

Carbon Dynamics
Of Global Land Use, Land-Use Change, and Forestry

by

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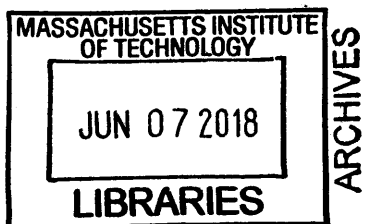
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Abstract

Forest harvest for bioenergy is growing rapidly, spurred by the European Commission's declaration that bioenergy is carbon-neutral. Bioenergy advocates argue that the carbon released upon the combustion of harvested wood should eventually be reabsorbed from the atmosphere when the harvested land regrows. Recent studies, however, find that wood bioenergy can exacerbate climate change because it is less efficient than the fossil fuels it displaces, and because regrowth takes time and is uncertain. Other land use, land-use change, and forestry (LULUCF) practices can also cause significant carbon fluxes to and from the atmosphere that vary over time as the carbon sequestered in the biomass and soils on each land type changes. Understanding these complex interactions requires an explicit dynamic model that accounts for various land uses and regions, each with carbon content and flux characteristics specific to their respective vegetation, soil distributions, and climatic domains. This work extends the widely used C-ROADS climate model, originally developed with a single biosphere, to incorporate this level of detail. Built up from a diverse set of highly resolved geospatial databases for land cover, soils, climatic domains, and other relevant characteristics, the model aggregates the data into six land use types (natural forest, harvested forest, cropland, pasture, permafrost, and developed/other land) within six major regions (the US, EU, China, India, Other Developed Nations, and Other Developing Nations). It is used to analyze the impact of harvesting forests for bioenergy. Because wood bioenergy is less efficient than the fossil fuels it displaces, the first impact is an increase in atmospheric CO₂. If the land regrows as forest, this carbon debt can eventually be repaid. However, the time required to do so is long, ranging from 20 to 186 years, depending on the region supplying the wood and whether the forest is thinned or clear-cut. Converting forest to cropland after harvest increases atmospheric CO₂ concentrations without payback. Results also show that afforestation programs are most effective in reducing atmospheric CO₂ when implemented in regions with more tropical climates due to the higher carbon density of these forests. This fast, regionally specific, multi-land-use model enables policy makers and other stakeholders to quickly design and evaluate a wide range of LULUCF and bioenergy policy scenarios and their climatic effects.

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1 INTRODUCTION

In the face of global climate change, nations are scrambling to enact diverse solutions they hope will reduce their impact on the climate while also satisfying their social and economic demands. Wood bioenergy is one such option whose advocates argue that it is “carbon neutral” because the carbon released upon combustion of the harvested wood should eventually be removed from the atmosphere when new forests grow. Under this reasoning, the European Commission declared wood bioenergy to be a “carbon-neutral” energy source, leading a number of European countries to increase wood use for heat and power (Cornwall, 2017). The UK, in particular, subsidizes wood bioenergy heavily to displace coal (Cornwall, 2017). More recently, the US Environmental Protection Agency announced it now considers wood to be carbon neutral (Pruitt, 2018).

Recent literature, however, contends that the declaration of wood bioenergy carbon-neutrality increasingly diverges from reality as the many assumptions of the bioenergy life cycle are challenged. In particular, Sterman, Siegel, and Rooney-Varga (2018) demonstrate how the argument for wood bioenergy can actually exacerbate climate change even when used to replace coal. Nevertheless, the bioenergy debate continues, fueled not only by the lack of understanding around the dynamics of carbon stocks and flows, but also by competing social and economic interests of the stakeholders involved.

Wood harvest for bioenergy is just one of the many land use changes that can contribute to the complex carbon flux dynamics between the biosphere and the atmosphere. The field of land use, land-use change, and forestry (LULUCF) addresses the effects of anthropologically determined land use on vegetation and soil characteristics (Deng, Zhu, Tang, & Shangguan, 2016). Specifically, the recognition of the strong influence that different modes of LULUCF has on carbon management and release within terrestrial ecosystems places LULUCF squarely in the context of climate change (Houghton & Nassikas, 2017; Jiyuan et al., 2016; Rattan Lal, 2013). Recently, advances in computing power, as well as the increasing collection and access to global land and carbon data, have enabled the LULUCF community to create dynamic earth system models to understand the global implications of LULUCF (Boysen et al., 2014; Quillet, Peng, Garneau, Quillet, & Garneau, 2010; Sterman et al., 2013).

This work is representative of this last trend. The land use model used in the Climate-Rapid Overview and Decision Support (C-ROADS) simulator was expanded to include six land uses (forest, harvested forest, cropland, pasture, permafrost, and other land) across six C-ROADS defined regions (the United States, the European Union, China, India, Other Developed Nations, and Other Developing Nations). The expanded model was parameterized to enable dynamically determined carbon flux between the biomass and soils of each land use within each region, as well as the atmosphere. Scenarios of bioenergy and other land-use change cases – including conversion of forest to cropland after harvest for bioenergy and afforestation – were simulated to examine their impact on atmospheric CO₂.

2 METHODS

2.1 MODEL STRUCTURE

The system dynamics land use model built by Sterman et al. (2018) simulated the carbon dynamics between three land uses, u – Forest, Harvested Forest, and Other – for a single region, r – the United States. This land use model constitutes an important component of the C-ROADS simulator, allowing scenarios of LULUCF and bioenergy policy to be studied within its system.

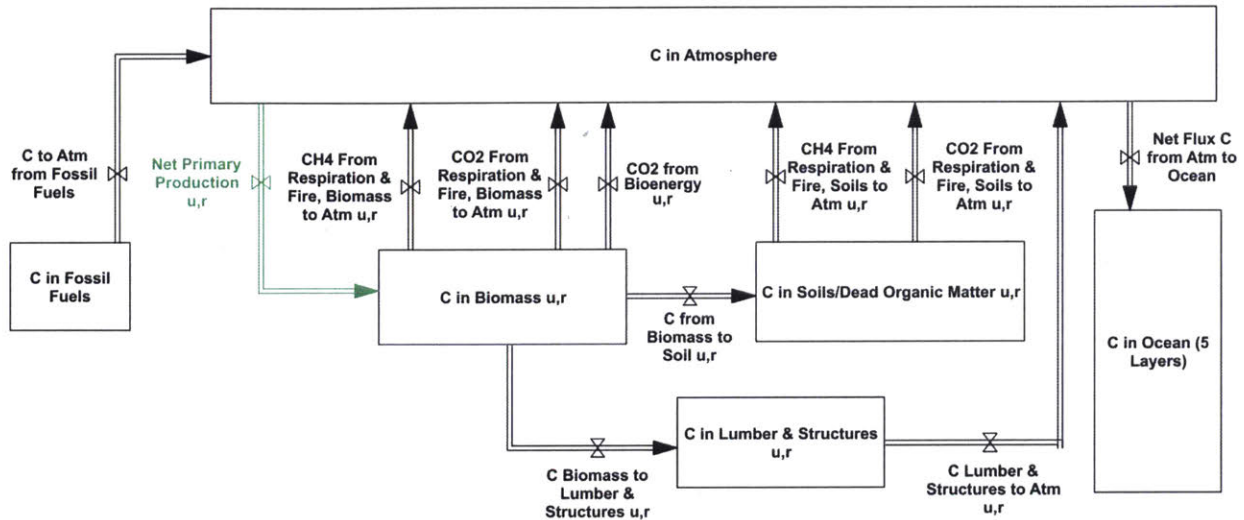


Figure 1. Modified carbon cycle in extended C-ROADS model (from Sterman et al., 2018, with permission of the authors).

The stocks of carbon in biomass and the soil are modeled separately for each land use and region. Biomass consists of living vegetation, including their stems, branches, foliage, and coarse roots. Soil consists of soil organic matter, dead roots, litter (dead foliage, dead branches, etc.), downed and standing dead trees, and living fine roots.

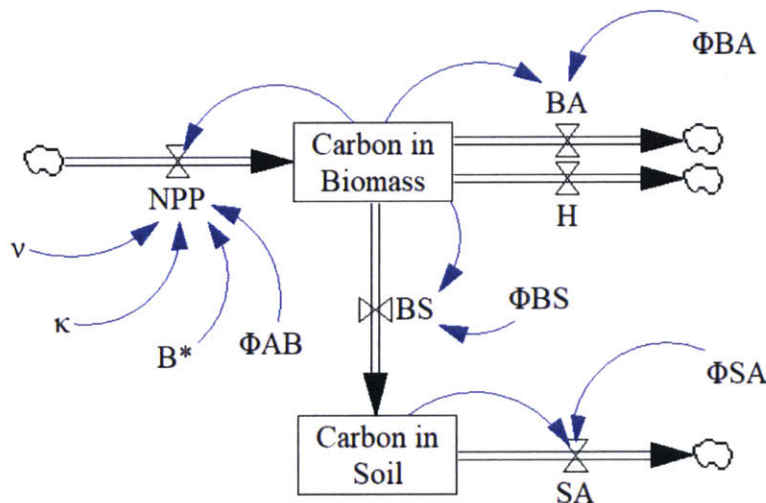


Figure 2. Simplified biomass and soil carbon flux stock and flow diagram

The state of any carbon stock is dictated by the flux of carbon into and out of the stock. Furthermore, these fluxes are dynamically determined, in part, by the stocks into which and from which they flow. (Figure 2) Equation (1) formalizes the change in the stock of carbon held in biomass.

$$\frac{dB_{u,r}}{dt} = NPP_{u,r} - B_{u,r}\varphi_{u,r}^{BS} - B_{u,r}\varphi_{u,r}^{BA} - H_{u,r} \quad (1)$$

Carbon leaves the stock of biomass via three different pathways: (i) it may move into the stock of carbon in the soil by litter fall, tree mortality, and carbon translocation into fine roots, (ii) it may move to the atmosphere via plant respiration or fire, or (iii) it may be removed via harvest or grazing and subsequent methanogenesis by animals, again making its way into the atmosphere. These mechanisms are formalized by the fractional rate of carbon flux from biomass to soil, φ^{BS} , the fractional rate of carbon flux from biomass to atmosphere, φ^{BA} , the stock of carbon in biomass, B , and the absolute amount of carbon harvested from the biomass, H .

$$NPP_{u,r} = \left(\varphi_{u,r}^{AB} B_{u,r} + \kappa_{u,r} B^*_{u,r} \right) \left(1 - \left(\frac{B_{u,r}}{B^*_{u,r}} \right)^{\nu_{u,r}} \right) \quad (2)$$

The inflow, net primary production, NPP , which represents the carbon fixation or assimilation into the biomass as it grows, is formulated as a modified Richards growth function (Richards, 1959; Sterman et al., 2018). It is composed of the a reference fractional rate of carbon flux from atmosphere to biomass, φ^{AB} , the stock of carbon in biomass, B , the maximum biomass for a given land type and region, B^* , the rate of carbon flux from atmosphere to biomass proportional to max biomass, κ , and a shape parameter in the Richards growth model for NPP, ν .

$$\frac{dS_{u,r}}{dt} = B_{u,r}\varphi_{u,r}^{BS} - S\varphi_{u,r}^{SA} \quad (3)$$

The stock of carbon in soils is grown via litter fall, tree mortality, and carbon translocation into fine roots, formulated as the same flux from biomass to soil in Equation (1). The outflow from the soil carbon stock is formulated as the product of the stock of soil carbon, S , and the fractional rate of carbon flux from soil to atmosphere, φ^{SA} , representing fire and soil respiration.

Biomass or soil carbon, the total amount of carbon within the respective land use and region-specific stock, is delineated in gigatons of carbon (GtC). Biomass or soil carbon intensity, the biomass or soil carbon present in a hectare of land, is delineated in metric tons of carbon per hectare (tC [ha]⁻¹). Absolute flux, the total amount of carbon moving from a particular stock to another, is measured in metric tons of carbon per year (tC [yr]⁻¹). Flux intensity, the amount of carbon moving from to or from a particular hectare of land, is delineated in metric tons of carbon per hectare per year (tC [ha yr]⁻¹).

2.1.1 Land Uses

The land uses chosen for the expanded model are meant to balance several considerations. The requirement of simulation run speed emphasized the need to consolidate land use categories where appropriate. The mapping of the C-ROADS land uses onto those used by the Food and Agriculture Organization of the United Nations (FAO) ensured that the land use areas were mutually exclusive and collectively exhaustive. (Table S2) Additionally, they were chosen to align as closely as possible with those used by the Intergovernmental Panel on Climate Change (IPCC) in order to take advantage of the Tier 1 methodologies for estimating carbon stocks and fluxes. Permafrost is delineated as its own land use to allow for the

capability to model the thawing of permafrost as an effect of rising global temperatures and its yet unquantified, but potentially disastrous, feedback on the climate system (Schuur et al., 2015).

Table 1. *Land use mapping*

IPCC	C-ROADS	FAO
Forest Land	Forest	Forest
	Harvested Forest	
Cropland	Cropland	Arable Land and Permanent Crops
Grassland	Pasture	Permanent Meadows and Pastures
Other Land	Permafrost	Other Land
	Other	

2.1.2 Regions

This model uses the six-region delineation used in the original C-ROADS model – the US, the EU, China, India, Other Developed Nations, and Other Developing Nations. As such, 224 individual countries, as recognized by FAO, were mapped into these regions (Fiddaman, Siegel, Sawin, Jones, & Sterman, 2017). (Table S1) Those nations that fail the official designation of “developing,” were included in that category nonetheless for completeness. Additionally, those nations that are territories of a host nation were not assigned to their host nation, but rather to the region (usually Other Developing Nations) most appropriate for their independent level of development.

2.2 MODEL PARAMETER ESTIMATION

2.2.1 Geospatial Data Sources

A geospatial data layer delineating national boundaries allowed for the disaggregation of the other global geospatial data layers into nation-level data. While the data could have been aggregated directly into the six C-ROADS regions, the disaggregation into nation-level data first allows for the capability to group the countries as future implementations of the model requires.

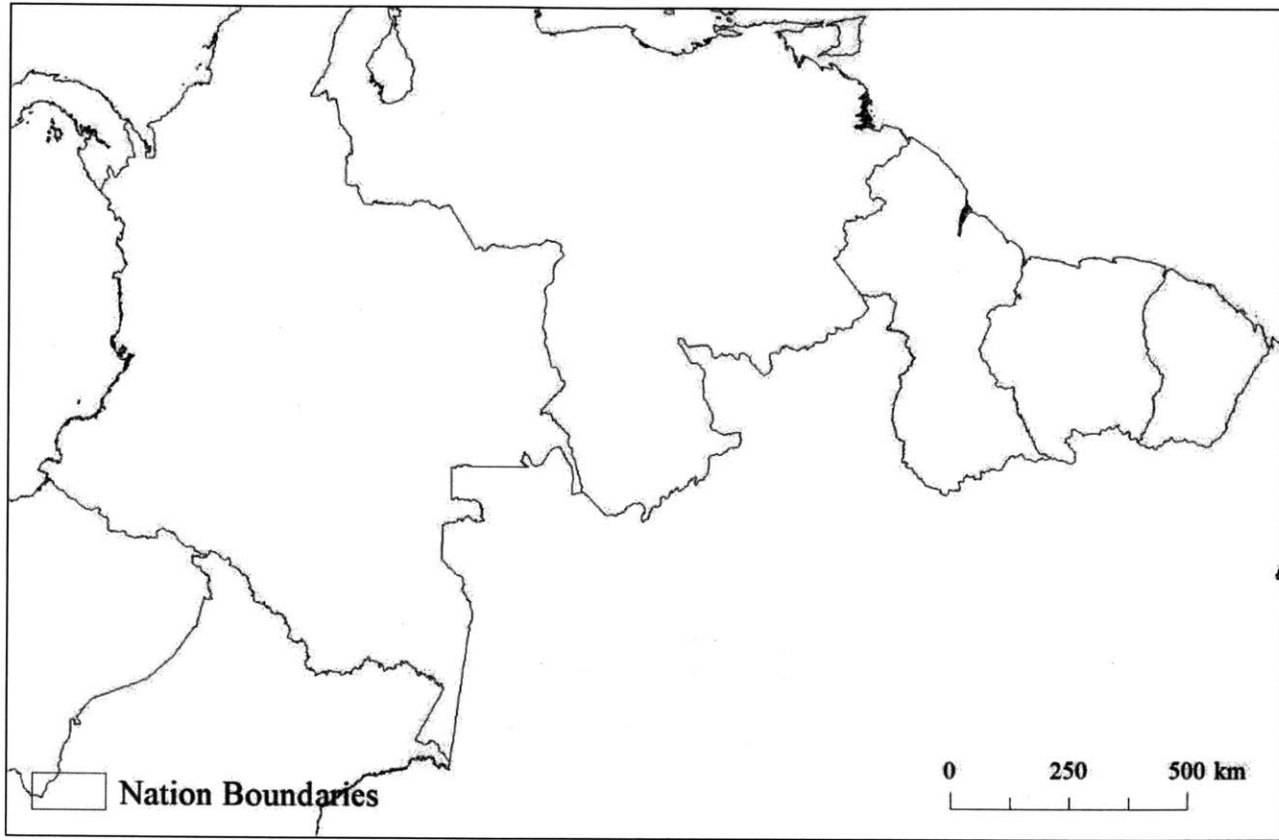


Figure 3. Geospatially specific nation boundaries: Northern Amazon.

Despite their definition of various land uses, neither the IPCC nor FAO provide geospatial land area data associated with their categories. Consequently, land cover classes, for which geospatial data were available (Figure 4), were used as proxies for land use. These land cover classes, defined by vegetation and coverage characteristics, were mapped onto the IPCC land use categories (Table S3), and then C-ROADS land use categories (Table 1).

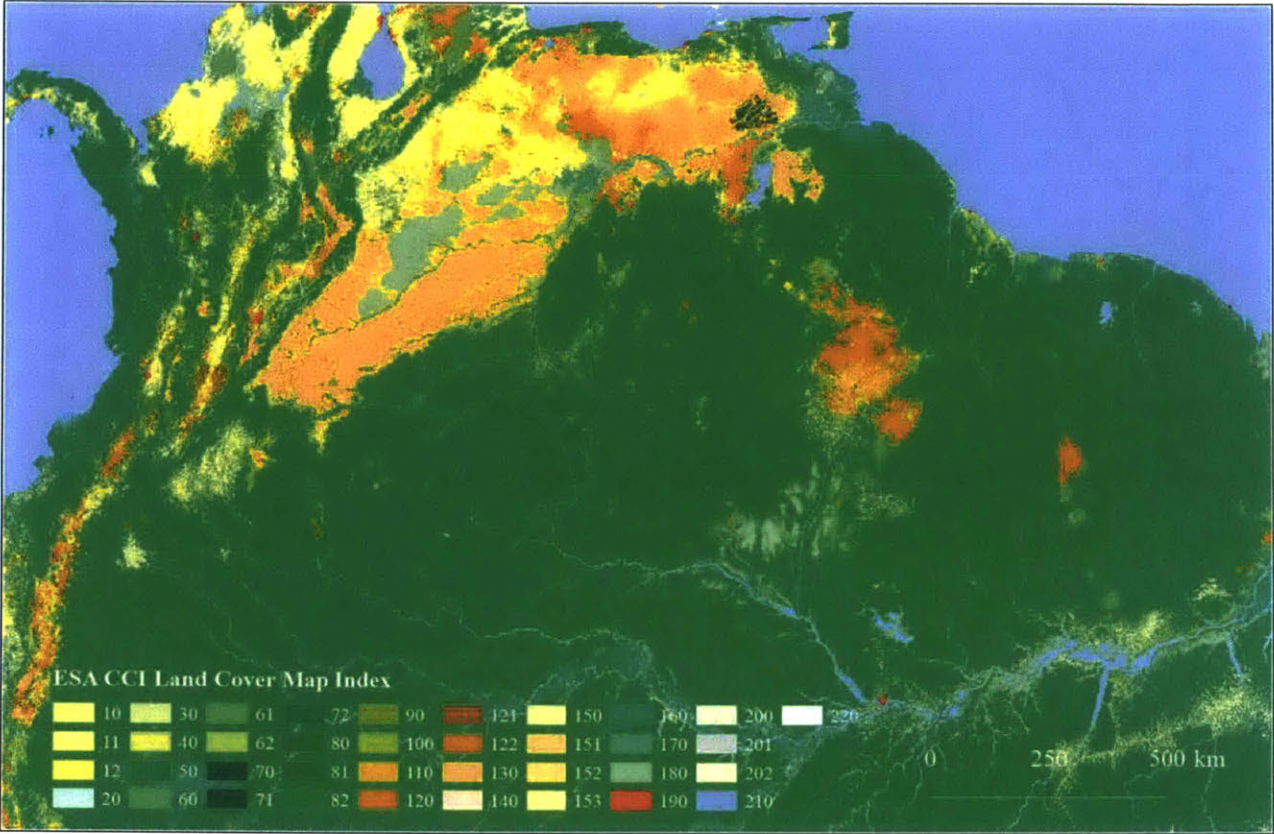


Figure 4. European Space Agency and Climate Change Initiative land cover map depicted by 300m x 300m pixels: Northern Amazon.

Recognizing that vegetation and biomass carbon intensity vary substantially across climatic domains, the distribution of these domains were accounted for within each country. This research uses the widely accepted FAO framework of climate domains – tropical, subtropical, temperate, boreal, and polar – and their constituent global ecological zones, or ecozones (Simons, 2001). (Figure 5 and Table S4)

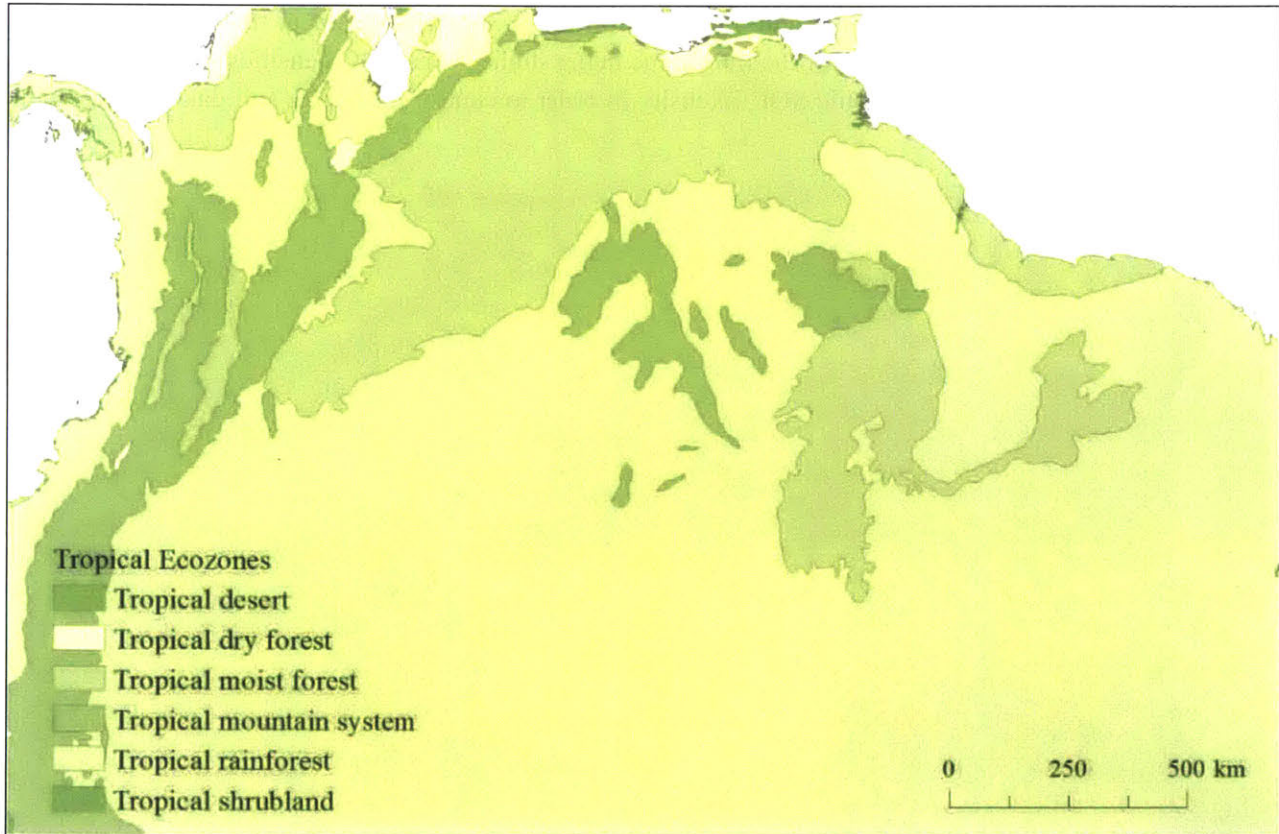


Figure 5. Global ecological zones within the tropical climatic domain: Northern Amazon.

Soil carbon for each land use and region was derived from the Digital Soil Map of the World (DSMW) (FAO, 2003). The DSMW provides 'soil unit symbols' and their associated values for soil characteristics including the percentages of sand, silt, and clay in the topsoil (0-30cm) and subsoil (30-100cm), as well as the soil organic carbon (SOC) in both as a percentage of mass. 'Soil mapping units' consist of various compositions of particular soil unit symbols. DSMW polygons, p , are geospatial area vectors of each characterized by a single soil mapping unit. Only the topsoil (0-30cm) was used in this study in order to reflect the importance of this layer over the timeframe being studied. The SOC densities were bounded by a ceiling defined by the 95th percentile SOC intensity in order to control for outlier soil data and resultant over-estimation of soil carbon.

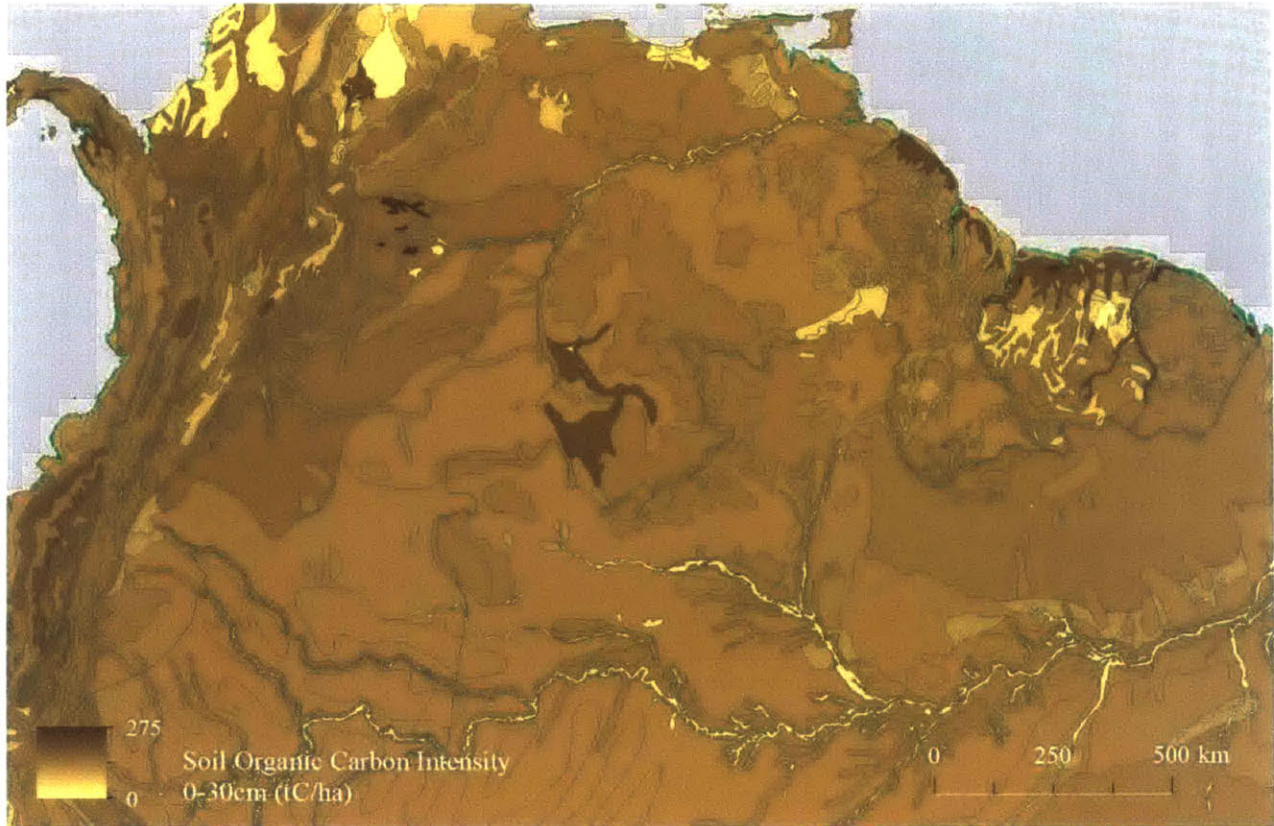


Figure 6. *Digital Soil Map of the World: Northern Amazon.*

Permafrost SOC intensities were estimated using the Northern Circumpolar Soil Carbon Database version 2 (NCSCDv2). (Figure 7) As described by Hugelius et al. (2014), “the SOC stocks estimates for the 0–0.3 and 0–1m depth ranges were calculated separately in each NCSCDv2-region (i.e. Alaska, Canada, Contiguous USA, Europe, Greenland, Iceland, Kazakhstan, Mongolia, Russia and Svalbard) following the methodology of Tarnocai et al. (2009) but using the revised and gap-filled data sets described by Hugelius et al. (Hugelius, Bockheim, et al., 2013; Hugelius, Tarnocai, et al., 2013).”

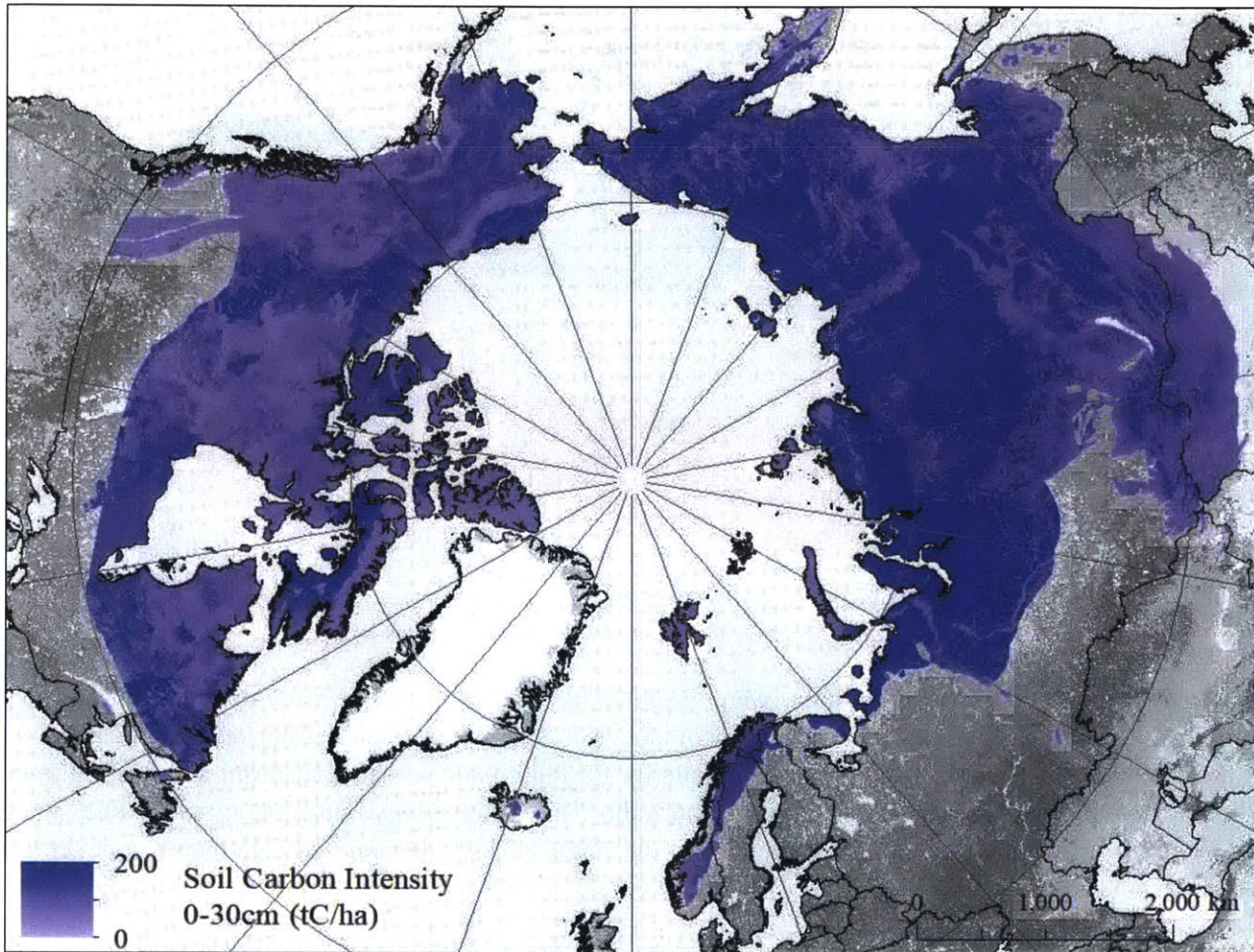


Figure 7. Northern Circumpolar Soil Carbon Database version 2.

The coordinated projection of these geospatial data layers (Figure 8) allowed for disaggregation and attribution of data from one layer to another. Specifically, the tabulation of area of land cover class within soil polygons enabled the calculation of the soil organic carbon underlying different land uses. Similarly, area of land cover classes within polygons of different ecozones enabled the calculation of the domain-level biomass carbon intensity of different land uses.

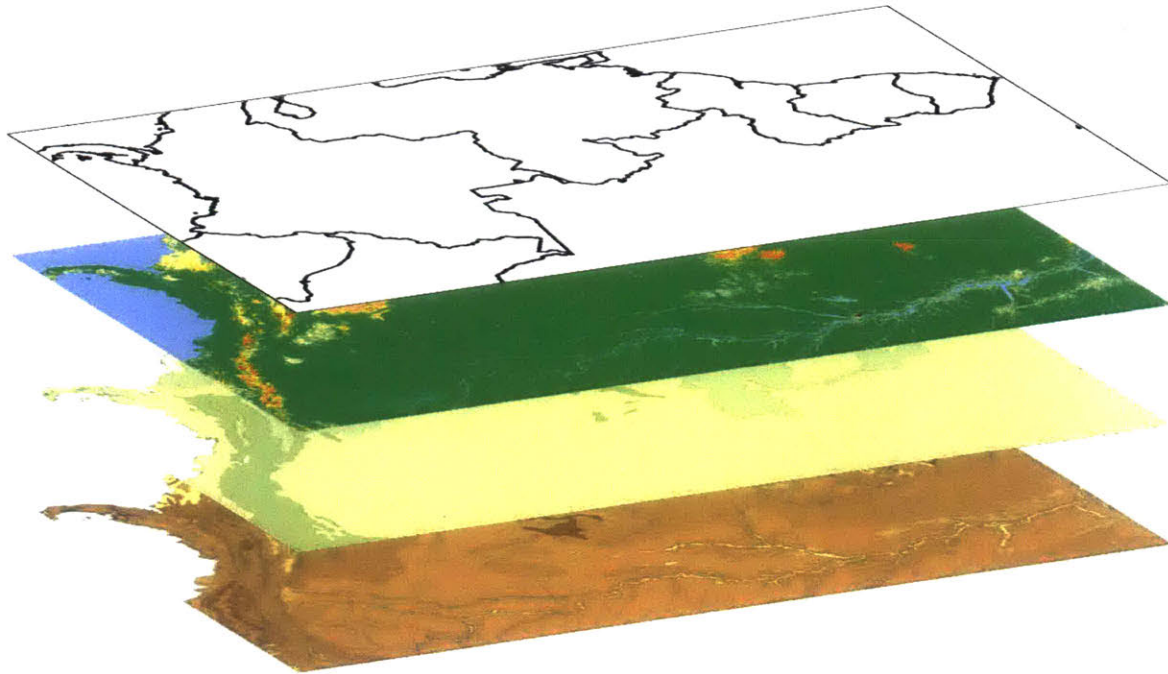


Figure 8. *Layering of geospatial data: Northern Amazon.*
Top: nations; Second: land cover; Third: ecozones; Bottom: soils

Furthermore, nation-level land use areas were weighted by the coverage of climatic domains within each nation. While this assumes that the distribution of land uses across each domain is uniform within a nation, it nonetheless provides a higher degree of granularity for those nations with significant areas in multiple climatic domains, particularly the US, China, and India. This methodology builds upon that of Keenan et al. (2015), in which each country was assigned to the single climatic domain that held the most coverage within it.

2.2.2 Biomass Carbon Intensity

Biomass carbon intensities by land use and region were reconstructed from the New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000 (GBCM) (Ruesch & Gibbs, 2008). The GBCM used the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) to estimate the biomass carbon intensity of land by land cover class, ecozone, and continental region – Africa, North America, South America, Europe, Continental Asia, Insular Asia, Australia, or New Zealand. As such, the biomass carbon intensities by land cover class, ecozone, and continental region were reconfigured to estimate biomass carbon intensities by land use and C-ROADS region.

First, biomass carbon intensities by land cover class, ecoregion, and continental region were averaged into their appropriate land use, climatic domain, and continental region (Table S3 and Table S4). The nation-level biomass carbon intensities were then constructed as the average of the appropriate continental region-level biomass carbon intensities, weighted by the coverage of each climatic domain within its national boundaries. Finally, the biomass carbon intensities for land uses by C-ROADS region were constructed as

the average of their constituent nation-level biomass carbon intensities, each weighted by the nation-level land use area as a fraction of the land use area within the C-ROADS region.

Each ecoregion and continental region had biomass carbon values for both frontier and non-frontier classes of vegetation, where ‘frontier’ is defined as “relatively unmanaged forests with little human disturbance” (Ruesch & Gibbs, 2008). Frontier and non-frontier values only differed for certain temperate, boreal, polar forest systems. For conservative estimates, only non-frontier values were used. The resulting biomass carbon intensities were used for all land uses except for the Forest types, for which FAO biomass carbon stock values and land areas were scaled up from the nation-level reported data.

2.2.3 Soil Carbon Intensity

Soil carbon intensities by land use and region were constructed from the DSMW, ESA/CCI Land Cover, and national boundary geospatial layers. First, the soil bulk densities of specific soil symbol units were constructed as the weighted average of the densities of sand, silt, and clay, according to their fractional composition of the soil symbol unit (Walter, Don, Tiemeyer, & Freibauer, 2016). Second, SOC intensities of soil symbol units were constructed as the product of the soil bulk densities and the organic carbon percentage for the specific soil unit elements. Third, SOC intensities of soil mapping units were constructed as the weighted average of their component soil unit elements. Fourth, nation-level SOC intensities of soils underlying specific land uses were constructed as the average of the soil mapping unit SOC intensities, each weighted by the fraction of the specific land use coverage within a specific polygon relative to the total specific land use coverage within all the soil mapping unit polygons in the country. Finally, C-ROADS region land use SOC intensities were constructed as the average of the nation-level land use SOC intensities, each weighted by the nation-level land use areas.

The soil carbon intensities of permafrost land use by region were constructed from NCSCDv2. Some of the pedons (soil samples) used to construct NCSCDv2 were overlain by forest vegetation. To prevent overlapping and consequent double counting of soil carbon under land uses, permafrost was constrained to be only that land area that was covered in tundra vegetation in addition to being underlain by gelisol, or permafrosted, soils (Hugelius, Tarnocai, et al., 2013; USDA, 1999). ESA/CCI land cover classes 140, 150, 151, 152, and 153 – including mosses and lichens, and sparse vegetation (tree, shrub, herbaceous cover), respectively – were used to delineate tundra land cover. SOC intensity values by NCSCDv2 polygons were weighted by fractional tundra cover and fractional composition. Because the land cover classes used for tundra fell under the other land category of FAO, the soil stocks and areas of permafrost land use were subtracted from those of other land use to prevent double counting of the permafrost carbon and land.

2.2.4 Land Uses

2.2.4.1 Forest

The forest parameters were estimated differently than those of the other land uses due to the importance of the ϕ^{AB} , κ , and ν parameters for forests in particular, as well as the availability of forest growth curves. The time series profiles of biomass carbon intensity and soil carbon intensity of land as specific tree species grew from seedlings or planting (Smith, Heath, Skog, & Birdsey, 2006) were used to estimate the individual forest parameters with the simultaneous optimization of parameters methodology used by Sterman et al. (2018). Tree species were then mapped into domain-level forest types – temperate, subtropical, and boreal. (Table S5) Due to the high degree of nonlinearity between the parameters within a specific forest system, the median value of each optimized parameter for each domain-level forest type was used to represent the

domain-level forests in order to reduce the influence of outlier parameter values. Parameter estimates for tropical forests were optimized using a similar optimization method, albeit with tropical forest carbon growth curves constructed from individual tropical tree growth curves and tropical forest tree density estimates (Glick et al., 2016; Köhl, Neupane, & Lotfiomran, 2017). Further detail on the estimation process for tropical forests can be found in the Appendix. The presence of multiple climatic domains per country, especially for larger countries with significant forest area in multiple domains, necessitated the weighted averaging of the forest type parameters to obtain C-ROADS region forest parameters.

2.2.4.2 *Harvested Forest*

The parameters for C-ROADS region forests were used for harvested forests.

2.2.4.3 *Cropland*

The equation used to represent NPP on cropland was simplified to reflect its relatively simple growth pattern relative to that of forests. Specifically, cropland biomass growth is less sensitive to the current state of the crop, allowing $\varphi^{AB} = 0$, and the Richards shape function is less important for the significantly lower biomass carbon intensity of croplands, allowing $\nu = 1$. Under these assumptions, Equation (2) becomes:

$$NPP_{u,r} = \kappa_{u,r} (B_{u,r}^* - B_{u,r}) \quad (4)$$

Furthermore, κ^{AB} for cropland is large compared to that of forests. Assuming that crops reach maturity, approaching 95% their equilibrium state, within one year sets $\kappa^{AB} = 3 \text{ yr}^{-1}$. Additional considerations on this assumption can be found in the Appendix.

Harvest in this research pertains only to the harvest of forest for wood bioenergy and does not appear in the cropland formulations. Rather, the crop harvest is contained within the term $B_{u,r} \varphi_{u,r}^{BA}$ from Equation (1).

The total nation-level flux of carbon from biomass to atmosphere on croplands was taken to be the combined carbon contained within harvested crop biomass and the crop residues produced during the crop harvesting process, summed for each crop of that country.

$$BA_i = CP_i * C + CR_i * C_{cell} \quad (5)$$

$$CR_i = CP_i * RP_i \quad (6)$$

BA_i is the carbon flux of a particular crop, CP_i is the crop production or amount of biomass harvested (FAO, 2018), C is the carbon content of the harvested portion of the crop (Monfreda, Ramankutty, & Foley, 2008), CR_i is the crop residue of the particular crop, and C_{cell} is the carbon content of the residue (Wolf et al., 2015). CR_i was formulated as the product of CP_i and the residue production ratio, RP_i , of the particular crops responsible for the grand majority of the world's crop residues (R Lal, 2005). The crop production (kg) of 161 unique crops in 216 countries in the year 2016 were gathered from FAOSTAT (FAO, 2018). Average residue:crop production ratios for each crop residue type used were calculated from production and residue production numbers from 1991 and 2001 (R Lal, 2005). These nation-level fluxes were divided by the reported cropland area of each nation (FAO, 2018) to estimate the nation-level biomass to atmosphere carbon flux intensities.

The total nation-level flux of carbon from biomass to soil was calculated as the belowground biomass carbon for those crops that also produced residue, under the assumption that not all crops (ex: fruit trees) produce significant annual residue and their roots do not become soil during the span of a year.

Contrastingly, crops that produce significant residues during harvesting and must be replanted with each growth cycle – including maize, millet, oats, etc. – were lose their roots and the carbon they contain to the soil between each harvest. These nation-level flux were divided by the reported cropland area of each nation (FAO, 2018) to estimate the nation-level biomass to soil carbon flux intensities.

The domain-level carbon flux intensities from soil to the atmosphere from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). (Table S6)

2.2.4.4 Pasture

The assumptions for φ^{AB} , ν , κ^{AB} on croplands were also applied to pasture. Based on their geographic coordinates, 31 carbon flux measurement sites (Scurlock, Johnson, & Olson, 2002) were mapped into the FAO climatic domains, for which the average NPP was calculated for each. Individual NPPs were calculated via method 5 according to Scurlock et al. (2002). The carbon mass per dry matter (d.m.) mass was set to be 0.44 (g C [g d.m.]⁻¹) under the assumption that the carbon mass per dry matter mass of pasture land is similar to that of agricultural roots and stocks (Wolf et al., 2015).

Domain-level carbon flux intensities from soil to atmosphere were based on the annual emission factors for drained grassland organic soils (IPCC, 2006). (Table S7) Domain-level carbon flux intensities from biomass to soil were assumed to equal those from soil to atmosphere values in equilibrium. Domain-level carbon flux intensities from biomass to atmosphere were calculated to be the difference between NPP and the carbon flux intensities from biomass to soil, and were constrained to be greater than or equal to zero.

2.2.4.5 Permafrost

It was assumed for this model that permafrost did not have active fluxes.

2.2.4.6 Other

It was assumed for this model that other land did not have active fluxes from biomass to atmosphere or from biomass to soil. Fractional parameters for carbon flux from soil to atmosphere were calculated directly from the annual change in organic carbon stocks in mineral soils with a time dependence of stock change factor of 20, as recommended for Tier 1 calculations for soils on other land (IPCC, 2006).

2.2.5 Fractional Flux Parameterization

Each of the input parameters to NPP, as well as those to the carbon flux from biomass to soil, biomass to atmosphere, and soil to atmosphere (Table 2), were estimated for each land use and region.

Table 2. Parameters of interest, specific to land use, u , and region, r

Parameter	Units	Definition
$\varphi_{u,r}^{AB}$	yr ⁻¹	Reference rate of C flux from atmosphere to biomass in Richards function for NPP, by land use and region
$\varphi_{u,r}^{BA}$	yr ⁻¹	Fractional rate of C flux from biomass to atmosphere, by land use and region
$\varphi_{u,r}^{BS}$	yr ⁻¹	Fractional rate of C flux from biomass to soils, by land use and region
$\varphi_{u,r}^{SA}$	yr ⁻¹	Fractional rate of C flux from soils to atmosphere, by land use and region
$B^*_{u,r}$	tC [ha] ⁻¹	Maximum biomass C intensity of the land, by land use and region
$\kappa_{u,r}$	yr ⁻¹	Rate of C flux from atmosphere to biomass proportional to max biomass in NPP model, by land use and region
$\nu_{u,r}$	D'less	Shape parameter in the Richards growth function for NPP

For the non-forest land uses, the parameters needed to be estimated individually. The fractional rate parameters – φ^{AB} , φ^{BA} , φ^{BS} , and φ^{SA} – never expressed in data or literature as fractional values, were

constructed by dividing the C-ROADS region flux intensities by their corresponding C-ROADS region biomass or soil carbon intensities. The flux intensities were reported in the literature or constructed from data in different scales: nation-level, domain-level, or ecozone-level. (Table S4) If obtained at the nation-level, the C-ROADS regional flux intensities were constructed by taking the average of the nation-level intensities, weighted by their specific land use area as a fraction of the C-ROADS region specific land use area. The C-ROADS region flux intensities were then used to calculate the fractional flux parameters. If obtained at the domain-level, the nation-level flux intensities were constructed by taking the average of the domain-level intensities, weighted by the climate domain coverage within the nation. The nation-level intensities were then used to construct the C-ROADS regional flux intensities, etc. If obtained at the ecozone-level, the domain-level flux intensities were constructed as the average of the reported ecozone-level intensities, etc.

With the fractional flux parameters estimated, the maximum biomass carbon intensity of the land, B^* , can be calculated. Assuming that the biomass carbon intensities estimated previously represent the vegetation in their respective states of equilibrium, combining Equations (1) and (2) gives:

$$B^*_{u,r} = \frac{B_{u,r}\varphi_{u,r}^{BS} + B_{u,r}\varphi_{u,r}^{BA}}{\kappa_{u,r}} + B_{u,r} \quad (7)$$

2.3 MODEL SETUP AND INITIALIZATION

Simulations were run from a state of equilibrium to allow a clearer interpretation of the highly interconnected dynamics at play. Equilibrium biomass intensities from which to initialize the stocks of the model were found individually for each land use and region. However, due to the magnitude of the global behavior over which these parameters have influence, upon importing these initial carbon intensities into the model, rounding errors produced a slight disequilibrium that affect the base case scenario. As such, the atmospheric concentration of carbon increases approximately 0.01 ppm over the course of a century in the base case. (Figure 9)

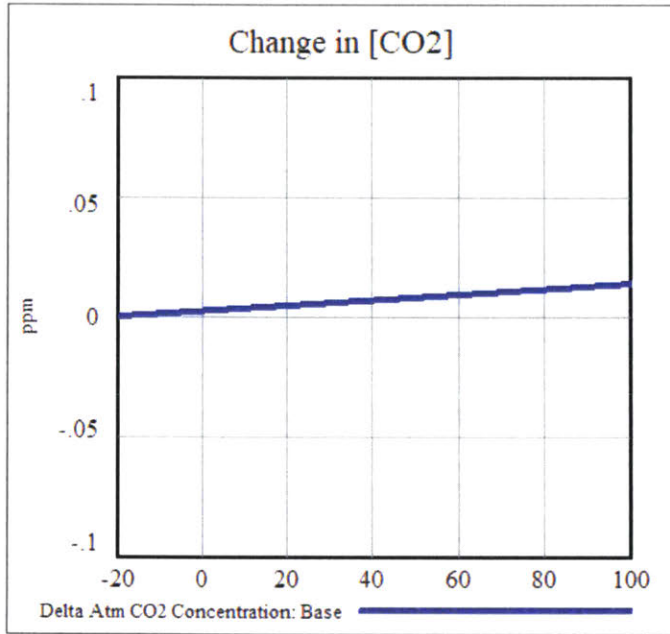


Figure 9. Base Case illustrates computational constraints to achieving pure equilibrium starting conditions.

Nevertheless, despite the dynamic carbon fluxes between biomass, soil, and atmosphere, over each land use, between each global region, over time, the total carbon in the global system modeled is conserved. (Figure 10)

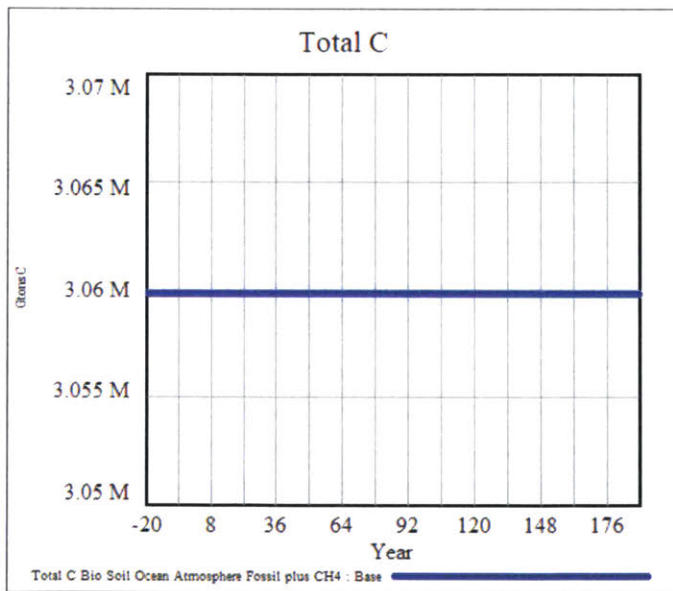


Figure 10. Conservation of global carbon mass across all stocks over time.

The extended model conserved land area and total carbon throughout the system for all of the LULUCF scenarios simulated. The full list of model equations, their units, and accompanying comments are documented in the appendix.

3 RESULTS

3.1 BIOENERGY SCENARIO

The behavior of a single pulse of end use bioenergy demand is simulated. This means that enough Forest to provide the appropriate fuel to satisfy the demand – accounting for the fraction of clearance during harvesting, land availability, combustion efficiency, and processing efficiency, each of which are fully interactive variables for rapid testing of assumptions – is harvested and converted to harvested forest. A $10e+9$ GJ end use bioenergy pulse, and its offset of energy generation of a customizable fossil fuel source for which coal was used here, is simulated at time step=0. This simulation also conservatively assumes that the land is thinned with a 0.25 fraction of biomass removed from harvested land by bioenergy harvest.

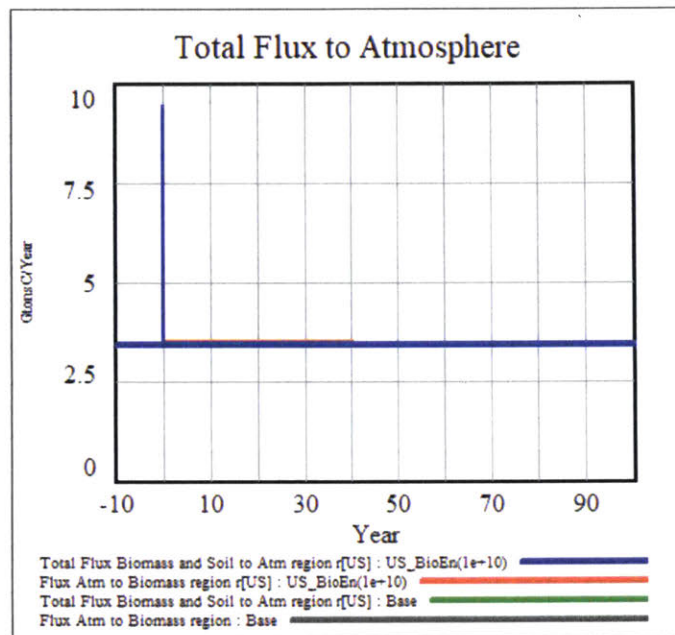


Figure 11. End use bioenergy pulse releases carbon to the atmosphere.
Blue: bioenergy pulse case.

The total flux of carbon into the atmosphere is greater than the base scenario – even when offsetting the combustion of coal – due to lesser combustion and processing efficiencies of wood bioenergy as compared to coal. Wood holds more moisture than does coal, and some of the energy that would have been used to generate useable energy during combustion is immediately dissipated by the evaporation of that moisture (Sterman et al., 2018). Additionally, the processing losses associated with the wood pellet processing and supply chain are greater than those associated with the supply chain of coal (Baruya, Mcculloch, & Ewart, 2012; Röder, Whittaker, & Thornley, 2014).

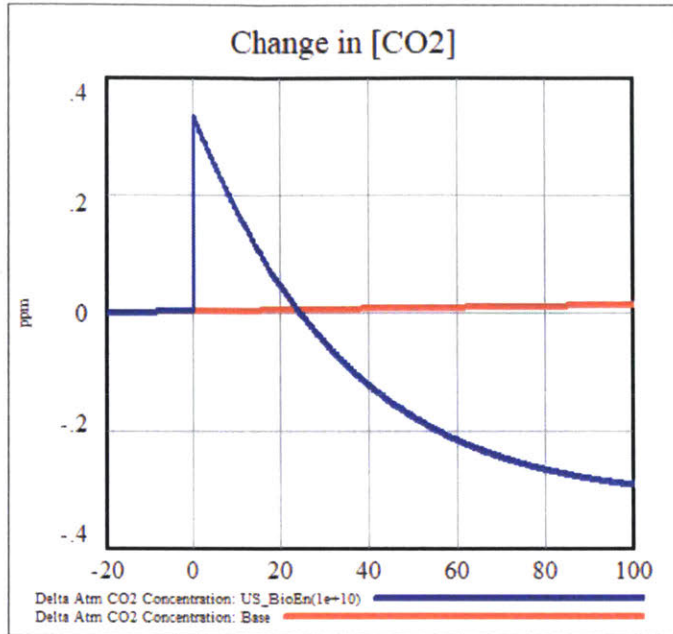


Figure 12. The increased atmospheric concentration of CO₂ decreases over time due to re-sequestration of carbon into growing biomass. Blue: bioenergy pulse case. Red: base case.

As the Harvested Forest regrows to its stable equilibrium, it removes carbon from the atmosphere until the concentration of carbon dioxide in the atmosphere drops below that of the base case after a period of 24 years. This is termed the payback period.

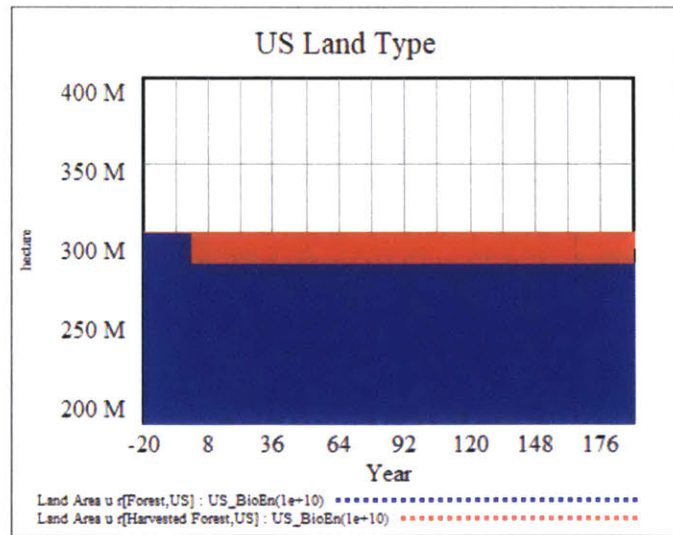


Figure 13. US forest to harvested forest conversion in bioenergy pulse case. Blue: forest area. Red: harvested forest area.

The total land use of during the transition of Forest to Harvested Forest is conserved. (Figure 13)

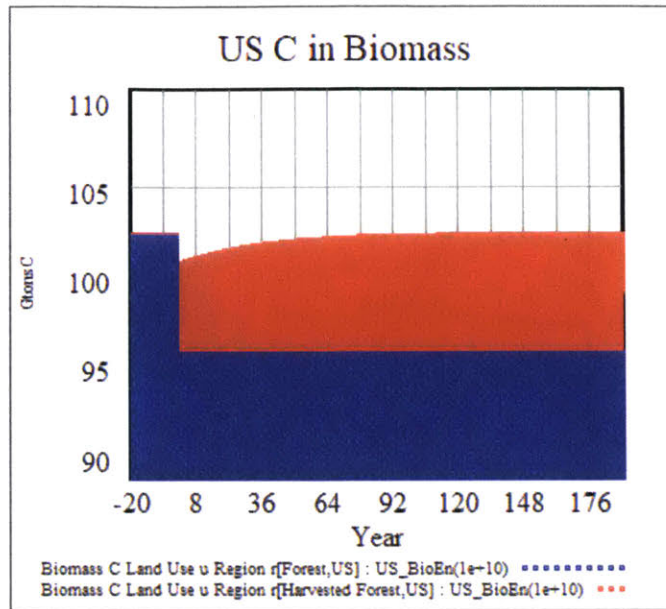


Figure 14. Stacked representation of the carbon stock in forests and harvested forests of the US in bioenergy pulse case. Blue: carbon in forest. Red: carbon in harvested forest.

The Fraction of Biomass Removed for Bioenergy of 0.25 dictates the portion of biomass carbon that was not transferred to the Harvested Forest stock, but was instead released into the atmosphere for bioenergy supply. (Figure 14)

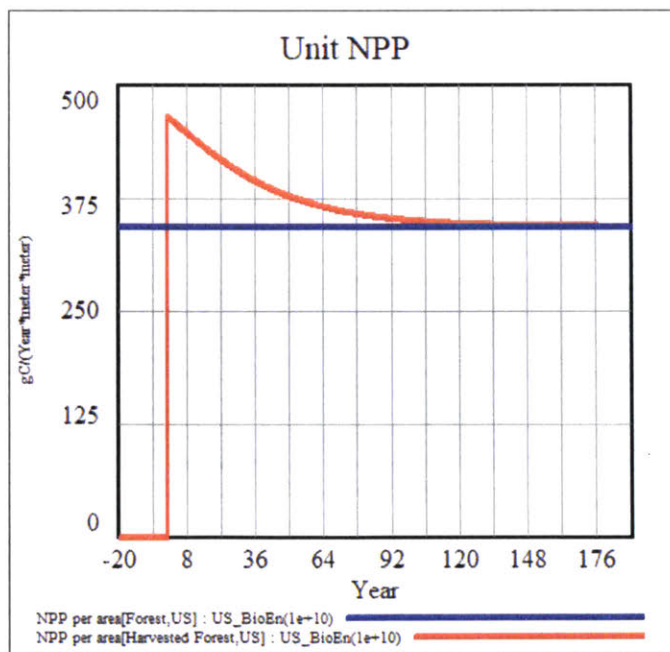


Figure 15. NPP per unit area for bioenergy pulse case. Blue: forest. Red: harvested forest

For low harvest fractions, NPP of the Harvest Forest begins at a higher rate than the steady-state Forest because, as detailed in the Richards formulation in Equation (2), it has room to grow before the approach of the maximum biomass carbon intensity produces a strong enough balancing feedback to reduce the NPP into equilibrium.

3.1.1 Harvest Fraction

Harvest often consists of clear-cutting the grand majority of a forest's biomass down. A fraction of biomass carbon removed from harvested forest for bioenergy of 0.95 was used to simulate the effect of clear-cutting scenarios.

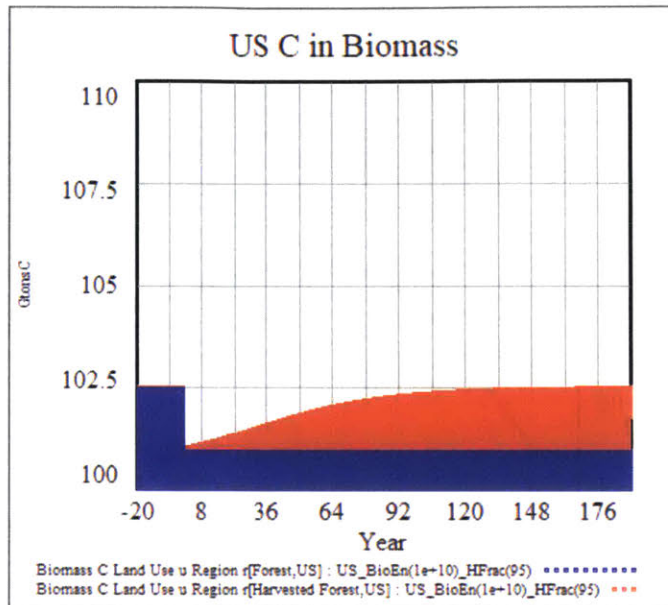


Figure 16 Stacked representation of the carbon stock in forests and harvested forests of the US in bioenergy pulse case with 95% clear-cut. Blue: carbon in forest. Red: carbon in harvested forest.

Both methods release the same amount of carbon at the pulse because the land area is scaled to inversely with harvest fraction to achieve the same end use bioenergy supply. (Figure 14 and Figure 16)

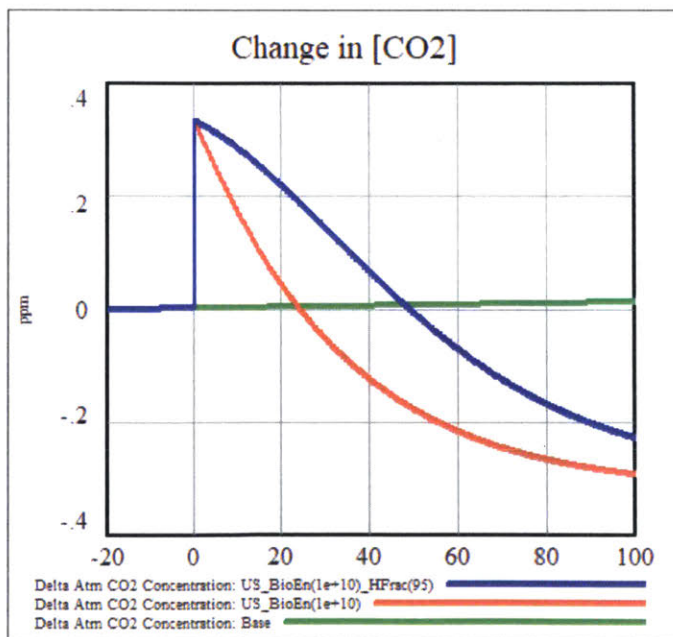


Figure 17. Change in atmospheric CO₂ concentration. Green: base case. Red: harvested forest from thinning (harvest fraction = 0.25) Blue: harvested forest from clear-cut (harvest fraction = 0.95)

However, not only does clear-cutting for bioenergy harvest release carbon into the atmosphere, as thinning also does, but it also takes away its capability to recapture that carbon quickly. The thinned harvested forest has enough biomass left on its land that it exhibits a higher NPP at the outset, allowing it to move towards its equilibrium quickly. Clear-cut land, on the other hand, starts with significantly less biomass carbon intensity with which to reabsorb carbon from the atmosphere. These dynamics can be seen in the second derivatives of atmospheric concentration or the values of unit NPPs of Harvested Forest scenarios. (Figure 17 and Figure 18)

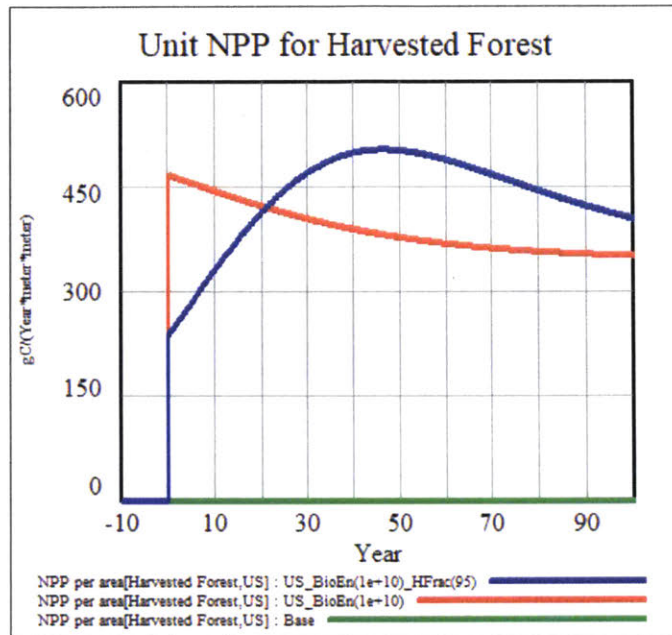


Figure 18. NPP per unit area of harvested forest. Green: base case. Red: thinned. Blue: clear-cut.

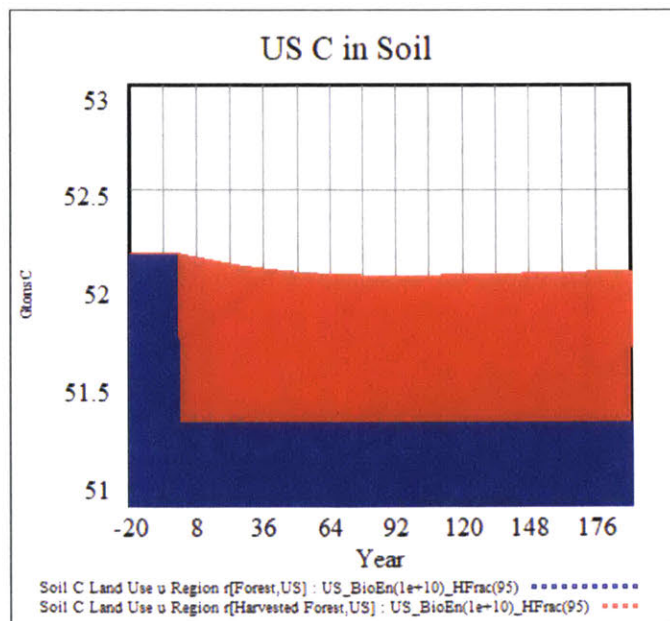


Figure 19. Soil carbon in forest and harvested forest in bioenergy pulse case. Blue: soil carbon in forest. Red: soil carbon in harvested forest.

Forest harvest also has significant effects on the dynamics of soil carbon. (Figure 19.) Upon clear-cutting of a forest, there is no more tree litter providing the input to the stock of soil carbon, yet the soil is still providing outgassing of its current soil carbon. The soil carbon drops in for that converted land until the trees grow back and increasingly provide litter to the soil again.

3.1.2 Harvest Region

The composition of tree types varies significantly across the six C-ROADS regions. As such, regions exhibit different shapes of harvested forest regrowth and produce different patterns of carbon flux between the land and atmosphere.

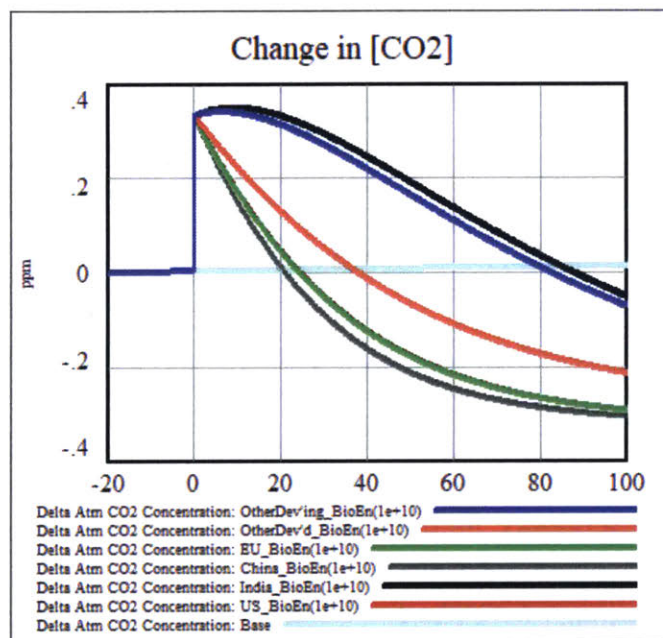


Figure 20. Change in atmospheric carbon concentration from bioenergy provided from forests of different regions. Light blue: base case (no harvest) Brown: US. Black: India. Gray: China. Green: EU. Red: other developed nations. Blue: other developing nations.

The regions with the highest percentage of tropical climate coverage exhibit the longest payback times. For India, clear-cutting a harvested forest results in a modeled payback time of 186 years. The lower end of the range for clear-cut forest was exhibited by China with a payback time of 42 years.

3.2 CONVERSION OF FOREST TO CROPLAND AFTER HARVEST FOR BIOENERGY

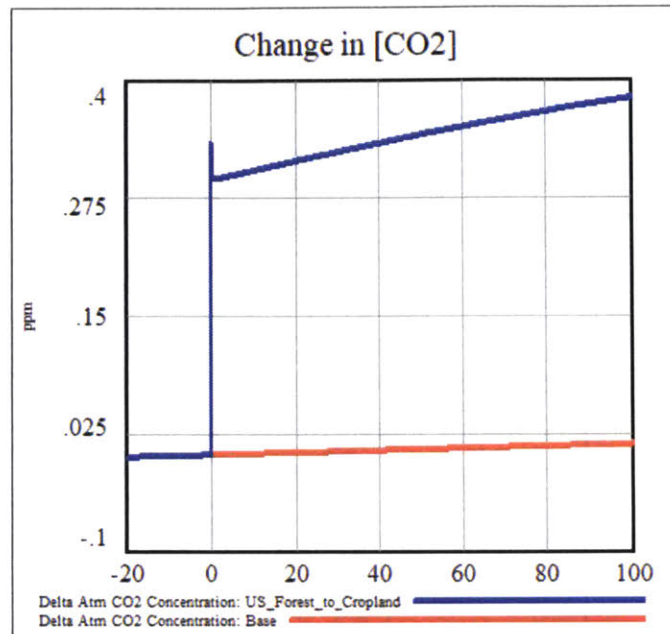


Figure 21. Using land for agriculture after clearcutting for bioenergy precludes the regrowth of sufficient biomass. Blue: forest to cropland conversion after harvest for biomass. Red: base case.

Necessary, but not sufficient, for the logic of carbon-neutrality to apply to wood bioenergy, the harvested forest must be allowed to grow back to its full pre-harvest stand. If it is converted to any other land use, it cannot recapture the carbon it released in new tree growth. Conversion to cropland exhibits a sudden reuptake of a very small fraction of the release carbon due to the modeled fast growth of annual crops on the converted land. (Figure 21.) Nevertheless, the change in atmospheric carbon concentration continues to rise at a greater clip than the base case due to residual soil carbon release.

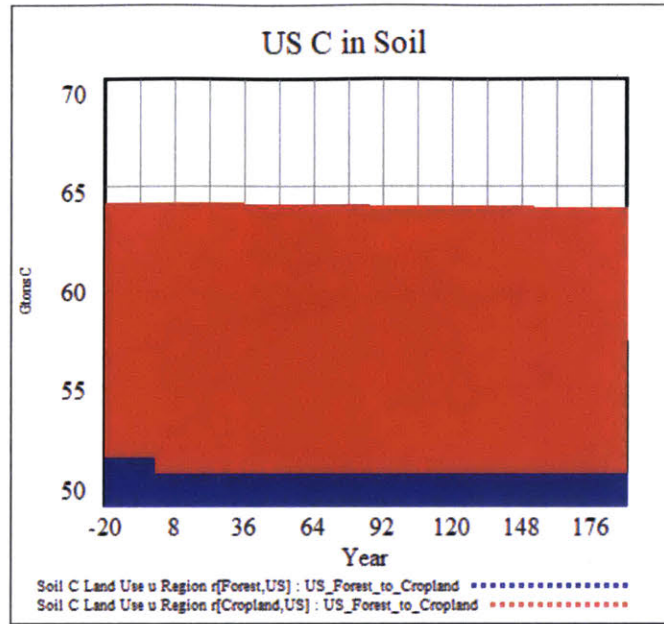


Figure 22. Soil in the converted cropland releases the organic carbon it accumulated as forest soil. Blue: forest soil carbon Red: cropland soil carbon.

3.3 AFFORESTATION

The effect of afforestation on atmospheric carbon concentration varies by region in which it takes place, as well as the land use that is being converted to new forest. The scenarios modeled here represent a linear increase in afforested area, such that a goal area of 10Mha is converted from a chosen land use source is achieved at time step=40, with the afforestation starting at time step=10.

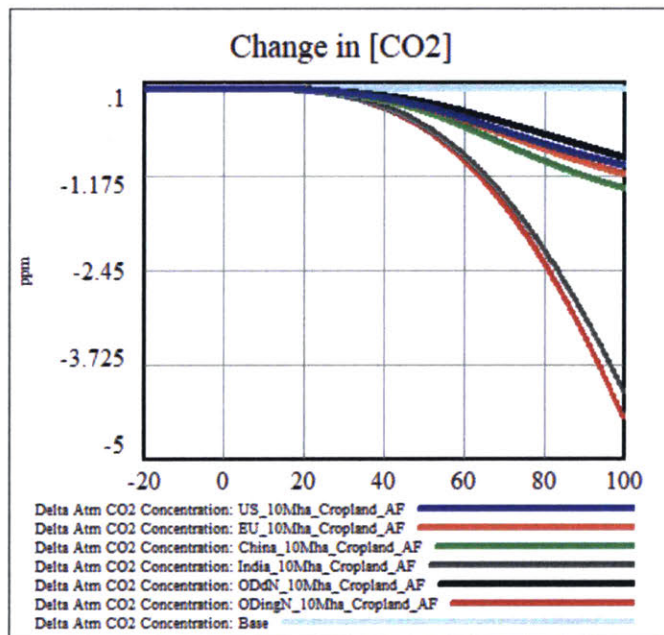


Figure 23. Change in atmospheric carbon concentration due to 10Mha of afforestation from cropland in different regions. Light blue: base case (no harvest). Blue: US. Red: EU. Green: China. Gray: India. Black: other developed nations. Brown: other developing nations.

Afforestation in the regions with the most tropical climate coverage exhibits the greatest downward effect on atmospheric carbon concentration. Additionally, it matters more, from a climate standpoint, where the afforestation occurs as opposed to the land use being replaced. That is to say, the scale of impact that there is a greater difference between forests in different climate regions than there is between the croplands and pastures within a given region.

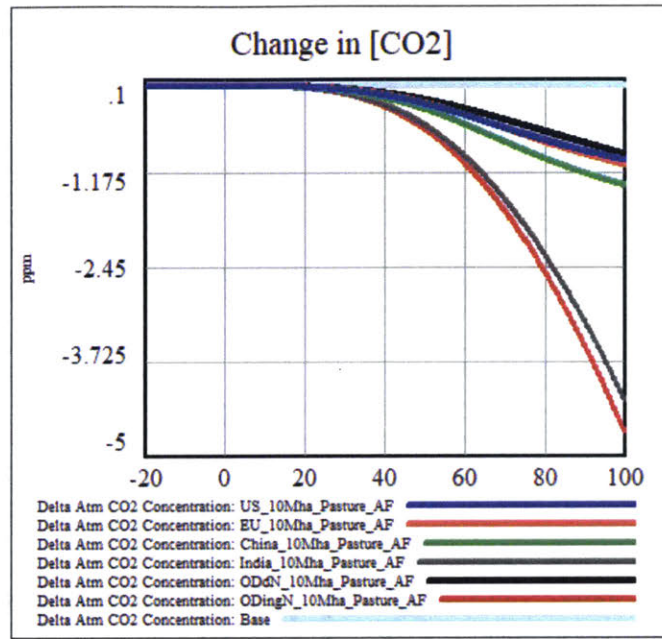


Figure 24. Change in atmospheric carbon concentration due to 10Mha of afforestation from pasture in different regions. Light blue: base case (no harvest). Blue: US. Red: EU. Green: China. Gray: India. Black: other developed nations. Brown: other developing nations.

4 DISCUSSION

This work supports the basic patterns of forest harvest for bioenergy, as well as the conversion of forest to other land use after harvest for bioenergy, identified by Sterman et al (2018). Furthermore, afforestation scenarios using either cropland or pasture for afforestation are observed to have largely similar outcomes. It is apparent from a longitudinal sample across the different scenarios simulated, with India and Other Developing Nations standing out in particular, that the majority climate domain present in each of the regions, which is to say, the type of forest being developed, is a major driver of this behavior.

This emphasizes the criticality of robust forest parameterization. The NPP parameters are extremely sensitive and nonlinear, and may be significantly impacted by the methods by which they are aggregated into climate domains and regions. Examination of different methods of parameter aggregation for retaining the unique nonlinear interactions between the variables is an area of future work. Furthermore, the forest growth profiles gathered from Smith et al. (2006) measured forests grown from seedlings or planting of young trees, whereas the forest growth profiles for tropical forest were constructed from individual tree growth profiles (Köhl et al., 2017) from trees that may or may not have grown in the presence of full tree stands. Environmental conditions of the tropical trees (shade from already grown tree canopies, etc.) may have affected the time it took for the measured trees to reach maturity, and thus affected the resulting parameters.

Other aspects of model parameterization that could be considered further include the data sources used. Values for crop-specific carbon content per unit of dry mass are available (Wolf et al., 2015) and may be used in the place of the single constant used in this research (Monfreda et al., 2008). Updated geospatial ecozone areas are available (Food and Agriculture Organization of the United Nations, 2012a, 2012b). However, corruption of vector geometries in the source file made it unusable for this analysis. Finally, the use of ecozone distribution within countries would provide another level of granularity untapped by the use of the aggregated climatic domains used in this model. However, as with all models, a trade-off must be made between form and function.

The challenge of rectifying land use and land cover definitions is explicitly acknowledged in the literature. Verburg, Neumann, and Nol (2011) explicitly identify the inconsistency between definitions and data selection and handling as particularly challenging. Significant effort was expended in attempt to align as closely as possible the various definitions of the land uses and land covers explored here, aggregating and disaggregating the data in a manner meant to minimize definitional inaccuracies, while conserving total land area. More explicit mapping between land uses and land coverage categories would not only make integrated earth system models more consistent with physical reality, but would also provide a more grounded basis with which to compare different models and facilitate useful communication between the realms of science and policy (Verburg, Neumann, and Nol, 2011). These challenges are no less apparent for land use and land cover change, especially in the context of modeling global carbon flux estimates in integrated earth system models (J Pongratz, Reick, Houghton, & House, 2014). Looking forward, a framework for the definitional mapping of land management practices that take place on single land uses, will become crucial as such land management is increasingly integrated into earth system models (Erb et al., 2017; Julia Pongratz et al., 2018).

5 CONCLUSION

There exist knowledge controversies for countless issues at the contested boundaries between science and policy. Such controversies are particularly difficult to tease apart when they pertain to large and complex socio-technical systems, let alone those that carry with them heavy political, social, and moral ramifications. The debate around wood bioenergy “carbon-neutrality” is one such controversy where lack of knowledge, lack of understanding, and the differences in the definitions of particular boundary objects converge to promote skewed mental models.

This work expands the C-ROADS land use model to incorporate six major land uses within six major global regions. Multiple granular global geospatial data sets were collated to derive a highly disaggregated data set of biomass and soil carbon intensities for land uses across countries and climatic domains. This was used to estimate model parameters pertaining to the carbon fluxes within and between the biosphere and the atmosphere.

While wood bioenergy can eventually result in net atmospheric carbon reduction when displacing coal, the initial increase of atmospheric carbon above that which coal would have produced creates a carbon debt that can take decades to repay, decades during which the increased atmospheric carbon could potentially spur irreversible climate dynamics. Forest harvest for bioenergy exhibited carbon payback times ranging from 20 to 186 years, depending on the region in which the harvest occurred and whether the forest was clear-cut or thinned. This assumes that the harvested forest was allowed to regrow to its full pre-harvest equilibrium state. In scenarios where the forest was converted to cropland after harvest, not only did atmospheric carbon increase permanently from the combustion of the wood, but the flux of carbon from the soil to the atmosphere increased due to the higher fractional rate of carbon flux from soil to atmosphere of cropland soils as opposed to that of forest soils. Afforestation was shown to remove carbon from the atmosphere, and simulations revealed that it was most effective in regions that had more tropical climate coverage.

The globally consistent integrated earth system model presented here enables the explicit dynamics embedded in a range of region specific LULUCF policies to be simulated in real-time and their climatic effects evaluated. As such, this work hopes to facilitate more intelligent climate-related goal setting and a greater appreciation for the unintended consequences of under-informed policy creation.

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7 APPENDIX

7.1 MODEL STRUCTURE

Table S1. Mapping: FAO Country to C-ROADS Regions

FAO Country	China	European Union	India	United States	Other Developed Nations	Other Developing Nations
Afghanistan	0	0	0	0	0	1
Albania	0	0	0	0	1	0
Algeria	0	0	0	0	0	1
American Samoa	0	0	0	0	0	0
Andorra	0	0	0	0	1	0
Angola	0	0	0	0	0	1
Anguilla	0	0	0	0	0	1
Antigua and Barbuda	0	0	0	0	0	1
Argentina	0	0	0	0	0	1
Armenia	0	0	0	0	1	0
Aruba	0	0	0	0	0	1
Australia	0	0	0	0	1	0
Austria	0	1	0	0	0	0
Azerbaijan	0	0	0	0	1	0
Bahamas	0	0	0	0	0	1
Bahrain	0	0	0	0	0	1
Bangladesh	0	0	0	0	0	1
Barbados	0	0	0	0	0	1
Belarus	0	0	0	0	1	0
Belgium	0	1	0	0	0	0
Belize	0	0	0	0	0	1
Benin	0	0	0	0	0	1
Bermuda	0	0	0	0	0	1
Bhutan	0	0	0	0	0	1
Bolivia (Plurinational State of)	0	0	0	0	0	1
Bosnia and Herzegovina	0	0	0	0	1	0
Botswana	0	0	0	0	0	1
Brazil	0	0	0	0	0	1
British Virgin Islands	0	0	0	0	0	1
Brunei Darussalam	0	0	0	0	0	1
Bulgaria	0	1	0	0	0	0
Burkina Faso	0	0	0	0	0	1
Burundi	0	0	0	0	0	1
Cabo Verde	0	0	0	0	0	1

Cambodia	0	0	0	0	0	1
Cameroon	0	0	0	0	0	1
Canada	0	0	0	0	1	0
Cayman Islands	0	0	0	0	0	1
Central African Republic	0	0	0	0	0	1
Chad	0	0	0	0	0	1
Channel Islands	0	1	0	0	0	0
Chile	0	0	0	0	0	1
China, Hong Kong SAR	0	0	0	0	0	1
China, Macao SAR	0	0	0	0	0	1
China, mainland	1	0	0	0	0	0
China, Taiwan Province of	0	0	0	0	0	1
Colombia	0	0	0	0	0	1
Comoros	0	0	0	0	0	1
Congo	0	0	0	0	0	1
Cook Islands	0	0	0	0	1	0
Costa Rica	0	0	0	0	0	1
Côte d'Ivoire	0	0	0	0	0	1
Croatia	0	0	0	0	1	0
Cuba	0	0	0	0	0	1
Cyprus	0	1	0	0	0	0
Czechia	0	1	0	0	0	0
Democratic People's Republic of Korea	0	0	0	0	0	1
Democratic Republic of the Congo	0	0	0	0	0	1
Denmark	0	1	0	0	0	0
Djibouti	0	0	0	0	0	1
Dominica	0	0	0	0	0	1
Dominican Republic	0	0	0	0	0	1
Ecuador	0	0	0	0	0	1
Egypt	0	0	0	0	0	1
El Salvador	0	0	0	0	0	1
Equatorial Guinea	0	0	0	0	0	1
Eritrea	0	0	0	0	0	1
Estonia	0	1	0	0	0	0
Ethiopia	0	0	0	0	0	1
Falkland Islands (Malvinas)	0	0	0	0	0	1
Faroe Islands	0	0	0	0	0	1
Fiji	0	0	0	0	0	1
Finland	0	1	0	0	0	0

France	0	1	0	0	0	0
French Guiana	0	0	0	0	0	1
French Polynesia	0	0	0	0	0	1
Gabon	0	0	0	0	0	1
Gambia	0	0	0	0	0	1
Georgia	0	0	0	0	1	0
Germany	0	1	0	0	0	0
Ghana	0	0	0	0	0	1
Gibraltar	0	0	0	0	0	0
Greece	0	1	0	0	0	0
Greenland	0	0	0	0	1	0
Grenada	0	0	0	0	0	1
Guadeloupe	0	0	0	0	0	1
Guam	0	0	0	0	0	1
Guatemala	0	0	0	0	0	1
Guinea	0	0	0	0	0	1
Guinea-Bissau	0	0	0	0	0	1
Guyana	0	0	0	0	0	1
Haiti	0	0	0	0	0	1
Honduras	0	0	0	0	0	1
Hungary	0	1	0	0	0	0
Iceland	0	1	0	0	0	0
India	0	0	1	0	0	0
Indonesia	0	0	0	0	0	1
Iran (Islamic Republic of)	0	0	0	0	0	1
Iraq	0	0	0	0	0	1
Ireland	0	1	0	0	0	0
Isle of Man	0	1	0	0	0	0
Israel	0	0	0	0	0	1
Italy	0	1	0	0	0	0
Jamaica	0	0	0	0	0	1
Japan	0	0	0	0	1	0
Jordan	0	0	0	0	0	1
Kazakhstan	0	0	0	0	1	0
Kenya	0	0	0	0	0	1
Kiribati	0	0	0	0	0	1
Kuwait	0	0	0	0	0	1
Kyrgyzstan	0	0	0	0	1	0
Lao People's Democratic Republic	0	0	0	0	0	1
Latvia	0	1	0	0	0	0
Lebanon	0	0	0	0	0	1
Lesotho	0	0	0	0	0	1

Liberia	0	0	0	0	0	1
Libya	0	0	0	0	0	1
Liechtenstein	0	0	0	0	1	0
Lithuania	0	1	0	0	0	0
Luxembourg	0	1	0	0	0	0
Madagascar	0	0	0	0	0	1
Malawi	0	0	0	0	0	1
Malaysia	0	0	0	0	0	1
Maldives	0	0	0	0	0	1
Mali	0	0	0	0	0	1
Malta	0	1	0	0	0	0
Marshall Islands	0	0	0	0	0	1
Martinique	0	0	0	0	0	1
Mauritania	0	0	0	0	0	1
Mauritius	0	0	0	0	0	1
Mayotte	0	0	0	0	0	1
Mexico	0	0	0	0	0	1
Micronesia	0	0	0	0	0	1
(Federated States of)						
Mongolia	0	0	0	0	0	1
Montenegro	0	0	0	0	0	1
Montserrat	0	0	0	0	0	1
Morocco	0	0	0	0	0	1
Mozambique	0	0	0	0	0	1
Myanmar	0	0	0	0	0	1
Namibia	0	0	0	0	0	1
Nauru	0	0	0	0	0	1
Nepal	0	0	0	0	0	1
Netherlands	0	1	0	0	0	0
Netherlands Antilles	0	0	0	0	0	1
(former)						
New Caledonia	0	0	0	0	0	0
New Zealand	0	0	0	0	1	0
Nicaragua	0	0	0	0	0	1
Niger	0	0	0	0	0	1
Nigeria	0	0	0	0	0	1
Niue	0	0	0	0	0	1
Norfolk Island	0	0	0	0	0	0
Northern Mariana	0	0	0	0	1	0
Islands						
Norway	0	1	0	0	0	0
Occupied Palestinian	0	0	0	0	0	1
Territory						
Oman	0	0	0	0	0	1
Pakistan	0	0	0	0	0	1

Palau	0	0	0	0	0	1
Panama	0	0	0	0	0	1
Papua New Guinea	0	0	0	0	0	1
Paraguay	0	0	0	0	0	1
Peru	0	0	0	0	0	1
Philippines	0	0	0	0	0	1
Pitcairn Islands	0	0	0	0	0	0
Poland	0	1	0	0	0	0
Portugal	0	1	0	0	0	0
Puerto Rico	0	0	0	0	0	1
Qatar	0	0	0	0	0	1
Republic of Korea	0	0	0	0	1	0
Republic of Moldova	0	0	0	0	0	1
Réunion	0	0	0	0	0	1
Romania	0	1	0	0	0	0
Russian Federation	0	0	0	0	1	0
Rwanda	0	0	0	0	0	1
Saint Helena, Ascension and Tristan da Cunha	0	0	0	0	0	1
Saint Kitts and Nevis	0	0	0	0	0	1
Saint Lucia	0	0	0	0	0	1
Saint Pierre and Miquelon	0	0	0	0	0	1
Saint Vincent and the Grenadines	0	0	0	0	0	1
Samoa	0	0	0	0	0	1
San Marino	0	0	0	0	1	0
Sao Tome and Principe	0	0	0	0	0	1
Saudi Arabia	0	0	0	0	0	1
Senegal	0	0	0	0	0	1
Serbia	0	0	0	0	0	1
Seychelles	0	0	0	0	0	1
Sierra Leone	0	0	0	0	0	1
Singapore	0	0	0	0	0	1
Slovakia	0	1	0	0	0	0
Slovenia	0	0	0	0	1	0
Solomon Islands	0	0	0	0	0	1
Somalia	0	0	0	0	0	1
South Africa	0	0	0	0	0	1
South Sudan	0	0	0	0	0	1
Spain	0	1	0	0	0	0
Sri Lanka	0	0	0	0	0	1
Sudan	0	0	0	0	0	1

Suriname	0	0	0	0	0	1
Swaziland	0	0	0	0	0	1
Sweden	0	1	0	0	0	0
Switzerland	0	1	0	0	0	0
Syrian Arab Republic	0	0	0	0	0	1
Tajikistan	0	0	0	0	1	0
Thailand	0	0	0	0	0	1
The former Yugoslav Republic of Macedonia	0	0	0	0	1	0
Timor-Leste	0	0	0	0	0	1
Togo	0	0	0	0	0	1
Tokelau	0	0	0	0	0	1
Tonga	0	0	0	0	0	1
Trinidad and Tobago	0	0	0	0	0	1
Tunisia	0	0	0	0	0	1
Turkey	0	0	0	0	0	1
Turkmenistan	0	0	0	0	1	0
Turks and Caicos Islands	0	0	0	0	0	1
Tuvalu	0	0	0	0	0	1
Uganda	0	0	0	0	0	1
Ukraine	0	0	0	0	1	0
United Arab Emirates	0	0	0	0	0	1
United Kingdom	0	1	0	0	0	0
United Republic of Tanzania	0	0	0	0	0	1
United States of America	0	0	0	1	0	0
United States Virgin Islands	0	0	0	0	0	1
Uruguay	0	0	0	0	0	1
Uzbekistan	0	0	0	0	1	0
Vanuatu	0	0	0	0	0	1
Venezuela (Bolivarian Republic of)	0	0	0	0	0	1
Viet Nam	0	0	0	0	0	1
Wallis and Futuna Islands	0	0	0	0	0	0
Western Sahara	0	0	0	0	0	1
Yemen	0	0	0	0	0	1
Zambia	0	0	0	0	0	1
Zimbabwe	0	0	0	0	0	1

Table S2. FAO Land Use Definitions (FAOSTAT, 2018)

Item Code	Item	Description
6610	Agricultural area	Agricultural area, this category is the sum of areas under Arable land, Permanent crops and Permanent pastures.
6621	Arable land	Arable land is the land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. Data for Arable land are not meant to indicate the amount of land that is potentially cultivable.
6620	Arable land and Permanent crops	Arable land and Permanent crops, this category is the sum of areas under Arable land and "Permanent crops.
6661	Forest	Forest area is the land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 metres (m) in situ. Areas under reforestation that have not yet reached but are expected to reach a canopy cover of 10 percent and a tree height of 5 m are included, as are temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate. Includes: areas with bamboo and palms provided that height and canopy cover criteria are met; forest roads, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific scientific, historical, cultural or spiritual interest; windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 ha and width of more than 20 m; plantations primarily used for forestry or protective purposes, such as: rubber-wood plantations and cork, oak stands. Excludes: tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems. The term also excludes trees in urban parks and gardens.
6670	Other land	Other land is the land not classified as Agricultural land and Forest area. It includes built-up and related land, barren land, other wooded land, etc.
6717	Other naturally regenerated forest	Naturally regenerated forest where there are clearly visible indications of human activities. Explanatory notes: 1. Includes selectively logged-over areas, areas regenerating following agricultural land use, areas recovering from human-induced fires, etc. 2. Includes forests where it is not possible to distinguish whether planted or naturally regenerated. 3. Includes forests with a mix of naturally regenerated trees and planted/seeded trees, and where the naturally regenerated trees are expected to constitute more than 50 percent of the growing stock at stand maturity.
6650	Permanent crops	Permanent crops is the land cultivated with long-term crops which do not have to be replanted for several years (such as cocoa and coffee); land under trees and shrubs producing flowers, such as roses and jasmine; and nurseries (except

those for forest trees, which should be classified under "forest"). Permanent meadows and pastures are excluded from land under permanent crops.

6655 Permanent meadows and pastures Permanent meadows and pastures is the land used permanently (for a period of five years or more) for herbaceous forage crops, either cultivated or naturally growing. A period of five years or more is used to differentiate between permanent and temporary meadows.

Table S3. Mapping between IPCC Land Use, ESA CCI Land Cover, and GLC2000 Land Cover

The land cover classification system (LCCS) used by the GBCM is the GLC2000 Global Legend from the European Commission (European Commission, 2015). This LCCS was mapped onto that used by the European Space Agency and Climate Change Initiative in their 300m x 300m land cover map using Section 9.2 – LCCS coding of the CCI-LC legend – of their Product User Guide Version 2.0 (Boettcher et al., 2015). This was then mapped to IPCC land uses using Table 3-3 of the same Product User Guide (Boettcher et al., 2015).

IPCC Classes Considered for the Change Detection	LCCS Legend used in the CCI-LC Maps Index	LCCS Legend used in the CCI-LC Maps Description	GLC2000 Global Legend (LCCS) Index	GLC2000 Global Legend (LCCS) Description
Agriculture	10, 11, 12	Rain fed cropland	16	Cultivated and managed areas
Agriculture	20	Irrigated cropland	16	Cultivated and managed areas
Agriculture	30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	16, 17, 18	Cultivated and managed areas
Agriculture	40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	16, 17, 18	Cultivated and managed areas
Forest	50	Tree cover, broadleaved, evergreen, closed to open (>15%)	1	Tree Cover, broadleaved, evergreen
Forest	60, 61, 62	Tree cover, broadleaved, deciduous, closed to open (> 15%)	2, 3	Tree Cover, broadleaved, deciduous, closed / Tree Cover, broadleaved, deciduous, open
Forest	70, 71, 72	Tree cover, needle leaved, evergreen, closed to open (> 15%)	4	Tree Cover, needle-leaved, evergreen
Forest	80, 81, 82	Tree cover, needle leaved, deciduous, closed to open (> 15%)	5	Tree Cover, needle-leaved, deciduous
Forest	90	Tree cover, mixed leaf type (broadleaved and needle leaved)	6	Tree Cover, mixed leaf type
Forest	100	Mosaic tree and shrub (>50%) / herbaceous cover (< 50%)	9	Mosaic: Tree cover/Other natural vegetation
Forest	160	Tree cover, flooded, fresh or brackish water	7	Tree Cover, regularly flooded, fresh water
Forest	170	Tree cover, flooded, saline water	8	Tree Cover, regularly flooded, saline water
Grassland	110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	9	Mosaic: Tree cover/Other natural vegetation
Grassland	130	Grassland	13	Herbaceous Cover, closed-open

Wetland	180	Shrub or herbaceous cover, flooded, fresh-saline or brackish water	15	Regularly flooded Shrub and/or Herbaceous Cover
Settlement	190	Urban	22	Artificial surfaces and associated areas
Other (Shrubland)	120, 121, 122	Shrubland	11,12	Shrub Cover, closed-open, evergreen / Shrub Cover, closed-open, deciduous
Other (Sparse vegetation)	140	Lichens and mosses	14	Sparse Herbaceous or sparse Shrub Cover
Other (Sparse vegetation)	150, 151, 152, 153	Sparse vegetation (tree, shrub, herbaceous cover)	14	Sparse Herbaceous or sparse Shrub Cover
Other (Bare area)	200, 201, 202	Bare areas	19	Bare areas
Other (Water)	210	Water	20	Water Bodies
Other (Snow and Ice)	220	Permanent snow and ice	21	Snow and Ice

Table S4. *FAO Framework for Climatic and Ecological Classification (Simons, 2001)*

EZ Level 1 - Domain	EZ Level 2 – Global Ecological Zone
Tropical	Tropical rain forest
	Tropical moist deciduous forest
	Tropical dry forest
	Tropical shrubland
	Tropical desert
Subtropical	Tropical mountain systems
	Subtropical humid forest
	Subtropical dry forest
	Subtropical steppe
	Subtropical desert
Temperate	Subtropical mountain systems
	Temperate oceanic forest
	Temperate continental forest
	Temperate steppe
	Temperate desert
Boreal	Temperate mountain systems
	Boreal coniferous forest
	Boreal tundra woodland
Polar	Boreal mountain systems
	Polar

7.2 MODEL PARAMETER ESTIMATION

7.2.1 Geospatial Data Sources

All 2-dimensional maps distort the geospatial information in some way. Choice of map projection is critical for preserving the required traits embedded in the geospatial data. For example, Mercator, true direction, and/or equidistant maps are generally used for navigational maps because direction distance are the most important aspects for navigation (ESRI, 2008). All geospatial data used in this work was re-projected onto a Behrmann Equal Area Cylindrical projection, which is a global map projection meant to preserve area values (ESRI, 2008).

7.2.2 Land Use

7.2.2.1 Forest

Table S5. *Mapping: Tree Species from Smith et al. (2006) into FAO Ecological Domains*

Forest Type	Temp.	Bor.	SubT.
NE Aspen birch	1	1	0
NE Maple beech birch	1	0	0
NE Oak hickory	1	0	0
NE Oak pine	1	1	0
NE Spruce balsam fir	1	1	0
NE White red jack pine	1	1	0
NLS Aspen birch	1	1	0
NLS Elm ash cottonwood	1	0	0
NLS Maple beech birch	1	0	0

NLS Oak hickory	1	0	0
NLS Spruce balsam fir	1	1	0
NLS White red jack pine	1	1	0
NPS Elm ash cottonwood	1	0	0
NPS Maple beech birch	1	0	0
NPS Oak hickory	1	0	0
NPS Oak pine	1	1	0
PSW Fir spruce mountain hemlock	1	1	0
PSW Mixed conifer	1	0	0
PSW Western oak	1	0	0
PWE Douglas fir	1	1	0
PWE Fir spruce mountain hemlock	1	1	0
PWE Lodgepole pine	1	1	0
PWE Ponderosa pine	1	1	0
PWW Alder maple	1	0	0
PWW Douglas fir	1	1	0
PWW Douglas fir high productivity and high management intensity	0	0	0
PWW Fir spruce mountain hemlock	1	1	0
PWW Hemlock Sitka spruce	1	1	0
PWW Hemlock Sitka spruce high productivity	0	0	0
RMN Douglas fir	1	0	0
RMN Fir spruce mountain hemlock	1	0	0
RMN Lodgepole pine	1	0	0
RMN Ponderosa pine	1	0	0
RMS Aspen birch	1	0	0
RMS Douglas fir	1	0	0
RMS Fir spruce mountain hemlock	1	0	0
RMS Lodgepole pine	1	0	0
RMS Ponderosa pine	1	0	0
SC Elm ash cottonwood	1	0	1
SC Loblolly shortleaf pine	1	0	1
SC Loblolly shortleaf pine high productivity and management intensity	0	0	0
SC Oak gum cypress	1	0	1
SC Oak hickory	1	0	1
SC Oak pine	1	0	1
SE Loblolly shortleaf pine	1	0	1
SE Loblolly shortleaf pine high productivity and management intensity	0	0	0
SE Longleaf slash pine	1	0	1
SE Longleaf slash pine high productivity and management intensity	0	0	0
SE Oak gum cypress	1	0	1
SE Oak hickory	1	0	1
SE Oak pine	1	0	1

The data embedded within the graphs of Fig. 6 (Köhl et al., 2017), illustrating the kg of carbon accumulated in individual trees by age for three different species of tropical trees (*C. odorata*, *G. glabra*, and *H. courbaril*), were extracted using WebPlotDigitizer x step algorithm with parameters of ΔX Step and Line width set to 1 unit and 5 Px, respectively (Rohatgi, 2018). Due to the fact the image lines overlap and converge at the origin, there are disproportionately fewer algorithmically defined points at lower age values, introducing a bias towards the behavior of carbon accumulation during the later years of their growth. However, this bias should be mitigated by forcing the growth function to travel through the origin. These three data collections were aggregated and averaged to produce one carbon stock per age.

The total biomass carbon per average tropical tree over time was then multiplied by the tree density, for which the average for tropical forests was found produced by averaging the modeled tree densities for the different tropical ecological classes.

Due to the absence of coordinated soil carbon intensity profiles for growing tropical forests, as was the case for the other forest types, several of the parameters were estimated separately and held constant so the other parameters could be optimized. Flux from tropical forest soil to atmosphere ($tC [ha yr]^{-1}$) is taken to be the combined value of soil respiration, R_h , and root respiration, R_r (Malhi, 2012). The fractional flux parameter was then calculated by dividing the flux over the average soil carbon intensity of 0-30cm depth tropical forest soils **Error! Reference source not found.**, constructed using the intersection of the soil polygons and the global ecological zones as opposed to the intersection of the soil polygons and countries. The carbon flux from biomass to atmosphere was calculated as the sum of the average fluxes of VOC production, leaf mass lost to herbivory, leaf mass lost to decomposition, leaching, reproductive losses to consumers, reproduction lost to pre-collection and decomposition (Clark et al., 2017). The carbon flux from biomass to soils was calculated as the sum of the average fluxes of branch-shedding by live trees, twig litterfall (twigs ≤ 1 cm in diameter), leaf litterfall, reproductive litterfall, surface-soil fine-root production (0-30cm), deeper fine-root production (0.3m to depth) and tree mortality carbon loss, which itself was the product of mortality biomass loss (Clark et al., 2017) and the average carbon fraction of aboveground tropical forest biomass (IPCC, 2006). These fluxes were then transformed into fractional fluxes by dividing them by the average of the aboveground live biomass carbon for tropical forests (Clark et al., 2017).

7.2.2.2 Cropland

The constraints and considerations on the choice of κ^{AB} for cropland and pasture is explained in detail in by John D. Sterman (2018):

In general, we find k is small for the managed plantations because they exhibit s-shaped curves for the growth over time from “planting” or seedlings. And in general, we find larger k 's for the unmanaged hardwoods that show more linear growth followed by the asymptotic slowdown as they reach maturity (as for e.g. oak, hickory, maple, etc.)...

For pasture and cropland, we have $NPP = k(B^ - B)$. But we also know that k is large (compared to forests) and large enough so that B goes to equilibrium quickly relative to a single year. Indeed, some crops have multiple plantings and harvests each year, which tells us that $k > 1/\text{year}$. Indeed, since a first-order negative feedback such as $NPP = k(B^* - B)$ will reach 95% of the equilibrium value by $t = 3/k$, then a crop that is grown once per year will have $k > 3$, and one with 2 harvests/year will have $k > 6$. In practice, this means that B will be in equilibrium essentially all the time. And since B^* is not observed, only the actual B , which will be close to equilibrium all the time, k and B^* don't matter: only the resulting B .*

Furthermore, the time step in C-ROADS is 0.25 year, which means the largest value of k we can use is $1/\text{time step} = 4$. So we can probably set $k = 3$ and then solve for B^* . (having $1/k < \text{time step}$ prevents integration error that might creep in if there is full adjustment in a single time step).

In fact, with such rapid growth, could assume that the growth and harvest process are always equal, so that $NPP = a \text{ constant}$. That is, we don't care that, say, wheat is planted in month x , track its growth through the harvest in month y , and treat the harvest as a Dirac delta function (pulse). We can assume constant growth and constant harvest (though we do need to ensure robustness so that if fluxes BA and BS change, and therefore equilibrium B changes, we capture how NPP and H change).

Table S6. IPCC Annual Emission Factors (EF) for Cultivated Organic Soils with FAO Mapping (IPCC, 2006)

Climatic Temperature Regime	FAO Ecological Domain Used	IPCC default (tC [ha yr] ⁻¹)	Error
Boreal / Cool Temperate	Boreal	5	"+-90%"
Warm Temperate	Temperate	10	"+-90%"
Tropical / Sub-Tropical	Tropical and Subtropical	20	"+-90%"

7.2.2.3 Pasture

Table S7. IPCC Annual Emission Factors (EF) for Drained Grassland and Organic Soils with FAO Mapping (IPCC, 2006)

Climatic temperature regime	FAO Ecological Domain Used	IPCC default (tC [ha yr] ⁻¹)	Error
Boreal / Cool Temperate	Boreal	0.25	"+-90%"
Warm Temperate	Temperate	2.5	"+-90%"
Tropical / Sub-Tropical	Tropical and Subtropical	5	"+-90%"

7.3 MODEL VALIDATION

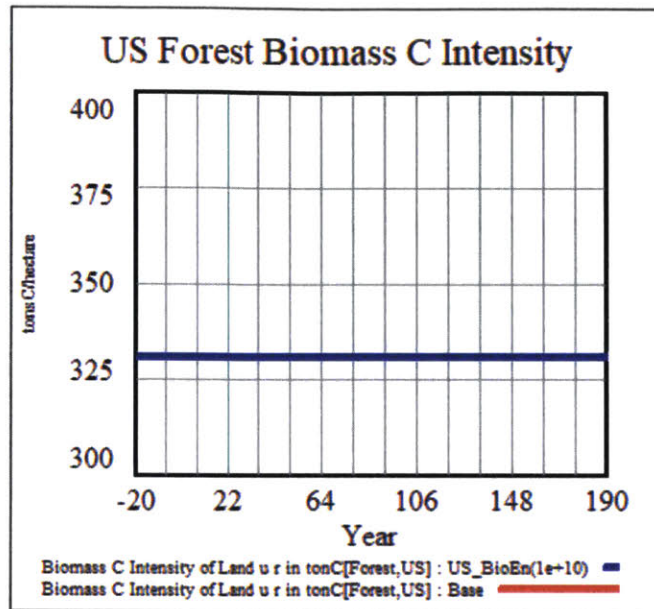


Figure S1. US forest biomass carbon intensity remains unchanged through bioenergy pulse.
Red: Base case. Blue: Bioenergy pulse case.

The area of forest harvested for bioenergy is converted to harvested forest. Thus, the fraction of biomass carbon removed by bioenergy harvest has no effect on the remaining forest, but only the harvested forest.

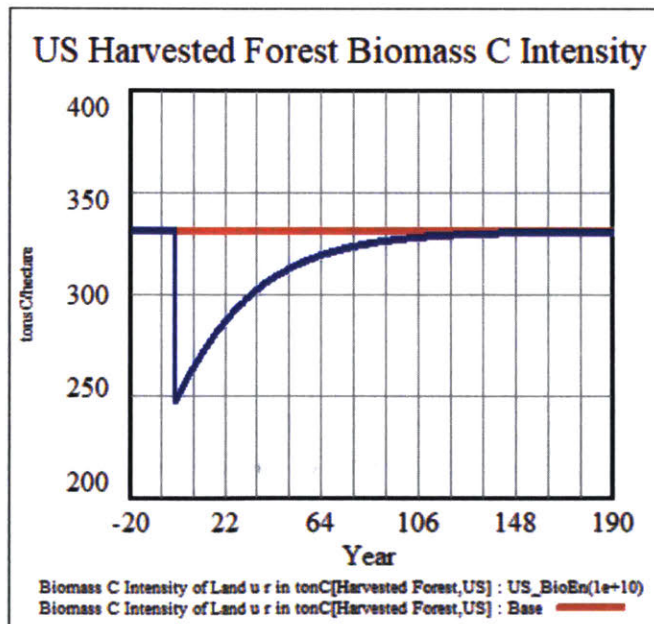


Figure S2. Harvested forest biomass carbon intensity.
Red: base case. Blue: bioenergy pulse case.

In the bioenergy pulse scenario Harvested Forest comes into existence at time zero with a lower Biomass Carbon Intensity than general US Harvested Forest because a fraction of its biomass has been removed by bioenergy harvest. The harvested fraction of the Harvested Forest then grows back overtime until it approaches its steady state Biomass Carbon Intensity.

7.4 MODEL DOCUMENTATION

.Control

Simulation Control Parameters

- (001) FINAL TIME = 2200
Units: Year
The final time for the simulation.
- (002) INITIAL TIME = 1990
Units: Year
The initial time for the simulation.
- (003) SAVEPER = TIME STEP
Units: Year [0,?]
The frequency with which output is stored.
- (004) TIME STEP = 0.25
Units: Year [0,?]
The time step for the simulation.
- *****
- .mdl
- *****
- (005) "100 percent" = 100
Units: percent
- (006) "20 years" = 20
Units: Years
- (007) AF Pulse Duration[Land use,region] = TIME STEP
Units: Year
Duration of pulse in biomass end use production. Set to time step for the numerical integration.
- (008) AF Pulse End Time[Land use,region] = 2500
Units: Year
The year repeated harvesting of land for bioenergy ends
- (009) AF Pulse Repeat Time[Land use,region] = 1000
Units: Year
The interval for repeated harvest of land for bioenergy.
- (010) All but forest and cropland : Harvested Forest,Pasture,Permafrost,Other
- (011) Atm Conc CO2 = C in Atmosphere * ppm CO2 per GtonC
Units: ppm
Converts weight of CO2 in atmosphere (GtonsC) to concentration (ppm CO2)
- (012) Atmospheric CO2 Law Dome = 284.7
Units: ppm
- (013) Average Residence Time for C in Structures u[Land use] = 20, 1, 1, 1, 1, 1
Units: Years

The average residence time of the C in biomass of each type contained in structures (the average time between construction and release to the atmosphere).

(014) Bioenergy C Intensity u[Land use] = 0.027, 0, 0, 0, 0, 0
Units: GtonsC/EJ [0,1,0.01]

Carbon intensity of biofuels produced on each type of land. a. Leturcq (2014), Table 1: 1.16 tC/toe, converted at 41.868 GJ/toe (<https://www.iea.org/statistics/resources/unitconverter/>) = 0.028 tC/GJ. b. EPA (2014): https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf, Table 1 Stationary Combustion Emissions Factors for Wood and Wood Residuals. Emission Factors for Greenhouse Gas Inventories: 93.80 kgCO₂/ mmBTU for for Wood and Wood Residuals and 106 kgCO₂/ mmBTU for Solid byproducts. Average = (93.8 kgCO₂/mmBTU + 105.5 kgCO₂/ mmBTU)/2 = 99.7 kgCO₂/ mmBTU 99.7 kgCO₂/ mmBTU * 0.9478 mmBTU /GJ / 1000 kgCO₂/ tCO₂ /(44/12) tC/tCO₂ = 0.026 tC/GJ Average of EIA and Leturcq estimates: 0.027 tC/GJ

(015) Bioenergy C Intensity u in tonC[Land use] = Bioenergy C Intensity u[Land use] * tonsC per GtonsC
Units: tonsC/EJ [0,1,0.01]

Carbon intensity of biofuels produced on each type of land. Forest: Calculated from LHV of 18.5 MJ/kg and assuming CO₂ = 50% of weight. LHV from Emission Factors for Greenhouse Gas Inventories 2014 (https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf). Conversion Factors for Bioenergy, ORNL. (<https://content.ces.ncsu.edu/conversion-factors-for-bioenergy>). JEC - Joint Research Centre-EUCAR-CONCAWE collaboration (<http://iet.jrc.ec.europa.eu/about-jec/downloads>)for Wood pellets - CHP, assumes 30% moisture for feedstock and 6% sawdust Also Letdurcq (2012), for wood burning (converted from 1.16 tC/toe = 2.77e-2 Gt/EJ) Shulze et al (2012), (calculated from global C flux per year and energy equivalent per year = 2.63e-2 GtC/EJ)

(016) Bioenergy C Intensity u in tonCAF[Land use] = Bioenergy C Intensity uAF[Land use] * tonsC per GtonsC
Units: tonsC/EJ [0,1,0.01]

Carbon intensity of biofuels produced on each type of land. Forest: Calculated from LHV of 18.5 MJ/kg and assuming CO₂ = 50% of weight. LHV from Emission Factors for Greenhouse Gas Inventories 2014 (https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf). Conversion Factors for Bioenergy, ORNL. (<https://content.ces.ncsu.edu/conversion-factors-for-bioenergy>). JEC - Joint Research Centre-EUCAR-CONCAWE collaboration (<http://iet.jrc.ec.europa.eu/about-jec/downloads>)for Wood pellets - CHP, assumes 30% moisture for feedstock and 6% sawdust Also Letdurcq (2012), for wood burning (converted from 1.16 tC/toe = 2.77e-2 Gt/EJ) Shulze et al (2012), (calculated from global C flux per year and energy equivalent per year = 2.63e-2 GtC/EJ)

(017) Bioenergy C Intensity uAF[Land use] = 0.027, 0, 0, 0, 0, 0
Units: GtonsC/EJ [0,1,0.01]

Carbon intensity of biofuels produced on each type of land. a. Leturcq (2014), Table 1: 1.16 tC/toe, converted at 41.868 GJ/toe (<https://www.iea.org/statistics/resources/unitconverter/>) = 0.028 tC/GJ. b. EPA (2014): https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf, Table 1 Stationary Combustion Emissions Factors for Wood and Wood Residuals. Emission Factors for Greenhouse Gas Inventories: 93.80 kgCO₂/ mmBTU for for Wood and Wood Residuals and 106 kgCO₂/ mmBTU for Solid byproducts. Average = (93.8 kgCO₂/mmBTU + 105.5 kgCO₂/ mmBTU)/2 = 99.7 kgCO₂/ mmBTU 99.7 kgCO₂/ mmBTU * 0.9478 mmBTU /GJ / 1000 kgCO₂/ tCO₂ /(44/12) tC/tCO₂ = 0.026 tC/GJ Average of EIA and Leturcq estimates: 0.027 tC/GJ

(018) Bioenergy End Use Scenario[Land use,region] = IF THEN ELSE (Switch for Global Land Use Demand , Global Bioenergy End Use Table (Time) * GJ per TWh * Fraction of global forest r[region] , GJ per EJ * Bioenergy End Use Table (Time))
Units: GJ/Year

An exogenously specified scenario for growth in end-use energy from biofuels. Specified as a look-up table.

(019) Bioenergy End Use ScenarioAF[Land use,region] = IF THEN ELSE (Switch for Global Land Use DemandAF , Global Bioenergy End Use TableAF (Time) * GJ per TWhAF , GJ per EJ * Bioenergy End Use TableAF (Time))

Units: GJ/Year

An exogenously specified scenario for growth in end-use energy from biofuels. Specified as a look-up table.

(020) Bioenergy End Use Table ([(1990,0)-(2200,4)],(1990,0),(2016,0.028),(2050,0.28),(2100,0.65),(2200,1.39))

Units: EJ/Year

Look up table for exogenous growth in end-use energy from biofuels.

(021) Bioenergy End Use TableAF ([(1990,0)-(2200,4)],(1990,0),(2016,0.028),(2050,0.28),(2100,0.65),(2200,1.39))

Units: EJ/Year

Look up table for exogenous growth in end-use energy from biofuels.

(022) Biomass C in Structures u r[Land use,region] = INTEG(Flux Biomass C to Structures u r[Land use,region] - Flux C in Structures to Atm u r[Land use,region] , Initial C in Structures[Land use,region])

Units: GtonsC

The stock of C from biomass contained in human structures (e.g., wood products).

(023) Biomass C Intensity of Land u r[Land use,region] = xidz (Biomass C Land Use u Region r[Land use,region] , Land Area u r[Land use,region] , Initial biomass intensity[Land use,region] / tonsC per GtonsC)

Units: GtonsC/hectare

The average carbon intensity of biomass for each land use and region.

(024) Biomass C Intensity of Land u r in tonC[Land use,region] = Biomass C Intensity of Land u r[Land use,region] * tonsC per GtonsC

Units: tonsC/hectare

The average carbon intensity of biomass for each land use, u, and region, r, presented in tonsC per hectare.

(025) Biomass C Land Use u Region r[Land use,region] = INTEG(Biomass C Transferred from Other Land u r[Land use,region] + Flux from atm to biomass C for Land u r[Land use,region] - Biomass C Transferred to Other Land u r[Land use,region] - Biomass to Soil C Land Use u r[Land use,region] - Flux Biomass C to CH4 Land u r[Land use,region] - Flux Biomass C to Structures u r[Land use,region] - Flux to Atm from Biomass C Land u r[Land use,region] , Initial biomass intensity[Land use,region] * Land Area u r[Land use,region] / tonsC per GtonsC)

Units: GtonsC

The carbon in biomass for each land use and region.

(026) Biomass C Transferred from Natural Processes to Other Land u r[Land use,region] = sum (Fractional Increase in Area from Natural Processes u[Land use!,Land use] * Transfer of Biomass C from Natural Processes from u r[Land use!,region])

Units: GtonsC/Year

The C in biomass lost from each land type j adds to each type i according to the fraction of biomass loss moving from each land type j to i.

(027) Biomass C Transferred from AF to Other Land u r[Land use,region] = sum (Fractional Increase from AF in Area from Land Use Change u[Land use!,Land use] * Transfer of Biomass C from AF from u r[Land use!,region])

Units: GtonsC/Year

When land is afforested, the biomass on that land is transferred from the source land category to the forest category.

(028) Biomass C Transferred from Bioenergy Harvest $u r[\text{Land use,region}] = \text{sum} (\text{Fractional Increase in Area from Bioenergy Production } u[\text{Land use}',\text{Land use}] * \text{Biomass C Transferred to Other Land } u r \text{ from Bioenergy}[\text{Land use}',\text{region}])$

Units: GtonsC/Year

When land is harvested for bioenergy, a fraction of the carbon in the biomass on that land is harvested. The remainder is transferred from the source land type to the harvested category. The total C affected by the harvest is the C used for bioenergy + C remaining on the harvested land, or $\text{Total C} * \text{Fraction Removed} + \text{Total C} * (1 - \text{Fraction Removed}) \rightarrow \text{Total C} = \text{C Removed for bioenergy} / \text{Fraction Removed} \rightarrow \text{Biomass transferred into the harvested category} = (1 - \text{Fraction Removed}) * \text{C removed for bioenergy from harvested} / \text{Fraction Removed}$.

(029) Biomass C Transferred From Human Activity to Other Land $u r[\text{Land use,region}] = \text{sum} (\text{Fractional Increase in Area from Land Use Change } u[\text{Land use}',\text{Land use}] * \text{Transfer of Biomass C from Human Activity from } u r[\text{Land use}',\text{region}])$

Units: GtonsC/Year

The C in biomass lost from each land type j adds to each type i according to the fraction of biomass loss moving from each land type j to i.

(030) Biomass C Transferred from Other Land $u r[\text{Land use,region}] = \text{Biomass C Transferred from Natural Processes to Other Land } u r[\text{Land use,region}] + \text{Biomass C Transferred From Human Activity to Other Land } u r[\text{Land use,region}] + \text{Biomass C Transferred from Bioenergy Harvest } u r[\text{Land use,region}] + \text{Biomass C Transferred from AF to Other Land } u r[\text{Land use,region}]$

Units: GtonsC/Year

For each region, the total biomass carbon added to each land use type from land use change is the sum of the increase from natural processes and human activity, including land that is transferred to the clear cut category and land that is newly afforested.

(031) Biomass C Transferred to Other Land $u r[\text{Land use,region}] = \text{Biomass C Intensity of Land } u r[\text{Land use,region}] * \text{Decrease in Land Area } u r[\text{Land use,region}] - \text{C in Biomass Removed by Land Use Change } u r[\text{Land use,region}] - \text{C from Bioenergy } u r[\text{Land use,region}]$

Units: GtonsC/Year

When land changes from one type to another the C in biomass on that land is transferred out of that category in proportion to the average C in biomass per hectare on that land type. When land is harvested for bioenergy or changes use as a result of human activity, the C emitted is deducted from the flux of C transferred to other land use types.

(032) Biomass C Transferred to Other Land $u r \text{ from Bioenergy}[\text{Land use,region}] = \text{Biomass C Intensity of Land } u r[\text{Land use,region}] * \text{Land Harvested for Bioenergy } u r[\text{Land use,region}] - \text{C from Bioenergy } u r[\text{Land use,region}]$

Units: GtonsC/Year

The amount of carbon left in the biomass remaining on the land after harvest.

(033) Biomass Combustion Efficiency $u[\text{Land use}] = 0.25$

Units: Dmnl [0,1,0.01]

The efficiency of combustion for biofuels produced on each land type. a. Netherlands Enterprise Agency (2011), <https://www.rvo.nl/file/1252>. "CO2-tool electricity gas and heat from biomass - version 1.0.1" 022317. Tool developed by Ecofys by order of Netherlands Enterprise Agency, Ministry of Economic Affairs, Agriculture and Innovation. Tab "Wood pellets – CHP", Conversion efficiency to electricity (Cell H12) = 25.4%. b. US Forest Service (2004). "Wood Biomass for Energy",

<https://www.fpl.fs.fed.us/documnts/techline/wood-biomass-for-energy.pdf>, p. 3:

Efficiency for wood-fired electric generation plants: 18-24% for utilities, 20-25 for industrial plants.

(034) Biomass Combustion Efficiency $u_{AF}[\text{Land use}] = 0.25$

Units: Dmnl [0,1,0.01]

The efficiency of combustion for biofuels produced on each land type. a. Netherlands Enterprise Agency (2011), <https://www.rvo.nl/file/1252>. "CO2-tool electricity gas and heat from biomass - version 1.0.1" 022317. Tool developed by Ecofys by order of Netherlands Enterprise Agency, Ministry of Economic Affairs,

Agriculture and Innovation. Tab “Wood pellets – CHP”, Conversion efficiency to electricity (Cell H12) = 25.4%. b. US Forest Service (2004). “Wood Biomass for Energy”, <https://www.fpl.fs.fed.us/documnts/techline/wood-biomass-for-energy.pdf>, p. 3: Efficiency for wood-fired electric generation plants: 18-24% for utilities, 20-25 for industrial plants.

(035) Biomass Processing Efficiency $u[\text{Land use}] = 0.725$
Units: Dmnl

The efficiency of the bioenergy supply chain (from harvest to point of combustion). Röder, Whittaker, Thornley (2015), Table 1. Value of .725 uses data for wood sourced from forest waste, assumes wood biomass used for pellet drying instead of diesel.

(036) Biomass Processing Efficiency $u_{AF}[\text{Land use}] = 0.725$
Units: Dmnl

The efficiency of the bioenergy supply chain (from harvest to point of combustion). Röder, Whittaker, Thornley (2015), Table 1. Value of .725 uses data for wood sourced from forest waste, assumes wood biomass used for pellet drying instead of diesel.

(037) Biomass Supply Chain C Intensity $u[\text{Land use}] = 0.0012$
Units: GtonsC/EJ

The carbon intensity of the energy used in the bioenergy supply chain. Source: Röder, Whittaker, Thornley (2015), Table 1. Assumes biomass used for pellet drying instead of diesel. Assumes average ship capacity of 35K DWT for pellet transit from US to UK.

(038) Biomass to Soil C Land Use $u_r[\text{Land use,region}] = \text{Switch for Active Soil C Fluxes}[\text{Land use}] * \text{Biomass C Land Use u Region } r[\text{Land use,region}] * \text{Fractional Rate of Biomass Transfer to Soils } u_r[\text{Land use,region}]$
Units: GtonsC/Year

The annual net flux of carbon from the biomass to the soil in each land use and region. Depends on the stock of biomass and the time constant for C transfer from biomass to soils.

(039) Biostim coeff = INITIAL(Biostim coeff index * Biostim coeff mean)
Units: Dmnl

Coefficient for response of primary production to carbon concentration.

(040) Biostim coeff index = 1
Units: Dmnl [0.6,1.7,0.05]

Index of coefficient for response of primary production to carbon concentration, as multiplying factor of the mean value.

(041) Biostim coeff mean = 0.42
Units: Dmnl [0.3,0.7]

Mean coefficient for response of primary production to CO₂ concentration. Reflects the increase in NPP with doubling the CO₂ level. Goudriaan and Ketner, 1984; Rotmans, 1990

(042) bottom : layer4
Bottom ocean layer

(043) Buff C Coeff = 3.92
Units: Dmnl

Coefficient of CO₂ concentration influence on buffer factor.

(044) Buffer Factor = ACTIVE INITIAL(Ref Buffer Factor * (C in Mixed Layer / Preind C in Mixed Layer) ^ Buff C Coeff , Ref Buffer Factor)
Units: Dmnl

Buffer factor for atmosphere/mixed ocean carbon equilibration.

- (045) $C \text{ debt repayment flag} = \text{IF THEN ELSE} (\text{Year} > 0 \text{ :AND: Change in Atm CO}_2 < 0 \text{ :AND: Carbon Debt Repayment Year} = 0, \text{Year}, 0) / \text{TIME STEP}$
 Units: 1
 Records the year in which the C debt is repaid
- (046) $C \text{ Emissions from Bioenergy} = \text{sum} (C \text{ Emissions from Bioenergy from Land Type } u[\text{Land use!}])$
 Units: GtonsC/Year
 Total global emissions of CO₂ (GtC/year) from bioenergy.
- (047) $C \text{ Emissions from Bioenergy from Land Type } u[\text{Land use}] = \text{sum} (C \text{ from Bioenergy } u r[\text{Land use,region!}])$
 Units: GtonsC/Year
 Global emissions of CO₂ from bioenergy, by land use type.
- (048) $C \text{ Emissions from Bioenergy Region } r[\text{region}] = \text{sum} (C \text{ from Bioenergy } u r[\text{Land use!,region}])$
 Units: GtonsC/Year
 Global emissions of CO₂ from bioenergy by region.
- (049) $C \text{ from Bioenergy } u r[\text{Land use,region}] = \text{Fraction of Indicated Land for Bioenergy Harvested } u r[\text{Land use,region}] * \text{Indicated C from Bioenergy } u r[\text{Land use,region}] / \text{tonsC per GtonsC}$
 Units: GtonsC/Year
 Total carbon from bioenergy is the sum of the carbon released from thinning and harvested operations.
- (050) $C \text{ from CH}_4 \text{ Oxidation} = \text{CH}_4 \text{ Uptake} / \text{CH}_4 \text{ per C} / \text{MtonsC per GtonsC}$
 Units: GtonsC/Year
 Flux of C into the atmosphere from the oxidation of CH₄, the mode of removal of CH₄ from atmosphere.
- (051) $C \text{ in Atm} = C \text{ in Atmosphere}$
 Units: GtonsC
 Initial C in the atmosphere used to calculate initial equilibrium conditions.
- (052) $C \text{ in Atmosphere} = \text{INTEG}(C \text{ from CH}_4 \text{ Oxidation} + \text{Emiss from Storage} + \text{Flux C from permafrost release} + \text{Global C Anthro Emissions} - \text{Flux Atm to Ocean} - \text{Total Net Flux to Land Sink} - \text{Total C removal}, \text{Init C in Atmosphere})$
 Units: GtonsC
 Carbon in atmosphere
- (053) $C \text{ in Biomass Released to Atm by Land Use Change } u r[\text{Land use,region}] = \text{Fraction of C in Biomass Harvest Released to Atm } u[\text{Land use}] * C \text{ in Biomass Removed by Land Use Change } u r[\text{Land use,region}]$
 Units: GtonsC/Year
 Land use change resulting from human activity removes some of the C in biomass on that land type, in proportion to the C intensity of biomass on that land type.
- (054) $C \text{ in Biomass Removed by Land Use Change } u r[\text{Land use,region}] = \text{Fraction of Biomass C released from Land Use Change } u[\text{Land use}] * \text{Decrease in Land Area from Human Land Use Change } u r[\text{Land use,region}] * \text{Biomass C Intensity of Land } u r[\text{Land use,region}]$
 Units: GtonsC/Year
 Land use change resulting from human activity removes some of the C in biomass on that land type, in proportion to the C intensity of biomass on that land type.
- (055) $C \text{ in Biomass to Atm from Land } u r[\text{Land use,region}] = \text{Switch for Zero C Flux Other Than Land Use Change} * \text{Biomass C Land Use } u \text{ Region } r[\text{Land use,region}] * \text{Fractional Rate of Biomass Released to Atm } u r[\text{Land use,region}]$
 Units: GtonsC/Year

For each region, the flux of C from biomass in land of each type entering the atmosphere as CO2 due to fire and microbial/fungal respiration.

(056) C in Deep Ocean[upper] = INTEG(Diffusion Flux[upper] - Diffusion Flux[lower] , Init C in Deep Ocean per meter[upper] * Layer Depth[upper])

C in Deep Ocean[bottom] = INTEG(Diffusion Flux[bottom] , Init C in Deep Ocean per meter[bottom] * Layer Depth[bottom])

Units: GtonsC

Carbon in deep ocean.

(057) C in Deep Ocean per Meter[layers] = C in Deep Ocean[layers] / Layer Depth[layers]

Units: GtonsC/meter

Concentration of carbon in ocean layers.

(058) C in Mixed Layer = INTEG(Flux Atm to Ocean - Diffusion Flux[layer1] , Init C in Mixed Ocean per meter * Mixed Depth)

Units: GtonsC

Carbon in mixed layer.

(059) C in Mixed Layer per Meter = C in Mixed Layer / Mixed Depth

Units: GtonsC/meter

Carbon in mixed layer of ocean per meter (vertical).

(060) C in Soil Released to Atm by Land Use Change u r[Land use,region] = Fraction of Soil C to Atm from Land Use Change u[Land use] * Decrease in Land Area u r[Land use,region] * Soil C Intensity of Land Use u r[Land use,region]

Units: GtonsC/Year

The fraction of the C in soil on each land type that is lost to the atmosphere as CO2 when that land type is converted to other uses.

(061) C in Soil to Atm from Respiration Land u r[Land use,region] = Fractional Rate of Soil C Released to Atm u r[Land use,region] * Soil C Land Use u Region r[Land use,region]

Units: GtonsC/Year

For each region, the flux of C from soil C in land of each type entering the atmosphere as CO2 due to fire and microbial/fungal respiration.

(062) C Sequestered = INTEG(Total C removal - Emiss from Storage , Init C Sequestered)

Units: GtonsC

C sequestered geologically (from, e.g., CCS). Does not include C "sequestered" in biomass, soils, or ocean.

(063) Carbon Debt Repayment Year = INTEG(C debt repayment flag , 0)

Units: Year

Records the year in which the C debt is repaid.

(064) CH4 per C == 1.33

Units: Mtons/MtonsC

Molar mass ratio of CH4 to C, 16/12

(065) CH4 Uptake = 0

Units: Mtons/Year

CH4 emissions set to zero for testing purposes.

(066) Change in Atm CO2 = Atm Conc CO2 - Initial Atm Conc CO2

Units: ppm

Difference between current and initial CO2 concentrations.

(067) CO2 land use biomass emissions[Land use,region] = IF THEN ELSE (Time <= Year to land use emissions forecast , Historic CO2 land use biomass emissions[Land use,region] , Projected RS CO2 land use biomass emissions[Land use,region])

Units: GtonsCO2/Year

Historical values of biomass gross emissions through 2015, after which projected values based on annual decrease from last historic value.

(068) CO2 land use gross emissions ratio over RS[Land use,region] = 1 + RAMP (zidz (LULUCF pct relative to RS / "100 percent" , LULUCF target year - LULUCF start year) , LULUCF start year , LULUCF target year)

Units: Dmnl

Ratio of actual to reference LULUCF gross emissions.

(069) Cumulative Net Direct C Emissions from Bioenergy = INTEG(Net Direct Bioenergy C Emissions , 0)

Units: GtonsC

Cumulative net direct C emissions from bioenergy. Considers the direct emissions from biofuel including combustion and supply chain less the avoided fossil emissions from combustion of fossil fuel including the fossil supply chain.

(070) Decrease in Land Area for AF u r[Land use,region] = MAX (0, MIN (Indicated Land for AF u r[Land use,region] , Maximum Land for AF u r[Land use,region]))

Units: hectare/Year

Decrease in nonforest land area resulting from conversion to forest land, i.e., afforestation.

(071) Decrease in Land Area from Human Land Use Change u r[Land use,region] = MIN (Indicated Decrease in Land Area from Human Activity u r[Land use,region] , Maximum Land Decrease from Human Activity[Land use,region])

Units: hectare/Year

The land lost from each type is the lesser of the indicated loss or the maximum loss, which is determined by the availability of land.

(072) Decrease in Land Area from Natural Processes u r[Land use,region] = Fractional Rate of Decrease in Land from Natural Processes u r[Land use,region] * Land Area u r[Land use,region]

Units: hectare/Year

For each region, the annual land area converted from natural processes for each land use to another land use.

(073) Decrease in Land Area u r[Land use,region] = Decrease in Land Area from Natural Processes u r[Land use,region] + Decrease in Land Area from Human Land Use Change u r[Land use,region] + Land Harvested for Bioenergy u r[Land use,region] + Decrease in Land Area for AF u r[Land use,region]

Units: hectare/Year

For each region, the decrease in area for each land use.

(074) Diffusion Flux[layer1] = (C in Mixed Layer per Meter - C in Deep Ocean per Meter[layer1]) * Eddy Diff Coeff / Mean Depth of Adjacent Layers[layer1]

Diffusion Flux[lower] = (C in Deep Ocean per Meter[upper] - C in Deep Ocean per Meter[lower]) * Eddy Diff Coeff / Mean Depth of Adjacent Layers[lower]

Units: GtonsC/Year

Diffusion flux between ocean layers.

(075) Eddy Diff Coeff = INITIAL(Eddy Diff Coeff Index * Eddy Diff Mean)

Units: meter*meter/Year

Multiplier of eddy diffusion coefficient mean

(076) Eddy Diff Coeff Index = 1

Units: Dmnl [0.85,1.15,0.05]

Index of coefficient for rate at which carbon is mixed in the ocean due to eddy motion, where 1 is equivalent to the expected value (defaulted to 4400 meter*meter/year).

(077) Eddy Diff Mean = 4400

Units: meter*meter/Year [2000,8000]

Rate of vertical transport and mixing in the ocean due to eddy diffusion motion.

(078) Effect of Temp on DIC pCO₂ = 1 - Sensitivity of pCO₂ DIC to Temperature * Temperature change from preindustrial

Units: Dmnl

The fractional reduction in the solubility of CO₂ in ocean falls with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100.

(079) Effect of Warming on C flux to biomass = 1 + Strength of Temp Effect on C Flux to Land * Temperature change from preindustrial

Units: Dmnl

The fractional reduction in the flux of C from the atmosphere to biomass with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100.

(080) Effect of Warming on CH₄ Release from Biological Activity = 1 + Sensitivity of Methane Emissions to Temperature * (Temperature change from preindustrial) / (Reference Temperature Change for Effect of Warming on CH₄ from Respiration)

Units: Dmnl

The fractional increase in the flux of C as CH₄ from humus with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100.

(081) Emiss from Storage = 0

Units: GtonsC/Year

Loss of CO₂ from sequestered storage back into atmosphere.

(082) Emissions from Fossil Fuel = Primary Energy from Fossil Fuels * (Fossil Fuel C Intensity + Fossil Fuel Supply Chain C Intensity) / GJ per EJ

Units: GtonsC/Year

CO₂ emissions from fossil fuels other than the fossil used to produce biofuels (GtC/yr) are given by the primary energy supplied by fossil sources divided by the combustion and supply chain efficiencies and including the carbon generated by the energy used in the extraction, transport and processing of fossil fuels to the point of combustion.

(083) End Use Bioenergy = sum (End Use Bioenergy u r[Land use!,region!])

Units: Gj/Year

Total end use energy from biomass is the sum of production from each land type and region.

(084) End Use Bioenergy Pulse[Land use,region] = 0

Units: Gj [0,1e+14]

Size of pulse in bioenergy end use demand, for testing purposes.

(085) End Use Bioenergy Pulse Duration[Land use,region] = TIME STEP

Units: Year

Duration of pulse in biomass end use production. Set to time step for the numerical integration.

(086) End Use Bioenergy Pulse End Time[Land use,region] = 2500

Units: Year

The year repeated harvesting of land for bioenergy ends

- (087) End Use Bioenergy Pulse Repeat Time[Land use,region] = 1000
Units: Year
The interval for repeated harvest of land for bioenergy.
- (088) End Use Bioenergy Pulse Start[Land use,region] = 2010
Units: Year
year to start pulse in bioenergy output for testing.
- (089) End Use Bioenergy Pulse StartAF[Land use,region] = 2010
Units: Year
year to start pulse in bioenergy output for testing.
- (090) End Use Bioenergy PulseAF[Land use,region] = 0
Units: GJ [0,1e+14]
Size of pulse in bioenergy end use demand, for testing purposes.
- (091) End Use Bioenergy u_r [Land use,region] = Fraction of Indicated Land for Bioenergy Harvested u_r [Land use,region] * Indicated End Use Energy from Biomass u_r [Land use,region]
Units: GJ/Year
Actual end use energy from biomass is the indicated value adjusted by the fraction of the land required to produce it actually harvested.
- (092) End Use Energy from Biomass = sum (End Use Energy from Biomass u [Land use!])
Units: GJ/Year
Total global bioenergy production from all land types and regions.
- (093) End Use Energy from Biomass r [region] = sum (End Use Energy from Biomass u_r [Land use!,region])
Units: GJ/Year
Total bioenergy production in region r , summed over all land use types.
- (094) End Use Energy from Biomass u [Land use] = sum (End Use Energy from Biomass u_r [Land use,region!])
Units: GJ/Year
Total end use energy from biomass produced globally on each land type.
- (095) End Use Energy from Biomass u_r [Land use,region] = Primary Energy from Biomass u_r [Land use,region] * Biomass Combustion Efficiency u [Land use] * Biomass Processing Efficiency u [Land use]
Units: GJ/Year
End use bioenergy from each land type and region is determined by the primary energy derived from biomass and the combustion and processing efficiencies.
- (096) End Use Energy from Fossil Fuels = Indicated End Use Energy from Fossil Fuels - End Use Bioenergy
Units: GJ/Year
End use energy from biofuels displaces end use energy from fossil fuels.
- (097) End Use Energy from Fossil Growth Rate = 0
Units: 1/Year [0,0.1,0.01]
Growth rate in end use energy demand from fossil fuels, for testing purposes.
- (098) Equilibrium C in Mixed Layer = Preind C in Mixed Layer * Effect of Temp on DIC p_{CO_2} * (C in Atmosphere / Preindustrial C) ^ (1 / Buffer Factor)
Units: GtonsC
Equilibrium carbon content of mixed layer. Determined by the Revelle buffering factor, and by temperature. For simplicity, we assume a linear impact of warming on the equilibrium solubility of CO₂ in the ocean. The user controls the strength of that effect.

- (099) $\text{Equilibrium C per meter in Mixed Layer} = \text{Equilibrium C in Mixed Layer} / \text{Mixed Depth}$
 Units: GtonsC/meter
 The equilibrium concentration of C in the mixed layer, in GtC/meter, based on the total quantity of C in that layer and the average layer depth.
- (100) $\text{Exogenous Decrease in Land Use } u r[\text{Land use,region}] = \text{Land for RS gross land use emissions}[\text{Land use,region}] * (\text{CO}_2 \text{ land use gross emissions ratio over RS}[\text{Land use,region}] - 1)$
 Units: hectare/Year
 Exogenous test input for land use converted from one type to others.
- (101) $\text{Flux Atm to Biomass Land Use } u r[\text{Land use}] = \text{sum} (\text{Flux from atm to biomass C for Land } u r[\text{Land use,region!}])$
 Units: GtonsC/Year
 Total global flux from atmosphere to biomass, by land use type.
- (102) $\text{Flux Atm to Biomass region } r[\text{region}] = \text{sum} (\text{Flux from atm to biomass C for Land } u r[\text{Land use!,region}])$
 Units: GtonsC/Year
 The annual flux of carbon from the atmosphere to biomass in each region due to primary production.
- (103) $\text{Flux Atm to Ocean} = \text{Switch for Flux Atm Ocean} * ((\text{Equilibrium C in Mixed Layer} - \text{C in Mixed Layer}) / \text{Mixing Time})$
 Units: GtonsC/Year
 Carbon flux from atmosphere to mixed ocean layer.
- (104) $\text{Flux Biomass C to CH}_4 \text{ Land } u r[\text{Land use,region}] = \text{Switch for Zero C Flux Other Than Land Use Change} * \text{Biomass C Land Use } u \text{ Region } r[\text{Land use,region}] * \text{Fractional Rate of CH}_4 \text{ Released from Biomass to Atm } u r[\text{Land use}] * \text{Effect of Warming on CH}_4 \text{ Release from Biological Activity}$
 Units: GtonsC/Year
 The annual natural flux of methane from C in biomass for each land use and region. The sum of the flux of methane from C in soil and the flux of methane from C in biomass yields the natural emissions of methane. Adjusted to account for temperature feedback.
- (105) $\text{Flux Biomass C to Structures } u r[\text{Land use,region}] = (1 - \text{Fraction of C in Biomass Harvest Released to Atm } u r[\text{Land use}]) * \text{C in Biomass Removed by Land Use Change } u r[\text{Land use,region}]$
 Units: GtonsC/Year
 The carbon in biomass that is not lost to the atmosphere or transferred to another land use, but is put into structures like wooden beams for housing.
- (106) $\text{Flux Biomass to Atm Land Use } u r[\text{Land use}] = \text{sum} (\text{Flux to Atm from Biomass C Land } u r[\text{Land use,region!}] + \text{Flux C in Structures to Atm } u r[\text{Land use,region!}])$
 Units: GtonsC/Year
 Total global C flux from Biomass plus C in structures to atmosphere as CO₂, by land use type.
- (107) $\text{Flux Biomass to Atm region } r[\text{region}] = \text{sum} (\text{Flux to Atm from Biomass C Land } u r[\text{Land use!,region}]) + \text{sum} (\text{Flux C in Structures to Atm } u r[\text{Land use!,region}])$
 Units: GtonsC/Year
 The annual net flux of carbon from the biomass to the atmosphere in each region due to land use conversions, plus the flux from C in biomass contained in human structures due to decay or combustion.
- (108) $\text{Flux Biomass to Soil region } r[\text{region}] = \text{sum} (\text{Biomass to Soil C Land Use } u r[\text{Land use!,region}])$
 Units: GtonsC/Year
 The total annual net flux of carbon from the biomass to the soil.

- (109) Flux Biosphere to CH4 = Total Flux Biomass to CH4 + Total Flux Soil to CH4
 Units: GtonsC/Year
 Carbon flux from biosphere as methane, in GtC/year, arising from anaerobic respiration.
- (110) Flux C from permafrost release = 0
 Units: GtonsC/Year
 The flux of carbon from permafrost soils to the atmosphere. Set to 0 as a default.
- (111) Flux C in Structures to Atm $u r[\text{Land use,region}] = \text{Biomass C in Structures } u r[\text{Land use,region}] / \text{Average Residence Time for C in Structures } u[\text{Land use}]$
 Units: GtonsC/Year
 The C in biomass contained in structures eventually burns or decays and enters the atmosphere as CO2.
- (112) Flux from atm to biomass C for Land $u r[\text{Land use,region}] = \text{Switch for Zero C atm to land}[\text{Land use}] * \text{NPP Land Use } u r[\text{Land use,region}] / \text{tonsC per GtonsC} * (1 + \text{Biostim coeff} * \text{LN} (\text{Init C in Atmosphere} / \text{Preindustrial C}))$
 Units: GtonsC/Year
 The annual flux of carbon from the atmosphere to biomass in each land use and region due to primary production.
- (113) Flux Soil C to Atm Land $u r[\text{Land use,region}] = \text{Switch for Active Soil C Fluxes}[\text{Land use}] * (\text{C in Soil to Atm from Respiration Land } u r[\text{Land use,region}] + \text{C in Soil Released to Atm by Land Use Change } u r[\text{Land use,region}])$
 Units: GtonsC/Year
 For each region, the flux of soil C to the atmosphere as CO2 is the sum of respiration and C flux due to land use change.
- (114) Flux Soil C to CH4 Land $u r[\text{Land use,region}] = \text{Switch for Active Soil C Fluxes}[\text{Land use}] * \text{Soil C Land Use } u \text{ Region } r[\text{Land use,region}] * \text{Fractional Rate of CH4 from Soil to Atm } u r[\text{Land use,region}] * \text{Effect of Warming on CH4 Release from Biological Activity}$
 Units: GtonsC/Year
 The annual natural flux of methane from C in soil for each land use and region. The sum of the flux of methane from C in soil and the flux of methane from C in biomass yields the natural emissions of methane. Adjusted to account for temperature feedback.
- (115) Flux Soil to Atm Land Use $u[\text{Land use}] = \text{sum} (\text{Flux Soil C to Atm Land } u r[\text{Land use,region}])$
 Units: GtonsC/Year
 Total global flux of C as CO2 from soils to atmosphere, by land use type.
- (116) Flux Soil to Atm region $r[\text{region}] = \text{sum} (\text{Flux Soil C to Atm Land } u r[\text{Land use!,region}])$
 Units: GtonsC/Year
 The annual net flux of carbon from the soil to the atmosphere as CO2 in each region due to land use conversions.
- (117) Flux to Atm from Biomass C Land $u r[\text{Land use,region}] = \text{C in Biomass to Atm from Land } u r[\text{Land use,region}] + \text{C in Biomass Released to Atm by Land Use Change } u r[\text{Land use,region}] + \text{C from Bioenergy } u r[\text{Land use,region}]$
 Units: GtonsC/Year
 For each region, the flux of C to the atmosphere as CO2 for each land type is the sum of the natural and human caused fluxes associated with land and land use change, plus emissions from biofuels harvested from that land type.
- (118) Forest and cropland : Forest,Cropland
- (119) Forest plus Harvested Forest : Forest,Harvested Forest

(120) Fossil Carbon = INTEG(- Global C Anthro Emissions , 3e+06)
Units: GtonsC

The stock of fossil carbon energy. Used to measure net change in total C in the biosphere, ocean, atmosphere and fossil stocks). Initial values estimated based on our En-ROADS defaults of 100000 EJ of coal, 12500 EJ for oil, and 12000 EJ for gas, each multiplied by their C intensity of 90 ton CO₂/TJ, 66 ton CO₂/TJ, and 51 tonsCO₂/TJ.

(121) Fossil Emissions from Bioenergy Supply Chain = sum (Fossil Emissions from Bioenergy Supply Chain u[Land use!])
Units: GtonsC/Year

Total fossil fuel emissions from bioenergy supply chains on all land types.

(122) Fossil Emissions from Bioenergy Supply Chain u[Land use] = sum (Fossil Emissions from Bioenergy Supply Chain u r[Land use,region!])
Units: GtonsC/Year

Fossil emissions from the bioenergy supply chain for each land type, summed over all regions.

(123) Fossil Emissions from Bioenergy Supply Chain u r[Land use,region] = Primary Energy from Biomass u r[Land use,region] * Biomass Supply Chain C Intensity u[Land use] / GJ per EJ
Units: GtonsC/Year

Fossil fuel emissions resulting from the bioenergy supply chain. Given by the carbon intensity of the bioenergy supply chain and the fossil energy used per unit of primary bioenergy produced.

(124) Fossil End Use Scenario = Fossil End Use Table (Time)
Units: Gj/Year

An exogenously specified scenario for growth in end-use energy from fossil fuels. Specified as a look-up table.

(125) Fossil End Use Table ([(1990,0)-(2100,5e+10)],(1990,1e+10),(2000,2e+10),(2050,2e+10),(2100,2e+10))
Units: Gj/Year

Look up table for exogenous growth in end-use energy from fossil fuels.

(126) Fossil Fuel C Intensity = 0.025
Units: GtonsC/EJ

Carbon intensity of fossil fuels. a. EIA (2016), https://www.eia.gov/environment/emissions/co2_vol_mass.php Release Date: February 2, 2016. "Carbon Dioxide Emissions Coefficients by Fuel": CO₂ intensity of coal (all types) = 95.35 kgCO₂/mmBTU; mmBTU per GJ = 0.9478 MMBtu /GJ (<https://www.iea.org/statistics/resources/unitconverter/>). 95.35 kgCO₂/MMBtu * 0.9478 MMBtu/GJ / 1000 kgCO₂/ tCO₂ / (44/12) tonC/tonCO₂ = 0.0246 tC/GJ b. IEA WEO (2016): Annex A Tables, pp. 550, 552, data for coal in 2014

(last year of historic data). Total Primary Energy Demand (TPED) = 3926 Mtoe; TJ per MToe = 41868 TJ/Mtoe (<https://www.iea.org/statistics/resources/unitconverter/>) TPED = 3926 Mtoe*41868 TJ/Mtoe*1000 GJ/TJ = 1.64e11 GJ/year; CO₂ = 14868 MtCO₂/year/(44/12) MtCO₂/MtC*1e6 tC/MtC = 4.05e9 tC/year; Carbon intensity = 4.05e9 tC/year/1.64e11 GJ/year = 0.025 tC/GJ c. <https://content.ces.ncsu.edu/conversion-factors-for-bioenergy> ORNL/North Carolina State Extension Service, Conversion Factors for Bioenergy used by the Bioenergy Feedstock Development Programs at ORNL. Carbon content of fossil fuels coal (average) = 25.4 tC/terajoule = 0.025 tC/GJ (p. 3).

(127) Fossil Fuel Combustion Efficiency = 0.35
Units: Dmnl

Combustion efficiency of fossil fuel use (at point of combustion). IEA (2016) World Energy Outlook Annex A Tables, pp. 550, 552, data for coal in 2014 (last year of historic data provided): Power generation = 9907 TWh/Year; converted by 11.63 TWh/MToe = 9907 TWh/year/11.64 TWh/MTOE = 834.7 Mtoe. Power generation input = 2408 Mtoe. Efficiency = Power generation/Power input = 834.7 Mtoe/2408 Mtoe = 0.35

(128) Fossil Fuel Emissions Avoided by Bioenergy = Indicated Emissions from Fossil Fuels - Total Fossil Fuel Emissions

Units: GtonsC/Year

CO₂ emissions (GtC/yr) avoided by bioenergy are given by total fossil fuel emissions less what emissions would be without biofuel production.

(129) Fossil Fuel Processing Efficiency = 0.89

Units: Dmnl

Efficiency of fossil fuel supply chain (1 - loss fraction from extraction to point of combustion). IEA (2016) World Energy Outlook Annex A Tables p. 550, values for coal in 2014: Total primary energy demand (TPED) = 3926 Mtoe; Total final consumption (TFC) = 1076 Mtoe; Power generation = 2408 Mtoe Losses = TPED - (TFC + Power generation input) = 3926 Mtoe - (2408 Mtoe + 1076 Mtoe) = 442 Mtoe Efficiency = 1 - Loss fraction = 1 - Losses/TPED = 1 - (442 Mtoe/3926 Mtoe) = 0.89.

(130) Fossil Fuel Supply Chain C Intensity = 0.0015

Units: GtonsC/EJ

Carbon intensity of the fossil fuel supply chain. Odeh and Cockerill (2008), Table 2. We consider the CO₂ from coal mining and transport, 20 gCO₂/kWh. Converted at .0036 GJ/kWh and 44/12 CO₂/C yields 0.0015 tC/GJ.

(131) Fraction of Biomass C released from Land Use Change u[Land use] = 1, 0.1, 0.1, 0.1, 0.1, 0.1;

Units: Dmnl [0,1]

The fraction of the C in biomass on each land type that is removed from each land use type when that land type is converted to other uses. The released C either directly enters the atmosphere as CO₂ through combustion or goes into human structures (such as lumber in buildings).

(132) Fraction of Biomass C released from Land Use Change u r[Land use] = 1

Units: Dmnl

(133) Fraction of Biomass Removed by Bioenergy Harvest u[Land use] = 0.25, 0.25, 0.25, 0.25, 0.25, 0.25

Units: Dmnl [0.1,1,0.01]

When land is harvested for bioenergy, a certain fraction of the biomass is harvested, with the rest remaining on the land.

(134) Fraction of Biomass Removed by Bioenergy Harvest uAF[Land use] = 0.25, 0.25, 0.25, 0.25, 0.25, 0.25

Units: Dmnl [0.1,1,0.01]

When land is harvested for bioenergy, a certain fraction of the biomass is harvested, with the rest remaining on the land.

(135) Fraction of C in Biomass Harvest Released to Atm u[Land use] = 1, 1, 1, 1, 1, 1

Units: Dmnl [0,1,0.01]

When biomass is harvested or destroyed as a result of human activity, some fraction enters the atmosphere directly as CO₂, and the rest is added to stocks of C embodied in human structures (e.g., some forest biomass is burned for biofuels and some is processed into lumber that goes into structures).

(136) Fraction of global forest r[region] = zidz (Land Use Area 2015 u r[Forest,region] , sum (Land Use Area 2015 u r[Forest,region!]))

Units: Dmnl

The fraction of the world's forest in a particular region.

(137) Fraction of Indicated Land for Bioenergy Harvested u r[Land use,region] = xidz (Land Harvested for Bioenergy u r[Land use,region] , Indicated Land Harvested for Bioenergy u r[Land use,region] , 1)

Units: Dmnl

The fraction of land desired for bioenergy actually harvested.

- (138) Fraction of Land for AF $u[\text{Land use}] = 0, 0, 1, 1, 0, 1$
 Units: Dmnl
 Fraction of land available for afforestation. Defaults to all of each nonforest type to be capable of afforestation.
- (139) Fraction of Soil C to Atm from Land Use Change $u[\text{Land use}] = 0$
 Units: Dmnl [0,1]
 The fraction of soil C entering the atmosphere at CO2
- (140) Fractional Increase from AF in Area from Land Use Change $u[\text{Land use}, \text{Land use}'] = 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 1, 0, 0, 0, 0; 0, 1, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 1, 0, 0, 0, 0;$
 Units: Dmnl
 For each region, matrix capturing the fraction of the increase in each land use of type j moving from type i as a result of land use change.
- (141) Fractional Increase in Area from Bioenergy Production $u[\text{Land use}, \text{Land use}'] = 0, 1, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0;$
 Units: Dmnl
 For each region, matrix capturing the fraction of the increase in each land use of type j moving from type i as a result of bioenergy production.
- (142) Fractional Increase in Area from Land Use Change $u[\text{Land use}, \text{Land use}'] = 0, 0, 0, 0, 0, 1; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0;$
 Units: Dmnl
 For each region, matrix capturing the fraction of the decrease in each land use of type j moving to type i as a result of land use change.
- (143) Fractional Increase in Area from Natural Processes $u[\text{Land use}, \text{Land use}'] = 0, 0, 0, 0, 0, 1; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0;$
 Units: Dmnl
 For each region, matrix capturing the fraction of the decrease in each land use of type j moving to type i.
- (144) Fractional Rate of Biomass Released to Atm $u r[\text{Land use}, \text{region}] = \text{GET XLS CONSTANTS}('Parameter Master Sheet', 'ΦBA', 'B2')$
 Units: 1/Year [0,1,0.001]
 Rate of biomass carbon release to the atmosphere, expresses as a fraction of the biomass carbon intensity, for each land use and region.
- (145) Fractional Rate of Biomass Transfer to Soils $u r[\text{Land use}, \text{region}] = \text{GET XLS CONSTANTS}('Parameter Master Sheet', 'ΦBS', 'B2')$
 Units: 1/Year
 Rate of C flux from biomass to soils, expressed as a fraction of biomass c intensity, by land use and region.
- (146) Fractional Rate of CH4 from Soil to Atm $u r[\text{Land use}, \text{region}] = 0$
 Units: 1/Year [0,0.00016]
 The rate of the natural flux of methane from C in humus. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane.
- (147) Fractional Rate of CH4 Released from Biomass to Atm $u[\text{Land use}] = 0, 0, 0, 0, 0, 0$
 Units: 1/Year [0,0.00014]
 The rate of the natural flux of methane from C in biomass. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane.
- (148) Fractional Rate of Decrease in Land from Natural Processes $u r[\text{Land use}, \text{region}] = 0$

Units: 1/Year

For each region, the fractional rate of converting area from natural processes for each land use to another land use.

(149) Fractional Rate of Soil C Released to Atmosphere[Land use,region] = GET XLS CONSTANTS('Parameter Master Sheet', 'ΦSA', 'B2')

Units: 1/Year

Rate of C flux from soils to atmosphere, expressed as a fraction of soil C intensity, by land use and region.

(150) gC per tonsC = 1e+06

Units: gC/tonsC

(151) GJ per EJ = 1e+09

Units: GJ/EJ

(152) GJ per TWh = 3.6e+06

Units: GJ/TWh

(153) GJ per TWhAF = 3.6e+06

Units: GJ/TWh

(154) Global Bioenergy End Use Table ([(1990,0)-(2000,20000)],(1990,0),(2014,430),(2050,3500),(2100,7760),(2200,17460))

Units: TWh/Year

Look up table for exogenous growth in global end-use energy from biofuels. IEA (2017) forecasts global electricity from bioenergy would grow from about 430 TWh in 2014 to approximately 3,500 TWh in 2050, approximately a factor of 8, increasing bioenergy from less than 2% to more than 8% of global generation electricity generation (<https://www.iea.org/publications/freepublications/publication/How2GuideforBioenergyRoadmapDevelopmentandImplementation.pdf>).

(155) Global Bioenergy End Use TableAF ([(1990,0)-(2000,20000)],(1990,0),(2014,430),(2050,3500),(2100,7760),(2200,17460))

Units: TWh/Year

Look up table for exogenous growth in global end-use energy from biofuels. IEA (2017) forecasts global electricity from bioenergy would grow from about 430 TWh in 2014 to approximately 3,500 TWh in 2050, approximately a factor of 8, increasing bioenergy from less than 2% to more than 8% of global generation electricity generation (<https://www.iea.org/publications/freepublications/publication/How2GuideforBioenergyRoadmapDevelopmentandImplementation.pdf>).

(156) Global C Anthro Emissions = Total Fossil Fuel Emissions * Switch for Flux FF to Atm

Units: GtonsC/Year

CO2 emissions from fossil fuels (plus cement), including the fossil fuel emissions generated by the bioenergy supply chain.

(157) Global RS CO2 FF Emissions = WITH LOOKUP(Time / one year , ((1990,6.01538),(1991,6.03037),(1992,6.06767),(1993,6.12838),(1994,6.15449),(1995,6.27758),(1996,6.46067),(1997,6.479),(1998,6.42226),(1999,6.53185),(2000,6.72556),(2001,6.76723),(2002,6.87943),(2003,7.25785),(2004,7.62933),(2005,7.84255),(2006,8.11829),(2007,8.33769),(2008,8.51958),(2009,8.41514),(2010,8.98022),(2011,9.31927),(2012,9.49141),(2013,9.51867),(2014,9.57693),(2015,9.55958),(2016,9.75345),(2017,9.99256),(2018,10.2354),(2019,10.4811)

,(2020,10.7289),(2021,10.9783),(2022,11.2286),(2023,11.4796),(2024,11.731),(2025,11.9825),(2026,12.2341),(2027,12.4852),(2028,12.7359),(2029,12.9859),(2030,13.2353),(2031,13.4838),(2032,13.7314),(2033,13.9781),(2034,14

.2239),(2035,14.4686),(2036,14.7124),(2037,14.9551),(2038,15.1967),(2039,15.4372),(2040,15.6764),(2041,15.9143),(2042,16.1508),(2043,16.386),(2044,16.6198),(2045,16.852),(2046,17.0826),(2047,17.3116),(2048,17.5389),(2049,17.7645),(2050,17.9882),(2051,18.21),(2052,18.4299),(2053,18.648)

,(2054,18.864),(2055,19.0781),(2056,19.2901),(2057,19.5002),(2058,19.7086),(2059,19.9156),(2060,20.1214),(2061,20.326),(2062,20.5296),(2063,20.7325),(2064,20.9348),(2065,21.1367),(2066,21.3384),(2067,21.54),(2068,21.7416),(2069,21.943),(2070,22.1444),(2071,22.3458),(2072,22.5473),(2073,22.749),(2074,22.9507),(2075,23.1524),(2076,23.3543),(2077,23.5564),(2078,23.7586),(2079,23.9611),(2080,24.1638),(2081,24.3668),(2082,24.5702),(2083,24.774),(2084,24.9786),(2085,25.1839),(2086,25.3901),(2087,25.5972)

,(2088,25.8052),(2089,26.0145),(2090,26.2249),(2091,26.4366),(2092,26.6494),(2093,26.8634),(2094,27.0785),(2095,27.2944),(2096,27.5112),(2097,27.7287),(2098,27.9467),(2099,28.1652),(2100,28.384))

Units: GtonsC/Year

(158) GtonsCO2 per GtonsC = 3.667
Units: GtonsCO2/GtonsC

(159) Historic CO2 land use biomass emissions[Forest,region] := GET XLS DATA('?Parameter Master Sheet', 'Hist CO2 biomass LUC emissions', '2', 'B3')
Historic CO2 land use biomass emissions[Cropland,region] := GET XLS DATA('?Parameter Master Sheet', 'Hist CO2 biomass LUC emissions', '2', 'B9')
Historic CO2 land use biomass emissions[All but forest and cropland,region] = 0
Units: GtonsCO2/Year

Historic LULUCF gross emissions from biomass, calculated from Houghton and Nassikas, 2017 and aggregated to 6 regions.

(160) Increase in Area for AF from Land Use Change $u_r[\text{Land use,region}] = \text{sum}(\text{Fractional Increase from AF in Area from Land Use Change } u[\text{Land use}', \text{Land use}] * \text{Decrease in Land Area for AF } u_r[\text{Land use}', \text{region}])$
Units: hectare/Year

For each region, the total land added to each type i as a result of land use change (such as deforestation) is the sum over all land types of the loss of each land type multiplied by the fraction of each land type lost from each type j moving to type i .

(161) Increase in Area for Land Use u Region $r[\text{Land use,region}] = \text{Increase in Land Area from Natural Processes } u_r[\text{Land use,region}] + \text{Increase in Area from Land Use Change } u_r[\text{Land use,region}] + \text{Increase in Area from Bioenergy Production } u_r[\text{Land use,region}] + \text{Increase in Area for AF from Land Use Change } u_r[\text{Land use,region}]$
Units: hectare/Year

For each region, the increase in area for each land use, summing the impact of natural changes, land use change from human activity such as deforestation and land use change from bioenergy production.

(162) Increase in Area from Bioenergy Production $u_r[\text{Land use,region}] = \text{sum}(\text{Fractional Increase in Area from Bioenergy Production } u[\text{Land use}', \text{Land use}] * \text{Land Harvested for Bioenergy } u_r[\text{Land use}', \text{region}])$
Units: hectare/Year

For each region, the total land added to each type i as a result of bioenergy production (such as deforestation) is the sum over all land types of the loss of each land type multiplied by the fraction of each land type lost from each type j moving to type i .

(163) Increase in Area from Land Use Change $u_r[\text{Land use,region}] = \text{sum}(\text{Fractional Increase in Area from Land Use Change } u[\text{Land use}', \text{Land use}] * \text{Decrease in Land Area from Human Land Use Change } u_r[\text{Land use}', \text{region}])$
Units: hectare/Year

For each region, the total land added to each type i as a result of land use change (such as deforestation) is the sum over all land types of the loss of each land type multiplied by the fraction of each land type lost from each type j moving to type i .

(164) Increase in Land Area from Natural Processes $u_r[\text{Land use,region}] = \text{sum}(\text{Fractional Increase in Area from Natural Processes } u[\text{Land use}', \text{Land use}] * \text{Decrease in Land Area from Natural Processes } u_r[\text{Land use}', \text{region}])$

Units: hectare/Year

For each region, the total land added to each type i as a result of natural processes is the sum over all land types of the loss of each land type multiplied by the fraction of each land type lost from each type j moving to type i .

(165) Indicated C from Bioenergy $u_r[\text{Land use,region}] = \text{Indicated Primary Energy from Biomass } u_r[\text{Land use,region}] * \text{Bioenergy C Intensity } u$ in tonC[Land use] / GJ per EJ

Units: tonsC/Year

For each region and land use type, the C emissions that would be generated by the indicated primary bioenergy use depend on the carbon intensity of bioenergy.

(166) Indicated C from Bioenergy $u_{rAF}[\text{Land use,region}] = \text{Indicated Primary Energy from Biomass } u_{rAF}[\text{Land use,region}] * \text{Bioenergy C Intensity } u$ in tonCAF[Land use] / GJ per EJ

Units: tonsC/Year

For each region and land use type, the C emissions that would be generated by the indicated primary bioenergy use depend on the carbon intensity of bioenergy.

(167) Indicated Decrease in Land Area from Human Activity $u_r[\text{Land use,region}] = \text{Exogenous Decrease in Land Use } u_r[\text{Land use,region}]$

Units: hectare/Year

The indicated rate at which land is converted from its current type to other types, set equal to an exogenous value for testing.

(168) Indicated Emissions from Fossil Fuels = Indicated Primary Energy from Fossil Fuels * (Fossil Fuel C Intensity + Fossil Fuel Supply Chain C Intensity) / GJ per EJ

Units: GtonsC/Year

What fossil fuel emissions would be if bioenergy production were zero. Given by the primary energy fossil would have to supply in the absence of biofuels and the carbon intensity of fossil fuels, plus the emissions resulting from the fossil supply chain.

(169) Indicated End Use Energy from Biomass $u_r[\text{Land use,region}] = \text{Switch for Bioenergy Scenario}[\text{Land use,region}] * \text{Bioenergy End Use Scenario}[\text{Land use,region}] + (1 - \text{Switch for Bioenergy Scenario}[\text{Land use,region}]) * (\text{End Use Bioenergy Pulse}[\text{Land use,region}] / \text{End Use Bioenergy Pulse Duration}[\text{Land use,region}]) * \text{PULSE TRAIN} (\text{End Use Bioenergy Pulse Start}[\text{Land use,region}] , \text{End Use Bioenergy Pulse Duration}[\text{Land use,region}] , \text{End Use Bioenergy Pulse Repeat Time}[\text{Land use,region}] , \text{End Use Bioenergy Pulse End Time}[\text{Land use,region}])$

Units: GJ/Year [0,?]

End use bioenergy sourced from each land use type. Switch for Bioenergy Scenario = 1 —> an exogenously specified scenario for growth in end use energy supplied by biomass; 0 —> bioenergy end use follows a pulse or pulse train for testing purposes.

(170) Indicated End Use Energy from Biomass $u_{rAF}[\text{Land use,region}] = \text{Switch for Bioenergy ScenarioAF}[\text{Land use,region}] * \text{Bioenergy End Use ScenarioAF}[\text{Land use,region}] + (1 - \text{Switch for Bioenergy ScenarioAF}[\text{Land use,region}]) * (\text{End Use Bioenergy PulseAF}[\text{Land use,region}] / \text{AF Pulse Duration}[\text{Land use,region}]) * \text{PULSE TRAIN} (\text{End Use Bioenergy Pulse StartAF}[\text{Land use,region}] , \text{AF Pulse Duration}[\text{Land use,region}] , \text{AF Pulse Repeat Time}[\text{Land use,region}] , \text{AF Pulse End Time}[\text{Land use,region}])$

Units: GJ/Year [0,?]

End use bioenergy sourced from each land use type. Switch for Bioenergy Scenario = 1 —> an exogenously specified scenario for growth in end use energy supplied by biomass; 0 —> bioenergy end use follows a pulse or pulse train for testing purposes.

(171) Indicated End Use Energy from Fossil Fuels = Switch for Fossil End Use Scenario * Fossil End Use Scenario + (1 - Switch for Fossil End Use Scenario) * Initial End Use Energy from Fossil Fuels * exp (End Use Energy from Fossil Growth Rate * (Time - INITIAL TIME))

Units: GJ/Year

Exogenous growth rate in end use energy demand from fossil fuels for testing purposes.
 Switch for Fossil End Use Scenario = 1 → End use fossil demand follows the values in Fossil End Use Scenario;
 Switch for Fossil End Use Scenario = 0 → End use energy from fossil sources is given by the initial value and may also grow exponentially at a specified rate.

(172) Indicated Land for AF $u_r[\text{Land use,region}] = \text{Land Area } u_r \text{ at AF start}[\text{Land use,region}] * \text{STEP} (\text{Percent of Max AF Potential } r[\text{region}] / "100 \text{ percent}" * \text{Fraction of Land for AF } u[\text{Land use}] / \text{Time to reach AF target}[\text{region}] , \text{Time for AF Change Start}[\text{region}]) * (1 - \text{STEP} (1, \text{Time for AF Change Start}[\text{region}] + \text{Time to reach AF target}[\text{region}]))$

Units: hectare/Year

Specify area of each nonforest land use for afforestation.

(173) Indicated Land Harvested for Bioenergy $u_r[\text{Land use,region}] = \text{zidz} (\text{Indicated C from Bioenergy } u_r[\text{Land use,region}] , \text{Biomass C Intensity of Land } u_r \text{ in } \text{tonC}[\text{Land use,region}] * \text{Fraction of Biomass Removed by Bioenergy Harvest } u[\text{Land use}])$

Units: hectare/Year

For each region, the land needed to supply the bioenergy harvested is given by the biomass needed and the biomass intensity of the land.

(174) Indicated Land Harvested for Bioenergy $u_r\text{AF}[\text{Land use,region}] = \text{zidz} (\text{Indicated C from Bioenergy } u_r\text{AF}[\text{Land use,region}] , \text{Biomass C Intensity of Land } u_r \text{ in } \text{tonC}[\text{Land use,region}] * \text{Fraction of Biomass Removed by Bioenergy Harvest } u\text{AF}[\text{Land use}])$

Units: hectare/Year

For each region, the land needed to supply the bioenergy harvested is given by the biomass needed and the biomass intensity of the land.

(175) Indicated Primary Energy from Biomass $u_r[\text{Land use,region}] = \text{Indicated End Use Energy from Biomass } u_r[\text{Land use,region}] / (\text{Biomass Combustion Efficiency } u[\text{Land use}] * \text{Biomass Processing Efficiency } u[\text{Land use}])$

Units: GJ/Year

The primary energy from biomass needed to generate a given end use amount depends on the efficiency of combustion and of the bioenergy supply chain, from harvest to point of combustion.

(176) Indicated Primary Energy from Biomass $u_r\text{AF}[\text{Land use,region}] = \text{Indicated End Use Energy from Biomass } u_r\text{AF}[\text{Land use,region}] / (\text{Biomass Combustion Efficiency } u\text{AF}[\text{Land use}] * \text{Biomass Processing Efficiency } u\text{AF}[\text{Land use}])$

Units: GJ/Year

The primary energy from biomass needed to generate a given end use amount depends on the efficiency of combustion and of the bioenergy supply chain, from harvest to point of combustion.

(177) Indicated Primary Energy from Fossil Fuels = Indicated End Use Energy from Fossil Fuels / (Fossil Fuel Combustion Efficiency * Fossil Fuel Processing Efficiency)

Units: GJ/Year

Primary energy from fossil fuels that would have been produced without use of biofuels. Given by indicated fossil end use energy (end use from fossil in the absence of bioenergy) and the combustion and processing efficiencies of fossil energy production.

(178) Init C in Atmosphere = INITIAL(760)

Units: GtonsC [500,1000]

1990 value from C-ROADS

(179) Init C in Deep Ocean per meter[layer1] = INITIAL(Equilibrium C per meter in Mixed Layer)

Init C in Deep Ocean per meter[lower] = INITIAL(Equilibrium C per meter in Mixed Layer)

Units: GtonsC/meter

Initial carbon concentration in deep ocean layers.

(180) Init C in Mixed Ocean per meter = INITIAL(Equilibrium C in Mixed Layer / Mixed Depth)

Units: GtonsC/meter

Initial carbon in mixed ocean layer.

(181) Init C Sequestered = 0

Units: GtonsC

Initial C sequestered geologically (from, e.g., CCS). Does not include C "sequestered" in biomass, soils, or ocean.

(182) Initial Atm Conc CO2 = INITIAL(Atm Conc CO2)

Units: ppm

Initial CO2 concentration.

(183) Initial biomass intensity[Land use,region] = GET XLS CONSTANTS('Parameter Master Sheet', 'Initial Biomass C Intensity', 'B2')

Units: tonsC/hectare

Initial carbon in biomass.

(184) Initial C in Structures[Land use,region] = 0

Units: GtonsC

The initial stock of C in biomass contained in human structures (e.g., lumber).

(185) Initial End Use Energy from Fossil Fuels = 0

Units: GJ/Year

Initial value of end use energy demand satisfied by fossil fuels, for testing purposes.

(186) Initial Land Use u r[Land use,region] = INITIAL(Land Use Area 2015 u r[Land use,region])

Units: hectare

The initial land area for each land use and region, based on FAO 1990 data.

(187) Initial NPP = 483

Units: gC/(Year*meter*meter)

Fahey et 2005

(188) Initial NPP Land Use u r[Land use,region] = INITIAL(Initial NPP / gC per tonsC * Land Area u r[Land use,region] * m2 per hectare)

Units: tonsC/Year

NPP in each region is determined by a function of the biomass C relative to the maximum biomass C that each land type can support in equilibrium.

(189) Initial Soil C as Ratio of Biomass C u r[Land use,region] = INITIAL(Initial biomass intensity[Land use,region] * Land Use Area 2015 u r[Land use,region] * Ratio of Soil C per Biomass C / tonsC per MtonsC)

Units: MtonsC

Aggregated from FAO Emissions_Land_Use_Forest_Land_E_All_Data_(Normalized), Emissions_Land_Use_Cropland_E_All_Data_(Normalized), Emissions_Land_Use_Grassland_E_All_Data_(Normalized), Last Updated February 8, 2016.

(190) Initial Soil C Intensity from DSMW data u r[Land use,region] = GET XLS CONSTANTS('Parameter Master Sheet', 'Soil C Intensity', 'B2')

Units: tonsC/hectare

Soil carbon intensity by land use and region, using the Digital Soil Map of the World (FAO) and ESA CCI Land Cover Map.

(191) Initial Soil C Intensity from Fractional Fluxes u r[NonPermafrost,region] = INITIAL(Initial biomass intensity[NonPermafrost,region] * Switch for Active Soil C Fluxes[NonPermafrost] * zidz (Fractional Rate of Biomass Transfer to Soils u r[NonPermafrost,region] , (Fractional Rate of Soil C Released to Atm u r[NonPermafrost,region])) + Fractional Rate of CH4 from Soil to Atm u r[NonPermafrost,region]))

Initial Soil C Intensity from Fractional Fluxes $u_r[\text{Permafrost,region}] = \text{GET XLS CONSTANTS}('Parameter Master Sheet', 'Soil C Intensity', 'B5')$

Units: tonsC/hectare

Initial soil C per hectare in equilibrium. Calculated using fractional rates into and out of soil stocks for non permafrost land uses. For permafrost land use, the soil carbon intensities by region were constructed from NCSCDv2. Some of the pedons (soil samples) used to construct NCSCDv2 were overlain by forest vegetation. To prevent overlapping and consequent double counting of soil carbon under land uses, permafrost was constrained to be only that land area that was covered in tundra vegetation

in addition to being underlain by gelisol, or permafrosted, soils. ESA/CCI land cover classes 140, 150, 151, 152, and 153 – including mosses and lichens, and sparse vegetation (tree, shrub, herbaceous cover), respectively – were used to delineate tundra land cover. SOC intensity values by NCSCDv2 polygons were weighted by fractional tundra cover and fractional gelisol composition.

(192) Initial Soil C Intensity from Ratio of Biomass C $u_r[\text{Land use,region}] = \text{INITIAL}(\text{zidz}(\text{Initial Soil C as Ratio of Biomass C } u_r[\text{Land use,region}], \text{Land Area } u_r[\text{Land use,region}]) * \text{tonsC per MtonsC})$

Units: tonsC/hectare

Initial soil carbon intensity if assuming it as a scaled value of biomass carbon intensity.

(193) Initial Soil C $u_r[\text{Land use,region}] = \text{INITIAL}(\text{Switch for Equilibrium Initial Soil C} * \text{Land Area } u_r[\text{Land use,region}] * \text{Initial Soil C Intensity from Fractional Fluxes } u_r[\text{Land use,region}] / \text{tonsC per GtonsC} + (1 - \text{Switch for Equilibrium Initial Soil C}) * \text{Initial Soil C } u_r \text{ btw BiomassRatio and DSMW}[\text{Land use,region}])$

Units: GtonsC

Initial soil C stocks, determined as either the equilibrium value or values from data.

(194) Initial Soil C $u_r \text{ btw BiomassRatio and DSMW}[\text{Land use,region}] = \text{INITIAL}(\text{Initial Land Use } u_r[\text{Land use,region}] * (\text{Switch for Initial Soil C from Biomass C Ratio} * \text{Initial Soil C Intensity from Ratio of Biomass C } u_r[\text{Land use,region}] + (1 - \text{Switch for Initial Soil C from Biomass C Ratio}) * \text{Initial Soil C Intensity from DSMW data } u_r[\text{Land use,region}]) / \text{tonsC per GtonsC})$

Units: GtonsC

Initial soil carbon, either calculated from initial biomass carbon or DSMW.

(195) Interpolate = 0

Units: Dmnl

Interpolation mode for GET DATA BETWEEN TIMES calls

(196) $k u_r[\text{Land use,region}] = \text{GET XLS CONSTANTS}('Parameter Master Sheet', 'κAB', 'B2')$

Units: 1/Year [0,5,0.001]

Rate of C flux from atmosphere to biomass proportional to max biomass in NPP model, by land use and region

(197) Land Area $u_r[\text{Land use,region}] = \text{INTEG}(\text{Increase in Area for Land Use } u_r \text{ Region } r[\text{Land use,region}] - \text{Decrease in Land Area } u_r[\text{Land use,region}], \text{Initial Land Use } u_r[\text{Land use,region}])$

Units: hectare

The area for each land use and region.

(198) Land Area $u_r \text{ at AF start}[\text{Land use,region}] = \text{SAMPLE IF TRUE}(\text{Time} \leq \text{Time for AF Change Start}[\text{region}], \text{Land Area } u_r[\text{Land use,region}], \text{Land Area } u_r[\text{Land use,region}])$

Units: hectare

Land area of land use, u, in region, r, at the start of afforestation scenario.

(199) Land for RS gross land use emissions $[\text{Land use,region}] = \text{zidz}(\text{CO}_2 \text{ land use biomass emissions}[\text{Land use,region}] / \text{GtonsCO}_2 \text{ per GtonsC}, \text{Biomass C Intensity of Land } u_r \text{ in } \text{tonC}[\text{Land use,region}]) * \text{tonsC per GtonsC} / \text{Fraction of Biomass C released from Land Use Change } u_r[\text{Land use}])$

Units: hectare/Year

Converts LULUCF gross emissions from biomass into land area according to biomass emissions and biomass intensity, accounting for fraction of biomass released from land use change, defaulted to 1 for all land use types.

(200) Land Harvested for Bioenergy $u_r[\text{Land use,region}] = \text{MIN} (\text{Indicated Land Harvested for Bioenergy } u_r[\text{Land use,region}] , \text{Maximum Land Harvest for Bioenergy } u_r[\text{Land use,region}])$

Units: hectare/Year

Actual land harvested for bioenergy is the lesser of the indicated amount, determined by indicated bioenergy demand, and the maximum amount, determined by land availability.

(201) Land Harvested for Bioenergy $u_{rAF}[\text{Land use,region}] = \text{MIN} (\text{Indicated Land Harvested for Bioenergy } u_{rAF}[\text{Land use,region}] , \text{Maximum Land Harvest for Bioenergy } u_{rAF}[\text{Land use,region}])$

Units: hectare/Year

Actual land harvested for bioenergy is the lesser of the indicated amount, determined by indicated bioenergy demand, and the maximum amount, determined by land availability.

(202) Land use : Forest,Harvested Forest,Cropland,Pasture,Permafrost,Other

(203) Land Use Area 2015 $u_r[\text{Land use,region}] = \text{GET XLS CONSTANTS}('Parameter Master Sheet', 'Land Use areas 2015', 'B2')$

Units: hectare

The initial land area for each land use and region, based on FAO 2015 data.

(204) Land use' : Land use

Land Use' is a vector whose elements are the same as the vector of Land Use types. Used to define the matrix representing the fraction of each land use type j moving to type i as a result of human or natural activity.

(205) Last biomass sources[Forest and cropland,region] = get data between times (Historic CO2 land use biomass emissions[Forest and cropland,region] , Year to land use emissions forecast , Interpolate)

Last biomass sources[All but forest and cropland,region] = 0

Units: GtonsCO2/Year

Historic biomass gross emissions in last available year, 2015.

(206) Layer Depth[layers] = 300, 300, 1300, 1800

Units: meter

Deep ocean layer thicknesses.

(207) Layer Time Constant[layer1] = INITIAL(Layer Depth[layer1] / (Eddy Diff Coeff / Mean Depth of Adjacent Layers[layer1]))

Layer Time Constant[lower] = INITIAL(Layer Depth[lower] / (Eddy Diff Coeff / Mean Depth of Adjacent Layers[lower]))

Units: Year

Time constant of exchange between layers.

(208) layers : (layer1-layer4)

Deep ocean layers.

(209) lower : (layer2-layer4) -> upper

Lower deep ocean layers.

(210) LULUCF pct relative to RS = 0

Units: percent [-100,100,1]

Percent change from RS LULUCF emissions, starting in LULUCF start year and achieved by LULUCF target year. A value > 0 indicates LULUCF emissions are greater than in RS and thus more land is

converted than in RS. Conversely, a value < 0 indicates LULUCF emissions are less than in RS and thus less land is converted than is RS, reflected as a negative decrease in area such that the area increases over RS.

(211) LULUCF start year = 2020
Units: Year [2015,2030,1]

(212) LULUCF target year = 2050
Units: Year [2015,2100,1]
Target year to achieve LULUCF pct relative to RS.

(213) m² per hectare = 10000
Units: meter*meter/hectare

(214) Maximum Biomass C Intensity u r[Land use,region] = GET XLS CONSTANTS('Parameter Master Sheet', 'B_max', 'B2')
Units: tonsC/hectare
Maximum biomass C intensity of the land, by land use and region

(215) Maximum Land Decrease from Human Activity[Land use,region] = Land Area u r[Land use,region] / Minimum Time for Land Use change[Land use]
Units: hectare/Year
The maximum loss of each type of land in each region is determined by the available land and the minimum time required to convert the land from one type to another.

(216) Maximum Land for AF u r[Land use,region] = Land Area u r[Land use,region] / Minimum Time for Land Use change[Land use] - (Decrease in Land Area from Human Land Use Change u r[Land use,region] + Land Harvested for Bioenergy u r[Land use,region])
Units: hectare/Year
Maximum area of land of each type available for afforestation. Determined by the land area and minimum time to implement land use change, less the total of other land use changes at that time.

(217) Maximum Land Harvest for Bioenergy u r[Land use,region] = Land Area u r[Land use,region] / Minimum Land Harvest Time u[Land use]
Units: hectare/Year
The maximum rate of land harvest for bioenergy is determined by available land of each type and the minimum time required to bring biomass on that land to a harvestable state.

(218) Maximum Land Harvest for Bioenergy u rAF[Land use,region] = Land Area u r[Land use,region] / Minimum Land Harvest Time uAF[Land use]
Units: hectare/Year
The maximum rate of land harvest for bioenergy is determined by available land of each type and the minimum time required to bring biomass on that land to a harvestable state.

(219) Mean Depth of Adjacent Layers[layer1] = INITIAL((Mixed Depth + Layer Depth[layer1]) / 2)
Mean Depth of Adjacent Layers[lower] = INITIAL((Layer Depth[upper] + Layer Depth[lower]) / 2)
Units: meters
The mean depth of adjacent ocean layers.

(220) Minimum Land Harvest Time u[Land use] = 1, 1, 1, 1, 1, 1
Units: Years
The minimum time to raise bioenergy feedstock crops, by land type.

(221) Minimum Land Harvest Time uAF[Land use] = 1, 1, 1, 1, 1, 1
Units: Years
The minimum time to raise bioenergy feedstock crops, by land type.

- (222) Minimum Time for Land Use change[Land use] = 1
Units: Year
The minimum time required to change land use from one type to another.
- (223) Mixed Depth = 100
Units: meter
Mixed ocean layer depth.
- (224) Mixing Time = 1
Units: Year [0.25,10,0.25]
Atmosphere - mixed ocean layer mixing time.
- (225) MtonsC per GtonsC = 1000
Units: MtonsC/GtonsC
- (226) Natural CH4 Emissions = Flux Biosphere to CH4 * CH4 per C * MtonsC per GtonsC
Units: Mtons/Year
Flux of methane from anaerobic respiration in the biosphere, in Mtons CH4/year.
- (227) Net Carbon Removal = Total C removal - Emiss from Storage
Units: GtonsC/Year
Difference between sequestration and emissions released from storage.
- (228) Net Direct Bioenergy C Emissions = Net Direct C Emissions from Bioenergy
Units: GtonsC/Year
Net direct C emissions from biofuels. Considers only the direct C debt or credit including combustion and supply chain energy use. Does not consider impacts on NPP or C fluxes to atmosphere from harvested lands or soils on them.
- (229) Net Direct C Emissions from Bioenergy = C Emissions from Bioenergy - Fossil Fuel Emissions Avoided by Bioenergy
Units: GtonsC/Year
Net global emissions of CO2 (GtC/year) from bioenergy are emissions from bioenergy less the avoided fossil fuel emissions.
- (230) Net Flux Atm to Land Sink region r[region] = Flux Atm to Biomass region r[region] - Flux Biomass to Atm region r[region] - Flux Soil to Atm region r[region]
Units: GtonsC/Year
The annual net flux of C from the atmosphere to biomass and soil, i.e., land sink, for each region.
- (231) NonPermafrost : Forest,Harvested Forest,Cropland,Pasture,Other
- (232) NPP Land Use u r[Land use,region] = Land Area u r[Land use,region] * ((Biomass C Intensity of Land u r in tonC[Land use,region] * Reference Fractional C Increase u r[Land use,region]) + (k u r[Land use,region] * Maximum Biomass C Intensity u r[Land use,region])) * (1 - xidz (Biomass C Intensity of Land u r in tonC[Land use,region] , Maximum Biomass C Intensity u r[Land use,region] , 1) ^ v u r[Land use,region])
Units: tonsC/Year
NPP in each region is determined by a function of the biomass C relative to the maximum biomass C that each land type can support in equilibrium.
- (233) NPP per area[Land use,region] = zidz (NPP Land Use u r[Land use,region] * gC per tonsC , Land Area u r[Land use,region] * m2 per hectare)
Units: gC/(Year*meter*meter)
Net primary production (flux of carbon from atmosphere to biomass) in grams of carbon per square meter, specific to land use and region.

- (234) one year = 1
Units: Year
- (235) Other plus Harvested Forest : Other,Harvested Forest
- (236) Percent of Max AF Potential $r[\text{region}] = 0$
Units: percent [0,100,1]
Percent of total available land for afforestation.
- (237) ppm CO2 per GtonC = 0.4695
Units: ppm/GtonsC
Restated per CDIAC, <http://cdiac.ornl.gov/pns/convert.html> , that reports: 1 ppm by volume of atmosphere CO2 = 2.13 Gt C (Uses atmospheric mass (Ma) = $5.137 * 10^{18}$ kg)
- (238) Preind C in Mixed Layer = INITIAL(Preind Ocean C per meter * Mixed Depth)
Units: GtonsC
Initial carbon concentration of mixed ocean layer.
- (239) Preind Ocean C per meter = 10.2373
Units: GtonsC/meter
Corresponds with 767.8 GtC in a 75m layer.
- (240) Preindustrial C = 590
Units: GtonsC
Preindustrial CO2 content of atmosphere.
- (241) Primary Energy from Biomass = sum (Primary Energy from Biomass u[Land use!])
Units: Gj/Year
Total primary energy from biomass summed over all regions and land use types.
- (242) Primary Energy from Biomass $r[\text{region}] = \text{sum} (\text{Primary Energy from Biomass } u[r[\text{Land use!},\text{region}]])$
Units: Gj/Year
Primary energy from biomass in each region from all land use types.
- (243) Primary Energy from Biomass $u[\text{Land use}] = \text{sum} (\text{Primary Energy from Biomass } u[r[\text{Land use},\text{region!}]])$
Units: Gj/Year
Primary energy use from biomass generated on each land type, summed over all regions.
- (244) Primary Energy from Biomass $u[r[\text{Land use},\text{region}]] = \text{zidz} (\text{C from Bioenergy } u[r[\text{Land use},\text{region}]] , \text{Bioenergy C Intensity } u[\text{Land use}]) * \text{GJ per EJ}$
Units: Gj/Year
Primary energy from biomass in each region and land use type is given by the carbon released from bioenergy and the carbon intensity of bioenergy. Converted from EJ to GJ
- (245) Primary Energy from Fossil Fuels = End Use Energy from Fossil Fuels / (Fossil Fuel Combustion Efficiency * Fossil Fuel Processing Efficiency)
Units: Gj/Year
Primary energy from fossil fuels actually produced, net of fossil displaced by biofuels. Given by actual fossil end use energy and the combustion and processing efficiencies of fossil energy production.
- (246) Projected RS CO2 land use biomass emissions[Land use,region] = Last biomass sources[Land use,region] * exp (RS annual reduction in land use emissions * (Time - Year to land use emissions forecast))
Units: GtonsCO2/Year
RS CO2 land use gross emissions from biomass projected from the last year of available data, decreasing at an annual rate of 1.5% per year.

- (247) Ratio of Soil C per Biomass C = 3
Units: Dmnl
A way to initialize the soil c intensity as a ratio of biomass c intensity.
- (248) Ref Buffer Factor = 9.7
Units: Dmnl
Normal buffer factor.
- (249) Reference Fractional C Increase $u_r[\text{Land use,region}] = \text{GET XLS CONSTANTS}('Parameter Master Sheet', 'ΦAB', 'B2')$
Units: 1/Year [0,1]
The fractional rate of increase of biomass C when C intensity relative to the maximum is very low. Calculated from Fahey et al, 2005. from NPP per area/(Biomass intensity*(1-Biomass intensity/Max biomass intensity) Using the Fahey numbers, I get a biomass intensity of 12006 g/m² = 120.06 tonsC/ha The NPP per area is 483 g/m²/year = 4.83 tonsC/ha/year With the Max bio intensity of 232 tonsC/ha, Reference Fractional C Increase $u = 4.83/(120.06*(1-120.06/232)) = 0.08$
- (250) Reference Temperature Change for Effect of Warming on CH₄ from Respiration = 5
Units: DegreesC
Temperature change at which the C as CH₄ release from humus doubles for the Sensitivity of Methane Emissions to Temperature=1.
- (251) region : US,EU,China,India,Other Developed Nations,Other Developing Nations
- (252) RS annual reduction in land use emissions = -0.015
Units: 1/Year
Estimated rate of annual global change in LULUCF gross emissions, set to be consistent with global RCP8.5.
- (253) Sensitivity of C Uptake to Temperature = 1
Units: Dmnl [0,2.5,0.1]
Allows users to control the strength of the feedback effect of temperature on uptake of C by land and oceans. 0 means no temperature-carbon uptake feedback and default of 1 yields the average value found in Friedlingstein et al., 2006. Climate-Carbon Cycle Feedback Analysis: ResuMCS from the C4MIP Model Intercomparison. Journal of Climate. p3337-3353.
- (254) Sensitivity of Methane Emissions to Temperature = 0
Units: Dmnl [0,2.5,0.1]
Allows users to control the strength of the feedback effect of temperature on release of C as CH₄ from humus. Default of 0 means no temperature feedback and 1 is mean feedback.
- (255) Sensitivity of pCO₂ DIC to Temperature = INITIAL(Sensitivity of C Uptake to Temperature * Sensitivity of pCO₂ DIC to Temperature Mean)
Units: 1/DegreesC
Sensitivity of pCO₂ of dissolved inorganic carbon in ocean to temperature.
- (256) Sensitivity of pCO₂ DIC to Temperature Mean = 0.003
Units: 1/DegreesC
Sensitivity of equilibrium concentration of dissolved inorganic carbon to temperature. Calibrated to be consistent with Friedlingstein et al., 2006. Climate-Carbon Cycle Feedback Analysis: ResuMCS from the C4MIP Model Intercomparison. Journal of Climate. p3337-3353. Default Sensitivity of C Uptake to Temperature of 1 corresponds to mean value from the 11 models tested.

(257) Soil C from Human Activity Transferred from Other Land Use $u_r[\text{Land use}, \text{region}] = \text{sum} (\text{Fractional Increase in Area from Land Use Change } u[\text{Land use}', \text{Land use}] * \text{Transfer of Soil C from Human Activity from Land } u_r[\text{Land use}', \text{region}])$

Units: GtonsC/Year

The C in soil lost from each land type j adds to each type i according to the fraction of soil C loss moving from each land type j to i.

(258) Soil C from Natural Processes Transferred from Other Land Use $u_r[\text{Land use}, \text{region}] = \text{sum} (\text{Fractional Increase in Area from Natural Processes } u[\text{Land use}', \text{Land use}] * \text{Transfer of Soil C from Natural Processes from Land } u_r[\text{Land use}', \text{region}])$

Units: GtonsC/Year

The C in soil lost from each land type j adds to each type i according to the fraction of soil C loss moving from each land type j to i.

(259) Soil C Intensity of Land Use $u_r[\text{Land use}, \text{region}] = \text{zidz} (\text{Soil C Land Use } u \text{ Region } r[\text{Land use}, \text{region}] , \text{Land Area } u_r[\text{Land use}, \text{region}])$

Units: GtonsC/hectare

The average carbon intensity of soil for each land use and region.

(260) Soil C Land Use $u[\text{Land use}] = \text{sum} (\text{Soil C Land Use } u \text{ Region } r[\text{Land use}, \text{region}'])$

Units: GtonsC

Total soil carbon in each land type, summed over all regions.

(261) Soil C Land Use $u \text{ Region } r[\text{Land use}, \text{region}] = \text{INTEG} (\text{Biomass to Soil C Land Use } u_r[\text{Land use}, \text{region}] - \text{Flux Soil C to Atm Land } u_r[\text{Land use}, \text{region}] - \text{Flux Soil C to CH}_4 \text{ Land } u_r[\text{Land use}, \text{region}] + \text{Soil C Transferred from Other Land Use } u_r[\text{Land use}, \text{region}] - \text{Soil C Transferred to Other Land Use } u_r[\text{Land use}, \text{region}] , \text{Initial Soil C } u_r[\text{Land use}, \text{region}])$

Units: GtonsC

The carbon in soil for each land use and region.

(262) Soil C Region $r[\text{region}] = \text{sum} (\text{Soil C Land Use } u \text{ Region } r[\text{Land use}', \text{region}])$

Units: GtonsC

Total soil carbon in each region, summed over all land types.

(263) Soil C Transferred from AF to Other Land $u_r[\text{Land use}, \text{region}] = \text{sum} (\text{Fractional Increase from AF in Area from Land Use Change } u[\text{Land use}', \text{Land use}] * \text{Transfer of soil C from AF from } u_r[\text{Land use}', \text{region}])$

Units: GtonsC/Year

When land is afforested and changes from a prior use to forest, the soil C in the affected land is transferred from the source category to the Forest category

(264) Soil C Transferred from Bioenergy Harvest $u_r[\text{Land use}, \text{region}] = \text{sum} (\text{Fractional Increase in Area from Bioenergy Production } u[\text{Land use}', \text{Land use}] * \text{Soil C Transferred to Other Land } u_r \text{ from Bioenergy}[\text{Land use}', \text{region}])$

Units: GtonsC/Year

When land is harvested for bioenergy, the C in the soil on that land changes type from forest to harvested forest.

(265) Soil C Transferred from Other Land Use $u_r[\text{Land use}, \text{region}] = (\text{Soil C from Natural Processes Transferred from Other Land Use } u_r[\text{Land use}, \text{region}] + \text{Soil C from Human Activity Transferred from Other Land Use } u_r[\text{Land use}, \text{region}]) * \text{Switch for Active Soil C Fluxes}[\text{Land use}] + \text{Soil C Transferred from Bioenergy Harvest } u_r[\text{Land use}, \text{region}] + \text{Soil C Transferred from AF to Other Land } u_r[\text{Land use}, \text{region}]$

Units: GtonsC/Year

For each region, the total soil carbon added to each land use type from land use change is the sum of the increase from natural processes and human activity, including land changing type from harvested forest to forest..

(266) Soil C Transferred to Other Land u r from Bioenergy[Land use,region] = Soil C Intensity of Land Use u r[Land use,region] * Land Harvested for Bioenergy u r[Land use,region] * (1 - Fraction of Soil C to Atm from Land Use Change u[Land use]) * Switch for Zero C Flux Other Than Land Use Change
 Units: GtonsC/Year

Soil carbon in the area that gets reclassified from forests when it is harvested for bioenergy.

(267) Soil C Transferred to Other Land Use u r[Land use,region] = (Soil C Intensity of Land Use u r[Land use,region] * Decrease in Land Area u r[Land use,region] - C in Soil Released to Atm by Land Use Change u r[Land use,region]) * Switch for Zero C Flux Other Than Land Use Change
 Units: GtonsC/Year

When land changes from one type to another, the C in soil on that land is transferred out of that category in proportion to the average C in soil per hectare on that land type.

(268) Strength of Temp Effect on C Flux to Land = INITIAL(Sensitivity of C Uptake to Temperature * Strength of Temp Effect on Land C Flux Mean)
 Units: 1/DegreesC

Strength of temperature effect on C flux to the land.

(269) Strength of Temp Effect on Land C Flux Mean = -0.01
 Units: 1/DegreesC

Average effect of temperature on flux of carbon to land. Calibrated to be consistent with Friedlingstein et al., 2006. Climate-Carbon Cycle Feedback Analysis: ResuMCS from the C4MIP Model Intercomparison. Journal of Climate. p3337-3353. Default Sensitivity of C Uptake to Temperature of 1 corresponds to mean value from the 11 models tested.

(270) Switch for Active Soil C Fluxes[Land use] = 1
 Units: Dmnl [0,1,1]

0 --> no C fluxes into or out of Soil C stocks; 1 --> fluxes active.

(271) Switch for Bioenergy Scenario[Land use,region] = 0
 Units: Dmnl [0,1,1]

Switch to select either an exogenous pathway for end use energy supplied by biofuels (1) or to use a pulse in end-use bioenergy for testing purposes (0)

(272) Switch for Bioenergy ScenarioAF[Land use,region] = 0
 Units: Dmnl [0,1,1]

Switch to select either an exogenous pathway for end use energy supplied by biofuels (1) or to use a pulse in end-use bioenergy for testing purposes (0)

(273) Switch for Equilibrium Initial Soil C = 1
 Units: Dmnl [0,1,1]

1 --> Soil C stocks initialized in equilibrium; 0 --> Soil C stocks initialized via DSMW data or as ratio of biomass C.

(274) Switch for Flux Atm Ocean = 0
 Units: Dmnl [0,1,1]

1 = C moves Atm <—> ocean; 0 = no flux

(275) Switch for Flux FF to Atm = 1
 Units: Dmnl [0,1,1]

1 = C moves FF stock <--> atm ; 0 = no flux

(276) Switch for Fossil End Use Scenario = 0
 Units: Dmnl [0,1,1]

Switch to select either an exogenous pathway for end use energy supplied by fossil fuels (1) or to use an exogenous value for testing purposes (0)

- (277) Switch for Global Land Use Demand = 0
Units: Dmnl [0,1,1]
1 -> Use Global Bioenergy End Use Table as input to Bioenergy End Use Scenario. 0 -> Use Bioenergy End Use Table as input to Bioenergy End Use Scenario.
- (278) Switch for Global Land Use DemandAF = 0
Units: Dmnl [0,1,1]
- (279) Switch for Initial Soil C from Biomass C Ratio = 0
Units: Dmnl [0,1,1]
1 -> Use Initial soil carbon intensity as calculated as a ratio of biomass carbon intensity 0
-> Use Initial soil carbon intensity as calculated by the Digital Soil Map of the World (FAO).
- (280) Switch for Zero C atm to land[Land use] = 1
Units: Dmnl [0,1,1]
Switch for testing purposes. Zero sets C flux from atmosphere to land to zero.
- (281) Switch for Zero C Flux Other Than Land Use Change = 1
Units: Dmnl [0,1,1]
Switch to force all fluxes of C other than those caused by land use change to zero for testing purposes.
- (282) Temperature change from preindustrial = 0
Units: DegreesC
Temperature of the Atmosphere and Upper Ocean, relative to preindustrial reference period
- (283) Test Ref CO2 FF = 0
Units: Dmnl [0,1,1]
Reference CO2 fertilization factor used for testing.
- (284) Time for AF Change Start[region] = 2020
Units: Year [1850,2100,10]
Year at which afforestation efforts begin.
- (285) Time to reach AF target[region] = 50
Units: Year [0,100,1]
Time for AF area target to be reached.
- (286) tonsC per GtonsC = 1e+09
Units: tonsC/GtonsC
- (287) tonsC per ktonC = 1000
Units: tonsC/ktonsC
- (288) tonsC per MtonsC = 1e+06
Units: tonsC/MtonsC
- (289) Total Biomass and Soil C to CH4[Land use,region] = INTEG(Flux Biomass C to CH4 Land u r[Land use,region] + Flux Soil C to CH4 Land u r[Land use,region] , 0)
Units: GtonsC
Carbon flux to atmosphere in the form of CH4 from both biomass and soils.
- (290) Total Biomass C = sum (Total Biomass C Land Use u[Land use!])
Units: GtonsC
The total carbon in biomass from all land uses and regions.

- (291) Total Biomass C Land Use u [Land use] = sum (Biomass C Land Use u Region r [Land use,region!])
Units: GtonsC
Total C in biomass for each land use type, summed over all regions.
- (292) Total Biomass C Region r [region] = sum (Biomass C Land Use u Region r [Land use!,region])
Units: GtonsC
Total C in biomass in each region is the sum of C in biomass for each land use type in that region.
- (293) Total C Bio Atm = C in Atmosphere + Total Biomass C
Units: GtonsC
Total Carbon in the biosphere and atmosphere.
- (294) Total C Bio Soil Atm = Total C Bio Atm + Total Soil C
Units: GtonsC
Total C in biomass, soils, atmosphere.
- (295) Total C Bio Soil Atm Structures = Total C Bio Soil Atm + Total C in Structures
Units: GtonsC
Total C in biomass, soils, atmosphere and structures
- (296) Total C Bio Soil Ocean Atm = Total C Bio Soil Atm Structures + Total C in Ocean
Units: GtonsC
Total C in Biomass, Soils, Atmosphere, Structures and Ocean
- (297) Total C Bio Soil Ocean Atm Seq = Total C Bio Soil Ocean Atm + C Sequestered
Units: GtonsC
Total C in biomass, soils, atmosphere, ocean and any C sequestered by human activity (by e.g. CCS)
- (298) Total C Bio Soil Ocean Atmosphere Fossil = Total C Bio Soil Ocean Atm Seq + Fossil Carbon
Units: GtonsC
Total Carbon including biomass, soils, atmosphere, ocean, structures, human sequestration and fossil stocks.
- (299) Total C Bio Soil Ocean Atmosphere Fossil plus CH₄ = Total C Bio Soil Ocean Atmosphere Fossil + sum (Total Biomass and Soil C to CH₄[Land use!,region!])
Units: GtonsC
Total Carbon including biomass, soils, atmosphere, ocean, structures, human sequestration and fossil stocks.
- (300) Total C in Ocean = C in Mixed Layer + sum (C in Deep Ocean[layers!])
Units: GtonsC
Total C in ocean, summing the mixed layer and all deep layers.
- (301) Total C in Structures = sum (Total C in Structures u [Land use!])
Units: GtonsC
Total C in structures, summed over all land use types in all regions.
- (302) Total C in Structures r [region] = sum (Biomass C in Structures u r [Land use!,region])
Units: GtonsC
Total C in structures by region, summed over land use types.
- (303) Total C in Structures u [Land use] = sum (Biomass C in Structures u r [Land use,region!])
Units: GtonsC

Total C in structures by land use type, summed across regions

- (304) Total C removal = 0
Units: GtonsC/Year
Sequestration via AF.
- (305) Total Decrease in Area region r from Human Activity[region] = sum (Land Harvested for Bioenergy u r[Land use!,region])
Units: hectare/Year
For each region, the total area being converted from human processes to another land use.
- (306) Total Decrease in Land Area region r from Natural Processes[region] = sum (Decrease in Land Area from Natural Processes u r[Land use!,region])
Units: hectare/Year
For each region, the total area being converted from natural processes to another land use.
- (307) Total Flux Atm to Biomass = sum (Flux Atm to Biomass Land Use u[Land use!])
Units: GtonsC/Year
The total annual flux of carbon from the atmosphere to biomass due to primary production.
- (308) Total Flux Biomass and Soil to Atm region r[region] = Flux Biomass to Atm region r[region] + Flux Soil to Atm region r[region]
Units: GtonsC/Year
The total annual net flux of carbon from the biomass to the atmosphere as CO₂ due to land use conversions including the flux from C in biomass contained in human structures due to decay or combustion.
- (309) Total Flux Biomass to Atmosphere = sum (Flux Biomass to Atm Land Use u[Land use!])
Units: GtonsC/Year
The total annual net flux of carbon from the biomass to the atmosphere as CO₂ due to land use conversions including the flux from C in biomass contained in human structures due to decay or combustion.
- (310) Total Flux Biomass to CH₄ = sum (Flux Biomass C to CH₄ Land u r[Land use!,region!])
Units: GtonsC/Year
Total flux from biomass to the atmosphere in the form of CH₄ across all regions.
- (311) Total Flux Soil to Atmosphere = sum (Flux Soil to Atm Land Use u[Land use!])
Units: GtonsC/Year
The total annual net flux of carbon as CO₂ from the soil to the atmosphere due to land use conversions.
- (312) Total Flux Soil to CH₄ = sum (Flux Soil C to CH₄ Land u r[Land use!,region!])
Units: GtonsC/Year
Total flux from soils to the atmosphere in the form of CH₄ across all regions.
- (313) Total Fossil Fuel Emissions = Emissions from Fossil Fuel + Fossil Emissions from Bioenergy Supply Chain
Units: GtonsC/Year
Total fossil fuel emissions are the emissions generated by the production of primary energy from fossil fuels plus the emissions from fossil fuels used in the bioenergy supply chain.
- (314) Total Land Area[region] = sum (Land Area u r[Land use!,region])
Units: hectare
The total land area of each region.
- (315) Total Land Area by type[Land use] = sum (Land Area u r[Land use!,region!])
Units: hectare
The total land area of each region.

(316) Total Net Flux Atm to Land Sink = sum (Net Flux Atm to Land Sink region r[region!])
Units: GtonsC/Year

The total annual net flux of C from the atmosphere to biomass and soil, i.e., land sink, across all regions.

(317) Total Net Flux to Land Sink = sum (Net Flux Atm to Land Sink region r[region!])
Units: GtonsC/Year

The total annual net flux of C from the atmosphere to biomass and soil, i.e., land sink.

(318) Total Soil C = sum (Soil C Land Use u[Land use!])
Units: GtonsC

The total carbon in soil from all land uses and regions.

(319) Transfer of Biomass C from AF from u r[Land use,region] = Biomass C Intensity of Land u r[Land use,region] * Decrease in Land Area for AF u r[Land use,region]
Units: GtonsC/Year

The transfer of C in biomass from one land type to others is proportional to the C intensity per hectare for that land type. When land use changes, a fraction of the C in biomass is released to the Atmosphere as CO₂, and the rest is transferred to other land use types. Land use changing type excludes changes in land use type from bioenergy, which handled elsewhere.

(320) Transfer of Biomass C from Human Activity from u r[Land use,region] = Biomass C Intensity of Land u r[Land use,region] * Decrease in Land Area from Human Land Use Change u r[Land use,region] * (1 - Fraction of Biomass C released from Land Use Change u[Land use])
Units: GtonsC/Year

The transfer of C in biomass from one land type to others is proportional to the C intensity per hectare for that land type. When land use changes, a fraction of the C in biomass is released to the Atmosphere as CO₂, and the rest is transferred to other land use types. Land use changing type excludes changes in land use type from bioenergy, which handled elsewhere.

(321) Transfer of Biomass C from Natural Processes from u r[Land use,region] = Biomass C Intensity of Land u r[Land use,region] * Decrease in Land Area from Natural Processes u r[Land use,region] * (1 - Fraction of Biomass C released from Land Use Change u[Land use])
Units: GtonsC/Year

The transfer of C in biomass from one land type to others is proportional to the C intensity per hectare for that land type. When land use changes, a fraction of the C in biomass is released to the Atmosphere as CO₂, and the rest is transferred to other land use types.

(322) Transfer of soil C from AF from u r[Land use,region] = Soil C Intensity of Land Use u r[Land use,region] * Decrease in Land Area for AF u r[Land use,region]
Units: GtonsC/Year

The carbon in the soil of land that is being traferred into land being used for afforestation.

(323) Transfer of Soil C from Human Activity from Land u r[Land use,region] = Soil C Intensity of Land Use u r[Land use,region] * Decrease in Land Area from Human Land Use Change u r[Land use,region] * (1 - Fraction of Soil C to Atm from Land Use Change u[Land use])
Units: GtonsC/Year

When land use changes, a fraction of the soil C is released to the Atmosphere as CO₂, and the rest is transferred to other land use types

(324) Transfer of Soil C from Natural Processes from Land u r[Land use,region] = Soil C Intensity of Land Use u r[Land use,region] * Decrease in Land Area from Natural Processes u r[Land use,region] * (1 - Fraction of Soil C to Atm from Land Use Change u[Land use])
Units: GtonsC/Year

The transfer of C in soil from one land type to others is proportional to the soil C intensity per hectare for that land type. When land use changes, a fraction of the soil C is released to the Atmosphere as CO₂, and the rest is transferred to other land use types.

(325) upper : (layer1-layer3) -> lower
Upper deep ocean layers.

(326) v u r[Land use,region] = GET XLS CONSTANTS("?Parameter Master Sheet", 'vAB', 'B2')
Units: Dmnl [0,1,0.01]
Shape parameter in the Richards growth function for NPP.

(327) VSATLEASTONE = 1
Units: Dmnl

(328) VSSUM == 0
Units: Dmnl

(329) Year = Time - INITIAL TIME - "20 years"
Units: Year

(330) Year to land use emissions forecast = 2015
Units: Year
Last year of available historic LULUCF data from Houghton and Nassikas (2017)