasture to forest	✓	✓			
Cropland-pasture to cropland	✓	✓	✓		

6.1.1 Conversion of forest to cropland

To account for emissions from the conversion of forests to cropland, we consider CO_2 emissions (and where burning is used, non-CO_2) from AGLB, BGB, deadwood, litter, and understory; CO_2 emissions from loss of SOC; foregone sequestration; and sequestration in harvested wood products, while accounting for the carbon residing in the crops after conversion. The calculations of changes in each pool are described below.

6.1.2 Conversion of forest to pasture

For forest-to-pasture conversion, we assume the same foregone sequestration rate and burning-related emissions as in forest-to-cropland transitions. We then assume a change in biomass to the pasture value for the relevant Region-AEZ. This is essentially the same as the modeling of forest-to-cropland, except that we assume no change in soil C, and the pasture regrowth results in a higher "replacement crop" C value.

6.1.3 Conversion of pasture to cropland

Conversion of pasture to cropland follows the same approach used for forest-to-cropland conversion, using the biomass and soil carbon stocks for pasture.

Two differences between forest-to-cropland and pasture-to-cropland conversion are the assumptions of neither foregone sequestration nor HWP. The IPCC's Tier I approach for grasslands assumes that accumulation through plant growth is balanced by grazing and disturbance. Following this, the AEZ-EF model does not currently include foregone sequestration for grassland.

6.1.4 Conversion of pasture to forest

For pasture-to-forest transitions, we assume no burning, just natural succession. We assume there is neither soil C change nor foregone sequestration, so the carbon sequestration is based only on the change in above-ground biomass C stocks, including the accumulation of understory biomass, litter, and deadwood.

6.1.5 Conversion of cropland to forest or pasture

The carbon sink associated with afforestation of cropland is calculated as the minimum of (i) IPCC regrowth rate or (ii) Region-AEZ total forest biomass minus half the litter. This calculation assumes that disturbances within the first 30 years of regrowth are rare (especially for managed forest) and will accumulate deadwood and 50% of the litter over that time horizon.

For cropland reversion to pasture, we assume that the biomass quickly reaches an equilibrium state equivalent to the sum of AGB, BGB, and litter for pasture in this Region-AEZ.

Initial soil carbon levels are taken from our soil carbon database for existing cropland in the same region. We then apply the IPCC's stock change factors, as described in section 6.4, to determine the SOC level after conversion.

Carbon sequestered during forest regrowth is computed as the sum of 20 years growth at the higher rate (stands less than 20 years old) and 10 years at the lower rate (stands over 20 years old). In both cases, root growth is included using a root:shoot ratio of 0.25. We also assume full restoration of the deadwood, litter, and understory carbon pools estimated for forested land in each region.

For pasture regrowth, we assume full restoration of AGB, BGB, and litter to the level of pasture in each region.

6.1.6 Conversions between Cropland-Pasture and Cropland

We assume that the conversion of cropland-pasture to cropland results in half the emissions caused by converting pasture to cropland in each region. For symmetry, we assume that conversion of cropland to cropland-pasture recovers the same amount of carbon lost when converting from cropland-pasture to cropland.

The AEZ-EF model doesn't include explicit modeling of these emissions, but rather calculates these changes in the "EF" worksheet by multiplying pasture-to-cropland emissions by the parameter CroplandPasture_EF_Ratio, which is set to 0.5.

6.1.7 Conversion of peatlands

Drainage of peatlands for use in agriculture or forestry results in very high CO_2 emissions (Couwenberg, Dommain et al. 2010). Thus it is important to account for the conversion of peatlands when estimating emissions from ILUC.

6.1.7.1 Estimates of emissions from peatland drainage

The drainage of peatlands causes irreversible lowering of the surface (subsidence) as a consequence of peat shrinkage and biological oxidation, resulting in a loss of carbon stock (Hooijer, Page et al. 2011). There are two basic methods for establishing emissions from peatland drainage: (i) direct measurements of gaseous fluxes using closed chambers, in which gases are trapped in a chamber placed on the soil and periodically measured; or (ii) estimates of total carbon loss based on peat subsidence rates. These methods yield wide ranges: 30 Mg CO_2 ha^{-1} y^{-1} to over 100 Mg CO_2 ha^{-1} y^{-1} for chamber-based flux measurements, and 54 to 115 Mg CO_2e ha^{-1} y^{-1} for subsidence monitoring of drainage to the depth range (60 – 85 cm), which is considered optimal for oil palm (Page, Morrison et al. 2011). This review of emissions from oil palm (OP) plantations concludes that the most robust current estimate of peat CO_2 emissions from OP and pulpwood, based on both estimation methods in the same plantation landscape is 86 Mg CO_2e ha^{-1} y^{-1}, equivalent to 23.45 Mg C ha^{-1} y^{-1}, assuming 50-year annualization. If the committed emissions from peat drainage are annualized over 30 years, the value is 95 Mg CO_2e ha^{-1} y^{-1}, equivalent to 26 Mg C ha^{-1} y^{-1}. We adopt this 30-year value in AEZ-EF.

We note that the IPCC default value for conversion of tropical and subtropical peatlands to agriculture is 20 Mg C ha^{-1} y^{-1} (73 Mg CO_2 ha^{-1} y^{-1}) with a nominal uncertainty range of ±90% (7 – 140 Mg CO_2 ha^{-1} y^{-1}), which represents two times the standard deviation as a percentage of the mean (IPCC 2006, Table 5.6).

6.1.7.2 Treatment of peatland emissions in AEZ-EF

Peatland areas are not explicitly represented in GTAP-BIO, so in AEZ-EF we make the following assumptions:

1. Conversion of peatlands occurs only in the Malaysia/Indonesia (Mala_Indo) region.
2. All forest loss in Mala_Indo, the result of biofuel shocks, is for oil palm expansion.
3. Conversion of peatland results in a loss, amortized over 30 years, of 95 Mg CO_2 ha^{-1} y^{-1} (Page, Morrison et al. 2011).
4. One-third (33%) of forest-to-cropland conversion in Mala_Indo occurs on peatland (Edwards, Mulligan et al. 2010, Appendix III).

The emissions from soil for this region are computed as the weighted sum of 33.3% peatland emissions (item 4 above) and 67% "normal" soil emissions as computed in all other regions. As noted earlier, the average value for soil C content excludes high carbon (> 500 Mg C ha^{-1}) lands in Mala_Indo to avoid double-counting peatland emissions.

We note that while we explicitly account for peatland in Malaysia and Indonesia, peatland carbon, when present, is averaged into the SOC values for all other regions/AEZs. Therefore we indirectly account for peatland conversion elsewhere by the inclusion of peat soil carbon in the SOC averages.

6.2 Sequestration in harvested wood products

The AEZ-EF model accounts for biomass that remains stored in harvested wood products after 30 years. As described in section 3.1.4, we use estimates of HWP storage from Earles, Yeh and Skog (2012). The fraction of harvested AGLB remaining in wood products after 30 years in each region is given in Table 6. We note that in previous modeling (based on WHRC data), ARB assumed no storage in HWP.

6.3 Emissions from clearing by fire

Land cleared by fire produces a wide range of emissions (Andreae and Merlet 2001), many of which affect climate directly by altering the earth's radiative balance, or indirectly by influencing the life span of other chemical species that have direct effects (Brakkee, Huijbregts et al. 2008).

Regions assumed to be cleared by fire are derived from the EPA RFS2 analysis by Winrock International, who consider fire the method of clearing cropland in all regions except China, Argentina, Russia, EU, US, and Mexico (Harris, Grimland et al. 2008). The fractions of forests cleared by fire in each GTAP-BIO region are listed in Table 18. Following Winrock, we assume that burning is used for land clearing in Brazil, India, Central and Caribbean Americas, East Asia, Malaysia and Indonesia, the rest of Southeast Asia, the rest of South Asia, and Sub-Saharan Africa. We assume 50% of land clearing uses fire in South and Other Americas (because fire is not used in Argentina but is used elsewhere), and that there is no clearing by fire in other regions.

Table 14. Fraction of forest clearing by fire in each GTAP-BIO region.

Region	**Fraction**
United States	0%
European Union 27	0%
Brazil	100%
Canada	0%
Japan	0%
China and Hong Kong	0%
India	100%
Central and Caribbean Americas	100%
South and Other Americas	50%
East Asia	100%
Malaysia and Indonesia	100%
Rest of South East Asia	100%
Rest of South Asia	100%
Russia	100%
East Europe and Rest of Former Soviet Union	0%
Rest of European Countries	0%
Middle Eastern and North Africa	0%
Sub Saharan Africa	100%
Oceania	0%

6.3.1.1 Combustion factors

Combustion factors that define the proportion of pre-fire biomass consumed by fire are derived from Table 2.6 of the IPCC GHG inventory guidelines (IPCC 2006). For tropical forests, we averaged the values given for primary (0.36), secondary (0.55), and tertiary (0.59) forests, resulting in a combustion factor of 0.50. For temperate forests, we averaged the values for land-clearing fires of Eucalyptus (0.49) and "other" temperate forests (0.51), again resulting in a combustion factor of 0.50. For boreal forests, we adopted the IPCC value for land-clearing fires (0.59). For pasture clearing, we averaged the values for savanna grasslands for early dry season burns (0.74) and mid/late dry season burns (0.77) to obtain a combustion factor of 0.755.

Combusted biomass is the product of fuel load and combustion factor, which is then used to determine the mass of emissions by species (Table 16). These emissions are converted to CO_2-equivalents and summed. AEZ-EF uses global warming potentials from the 2007 IPCC report (Forster, Ramaswamy et al. 2007), as shown in Table 15.

The fuel load includes total AGB (AGLB, litter, and deadwood), minus the portion of AGLB assumed to be sequestered for 30 years in products made from harvested wood. Above-ground biomass (AGLB, litter, and deadwood) believed not to be combusted (the fraction given by one minus the combustion factor) is assumed to decompose to CO_2 during the analytic horizon, and is thus counted as "committed" CO_2 emission.

6.3.1.2 Combustion emissions

In AEZ-EF, we consider emissions of three greenhouse gases CO_2, CH_4, N_2O, including the CO_2 produced by oxidizing the carbon fraction of CO and non-methane hydrocarbons (NMHCs). Following the GREET model (Wang 2008), we assume the complete oxidation of CO to CO_2 by applying an oxidation factor of 44/28 = 1.6 (the molecular weight of CO_2 divided by that of CO), and we assume that NMHCs are 85% carbon on average, which oxidizes to CO_2. Thus the oxidation factor for NHMC is 0.85 × 44/12 = 3.12.

The emission fractions (kg gas per Mg biomass burned) for CO_2, CO, CH_4, and N_2O are presented in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Table 2.5, reproduced below in Table 17. These values are from Andreae and Merlet (2001), and also include estimates for NMHC and CO. We note that Brakee, Huijbregts et al. (2008) estimate CO_2-equivalent global warming potentials for CO and NMHC (3 and 8 respectively) that are approximately double those used in AEZ-EF. In addition, clearing by fire also emits NO_X, black carbon, and organic carbon, all of which affect climate. These emissions are not currently included in AEZ-EF.

Table 15. Global warming potentials used in AEZ-EF.

Gas	GWP
CO_2	1
CH_4	25
N_2O	298

Source: IPCC (2007)

Table 16. Forest burning emission factors (kg Mg^{-1} dry matter).

Latitude	CO_2	CO	CH_4	N_2O	NMHC
Tropical	1580	104	6.8	0.20	8.1
Temperate	1569	107	4.7	0.26	5.7
Boreal	1569	107	4.7	0.26	5.7

Source: Andreae and Merlet (2001)

Table 17. Pasture burning emission factors (kg Mg^{-1} dry matter).

Latitude	CO_2	CO	CH_4	N_2O	NMHC
Tropical	1613	65	2.3	0.21	3.4
Temperate	1613	65	2.3	0.21	3.4
Boreal	1613	65	2.3	0.21	3.4

Source: Andreae and Merlet (2001)

6.3.1.3 Sequestration in char

Conversion by fire also produces char, which is relatively recalcitrant, i.e., slow to decay. The IPCC GHG inventory guidelines exclude char from emission calculations owing to insufficient data (IPCC 2006, p. 2.42). In the AEZ-EF model, the use of emission factors for combustion of biomass that are less that 100% recognize that a portion of carbon is not emitted to the atmosphere, which can be presumed to be char. For the conversion of forest to cropland, the implicit range of char production ranges from 0 to 3 Mg C ha^{-1}, with the highest values associated with peat burning in Indonesia and Malaysia.

Table 18. Fraction of forest clearing by fire in each GTAP-BIO region.

Region	Fraction
United States	0%
European Union 27	0%
Brazil	100%
Canada	0%
Japan	0%
China and Hong Kong	0%
India	100%
Central and Caribbean Americas	100%
South and Other Americas	50%
East Asia	100%
Malaysia and Indonesia	100%
Rest of South East Asia	100%
Rest of South Asia	100%
Russia	100%
East Europe and Rest of Former Soviet Union	0%
Rest of European Countries	0%
Middle Eastern and North Africa	0%
Sub Saharan Africa	100%
Oceania	0%

6.4 Foregone sequestration

The CO_2 that would have been absorbed by trees that are removed through LUC is considered equivalent to an emission of the same quantity of CO_2. Foregone sequestration estimates are used when estimating emissions from deforestation and from avoided reforestation. These values differ because deforestation foregoes the growth of relatively mature trees, whereas avoided reforestation foregoes growth of new trees.

For loss of existing forests (deforestation), we estimate an annual growth rate based on Lewis, Lopez-Gonzalez et al. (2009) for tropical forests. We use values from Myneni, Dong et al. (2001) for temperate and boreal forests, except for Brazil and C_C_Amer, which use the tropical values in the temperate zone as well.[12] Since these values represent only above-ground tree biomass, we add growth in root biomass using the root:shoot ratio for the corresponding Region-

[12] See the "Growth Rate" column in the FOREGONE_SEQ_TABLE on the *Foregone* worksheet, and the FOREST_REGROWTH_RATE table on the *Tables* worksheet.

AEZ.[13] We note that in the carbon database with values for 246 countries by 18 AEZs, we assigned the values below to all countries in each corresponding region, by AEZ.

Table 19. Foregone sequestration rates (Mg C ha^{-1} y^{-1}).

Region	Tropical	Temperate	Boreal	Notes
Brazil	0.85	0.85	0	Used Tropical rate for temperate region
C_C_Amer	0.85	0.85	0	Used Tropical rate for temperate region
Canada	0	0.31	0.31	No tropical AEZs
ChiHkg	0.69	0.27	0.27	
E_Asia	0.69	0.27	0.27	
EU27	0.67	0.84	0.84	Used "All tropics" rate for Tropical region.
India	0.69	0.27	0.27	
Japan	0	0.63	0.63	No tropical AEZs
Mala_Indo	0.69	0	0	Only tropical AEZs
ME_N_Afr	0.86	0.84	0	Used EU27 rate for temperate region. No boreal AEZs.
Oceania	0.67	0.63	0.63	Used "All tropics" rate for Tropical region, and Japan for temperate and boreal.
Oth_CEE_CIS	0	0.99	0.99	No tropical AEZs
Oth_Europe	0	0.84	0.84	No tropical AEZs
R_S_Asia	0.69	0.27	0.27	Used China for temperate and boreal regions
R_SE_Asia	0.69	0.63	0.63	Used Japan for temperate and boreal regions
Russia	0	0.44	0.44	No tropical AEZs
S_O_Amer	0.85	0.63	0.63	Used Japan for temperate and boreal regions
S_S_Afr	0.86	0.63	0	No boreal AEZs. Used Japan for temperate.
USA	0	0.66	0.66	No tropical AEZs

For forest area reduction associated with avoided reforestation, we use growth rates from the IPCC for forest stands less than and greater than 20 years of age, computing the 30 year total foregone growth as 20 times the accumulation rate for young stands and 10 years times the rate for older stands. (See the "Regrowth" column in the FOREGONE_SEQ_TABLE on the Tables sheet.)

6.5 Soil carbon changes

In CARB's previous modeling of ILUC emissions, the agency, following Searchinger, Heimlich et al. (2008), assumed a 25% loss of soil carbon from the top 100 cm upon conversion of forest and pasture to cropland.

The AEZ-EF model uses a modified version of the IPCC's soil stock change approach to estimate emissions from soil carbon changes. The IPCC provides default carbon stocks (to 30 cm) for different soil types and climate regions (IPCC 2006 GHG guidelines table 2.3), and multiplies these values by various factors based on different land use and management practices in order to estimate carbon stocks before and after conversion. The SOC loss is the difference between these estimates.

[13] See the FOREST_BIOMASS table on the *Biomass* worksheet.

Since our soil carbon database includes regionally-averaged C stocks for cropland, forest, and pasture, we use our soil carbon data to represent the SOC stock before conversion. We divide this value by the product of the management factors to produce a reference value to which we then apply the IPCC stock change factors to produce a value representing the SOC stock after conversion. (The algebraic manipulation is described in the equations below.)

Following the IPCC guidance, all stock change factors for forest are one. For crops, we use the land use and management factors representing long-term cultivation, medium input, and full tillage. For conversion of forest or pasture to cropland, we apply Land Use factors for "Long-term cultivated" cropland based on the temperature/moisture regime (AEZ). Harris et al (2008) consolidates these in Table 8 of the first Winrock report for RFS2. The values there range from 0.48 to 0.80, i.e., a 20% to 52% loss of soil C. (They assume management and input factors are 1.0 in all cases.)

We assume pasture is nominally managed (all three land-use factors are equal to one.) However, there may be a greater level of management of pasture in some Region-AEZ combinations. Some pasture land may receive one or more types of management improvement such as fertilizer, species improvement, or irrigation.

The IPCC approach accounts for losses in the top 30 cm only, though recent evidence indicates that SOC changes occur at deeper levels. Although the model is structured to account for subsoil carbon losses, we currently have data for only temperate regions. Following Poeplau, Don et al. (2011), AEZ-EF counts subsoil (30 – 100 cm in depth) carbon loss for Pasture-to-Cropland conversion in temperate AEZs, assuming that 27% of the total soil loss upon conversion is from subsoil. The model does not count subsoil C loss for other transitions.

The algebraic basis for our use of the IPCC factors is shown below. Our treatment of peatland emissions is discussed in section 6.1.7.

Following the IPCC guidelines, the change in SOC is given by these three equations:

$$\Delta SOC = SOC_{before} - SOC_{after}$$

$$SOC_{before} = SOC_{ref} \cdot F_{LU,before} \cdot F_{MG,before} \cdot F_{I,before}$$

$$SOC_{after} = SOC_{ref} \cdot F_{LU,after} \cdot F_{MG,after} \cdot F_{I,after}$$

Rearranging them gives:

$$SOC_{ref} = \frac{SOC_{before}}{F_{LU,before} \cdot F_{MG,before} \cdot F_{I,before}}$$

Substituting gives the soil change in terms of initial SOC stock:

$$\Delta SOC = SOC_{before} - \left(\frac{SOC_{before}}{F_{LU,before} \cdot F_{MG,before} \cdot F_{I,before}} \right) \cdot F_{LU,after} \cdot F_{MG,after} \cdot F_{I,after}$$

Simplifying, we have:

$$\Delta SOC = SOC_{before} \cdot \left(1 - \frac{F_{LU,after} \cdot F_{MG,after} \cdot F_{I,after}}{F_{LU,before} \cdot F_{MG,before} \cdot F_{I,before}}\right)$$

The three stock change factors (F_{LU}, F_{MG}, F_I) are multipliers that adjust the reference soil carbon stock based on land use (LU), management (MG) or inputs (I). For forests, we assume all three factors are 1 (IPCC 2006, p. 4.40). For grasslands, we also assume a value of 1 for all three: LU (following the IPCC recommendation for all grassland); MG, assuming the land is "nominally managed (non-degraded)"; and I, assuming "medium" inputs (IPCC 2006, Table 6.2). For cropland, we use the factors described in Table 20 and Table 21.

Table 20. Soil carbon stock change factors used in AEZ-EF.

Factor	Variable	Level	Temperature regime	Moisture	IPCC Default
Management	F_{MG}	Nominally managed	All	All	1
Input	F_I	Medium	All	All	1
Land use	F_{LU}	Native forest/grassland	All	All	1
Land use	F_{LU}	Perennial/tree crop	All	All	1
Land use	F_{LU}	Long-term cultivated	Temperate/boreal	Dry	0.80
				Moist	0.69
			Tropical	Dry	0.58
				Moist/Wet	0.48
			Tropical Montane	N/A	0.48

Table 21. Mapping of stock change factors to AEZs in AEZ-EF.

Latitude	Humidity	AEZ	Crop F_{LU}	Tree F_{LU}
Tropical	Arid	1	0.58	1
Tropical	Dry semi-arid	2	0.58	1
Tropical	Moist semi-arid	3	0.58	1
Tropical	Sub-humid	4	0.48	1
Tropical	Humid	5	0.48	1
Tropical	Humid (year round)	6	0.48	1
Temperate	Arid	7	0.80	0.80
Temperate	Dry semi-arid	8	0.80	0.80
Temperate	Moist semi-arid	9	0.80	0.80
Temperate	Sub-humid	10	0.69	0.69
Temperate	Humid	11	0.69	0.69
Temperate	Humid (year round)	12	0.69	0.69
Boreal	Arid	13	0.80	0.80
Boreal	Dry semi-arid	14	0.80	0.80
Boreal	Moist semi-arid	15	0.80	0.80
Boreal	Sub-humid	16	0.69	0.69

Boreal	Humid	17	0.69	0.69
Boreal	Humid (year round)	18	0.69	0.69

The land use factors for "Perennial/tree crop" are used to estimate soil C changes on land converted to either sugarcane or oil palm. The fraction of conversion to these two crops (of the total area Forest-to-Cropland and Pasture-to-Cropland area) is computed for each Region-AEZ combination, and the equations above are applied to compute the post-conversion soil C in land converted to sugarcane, oil palm, and all other (presumed annual) crops. The soil loss in each Region-AEZ is calculated as the area-weighted average of these three values and SOC loss from the percentage of the area change assumed to be in peat soils. (See section 6.1.7 for a description of the treatment of peatlands.)

6.5.1 N_2O emissions associated with loss of SOC

We follow the IPCC inventory procedure for estimating N_2O emissions resulting from a loss of soil organic matter (IPCC 2006, section 11.2.1.3). We estimate the N_2O emissions by dividing the estimated SOC loss to a depth of 100 cm by a C:N ratio which is assumed to be 15 (uncertainty range from 10 to 30) worldwide. The value obtained represents the quantity of nitrogen liberated (Mg N ha^{-1}). The nitrogen is then treated as though it had been applied as fertilizer: the quantity N is multiplied by an emission factor of 1.325% to represent the quantity released as N_2O. This includes direct (1%) and indirect (0.325%) emissions of N_2O. The resulting quantity of N_2O is then multiplied by 44/28 (the molecular weight of N_2O divided by the weight of two N atoms) to compute emissions of N_2O as Mg N_2O ha^{-1}. Finally, this value is multiplied by the 100-year global warming potential for N_2O, which is 298 in the Fourth Assessment Report (Forster, Ramaswamy et al. 2007). This final quantity, in CO_2-equivalents, is added to the CO_2 released directly from the soil.

7. UNCERTAINTY

Any detailed estimate of ILUC emissions involves hundreds of model parameters and assumptions, from the core data underlying the GTAP database, to the elasticities that drive GTAP results, to the numerous assumptions required to perform the ecosystem carbon accounting described herein. Although the current version of AEZ-EF does not quantify uncertainty, a stochastic version of the joint GTAP/AEZ-EF modeling system has been implemented, and is the subject of a forthcoming publication. This system allows us to identify those parameters whose uncertainty contributes the bulk of the variance in the final ILUC emission factor, thereby helping to focus future research.

In this section we provide a qualitative discussion of some of the key uncertainties in the model.

7.1 GTAP model

Quantitative analysis of uncertainty in GTAP projections is beyond the scope of this report. However, we do note a few key areas that relate directly to estimates of emissions from land use change.

Ideally, the economic and ecosystem models would both represent *all* available land and allow for the conversion of unmanaged, natural land. However, GTAP represents only land in economic use for forestry, livestock grazing, and cropping. Since GTAP doesn't represent "inaccessible" forest, the model cannot project any conversion of this land. This model uncertainty is difficult to quantify. Other CGE models such as MIT's EPPA model and IFPRI's MIRAGE model include conversion of unmanaged land to economic use, so these models could potentially be used to estimate the differential among outcomes when including and excluding unmanaged land in an ILUC projection. It would be helpful if GTAP could be modified to include this capability.

As discussed earlier, the biomass and soil carbon stock estimates by Gibbs, Yui et al. (2014) are not limited to areas in economic use, so the assumptions underlying the economics of land conversion and the emissions they produce differ, and it is unclear how this may introduce bias into the resulting ILUC emissions factor.

7.2 Soil carbon stocks

The documentation for the Harmonized World Soil Database includes no mention of uncertainty (FAO/IIASSA/ISRIC/ISS-CAS/JRC 2009). They do say, however:

> Reliability of the information contained in the database is variable: the parts of the database that still make use of the Soil Map of the World such as North America, Australia, West Africa and South Asia are considered less reliable, while most of the areas covered by SOTER databases are considered to have the highest reliability (Central and Southern Africa, Latin America and the Caribbean, Central and Eastern Europe).

Results from the IPCC soil carbon stock change method are approximate. The IPCC's stock change factors are defined relative to reference soil carbon stocks, defined by soil type, while we apply them to our GIS-based soil carbon stocks. Bias that might be introduced by this method is unknown.

7.3 Biomass carbon stocks

7.3.1 Forest carbon

Forest carbon estimates are subject to numerous uncertainties, including:

- Satellite remote-sensing errors.
- Uncertainties in M3 (formerly SAGE) data, including imprecise definitions of cropland and pasture and the variable quality of global census data (Ramankutty, Evan et al. 2008).
- Estimates of percentages of accessible versus inaccessible forest within each AEZ. Treating more or less land as accessible would likely alter the amount of extensification projected.
- Limitations of converting DBH (diameter at breast height) measurements to volume and then to carbon.
- Litter estimates include variability in original data, imperfect mapping to Region-AEZs, uncertainty in the ratio of broadleaf to needleleaf forests, and uncertainty whether these estimates represent forests actually converted, both in terms of the ratio of forest types and in the use of "mature forest" litter values, as not all converted forests will be mature.

- Deadwood estimates from Pan et al. are not reported with uncertainty ranges.
- Understory carbon is highly variable and our estimates are coarse.
- Forest carbon averages include areas that are not considered by GTAP-BIO to be accessible.
- Carbon stocks in forests that have actually been converted may not be well represented by average values.
- Estimates of BGB are based on default IPCC root:shoot ratios or allometric equations, while actual quantities vary with species and location.

7.3.2 Pasture carbon

Uncertainty around IPCC's grassland biomass estimates are given nominally as ±75% for all regions, representing two standard deviations as a percentage of the mean.

Uncertainty around IPCC's default root:shoot ratios is also substantial: for grasslands, IPCC lists error bands of ±95% for semi-arid grasslands to ±150% for steppe/tundra/prairie grasslands. These figures represent two standard deviations as a percentage of the mean (IPCC 2006, Table 6.1).

Finally, the carbon fraction of grassland biomass is estimated to be 0.47. IPCC does not characterize the uncertainty in this value.

As with forests, the carbon stock estimates of pasture include lands not considered by GTAP-BIO to be in use for livestock grazing.

7.4 Land cover conversion and emissions

7.4.1 Identifying land conversion

GTAP-BIO is not a spatially explicit model, so the mapping of economic data to ecosystem data must bridge the gap from non-spatial to spatial reasoning. The average carbon stocks and emissions estimates computed in AEZ-EF may or may not accurately represent the land actually converted. Moreover, it is impossible to pinpoint the location of these conversions.

As noted earlier, GTAP-BIO presents only net area changes with no indication of specific conversion sequences. Although we infer specific conversion sequences from these results, the potential bias this introduces is difficult to assess.

7.4.2 Land clearing by fire

The fraction of land cleared by fire that was induced by biofuel expansion is unknown. In the current model, the fraction of clearing by combustion has a very small impact on the final ILUC factor, though under a more complete analysis of uncertainty, the impact would be greater.

As noted earlier, clearing by fire also emits NO_X, black carbon, and organic carbon, all of which affect climate. These emissions are not currently included in AEZ-EF, but are discussed here because their exclusion creates model uncertainty related to the magnitude of the bias this creates. We note that the climate effects of these emissions are not included in most life cycle assessments or in IPCC GHG inventory guidelines.

Black carbon (BC) and organic carbon (OC) have strong climate forcing effects, but unlike well-mixed GHGs, these effects vary regionally and their climate forcing effects are more uncertain. The quantity of BC emitted varies with the type of fire; with flames produce more BC, while smoldering fires produce less BC but more carbon monoxide. The ratio of flaming versus smoldering will vary by the specific practices of clearing. Finally, the short atmospheric lifetime of BC results in very high global warming potential (GWP) values over shorter time horizons. Thus the choice of using 100-year GWPs rather than integration periods matched to the analytic horizon (30 years) reduces the estimated effect of BC. On the other hand, harmonizing the integration period with the analytic horizon (i.e., to 30 years) would substantially increase the estimated warming effect of BC (as well as methane). The choice of integration period for estimating CO_2 equivalence is political rather than scientific.

7.4.3 Harvested wood products

Data are lacking for harvested wood products in many regions. Uncertainty surrounding the estimates derived from Earles, Yeh, and Skog is unknown.

7.4.4 Foregone sequestration

The IPCC's net above-ground biomass growth rates are defined on coarse regional boundaries and uncertainty ranges are not specified. Mapping these growth rates to Region-AEZs is imprecise and is based on expert judgment. We have used growth rates for natural forests, since these are available for all regions and not species-specific. IPCC also offers separate (generally higher) growth rates for tropical and subtropical plantations, though these are species-specific and not available for all climatic zones.

Growth is faster in younger stands than in older stands, but we don't have data on the relative proportion of young and old stands, and stand age generally increases over our 30-year analytical horizon (though disturbance can "reset" the age.)

7.4.5 Cropland and Cropland-pasture

Cropland-pasture is vaguely defined but is an important factor in the present system as GTAP-BIO projects substantial conversion of cropland-pasture to cropland. Our assumption that the carbon emissions for conversion of cropland-pasture to cropping ranges are half those of converting pasture is not empirically-based. Uncertainty surrounding these estimates is likely quite high.

8. MODEL IMPLEMENTATION

The AEZ-EF model is implemented as a multi-worksheet Excel™ workbook. Externally-sourced data (e.g., carbon stocks, IPCC defaults) are stored in matrices that are treated like database records, with relevant records accessed using Excel's look-up functions. The model uses named cells and regions to make formulas more legible and to facilitate changing key parameters.

To allow the model to be used easily with various sets of GTAP results, these results are not built into the model, but are instead accessed from a separate, external workbook. The format of the external GTAP results workbook is described in section 8.2.

The workbook currently contains two implementations of the model: (i) the original version (see worksheet "Legacy Model") was designed to work with the 19 regions used by GTAP-BIO-ADV, and (ii) a new implementation that uses a series *N* column by 18 row matrices, where *N* is the number of regions and 18 is the (constant) number of AEZs. The legacy version of the model may be deleted in a subsequent release. Instructions for using the model with a different number of regions are presented in section 8.3.

8.1 AEZ-EF model worksheets

AEZ-EF contains several data, analysis, and documentation worksheets. The individual worksheets are described below.

8.1.1 Results worksheet

The **Results** worksheet produces the final ILUC factor by summing total emissions by land cover conversion sequence, divided by total fuel production associated with the emissions.

8.1.2 LegacyModel worksheet

The **LegacyModel** worksheet holds the original version of AEZ-EF, provided for continuity. It combines above- and below-ground stocks, combustion factors, foregone sequestration, and so on, into emissions by AEZ, region, and conversion sequence. The sheet is divided into an upper section dedicated to changes from forest to cropland and to pasture, and for reversion of cropland to forest. The lower section calculates emissions for conversions of pasture to cropland and to forest, and reversion of cropland to pasture.

The legacy model offers alternative treatments of post-conversion crop biomass and soil changes under perennial crops, controlled by (i) the Crop Biomass Data selector (see pull-down menu in cell LegacyModel!L1), and (ii) the presence or absence in the external GTAP workbook (see section 8.2) of data matrices containing the changes in Sugar Crops and Oil Palm area. If present, the Sugar Crops and Oil Palm matrices are used in all cases to determine the soil carbon changes under these two crops, which are treated as perennial. All other crops are treated as annuals. See section 9.1 for TABLO code that saves the Sugar Crop and Oil Palm data to a file for easy copying to Excel.

If the Crop Biomass Data selector is set to "Exogenous", then the user must provide an exogenously-computed value for total post-conversion change in crop biomass, as generated by the separate TABLO program "cropcarbon" provided with the AEZ-EF model and documented in section 9.2. If the selector is set to "TEM" or "CLM", then estimates of annual net primary productivity (NPP) derived from either the Terrestrial Ecosystem Model or the Community Land Model and halved to estimate average annual storage of carbon in annual crops. The TEM data are based on C4 crops; the CLM on C3 crops.

If the Crop Biomass Data selector is set to "TEM" or "CLM", and no Sugar Crop or Oil Palm data are present (or are all zeroes), then all crops are treated as annual. If the Sugar Crop and/or Oil Palm data are present, those crops are treated separately: Sugar Crops are assumed to have an annualized average carbon stock of 10 Mg C ha^{-1}, and Oil Palm is assumed to hold 35 Mg C ha^{-1}. Both of these values are then adjusted using the "ETA" values used in GTAP to express the ratio of the average productivity of land not in crop production to that of land in crop production. Thus, the values of 10 and 35 Mg C ha^{-1} are adjusted up or down according to the relative productivity of the given Region-AEZ.

8.1.3 Forest worksheet

This worksheet performs the calculations required to estimate the emissions from conversion of forestry to cropland, cropland to forestry, and forestry to pasture.

8.1.4 Pasture worksheet

This worksheet performs the calculations required to estimate the emissions from conversion of pasture to cropland, cropland to pasture, and pasture to forestry.

8.1.5 CarbonData worksheet

The **CarbonData** worksheet provides a database of carbon stocks for above- and below-ground biomass, foregone sequestration, and soil carbon, by region and AEZ. This database is documented in the accompanying report by Gibbs, Yui, and Plevin (2014).

8.1.6 IPCC worksheet

This worksheet provides matrix versions of IPCC stock change data.

8.1.7 CropBiomass worksheet

The **CropBiomass** worksheet provides estimates of the annual rates of net primary productivity by region based on work by Purdue University researchers, based on a C4 crop (corn) using the TEM model (Taheripour, Zhuang et al. 2012), and based on a prototypical C3 crop unpublished work by Andrew Jones (Lawrence Berkeley National Lab) using the Community Land Model (CLM). The TEM values are used within GTAP-BIO to determine the productivity of new croplands relative to that of existing croplands. Here, we optionally use these values to determine the quantity of biomass on cropland after conversion.

The preferred method of calculating post-conversion crop biomass carbon is to use the “cropcarbon” program (see section 9.2) to produce region- and crop-specific values that are based on changes in yield estimated by GTAP. If that is not possible or convenient, the CLM and TEM biomass values can be used as an approximation, however, these values are based on parameterizing the TEM and CLM models to represent a single C4 or C3 crop, respectively.

8.1.8 Factors worksheet

The **Factors** worksheet comprises various constants, parameters, and conversion factors required by the model.

8.1.9 Tables worksheet

The **Tables** worksheet consists of look-up tables used in the model containing data from external sources.

8.1.10 GTAP worksheet

The **GTAP** worksheet imports the results of GTAP model runs that define LUC by region, AEZ, and land use from an external workbook. The format of the external worksheet is described in Section 8.2.

8.1.11 Transitions worksheet

The **Transitions** worksheet determines which land transitions are implied by the area changes in the GTAP results.

8.1.12 YieldTables worksheet

This worksheet isn't an active part of the model; it calculates the data used by the *cropcarbon* program to convert crop yield to crop biomass carbon.

8.1.13 F-to-C Breakdown worksheet

This worksheet disaggregates emissions sources for forest-to-cropland transitions, and generates a bar graph as shown in Figure 3.

8.1.14 ExportTables worksheet

This worksheet compiles data in a convenient format for use by the Python version of the AEZ-EF model.

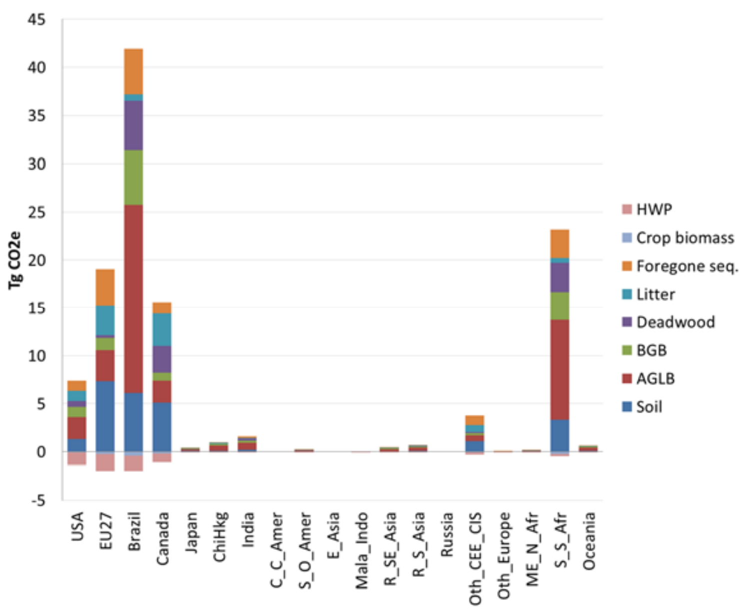

Figure 3. Sample breakdown of emission sources for forest to cropland transition.

8.2 External GTAP workbook

To allow AEZ-EF to be used with a variety of GTAP model results, they are incorporated into the model via an external workbook that is named on the GTAP sheet of the AEZ-EF workbook. The external workbook must be structured as follows:

- There must be a worksheet named “Notes” that contains a list of result worksheet names in row 1 starting in column B. Currently, up to 51 results worksheets can be named in cells B1 through AZ1. These values are used by the main model workbook to produce a pull-down menu of result sets to evaluate.
- Each results worksheet contains basic data about the run and all results by region, AEZ, and land use category. In each results worksheet:
  - cell B1 must contain a short description of the scenario
  - cell B2 names the feedstock, e.g., corn, soybeans, oil palm, miscanthus, etc.
  - cell B3 names the final fuel, which must be one of: **ethanol**, **butanol**, **FAME**, **RD-1** (renewable diesel), **RD-2**, **FT-diesel** (Fischer-Tropsch diesel), **FT-gasoline**, **RG** (renewable gasoline), or **bio-gasoline**. This choice determines the energy density value used to convert gallons to megajoules. (N.B. New fuels and energy densities can be added to the FUEL_ENERGY_DENSITY_TABLE on the Tables worksheet.)
  - cell B4 states the increment in fuel quantity (in gallons of the stated fuel type) used to shock GTAP.
  - Following these meta-data there must be four to six matrices of *N* regions (e.g., for GTAP-BIO-ADV, *N*=19 columns, B through T) by 18 AEZs (row). The starting row and land cover types represented by each are shown in Table 22. The matrices for Sugar Crops and Oil Palm are optional. If present and the Crop Biomass selector is *not* set to “Exogenous”, then the Sugar Crops and Oil Palm matrices are used to determine the fraction of cropland change in each Region-AEZ that occurs on these two crops, and crop-specific post-conversion crop biomass and soil C change values are used. If either matrix is missing (or all zeroes) then the entire cropland change is treated as C4 annual crops if “TEM” is selected, or C3 annual crops if “CLM” is selected. If the Crop Biomass selector is set to “Exogenous”, these two matrices are ignored

The user can select from available results worksheets using a pull-down menu in the “GTAP” worksheet of the main AEZ-EF model workbook. The corresponding ILUC factor is then computed and displayed in the Results sheet, the Model sheet, and the GTAP sheet.

Table 22. Starting row for land cover change matrices.

Starting row	**Land cover**
6	Forestry
27	Livestock
48	Crops
69	Cropland-pasture
90	Sugar crops
111	Oil palm

8.3 Changing the regionalization

The AEZ-EF model is designed to work with an arbitrary number of regions. Most of the required data is (i) provided by the carbon database in the CarbonData worksheet, or (ii) computed from AEZ number. Other regional data is taken from a variety of sources cited in the workbook (in the Tables and Factors worksheets.)

The spreadsheet model uses named regions to refer to tables and vectors of data to make formulae more readable and to centralize changes. The data matrices are defined to contain 50 regions, although in the default version of the model, only 19 regions are used. If you extend the number of regions beyond 50, you will need to redefine the boundaries of the named regions, after which all references should work without further editing.

The steps required to change the number of regions are as follows:

1. Run the *FlexAgg* program[14] to aggregate all GTAP data—including the carbon data—to the desired regional boundaries. The *aggcarbon* program produces a HAR file containing all the aggregated carbon and area data in matrix format that can be copied and pasted into the CarbonData worksheet.
2. Adjust the regional data at the top of the Tables worksheet.
    a. Add data to, or remove data from, the lines labeled:
        i. Region number
        ii. Region code
        iii. NORMALIZED_REGION_CODE
        iv. HWP_FRACTION_VECTOR
        v. FIRE_FRACTION_VECTOR
        vi. SUGARCANE_FRACTION_VECTOR
        vii. DEFORESTATION_FRACTION_VECTOR
    b. Note that the rows labeled with CAPITAL_LETTERS are named regions for which the number of columns must match the number of regions being used. These are currently defined to allow for 50 regions. Redefined the named vectors is you are using more than 50 regions.
3. If needed, add rows to the DEADWOOD_BY_REGION_TABLE (in the Tables workbook, starting at row 232) and adjust the definition of the named region accordingly.

[14] Available from https://www.gtap.agecon.purdue.edu/databases/flexagg2.asp

The region should encompass all the rows for the three columns of values, but not the headings.

4. Adjust the FOREST_REGROWTH_RATE table (starts at row 301 of the Tables worksheet) either using data available in that worksheet (follow the links to data from Myneni et al. (2001) and Lewis et al. (2009)) or from other sources.
5. Add columns to or remove[15] columns from, the data matrices in the following workbooks:
    a. Results – Note that these matrices use array formulas, so you must select the correct number of regions and enter the array formula by pressing Control-Shift-Enter simultaneously.
    b. Forest
    c. Pasture
    d. IPCC
    e. ChangeMatrices
6. The GTAP worksheet is designed to automatically display up to 50 regions. Note that the number of regions must be set in cell B3 of that worksheet. If the external GTAP workbook (cell B4) contains 50 or fewer regions, no other changes should be required to the GTAP worksheet in AEZ-EF. To add more than 50 regions requires adding columns as described above, including redefining the named regions.
7. The built-in crop biomass estimates from the TEM and CLM models cannot easily be used with other regionalizations as these data are computed externally. Thus with alternative regionalizations, the exogenous crop biomass feature is preferable. The matrices on the CropBiomass sheet *are not* predefined to allow 50 regions.
8. The "F-to-C Breakdown" worksheet is informational only and is not currently setup to accommodate 50 regions.

9. RECOMMENDED MODIFICATIONS TO THE GTAP TABLO FILE

The following modifications to the TABLO code facilitate transmission of GTAP results to the AEZ-EF model.

9.1 Land cover changes

The following code creates a file with the land cover changes in a convenient format for copying and pasting into the external "GTAP results" workbook required by AEZ-EF.

```
! Save land cover changes !
File (new) ChangedLandcover;

! Simplify extraction of landcover changes !

Coefficient (all,i,AEZ_COMM)(all,r,REG)
    cPASTURECROP(i,r) # change in cropland-pasture (ha) by AEZ and region #;
Formula (initial) (all,i,AEZ_COMM)(all,r,REG)
    cPASTURECROP(i,r)=0;
Update (change) (all,i,AEZ_COMM)(all,r,REG)
    cPASTURECROP(i,r) =
      HARVSTAREA_L(i,"Pasturecrop",r) * p_HARVSTAREA_L(i,"Pasturecrop",r)/100;
```

[15] Removing unused columns is not strictly necessary, but may be preferable aesthetically.

```
Coefficient (all,i,AEZ_COMM)(all,r,REG)
    cSUGARCROP(i,r) # change in sugar_crop land (ha) by AEZ and region #;
Formula (initial) (all,i,AEZ_COMM)(all,r,REG)
    cSUGARCROP(i,r)=0;
Update (change) (all,i,AEZ_COMM)(all,r,REG)
    cSUGARCROP(i,r) =
      HARVSTAREA_L(i,"Sugar_Crop",r) * p_HARVSTAREA_L(i,"Sugar_Crop",r)/100;

Coefficient (all,i,AEZ_COMM)(all,r,REG)
   cOILPALM(i,r) # change in oil palm land (ha) by AEZ and region #;
Formula (initial) (all,i,AEZ_COMM)(all,r,REG)
    cOILPALM(i,r)=0;
Update (change) (all,i,AEZ_COMM)(all,r,REG)
    cOILPALM(i,r) =
      HARVSTAREA_L(i,"palmf",r) * p_HARVSTAREA_L(i,"palmf",r)/100;

write (postsim) cLANDCOVER   to file ChangedLandcover header "CLND";
write (postsim) cPASTURECROP to file ChangedLandcover header "CPCR";
write (postsim) cSUGARCROP   to file ChangedLandcover header "CSUG";
write (postsim) cOILPALM     to file ChangedLandcover header "CPLM";
```

9.2 cropcarbon.tab

The *cropcarbon* package calculates the total post-conversion change in carbon associated with crop biomass. The package includes:

- `cropcarbon.tab` – a TABLO program that performs the required calculations
- `CropBiomassIn.har` – data required by cropcarbon.tab

The TABLO file must be converted to FORTRAN and compiled. When run, it requires the names of the “update” file (e.g., gtap.upd) and the base data file (e.g., basedata.har) from which post-conversion yield and changes in area are calculated. The yield values—specific to each combination of crop, region, and AEZ—are then converted to annualized biomass C factors following the procedure described in section 3.3.

```
!<
  Read in the dry matter fractions, harvest indices, and root:shoot
  ratios for the crop sectors to compute a carbon multiplier that
  converts Region-AEZ-crop-specific yield values to the amount of
  carbon kept out of the atmosphere on average over time. We compute
  this as half the total above-ground + below-ground biomass value.

  Also read in the crop area changes generated by the modified GTAP
  TABLO code to generate a value (in Mg) for the total post-conversion
  change in biomass C for all changes in crop area, given local yields.

  Author:  Richard Plevin (plevin@ucdavis.edu)
  Created: August 14, 2013
>!

! Indicate that there will be no equations in this file !
EQUATION (NONE);

File
       GTAPSETS    # file with set specification #;
       GTAPDATA    # GTAP basedata #;
       GTAPUPD     # Simulation results #;
```

```
       CropBiomass # input file #;
 (new) OutFile     # output file #;


Set
    CROP_INDS # crop commodities #
    read elements from file GTAPSETS header "CROP";

    REG # regions in the model #
    read elements from file GTAPSETS header "H1";

    AEZ_COMM
    read elements from file GTAPSETS header "AEZ";

Coefficient
(all,c,CROP_INDS) crp_dry_frac(c)
 # Crop dry fraction as harvested #;

(all,c,CROP_INDS) harvest_idx(c)
 # Harvest index (fraction of above-ground biomass collected in harvest) #;

(all,c,CROP_INDS) root_shoot(c)
 # Root:Shoot ratio #;

(all,c,CROP_INDS) crop_c_frac(c)
 # Crop carbon fraction #;

palm_carbon  # Biomass carbon of oil palm trees (Mg C/ha) #;

c_avg_factor # Factor to convert crop C to avg sequestered C #;

! Computed here !
(all,c,CROP_INDS) yield_to_agc(c)
 # Multiply by yield to get above-ground biomass carbon #;

(all,c,CROP_INDS) yield_to_c(c)
 # Multiply by yield to get average stored crop carbon #;

Coefficient
(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    HARVSTAREA_L(i,j,r)
    # cropland harvested area (ha) #;
Read
    HARVSTAREA_L from file GTAPDATA header "AREA";

Coefficient
(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    HARVSTAREA_U(i,j,r)
    # post-sim cropland harvested area (ha) #;
Read
    HARVSTAREA_U from file GTAPUPD header "AREA";

Coefficient
(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    PRODUCTION_U(i,j,r)
    # tonnes #;
Read
    PRODUCTION_U from file GTAPUPD header "PRDN";

! Compute crop area changes for all crops !
Coefficient
(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    AREACHANGE(i,j,r)
```

```
    # hectares #;

Coefficient
(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    YIELD(i,j,r)
    # tonnes per hectare #;

Coefficient
(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    crop_carbon(i,j,r)
    # Crop carbon computed from yield (Mg/ha) #;

Coefficient
(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    chg_crpbio_c(i,j,r)
    # Net change in post-conversion crop biomass carbon (Mg) #;

Coefficient
    tot_crpbio_c
    # Total change in sequestered biomass C (Mg) #;

Read
 crp_dry_frac from file CropBiomass header "DRYF";
 harvest_idx  from file CropBiomass header "HIDX";
 root_shoot   from file CropBiomass header "RTST";
 palm_carbon  from file CropBiomass header "PLMC";
 crop_c_frac  from file CropBiomass header "CFRC";
 c_avg_factor from file CropBiomass header "CAVG";

Zerodivide default 0;

Formula
(all,c,CROP_INDS) yield_to_agc(c) =
  crp_dry_frac(c) * crop_c_frac(c) / harvest_idx(c);

(all,c,CROP_INDS) yield_to_c(c) =
  (1 + root_shoot(c)) * yield_to_agc(c);

(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    YIELD(i,j,r) = PRODUCTION_U(i,j,r) / HARVSTAREA_U(i,j,r);

(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    AREACHANGE(i,j,r) = HARVSTAREA_U(i,j,r) - HARVSTAREA_L(i,j,r);

(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    crop_carbon(i,j,r) = YIELD(i,j,r) * yield_to_c(j);

(all,i,AEZ_COMM)(all,j,CROP_INDS)(all,r,REG)
    chg_crpbio_c(i,j,r) = AREACHANGE(i,j,r) * crop_carbon(i,j,r);

palm_area_ch =
      sum(i,AEZ_COMM,sum(r,REG,AREACHANGE(i,"palmf",r)));

!<
  Since palm is a tree, the biomass C is not related to the fruit
  yield. It's carbon is added in at the end and NOT halved for an
  annual amount since the tree isn't harvested
>!
tot_crpbio_c =
    sum(i,AEZ_COMM,sum(j,CROP_INDS,sum(r,REG,chg_crpbio_c(i,j,r)))) *
    c_avg_factor + palm_area_ch * palm_carbon;

Write
```

```
 yield_to_agc to file OutFile header "YAGC" longname
  "Conversion factor to compute above-ground biomass C from yield";

 yield_to_c   to file OutFile header "YTLC" longname
  "Conversion factor to compute total crop carbon from yield";

! Also write the input data to the output file, for reference !

 crp_dry_frac to file OutFile header "DRYF" longname
  "Crop dry fraction as harvested";

 harvest_idx to file OutFile header "HIDX" longname
  "Harvest index (fraction of above-ground biomass collected in harvest)";

 root_shoot to file OutFile header "RTST" longname "Root:Shoot ratio";

 crop_c_frac to file OutFile header "CFRC" longname
  "Crop carbon fraction";

 crop_carbon to file OutFile header "CRPC" longname
  "Crop carbon computed from yield (Mg/ha)";

 c_avg_factor to file OutFile header "CAVG" longname
  "Factor to convert crop C to avg sequestered C";

 palm_carbon to file OutFile header "PLMC" longname
  "Biomass carbon of oil palm trees (Mg C/ha)";

! Computed values !

 YIELD to file OutFile header "CYLD" longname
  "Crop yield (Mg/ha)";

 AREACHANGE to file OutFile header "ACHG" longname
  "Area change (ha)";

 chg_crpbio_c to file OutFile header "CCRC" longname
  "Net change in post-conversion crop biomass carbon (Mg)";

 tot_crpbio_c to file OutFile header "TLBC" longname
  "Total change in sequestered biomass C (Mg)";
```

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