Agro-ecological Zone Emission Factor Model

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1 Overview

The purpose of the agro-ecological zone emission factor (AEZ-EF) model is to estimate the total CO_2-equivalent emissions induced by expanded biofuel production. The model combines matrices of carbon fluxes (Mg CO_2 ha^{-1} y^{-1}) with matrices of changes in land use (ha) by land-use category projected by the GTAP model. The carbon fluxes in AEZ-EF are aggregated to the same 19 regions (Table 1) and 18 AEZs (Figure 1) used by GTAP-BIO-ADV, the version of GTAP currently used by Purdue University researchers for ILUC modeling (e.g., Tyner, Taheripour et al. 2010).

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

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

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

- Above-ground live biomass (AGLB): trunk, branches, and foliage
- Dead organic matter (DOM): standing & down dead trees, coarse woody debris, and litter

[1] Future versions of the model will include estimates of uncertainty in all parameters, thereby enabling quantitative analysis of uncertainty in the AEZ-EF model separately or in conjunction with the GTAP model.

- 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. Region definitions from the GTAP model (Source: Tyner, Taheripour et al. 2010)

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

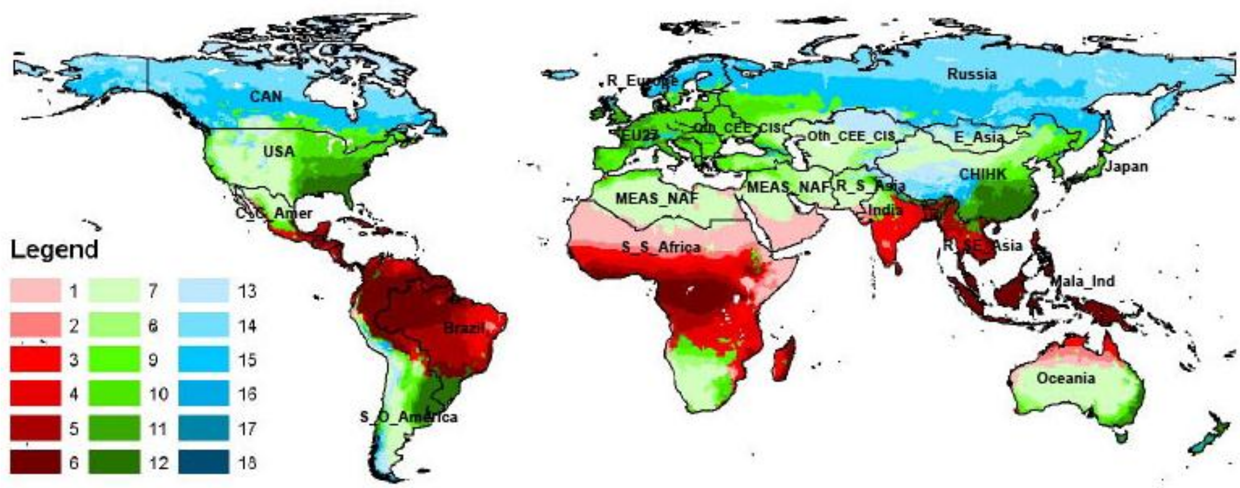
1.2 Data sources

The AEZ-EF model includes global data describing carbon stocks in above- and below-ground live biomass and in soils for 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 AEZ-region (Gibbs and Yui 2011). Below-ground biomass carbon for all land cover types is based primarily on root:shoot ratios, except for (Saatchi, Harris et al. 2011) for the pan-tropics . Peatland, deadwood, and litter carbon stocks are taken from the literature. (Specific sources are detailed in the sections below.)

The AEZ-EF model combines these carbon stock data with a series of assumptions about carbon dynamics that together determine the CO_2-equivalent emissions associated with land-use conversion. These assumptions, detailed in the remainder of 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 prior pasture or cropland
- The fraction of conversion achieved using fire
- The non-CO_2 emissions associated with land clearing by fire
- The fraction of forest AGLB still sequestered in harvested wood products at the end of the analytical horizon (currently 30 years.)

Figure 1. Distribution of agro-ecological zones (AEZs 1-18) and regions used in GTAP.



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 match GTAP region and AEZ (denoted "AEZ-region") boundaries (Gibbs and Yui 2011).

The chosen method of aggregation affects the emission factors generated. Computing area-weighted averages is clearly the simplest approach, and does not require any 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 (though data-challenged and not necessarily more accurate) approach 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 might weight likelihood of conversion by relative proximity to roadways.[2]

[2] A "road-proximity rule" will not be appropriate across the entire tropics. Depending on historical land use, roads may actually reduce likelihood of clearing in regions with sparse forest cover. It may only be relevant for the heart of the Amazon and Congo basins and Papua in Indonesia. But roads and ports are planned in these regions so conditions will be dynamic over the next 5-10 years. So we could consider making some rough assumptions and seeing if it has an impact on the results, but it's not necessarily an improvement.

Applying a likelihood-of-conversion criterion produces a preference order for land conversion, converting 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 demanded 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 (i.e., in light of crop losses from extreme weather events.)

2.1 Comparing carbon stocks with those in prior CARB ILUC modeling

We note that the prior emission factor model used by 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 ecosystems types. Therefore, the regional carbon stock estimates from the AEZ-EF model are incommensurable with those of the prior model as the former uses area weighting and the latter uses historical conversion weightings: these two approaches—by definition—estimate different quantities. However, the final emission factors are commensurable as both models estimate the emissions associated with biofuels-induced LUC, albeit using different methods and data.

2.2 Mapping to GTAP boundaries and economic uses

GTAP considers land to be in one of 5 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 (forest land that cannot supply timber)

However, GTAP considers land competition and conversion only among forestry, pasture and cropland, excluding land deemed unmanaged and inaccessible per modeling assumptions.

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

2.3 Yield calculations and land available in the GTAP database

We note here an area of potential inconsistency in the overall economic-ecosystem model. GTAP currently uses data on net primary productivity taken from the Terrestrial Ecosystem Model (TEM) to determine the ratio of yield on land newly converted to cropping to that on land already used for crops. The yield ratios are based on TEM results that exclude pasture and forest land with a slope greater than 5 percent. Since yields will decrease with increasing slope, this exclusion will tend to bias the yield ratios higher—assuming that available forest and pasture has a greater percentage of land with slope above 5 percent than does existing cropland. Purdue researchers argue that land with a slope greater than 5 percent is not suitable for conversion to crops but this doesn't mean that it isn't being used or won't be used in the future. Indeed, the average slope of land in corn in Iowa is 5 percent (Secchi, Gassman et al. 2009), suggesting that approximately half of the land now in corn production has a slope greater than 5 percent. If we exclude these lands from the yield ratio calculation, consistency dictates excluding this land from the land pools available for conversion to cropland in GTAP. It is likely that a substantial amount of cropland pasture and especially CRP land has a slope greater than 5 percent. Indeed in Iowa, CRP land has an average slope of 8 percent (Secchi, Gassman et al. 2009).

3 Biomass stocks

3.1 Below-ground biomass

Below-ground biomass stocks are generally estimated using root:shoot ratios, which vary by species and region. Below-ground biomass was not accounted for explicitly in ARB's previous model of ILUC emissions, but was included in estimates of biomass carbon from the Woods Hole Research Center. The AEZ-EF model includes estimates of below-ground biomass and the gain or loss thereof for conversions of among forest, pasture, and cropland.

3.2 Forestry

Ideally, the carbon stocks for an AEZ-region would represent the land GTAP reasons about, e.g., accessible forest rather than all forest in a given AEZ. However, the data that quantify accessible versus inaccessible forest are not spatially explicit, but based on FAO national data and percentages in each category (Gibbs and Yui 2011).

For forests, we followed the approach taken by WHRC and Winrock to produce average C stocks that combine accessible and inaccessible forest. We also mask out land identified by the GTAP land maps as "unmanaged", since this includes shrubland and grassland not used for grazing. Forest areas are not based on the GTAP definition, however, because the GTAP forest map does not account for forest cleared for logging or other non-agricultural purposes. Thus, we use the GTAP cropland and pasture boundaries but rely on a satellite-derived map for forest boundaries.

3.2.1 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 can also 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), however, these ratios vary across climatic zones.

DOM consists of litter and deadwood. Deadwood (also known as coarse woody debris) includes all non-living tree biomass not included in litter, including standing dead trees, down dead trees, dead roots, and stumps larger than a given 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 considers litter to be restricted to freshly fallen leaves, with decomposing leaves considered humus (Takahashi, Ishizuka et al. 2010).

The IPCC guidelines assume that dead organic matter stocks are zero for non-forest land-use categories.

The quantity of dead wood in a forest depends on several factors, including the density of live trees, the age of the forest, temperature, humidity, harvest frequency, self-thinning mortality, the time since the last disturbance—and whether this was fire, which removes dead wood, or an event which contributes dead wood, such as blow-downs, disease, or pests. Because of these diverse influences, there is no predictive relationship between the stocks of live tree biomass carbon and dead wood carbon (Woodall and Westfall 2009). Ratio methods fail spectacularly in cases of low live and high dead biomass.

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

DOM levels are highly variable around the world, ranging from 0 to >600 Mg ha^{-1}, but with most forests containing 30 to 200 Mg ha^{-1} of dead wood (Richardson, Peltzer et al. 2009).

In a study of dead wood 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 dead wood, and a negative relationship between percent of above-ground biomass as dead wood 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 dead wood is approximately 16% of the mass of live tree biomass. For the scale of analysis in GTAP and the AEZ-EF model, it is reasonable to estimate the size of the dead wood pool based on the pool of above-ground live biomass.

In Japan, Takahashi, Ishizuka et al. (2010) found that dead wood 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, dead wood 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 equivalent to assigning a value of zero) would bias estimates of emissions downward. 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.

The Tier 1 IPCC GHG inventory guidelines assume that dead wood and litter carbon stocks are in equilibrium, i.e., there are no net emissions from this pool. However, the inventory guidelines provide estimates for litter but not for dead wood, which is defined 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).

3.2.1.1 Litter

Table 2 lists the IPCC’s default values for litter in mature forests. The AEZ-EF model simply averages the values for broadleaf deciduous and needleleaf evergreen forests, and averages the two values for (cold and warm) dry temperate forests and for moist temperate forests. Table 3 lists the values used in AEZ-EF, by AEZ.

The IPCC gives litter values for mature forests, for two categories: Broadleaf deciduous and needleleaf evergreen, and their regional boundaries do not map exactly to AEZs. To use these values, three sets of assumptions must be made:

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

In AEZ-EF, the named arrays IPCC_LITTER_TABLE (Table 2) and LITTER_TABLE (Table 3) provide the litter values used in the mode. IPCC_LITTER_TABLE simply averages the values for the two types of forests. The value in each IPCC region is then mapped to an AEZ in the LITTER_TABLE, which is referenced in the Model sheet's Litter column.

Table 2. IPCC default values for litter in mature forests (Mg C ha^{-1}). (Source: IPCC 2006, Table 2.2)

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

[a] Values in parentheses marked by subscript “a” are the 5th and 95th percentiles from simulations of inventory plots, while those without subscript “a” indicate the entire range.

Table 3. 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
13	Boreal-Arid	Boreal, dry	28
14	Boreal-Dry semi-arid	Boreal, dry	28
15	Boreal-Moist semi-arid	Boreal, dry	28
16	Boreal-Sub-humid	Boreal, Moist	47
17	Boreal-Humid	Boreal, Moist	47
18	Boreal-Humid (year round)	Boreal, Moist	47

3.2.1.2 Dead wood

Estimates of carbon stored in dead wood used in AEZ-EF are derived from Pan et al. (2011). The US, Europe, and Canada are broken out in the Pan et al. data, and since these correspond to regions used in the GTAP model, the values are adopted directly into AEZ-EF. 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 4.

Table 4. Estimates of deadwood by region or latitude (Mg C ha^{-1}). (Source: Pan, Birdsey et al. 2011)

Region or latitude	Deadwood
USA	11
EU27	2
Canada	22
Boreal	14
Temperate	4
Tropical	27

3.2.2 Understory

The forest understory consists of shrubs, herbs, grasses, mosses, lichens, and vines. Carbon stocks in understory increase as gaps appear in canopy and decrease as canopy closes, so these are somewhat inversely proportional to forest carbon stock (Plantinga and Birdsey 1993). Thus for regrowing forests with lower carbon densities, the exclusion of understory biomass would be expected to undercount carbon stocks and thus emissions. Understory carbon is currently excluded from biomass stock estimates in AEZ-EF except for those for Russia.

Woodbury et al. (2007) examined carbon sequestration in the US forest sector, suggesting that the minimum understory carbon density is about 0.5% of the tree carbon density, occurring in mature stands with high tree carbon density. Overall, their model predicted understory carbon density in the US forest sector of 1.8 to 4.8 Mg C ha^{-1}. Woodbury et al. write: "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. The minimum understory carbon density values are predicted to be 0.5% of the tree carbon density; this minimum occurs in mature stands with high tree carbon density."

From these we can use the minimum of 0.5% * AGLB or to a maximum of 4.8 Mg C ha^{-1}, at least in US forests. Some studies note that understory biomass has an approximately negative exponential relationship to tree biomass, since canopy openings increase understory growth and closed canopies reduce it, raising questions about any factor multiplied by AGLB.

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 fraction of this.

Studying Amazonian rainforest, 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 (a woody climbing plant that hangs from trees), so 9.6 Mg biomass, or about 4.8 Mg C ha^{-1} in addition to 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, suggesting that a value of 4.5 to 5 Mg C ha^{-1} for understory carbon in tropical rainforest would be conservative.

Cummings et al. (Cummings, Boone Kauffman et al. 2002) find a mean biomass of live "non-tree" components in the Brazilian Amazon of 22 Mg biomass or about 11 Mg C ha^{-1}. This includes palm that they consider "non-tree". They find a total of 18.5 Mg biomass ha^{-1} of non-tree live biomass (seedlings + palm + vine) 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.

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

Latitude	Mg C ha^{-1}
Boreal	1.5
Temperate	1.5
Tropical	4.5

3.2.3 Carbon stored in harvested wood products

Some forest carbon remains sequestered in harvested wood products for the full analytic time horizon used in AEZ-EF, i.e., 30 years. Estimating the carbon remaining after 30 years requires more data than is available, regarding the volume of wood harvested, the fraction that is converted to long-lived products, and the fate of those products over time, including the fractions landfilled and the fractions of the landfilled biomass sequestered long term, emitted as CH_4, or combusted (as biomass or CH_4) for energy generation.

CARB is presently evaluating a model of carbon sequestration of HWP which may be used in future versions of AEZ-EF. Presently, the model includes two placeholder parameters defining the fraction of AGLB stored for at least 30 years, for developed (20%) and developing (5%) countries.

We note that fraction of HWP that remains sequestered after 30 years is lower than the fraction removed from the fuel load. More wood is removed, some is lost in production of wood products. The model currently uses a single parameter to represent both reduction in fuel load and long-term sequestered carbon. However, since the fate of wood that is removed but not sequestered is unclear, we feel that this is an acceptable approximation.

3.3 Pasture

Pasture carbon stock values are based on IPCC 2006 GHG Inventory Guidelines, using Tier I defaults for grasslands. Table 6 lists IPCC grassland biomass data (IPCC 2006, Table 6.4); Table 7 shows how these values are mapped to AEZs in the AEZ-EF model.

Table 6. IPCC grassland biomass data (Mg d.m. ha^{-1}). Source: IPCC 2006 GHG Inventory Guidelines, table 6.4. IPCC indicates a nominal estimate of error of ±75% (two times standard deviation, as a percentage of the mean) for the total biomass stocks.

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

Table 7. Grassland biomass data used in AEZ-EF, based on IPCC grassland data (Mg d.m. ha^{-1}). The column labeled "Zone ID" links this table to IPCC default values in the table above.

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

3.4 Cropland

To estimate the AGB on cropland after conversion of pasture, cropland pasture, or forest, or of cropland prior to reversion to these categories, we use an estimate of annual NPP of C-4 plants by AEZ and region from the TEM model. (See the TEM worksheet in the AEZ-EF model.)

3.4.1 Cropland-Pasture

The cropland-pasture category is treated as a subcategory of cropland in the current version of GTAP. This land-use category is considered by GTAP only in US and Brazil.

Cropland-pasture is poorly characterized. According to the USDA[3],

> **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 land category. The treatment of this land has varied widely across studies, with one paper by Purdue modelers concluding that cropland pasture should be treated as pasture (Birur, Hertel

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

et al. 2010, p. 36)[4] while a subsequent report treats these land as cropland, i.e., there are zero emissions associated with bringing this land back into production (Taheripour and Tyner 2011).[5]

Because management of cropland-pasture ranges from long-term crop rotation to permanent grassland pasture, we assume an emission factor equal to half the pasture-to-cropland emission factor for the same AEZ-region. This assumption is also supported by IPCC SOC stock change factors for reduced tillage and no-till, which are assumed to produce a 2–15% and 10–22% increase in soil carbon, respectively, compared to full conventional tillage. We assume that cropland-pasture would likely fit into reduced or no-till management, and that conversion to crop production requires tillage.

3.4.2 Conservation Reserve Program

Conservation Reserve Program (CRP) lands include forest and shrub cover in addition to grasslands. Bringing CRP land back into crop production is subject 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 decades for corn– soybean and continuous corn, respectively, and 89 to 123 years under conventional tillage. In contrast, they project modest, immediate GHG savings from converting CRP land to the production of cellulosic biofuel feedstocks.

The current version of GTAP does not allow conversion of CRP land, thus the current version of AEZ-EF does not model emissions from bringing this land back into production.

4 Soil carbon stocks

Soil carbon stocks estimates to both 30 and 100 cm depths were produced by aggregating data from the Harmonized World Soil Database (HWSD) to AEZ and region boundaries, filtering out land categorized as wetland (Gibbs and Yui 2011). In addition, land with carbon stocks greater than 500 Mg C ha^{-1} was filtered out for the Malaysia and Indonesia. The treatment of emissions from peatland conversion is presented in section 6.3.

5 Land cover transitions

The GTAP model projects the 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 land use transitions (e.g., forest to pasture, forest to cropland, cropland-pasture to cropland) we must deduce these specific transitions from the net area changes provided by GTAP.

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[4] Explaining their use of emission factors Birur, Hertel et al. write: “Though these carbon factors pertain to forest and pasture cover conversion, we consider that conversion of idled or marginal croplands also emit carbon in the same way as that of pasture-cover since most of the croplands grow grasses when they are kept idle.”

[5] Explaining their use of emission factors, Taheripour and Tyner write: “We apply these emission factors to the changes in natural land. Hence, we exclude emissions from cropland pasture as these lands are not assumed to be in natural state of land cover.

5.1 Assumed transitions given net changes

The AEZ-EF model estimates the CO_2-equivalent emissions released or sequestered upon conversion of land among land cover classes. Table 8 shows the eight transitions considered in the AEZ-EF model, with X indicating that a transition is considered.

Table 8. 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 does not provide for the conversion of unmanaged land to or from managed land, all land-use changes are assumed to occur within the pool of land in the four land-use classes, and the sum of the changes is approximately zero in each AEZ-region combination. For the AEZ-EF model, 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 the opposite sign from the two other classes. (Negative signs indicate a reduction in area of a given land-use class; positive sign indicates a gain.) Lacking more detailed information, we assume that the remaining transitions occur either (i) from the two land-use classes losing area to the one gaining area, or (ii) from the one losing area to the two gaining area.

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 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 and 6,000 ha of cropland. If, instead, the region were to lose 18,000 ha of forestry 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 is not zero, the "extra" may or may not be included, depending on the nature of the transition.

5.2 Net changes may underestimate emissions

GTAP reports the net changes in land use between the starting equilibrium and the equilibrium reached after applying a shock. This net 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 upon 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.

By using the stock change approach for conversion factors and the regrowth approach for reversion factors, we are essentially taking the GTAP results at face value. If GTAP predicts an increase in forest area then we are treating it as such with a regrowth (afforestation) emission factor. Likewise, if GTAP predicts a reduction in forest area then we are treating it as such with a deforestation emission factor.

5.3 Deforestation versus avoided afforestation

More detailed long-term research is necessary to determine which AEZ-regions are undergoing deforestation (in which case conversion factors are appropriate), which are undergoing afforestation (for which reversion factors are appropriate), and for which both afforestation and deforestation occurs. This information is not available from country level data which only gives net changes in forest land cover. Long-term work is also necessary to determine appropriate rates of reversion.

6 Emissions from land cover conversion

6.1 General approach

We follow the IPCC GHG inventory approach to estimating emissions (IPCC 2006). For each AEZ-region 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 non-CO_2 emissions from land clearing by fire
4. Carbon emitted as CO_2 through decay processes
5. 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 AEZ-region combination is multiplied by the corresponding hectares projected to be gained or lost by GTAP 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 to produce an ILUC factor in g CO_2e MJ^{-1}.

6.1.1 Clearing by fire

Land clearing 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 lifetime of other chemical species that have direct effects (Brakkee, Huijbregts et al. 2008).

In AEZ-EF, we consider only those emissions that are considered in the CA-GREET model: the three greenhouse gases CO_2, CH_4, N_2O, as well as the CO_2 produced by oxidizing the carbon fraction of CO and non-methane hydrocarbons (NMHCs). Following GREET, 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.

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.

The fuel load includes AGLB, litter, and deadwood, and excludes the fraction of AGLB assumed to be sequestered for 30 years in harvested wood products.

Regions assumed to be cleared by fire are derived from the EPA RFS2 analysis by Winrock International, who consider fire to be used for clearing of cropland in all regions except for except China, Argentina, Russia, EU, US, and Mexico (Harris, Grimland et al. 2008).

Combustion factors which 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 in Eucalyptus (0.49) and “other” (0.51) temperate forests, again resulting in a combustion factor of 0.50. For boreal forests, we adopted the value for land-clearing fires (0.59). For clearing pastures, we averaged the values for savanna grasslands for early dry season burns (0.74) and mid/late dry season burns (0.77) yielding 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 (shown in Table 10). 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 9.

Above-ground biomass (AGLB, litter, and deadwood) that is assumed not to be combusted (the fraction given by 1 minus the combustion factor) is assumed to decompose to CO_2 during the analytic horizon, and is thus counted as “committed” CO_2 emissions.

6.1.2 Sequestration in char

Conversion by fire also produces char, which is relatively recalcitrant. 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 implicitly estimates a portion of carbon that is not emitted to the atmosphere and 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 9. Global warming potentials used in AEZ-EF. Source: IPCC (2007)

Gas	GWP
CO_2	1
CH_4	25
N_2O	298

6.1.2.1 Combustion emission factors

The values for CO_2, CO, CH_4, and N_2O are presented in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Table 2.5. These values are from Andreae and Merlet (2001), which also includes estimates for NMHC and CO.

Table 10. Forest burning emission factors (kg per Mg dry matter). Source: Andreae and Merlet (2001)

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

Table 11. Pasture burning emission factors (kg per Mg dry matter). Source: Andreae and Merlet (2001)

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

6.1.2.2 Regions using fire for land cover conversion

Winrock assumed conversion by fire in most locations other than Argentina, though, to our knowledge, the reason for this exception was not documented. Following Winrock, we assume that burning is used for land clearing in Brazil, India, Central and Caribbean Americas, East Asia, Malaysia and Indonesia, Rest of Southeast Asia, Rest of South Asia, and Sub-Saharan Africa. We assume 50% of land clearing uses fire in South and Other Americas (because fire isn't used in Argentina but is used elsewhere), and no clearing by fire in other regions.

Table 12. Fraction of forest clearing by fire in each GTAP 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	100%
East Asia	100%
Malaysia and Indonesia	100%
Rest of South East Asia	100%
Rest of South Asia	100%
Russia	0%
East Europe and Rest of Former Soviet Union	0%
Rest of European Countries	0%
Middle Eastern and North Africa	0%
Sub Saharan Africa	50%
Oceania	0%

6.2 Soil carbon changes

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

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 to estimate carbon stocks before and after conversion. The SOC loss is the difference between these estimates.

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 and 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.

Per 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 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 inputs factors are 1.0 in all cases.)

For pasture, we assume nominally managed (all factors 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 (e.g., fertilizer, species improvement, or irrigation.)

The IPCC approach accounts for losses in top 30 cm only, though recent evidence indicates SOC changes occur at deeper levels, too. Although the model is structured to account for subsoil carbon losses, we currently have data only for temperate regions (Poeplau, Don et al. 2011).

The algebraic basis for our use of the IPCC factors is shown below. Our treatment of peatland emissions is discussed in section 6.3.

Following the IPCC guidelines, the change in SOC is given by the following 3 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 the above 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 starting 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 factors: 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 13 and Table 14.

Table 13. 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}	Perennia/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 14. Mapping of stock change factors to AEZs in AEZ-EF.

Latitude	Humidity	AEZ	F_{LU}
Tropical	Arid	1	0.58
Tropical	Dry semi-arid	2	0.58
Tropical	Moist semi-arid	3	0.58
Tropical	Sub-humid	4	0.48
Tropical	Humid	5	0.48
Tropical	Humid (year round)	6	0.48
Temperate	Arid	7	0.80
Temperate	Dry semi-arid	8	0.80
Temperate	Moist semi-arid	9	0.80
Temperate	Sub-humid	10	0.69
Temperate	Humid	11	0.69
Temperate	Humid (year round)	12	0.69
Boreal	Arid	13	0.80
Boreal	Dry semi-arid	14	0.80
Boreal	Moist semi-arid	15	0.80
Boreal	Sub-humid	16	0.69
Boreal	Humid	17	0.69
Boreal	Humid (year round)	18	0.69

6.3 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 possible conversion of peatlands when estimating emissions from ILUC.

6.3.1 Estimates of emissions from peatland drainage

There are two primary methods for establishing the emissions from peatland drainage: (i) direct measurements of gaseous fluxes using closed chambers, or (ii) estimates of total carbon loss based on peat subsidence rates (Page, Morrison et al. forthcoming). These methods result in wide ranges, e.g., 30 Mg CO_2 ha^{-1} y^{-1} to above 100 Mg CO_2 ha^{-1} y^{-1} for flux measurements and 54 to 115 Mg CO_2e ha^{-1} y^{-1} for the optimal drainage depth range for oil palm (60 – 85 cm) (Page, Morrison et al. forthcoming). A forthcoming review of emissions from oil palm plantations commissioned by ICCT concludes that "the most robust currently available empirical estimate of peat CO_2 emissions from OP [oil palm] and pulpwood, based on combined subsidence measurements and independent closed chamber measurements in the same plantation landscape" is 86 Mg CO_2e ha^{-1} y^{-1}., equivalent to 23.45 Mg C ha^{-1} y^{-1}. This value is based on a 50-year annualization: if the "committed" emissions from peat drainage were amortized over 30 years, the value rises to 95 Mg CO_2e ha^{-1} y^{-1}., equivalent to 26 Mg C ha^{-1} y^{-1}.

The IPCC default for conversion of tropical and subtropoical peatlands to agriculture is 20 Mg C ha^{-1} y^{-1}, with a nominal uncertainty range of ±90%, representing two times the standard deviation as a percentage of the mean (IPCC 2006, Table 5.6).

6.3.2 Treatment of peatland emissions in AEZ-EF

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

1. Conversion of peatlands occurs only in the Malaysia/Indonesia (Mala_Indo) region.
2. Conversion of peatland results in a loss of 86 Mg CO_2 ha^{-1} y^{-1} , or 23.45 Mg C ha^{-1} y^{-1} (Page, Morrison et al. forthcoming). We count these emissions over the model's analytical horizon of 30 years, resulting in total emissions of (23.45 * 30) = 704 Mg C ha^{-1}.
3. We assume that 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 is then computed as the weighted sum of 33.3% peatland emissions (as described above) and 66.6% "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.

6.4 Conversion of forest to cropland

To account for emissions from the conversion of forest to cropland, we consider CO_2 (and where burning is used, non-CO_2) emissions 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 fluxes to/from each pool are described below.

6.4.1 Foregone sequestration

The removal of trees that would otherwise have sequestered more CO_2 as biomass carbon over time is considered equivalent to emitting that quantity of CO_2.

AEZ-EF uses estimates of net above-ground live biomass growth from IPCC 2006 GPG table 4.9, mapped to regional values by Holly Gibbs based on expert judgment. Since these values are documented as representing above-ground tree biomass, we added growth in root biomass using a root:shoot ratio of 0.25; we recognize that this varies by region, forest density, and stand age, but lacked data to improve this reliably. Foregone sequestration is higher when younger, faster-growing forest stands are removed, so accounting for the possibility of younger stands is important. For each region, we produced a weighted average based on the fraction of young (< 20 year old) stands and old (> 20 year old) stands, currently set to 10% and 90%, respectively. The weighted average of total tree annual growth for each region is multiplied by our analytical horizon of 30 years to produce values representing foregone sequestration from tree growth. We feel that the assumption of 10% young forests is conservative, yet accounts for some of the faster growth and greater loss of sequestration. (We considered that perhaps 30% of conversion occurred in younger stands, but over 30 years, some of these stands would age and sequester carbon more slowly. We chose the lower value of 10% to account for this aging effect.)

6.4.2 Harvested wood products

The AEZ-EF model currently uses placeholder values representing the fraction of AGLB that remains sequestered in HWP after 30 years, with different values for developed (15%) and developing (5%) regions. We are examining a new analysis of HWP produced by UC Davis for inclusion in AEZ-EF.

6.4.2.1 Comparison with Tyner et al. approach

Comparison with the HWP assumption used by Tyner, Taheripour et al. (2010) is challenging as there is some uncertainty as to which stock of biomass this fraction is applied. Apparently, Tyner et al. assume 25% of above-ground live tree biomass is retained long term (at least 30 years) in harvested wood products (HWP) upon conversion. We note that ARB previously assumed no storage in HWP.

Tyner et al. write “we assume 75% of carbon stored in the forest type vegetation and 100% percent of carbon stored in the grassland vegetation will be released into the atmosphere at the time of land conversion." Unfortunately, “vegetation” does not precisely identify which subset of the available biomass carbon pools was included. A footnote in that paper says: "In essence, we are assuming that 25% of the carbon in wood is stored in buildings, furniture, etc." So although Tyner et al. never say 25% of above-ground live tree biomass ends up in HWP, though the word "wood" in the footnote implies this.

The Tyner et al. report relies on the values presented in Searchinger, Heimlich et al. (2008a), which also identifies these as “vegetation”. However, the report underlying these data (Houghton 1999) indicates that these “vegetation” values include both above- and below-ground live biomass of trees as well as ground cover. So apparently Searchinger’s "vegetation" C values (and thus Tyner's) represent all live AGB (tree and understory) and BGB, and may exclude dead biomass. It’s unclear whether "ground cover" is limited to live understory or includes dead biomass.

We note also that the CCLUB model (which is distributed with GREET and implements the approach the used by Tyner et al.) applies the 25% HWP fraction to these same vegetation values but labels them “above ground biomass”. In addition, CCLUB labels what appears to be just soil C as "below-ground biomass".

6.5 Conversion of forest to pasture

For forest-to-pasture conversion, we assume the same foregone sequestration rate and burning-related emissions as for forest-to-cropland transitions. We then assume a gain in biomass to the pasture value for the relevant AEZ-region. 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.

6.6 Conversion of pasture to cropland

6.6.1 Foregone sequestration

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.

6.7 Conversion of pasture to forest

For pasture-to-forest transitions, we assume no burning, just natural succession. In this case, 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 litter and deadwood.

6.8 Conversion of cropland to forest or pasture

For cropland and pasture conversion to forest, we limit the sequestration over 30 years to no more than the sum of above- and belowground live biomass, litter, and deadwood value for each AEZ-region.

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 6.2, 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 (for stands less than 20 years old) and 10 years at the lower rate for stands (greater than 20 years old), in both cases, including root growth 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.

6.9 Conversions between Cropland-Pasture and Cropland

As noted in section 3.4.1, we assume that the conversion of cropland-pasture to cropland results in half the emissions of 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.

7 Uncertainty

Any detailed estimate of an ILUC emissions factor 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 model is presently under development. This will allow 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.

7.1.1 GTAP model

Discussion 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 unmanaged 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 outcomes when including and excluding unmanaged land in an ILUC projection. Ideally, GTAP would be modified to include this capability.

As discussed earlier, the biomass and soil carbon stock estimates by Gibbs and Yui (2011) are not limited to areas in economic use, so the assumptions underlying the economics of land conversion and the emissions therefrom differ, and it's unclear how this biases 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).

Use of the IPCC soil carbon stock change method is coarse. 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. The potential bias introduced by this method is unknown.

7.3 Biomass 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 per-AEZ percentages of accessible versus inaccessible forest
- Conversion of DBH measurements to volume and then to carbon
- Litter estimates include variability in original data, imperfect mapping to AEZ-regions, uncertainty in the ratio of broadleaf to needleleaf forests, and uncertainty whether these estimates represent forests actually converted, both in terms of ratio of forest types and the use of "mature forest" litter values, as not all converted forests will be mature.
- Dead wood 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 to be accessible forest.
- Carbon stocks in forests actually converted may not be well represented by average values.

7.3.2 Pasture carbon

Uncertainty around IPCC's grassland biomass estimates are given nominally as ±75% for all regions, representing 2 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, representing 2 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 to be in use for livestock grazing.

7.4 Land cover conversion and emissions

7.4.1 Identifying land conversion

GTAP 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 represent well the land actually converted, although it is impossible to pinpoint the location of these conversions.

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

7.4.2 Land clearing by fire

The fraction of the land clearing by fire 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.

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 flaming fires producing more BC, while smoldering fires produce less BC but more carbon monoxide. The ratio of flaming versus smoldering will vary by the precise mechanics of clearing. Finally, the short atmospheric lifetime of BC results in very high GWP values over shorter time horizons. Thus the choice of using 100-year GWPs rather than integration periods matched to the analytic horizon used (30 y) reduces the estimated effect of BC, while 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).

7.4.3 Harvested wood products

Data is lacking for harvested wood products in many regions. While Pan et al. estimate the quantity of annual "lateral transfers" from the forest pool to the HWP pool, the AEZ-EF model requires estimates of the fraction of AGLB that remains sequestered after 30 years. This requires additional data on the fate of HWP in each region. Uncertainty surrounding our estimates is likely quite high.

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 of these growth rates to our AEZ-regions 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.

Estimates of root growth are based on a global root:shoot ratio of 0.25, though the actual value is highly variable.

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.) We use a ratio of 10:90 (young:old) globally to recognize that the fraction of young stands is unlikely to be zero, though the specific ratio will vary with location.

7.4.5 Cropland and Cropland-pasture

Cropland-pasture is vaguely defined but an important factor in the present system as GTAP 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 very coarse. Uncertainty surrounding these estimates is likely quite high.

8 Model implementation

The AEZ-EF model is implemented as a multi-worksheet Excel™ workbook. External 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, the GTAP results are not built into the model, but instead accessed from an external workbook. The format of the external GTAP results workbook is described in section 8.1.13.

8.1 Model structure

AEZ-EF is implemented with 12 data or analysis worksheets plus two 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 EF worksheet

The **EF** worksheet computes emission factors for each AEZ and region by land cover conversion sequence. The results are compiled in matrix form to facilitate matrix multiplication with GTAP area changes.

8.1.3 Model worksheet

The **Model** worksheet is the core of the model, combining 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

8.1.4 Biomass worksheet

The **Biomass** worksheet provides a database of above- and below-ground biomass stocks by region and AEZ. This database is documented in the accompanying report by Gibbs and Yui (2011).

8.1.5 Soil worksheet

The **Soil** worksheet provides a database of soil carbon stocks to 30 and 100 cm depths, by region and AEZ, for forests, pasture, and cropland. This database is documented in the accompanying report by Gibbs and Yui (2011).

8.1.6 Foregone worksheet

The **Foregone** worksheet includes estimates of the annual growth rates for forests, based on a weighted average of young and old stands from the IPCC. These values are used to determine the amount of C sequestration foregone by land cover change.

8.1.7 Factors worksheet

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

8.1.8 Tables worksheet

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

8.1.9 TEM worksheet

The **TEM** table provides estimates of annual rates of net primary productivity by region based on the TEM model. These values are used to determine the amount of biomass on cropland after conversion.

8.1.10 GTAP worksheet

The **GTAP** worksheet imports from an external workbook the results of GTAP model runs defining LUC by region, AEZ, and land use. The format of the external worksheet is described in Section 8.1.13.

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 ChangeMatrices worksheet

The **ChangeMatrices** worksheet parse the results from the Transitions sheet into matrices representing specific land use transitions. In the Results sheet, these are multiplied with the corresponding EF matrices from the EF sheet.

8.1.13 External GTAP workbook

To allow AEZ-EF to be used with a variety of GTAP model results, the GTAP results are incorporated into the model via an external workbook which 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” which contains a list of result worksheet names in row 1 starting in column B. Currently, up to 20 results worksheets can be named in cells B1 through U1.
- Each results worksheet contains basic info about the run and all results by region, AEZ, and land use category. In each results worksheet
    - cell B1 must contain the name of the “run”
    - cell B2 names the feedstock, e.g., corn, soybean, palm, miscanthus, etc.
    - cell B3 names the final fuel, e.g., ethanol, butanol, biodiesel, renewable diesel, etc.
    - cell B4 states the increment in fuel quantity (in gallons) used to shock GTAP
    - Following this meta-data must be 4 matrices of 19 regions (columns) by 18 AEZs (row). The first matrix, starting at row 6, holds area changes (ha) by AEZ-region for forestry. The second matrix, starting at row 27, holds area changes for pasture. The third matrix, starting at row 48, holds area changes in cropland. The fourth and final matrix, starting at row 69 holds area changes in cropland-pasture.

The user can select from available worksheets using pull-down menu in "GTAP" worksheet. The corresponding ILUC factor is then computed and presented in the Results sheet.

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