Carbon Density and Anthropogenic Land Use Influences on Net Land-Use Change Emissions

Supplementary Material

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CONTENTS

1. G-CARBON Model

1.1. **G-CARBON Model Parameters**

Annual net carbon flow coefficients, a_i^j in Equation 1, are given in the following table.

Original carbon box	**NPP**	**NPP**	**NPP**	**veg**	**veg**	**veg**	**litter**	**litter**	**soil**
Destination carbon box	**veg**	**litter**	**soil**	**litter**	**soil**	**atm**	**soil**	**atm**	**atm**
Primary non-boreal forest	vary by region			94%	6%	0%	6%	94%	100%
Secondary non-boreal forest				94%	6%	0%	6%	94%	100%
Boreal forest				94%	6%	0%	6%	94%	100%
Cropland	20%	65%	15%	88%	12%	0%	10%	90%	100%
Pasture	35%	60%	5%	67%	33%	0%	6%	94%	100%
Grassland	35%	60%	5%	67%	33%	0%	6%	94%	100%
Shrubland	35%	60%	5%	67%	33%	0%	6%	94%	100%
Tundra	35%	60%	5%	67%	33%	0%	6%	94%	100%
Rock, ice, & desert	35%	60%	5%	67%	33%	0%	6%	94%	100%
Urbanland	35%	60%	5%	67%	33%	0%	6%	94%	100%
High latitude wetland/peatland	35%	60%	5%	67%	33%	0%	6%	94%	100%
Mid & low latitude wetland	35%	60%	5%	67%	33%	0%	6%	94%	100%

Aggregate land-transfers are tracked for each region. These are accounted for as follows. If, during a timestep, area in an ecosystem is decreased, then all carbon pools in that carbon box model are proportionately decreased. The aggregate amount of carbon in areas that transition to new ecosystem types is re-apportioned to ecosystem types within that region that gain land during that time step. Immediate LUC emissions are assigned to the ecosystem losing land, and delayed LUC emissions (litter decay and non-immediate soil changes) are assigned as emissions from the new ecosystem. This procedure efficiently approximates the carbon flows that would occur under a more spatially explicit carbon model. Total carbon amount, including amounts transferred to or from the atmosphere, is preserved within each model region.

When forest is converted to cropland, for example, most of the above ground carbon is assumed to be lost to the atmosphere, although some could be transferred to other carbon pools. The majority of soil carbon is assumed to stay in the soil.

Carbon flows due to LUC in the central scenario, represented by $f_i(LUC)$ in Equation 1, are given in the following table. Destination marked "stay" indicates the fraction of carbon that was assumed to remain in the same carbon pool, albeit assigned to the destination ecosystem.

Original carbon box	**veg**	**veg**	**veg**	**litter**	**litter**	**litter**	**soil**	**soil**
Destination carbon box	**atm**	**litter**	**soil**	**stay**	**soil**	**atm**	**stay**	**atm**
Primary non-boreal forest	78%	20%	2%	25%	0%	75%	95%	5%
Secondary non-boreal forest	78%	20%	2%	25%	0%	75%	95%	5%
Boreal forest	78%	20%	2%	25%	0%	75%	95%	5%
Cropland	80%	18%	2%	100%	0%	0%	100%	0%
Pasture	80%	18%	2%	100%	0%	0%	100%	0%
Grassland	80%	18%	2%	25%	0%	75%	95%	5%
Shrubland	80%	18%	2%	25%	0%	75%	95%	5%
Tundra	80%	18%	2%	25%	0%	75%	95%	5%
Rock, ice, & desert	80%	18%	2%	25%	0%	75%	95%	5%
Urbanland	80%	18%	2%	25%	0%	75%	95%	5%
High latitude wetland/peatland	80%	18%	2%	25%	0%	75%	95%	5%
Mid & low latitude wetland	80%	18%	2%	25%	0%	75%	95%	5%

1.2. **Model Carbon Calibration**

ISAM forest vegetation carbon densities were assumed to include dead wood; FAO data providing vegetation and deadwood carbon densities for each region was used to adjust the ISAM values to remove deadwood. FAO litter-to-vegetation ratios were used to calculate litter carbon densities from the adjusted vegetation values, and the deadwood carbon was added to the litter pool.

Litter carbon density values for grassland and shrubland were set to be 10% of the soil values of each ecosystem. Grassland vegetation density values were set to be 33% of the litter values. These values are small and have little impact on the results.

Wetland ecosystems were assumed to have a NPP value of 0.25 kgC/m^2/yr (Blodau 2002). Wetland vegetation and soil carbon density values are from Bridgham et al. (2007). For tundra, global values for NPP, vegetation, and soil, from Table 1 of Jain and Yang (2005), were used for all regions. Because litter carbon is not accounted for in these tables, the regional litter values of shrubland were used as litter values for all wetlands and tundra; in each region the soil values were reduced by the amounts attributed to litter. Because wetland ecosystems are currently still carbon-sinks, soil turnover timescales were set such that wetlands have a net sequestration of 0.015 kg C/m^2 per year (Bridgham et al., 2007) in 1500.

For NPP for rock, ice, and desert areas, and for urbanland, data from the NASA-Carnegie-Ames-Stanford Approach (CASA) Project was used (Potter, 2012). For the vegetation and soil boxes, values used in the GCAM model were used; for rock, ice, and desert, from Table 3 of King et al. (1997), adjusted for each region. Litter values in both land-uses were set based on the ratio of litter to soil of the same land-uses in the NASA-CASA data.

Because this model runs with an annual time-step, some portion of NPP, which over a short timescale flows to vegetation, is transferred over a year to litter (and a small portion to soil). For non-forest ecosystems, transfer coefficients are taken from Wigley (1993) and turnover timescales, τ_i , are calculated by solving the above equations with the corresponding NPP and carbon densities. For boreal and non-boreal forests, the annual NPP flow fractions are determined in each region by setting the vegetation turnover timescale to match the general values given in Houghton and Hackler (1995) of 65, 50, and 30 years for boreal, temperate, and tropical forests, respectively. Forest vegetation, litter, and soil carbon box models use transfer coefficients from Harvey (1989), based on Emanuel et al. (1984).

1.3. Cropland and Pasture

Representing cropland requires an estimate of the area of land actually planted in crops along with the productivity of those crops. Total cropland areas from Hurtt et al. (2011) represent reported arable land, which is larger than harvested crop area. The difference can be due to areas of: fallow land, conservation reserves, failed crops, and land temporarily used for other purposes.

Harvested crop areas for recent decades are obtained from FAO data, adjusted for double cropping using the GCAM data processing methodology (Kyle et al., 2011). For the future, harvested areas were estimated made by scaling FAO 2005 data by the trend in cropland area in the GCAM 4.5 scenario. Harvested area in the past is obtained from the data sources described below. Other arable land is estimated by subtracting the harvested area from the total cropland areas from by Hurtt et al. For other arable land in the future, the 2005 value is adjusted by the trend in other arable land area in the GCAM 4.5 scenario.

For recent years, crop NPP values are calculated from harvest data using the methods of Hicke and Lobell (2004) as implemented in GCAM (Kyle et al., 2011). Regional values were calculated for years centered on 1962, 1970, 1980, 1990, 2000, and 2005, based on harvest data from the Food and Agriculture Organization (FAO) of the United Nations (“FAOSTAT Production,” 2012). Values were also estimated for the years 1950, 1940, 1900, and 1870 (where available) based on harvest data from various data sources (Mitchell, 1975, 1988, 2007a, 2007b, 2007c; Trant 1999; USDA NASS). In all cases, the aggregate cropland NPP value is the production-weighted average across crop categories.

The equilibrium soil and litter carbon values for harvested cropland in 2005 are taken from Thomson et al. (2008); with litter apportioned as 3-15% of the carbon, based on regional conditions. For vegetation, present day carbon densities were obtained from Table 1 of Houghton (1999), as used in GCAM (Kyle et al., 2011). Equilibrium cropland carbon values for the 1870 starting point were estimated by scaling the 2005 values based on the relative magnitude of the change in NPP between 1870 and 2005. Turnover timescales were assumed to have been lower in the past, and to have increased from 1940 to 1960 by 20% due to general improvements in tillage practices.

The values above are applied to the harvested cropland area. Regional grassland values are used for other arable land. The area-weighted combination is used for the total cropland area (which consists of harvested cropland + other arable land) in the carbon model.

The regional trends in cropland effective NPP are given in the following table. Note that NPP trends reflect the combination of changes in productivity and changes in crop mix.

Year	Africa	Australia NZ	Canada	China	E Europe	Former Soviet Union	India	Japan	Korea	Latin America	Middle East	SE Asia	USA	W Europe
1870	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1900	1.00	0.83	0.98	1.00	1.00	1.39	1.00	1.00	1.00	1.00	1.00	1.00	0.91	1.00
1940	1.00	1.18	0.89	1.00	0.52	1.40	1.00	0.90	1.00	1.00	1.00	1.00	0.99	1.09
1950	0.71	1.28	0.90	0.86	0.48	1.62	0.94	0.84	1.01	1.22	0.85	0.82	1.03	1.26
1962	0.94	1.27	0.88	0.74	0.73	1.45	0.98	1.03	1.14	1.19	0.82	0.89	1.15	1.32
1970	0.85	1.23	0.89	0.99	1.00	1.72	0.98	1.08	1.16	1.24	0.78	0.90	1.23	1.40
1980	0.96	1.15	0.85	1.23	1.14	1.70	0.98	1.00	1.34	1.30	0.71	0.97	1.21	1.40
1990	0.82	1.23	0.82	1.46	1.16	1.97	1.07	1.06	1.43	1.36	0.69	1.08	1.36	1.46
2000	0.80	1.22	0.87	1.54	1.15	1.96	1.19	0.99	1.33	1.43	0.72	1.25	1.42	1.57
2005	0.84	1.20	0.90	1.54	1.19	2.29	1.23	0.97	1.23	1.55	0.84	1.43	1.45	1.57
2020	0.92	1.17	0.80	1.77	1.19	2.18	1.36	0.98	1.24	1.89	0.87	1.81	1.51	1.64
2035	0.94	1.02	0.85	1.77	1.12	2.07	1.56	0.94	1.23	2.00	0.92	2.27	1.49	1.68
2050	0.95	0.99	0.89	1.71	1.04	2.19	1.63	0.87	1.22	2.05	0.90	2.35	1.47	1.68
2065	0.96	1.01	0.92	1.73	1.03	2.18	1.61	0.83	1.22	2.07	0.90	2.37	1.53	1.71
2080	0.96	1.03	0.97	1.79	1.04	2.16	1.55	0.82	1.23	2.09	0.91	2.36	1.62	1.76
2095	0.97	1.04	1.00	1.85	1.07	2.16	1.54	0.86	1.29	2.08	0.93	2.37	1.70	1.82
2100	0.98	1.05	1.01	1.87	1.09	2.15	1.54	0.87	1.30	2.07	0.94	2.37	1.72	1.85

1.4. **Potential Vegetation**

The SAGE global potential vegetation dataset is reclassified to G-CARBON ecosystems using the reclassification system shown in the following table:

SAGE Potential Vegetation Type	G-CARBON Ecosystem
Tropical Evergreen Forest/Woodland	Non-boreal Forest
Tropical Deciduous Forest/Woodland	Non-boreal Forest
Temperate Broadleaf Evergreen Forest/Woodland	Non-boreal Forest
Temperate Needleleaf Evergreen Forest/Woodland	Non-boreal Forest
Temperate Deciduous Forest/Woodland	Non-boreal Forest
Boreal Evergreen Forest/Woodland	Boreal Forest
Boreal Deciduous Forest/Woodland	Boreal Forest
Evergreen/Deciduous Mixed Forest	MODIS reclassification
Savanna	Grassland
Grassland/Steppe	Grassland
Dense Shrubland	Shrubland
Open Shrubland	Shrubland
Tundra	Tundra
Desert	Rock, Ice, & Desert
Polar Desert/Rock/Ice	Rock, Ice, & Desert

A large portion of high latitude areas, in particular, are classified as Mixed Forest in the SAGE data. This results an unrealistically large amount of high latitude forests. Where possible, the SAGE Evergreen/Deciduous Mixed Forest categories were replaced by the following MODIS IGBP Land Cover Types, mapped to G-CARBON ecosystems as follows:

MODIS IGBP Land Cover Type	G-CARBON Ecosystem
Evergreen Needleleaf Forest	Boreal Forest
Evergreen Broadleaf Forest	Non-boreal Forest
Deciduous Needleleaf Forest	Boreal Forest
Deciduous Broadleaf Forest	Non-boreal Forest
Mixed Forests	Non-boreal Forest
Closed Shrublands	Shrublands
Open Shrublands	Shrublands
Woody Savannas	Shrublands
Savannas	Grassland
Grasslands	Grassland
Permanent Wetlands	High or Low Latitude Wetlands
Croplands	Non-boreal Forest
Urban and Built-up	Non-boreal Forest
Cropland/Natural Vegetation Mosaic	Non-boreal Forest
Snow and Ice	Rock, Ice, & Desert
Barren or Sparsely Vegetated	Rock, Ice, & Desert

Note that three MODIS categories which are modern land uses (Croplands, Urban and Built-up, and Cropland/Natural Vegetation Mosaic) are reclassified as Non-boreal Forest for the G-CARBON ecosystem data (these are small, since this re-classification is only being applied to SAGE areas classified as mixed forest). The MODIS category Mixed Forests is reclassified as Non-boreal Forest. Note that there is a smaller area in the MODIS data classified as mixed forest as compared to the SAGE data.

1.5. **Wetlands**

In order to estimate the location and extent of wetlands, the Global Lakes and Wetlands Database (GLWD) data was compared to SAGE at 5 min resolution. For any cell classified as 100% wetlands in the GLWD, corresponding cells in the SAGE dataset that were classified as Mixed Forest, Shrubland, Grassland, and Rock, Ice, and Desert were re-classified as Wetlands. For any cell classified as <100% wetlands, this percentage is used to replace that percentage of all ecosystem types in the SAGE data. This procedure yields 447 million ha of global wetlands in 2000. The resulting estimate of wetland areas in the USA in 2000 (79 million ha) is slightly lower than the area given in the first State of the Carbon Cycle Report (SOCCR) (112 million ha), while the Canada estimate (131 million ha) matches SOCCR exactly (King et al. 2007). We recognize that these estimates are quite uncertain, but given the importance of wetlands to regional and global carbon-cycle, we feel this procedure provides a reasonable estimate.

1.6. **Wood Products**

Total wood product production was split into the following categories (Winjum et al. 1998, Buchanan & Levine 1999).

Commodity	Term	Fraction
SawnWood	long-term	0.12
PaperPulpwood	long-term	0.09
OtherRoundwood	long-term	0.05
ShortTerm	short-term	0.74

Where the short-term product pool is a generic category for both products and waste that is assumed to quickly decay to the atmosphere.

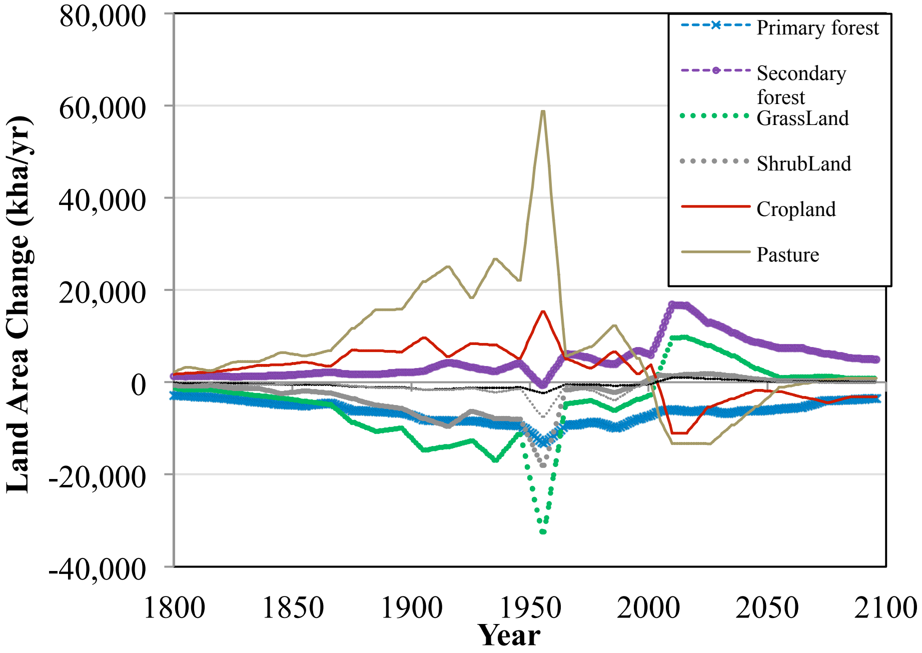
The turnover timescale is assumed to vary regionally by product pool as follows (Winjum et al. 1998):

Turnover-timescale (yr)

		Forest Region		
Commodity	Term	Boreal	Temperate	Tropical
SawnWood	long-term	200	100	50
PaperPulpwood	long-term	200	100	10
OtherRoundwood	long-term	50	25	12.5
ShortTermRoundwood	short-term	0.5	0.5	0.5

2. Results: Additional Detail

Annual global land area changes (kha/yr) by ecosystem (smoothed by 9 year averaging).



Net global land area changes (1000 kha) by ecosystem.

Land-Use	Total 1700-2000	Total 1850-2000	Total 2000-2100	Average 1980-1989	Average 1990-1999
Primary non-boreal forest	-1,653.6	-1,217.7	-546.4	-9.7	-8.2
Secondary non-boreal forest	678.3	475.9	916.6	4.0	6.6
Grassland	-1,809.6	-1,590.2	347.9	-5.8	-4.0
Shrubland	-933.8	-817.3	81.6	-2.1	-0.8
Cropland	1,231.7	973.1	-405.2	6.3	2.4
Pasture	2,995.7	2,596.7	-487.4	11.8	5.9
High latitude wetland/peatland	-19.5	-18.3	9.8	-0.1	-0.2
Mid & low latitude wetland	-161.0	-136.4	27.0	-0.7	-0.5
Boreal forest	-31.4	-26.2	20.2	0.0	-0.4
Tundra	-132.0	-104.1	28.4	-2.3	-0.5
Rock, Ice, & Desert	-217.0	-183.4	1.5	-2.1	-1.2
Urbanland	52.2	48.0	5.9	0.7	0.9

2.1. **Comparison to Hayes et al.**

Average annual total NEE (Hayes et al., 2011) and net land-use change emissions for the USA and Canada

	USA		**Canada**	
Ecosystem	**Hayes et al. (2011)**	**G-CARBON**	**Hayes et al. (2011)**	**G-CARBON**
Forest lands	-244.4	-118.3	-31.0	-16.8
Cropland soil	-17.9	-11.8	-2.7	44.9
Grassland	-13.2	0.2	-3.1	0.6
Otherlands	-26.5	5.8	-6.8	-8.1
Total	-302.0	-124.1	-43.6	20.5

Note that the category otherlands contains the net effect of crop consumption and release in addition to NEE for all other ecosystem types.

3. Sensitivity Test Details

3.1. **Sensitivity Test Results**

The absolute change in carbon release (positive numbers indicate net carbon transfer from the terrestrial system) for a range of sensitivity tests.

Scenario	**Total 1700-2000**	**Total 1850-2000**	**Total 2000-2100**	**Average 1980-1989**	**Average 1990-1999**
Central Scenario	253	211	-68	1.21	0.73
Land-Use History					
No Shifting Cultivation, Primary Land Priority	256	211	-75	1.22	0.67
No Shifting Cultivation, Secondary Land Priority	247	205	-63	1.22	0.69
Shifting Cultivation, Primary Land Priority	260	216	-80	1.28	0.80
Shifting Cultivation, Secondary Land Priority	250	207	-59	1.26	0.75
Carbon Density & NPP Assumptions					
C densities based on GCAM model (not crop or wetland)	277	232	-79	1.24	0.72
All forest C densities based on GCAM model (not soil)	267	224	-71	1.37	0.87
All forest C densities based on CASA model (not soil)	342	286	-90	1.96	1.23
Non-boreal forest C densities based on VEGAS model (not soil)	207	174	-62	0.90	0.32
Non-boreal forest C densities based on CESM model (not soil)	239	203	-58	1.33	0.62
Soil C densities based on CESM model for all ecosystems available	213	170	-76	0.89	0.44
Soil C densities based on CESM model for ecosystems with organic soils	232	185	-78	0.97	0.49
Harris et al. Vegetation and litter C densities for tropical forests	225	186	-62	1.02	0.54

Cropland And Pasture					
Cropland with grassland C values	178	146	-87	0.59	0.13
Pasture with grassland C values	226	185	-73	1.03	0.58
Land-Use Change Carbon Disturbance					
5% soil loss to atmosphere from cropland and pasture under LUC	254	211	-67	1.22	0.74
50% litter loss to atmosphere from all forest under LUC	253	210	-68	1.20	0.74
No soil loss from grassland and shrubland under LUC	249	207	-66	1.23	0.76
10% higher soil loss to atmosphere under LUC	276	230	-73	1.30	0.73
No soil loss to atmosphere under LUC	242	201	-65	1.17	0.74
Carbon Box Flow					
Forest NPP to veg flow 25% higher	250	207	-72	1.17	0.67
Forest NPP to veg flow 25% lower	257	215	-62	1.27	0.81
Forest NPP 100% to vegetation	240	198	-78	1.09	0.55
Pasture/grass/shrubland NPP to veg flow 25% higher	253	210	-69	1.21	0.73
Pasture/grass/shrubland NPP to veg flow 25% lower	254	211	-68	1.22	0.74
Crop NPP to litter flow 40%	259	214	-73	1.12	0.64
Other					
No wetlands	247	196	-75	1.04	0.57
Rapid tropical forest growth	250	208	-71	1.16	0.66
Slow forest growth	257	214	-62	1.27	0.80
No Forest Nitrogen Feedback	264	222	-59	1.49	1.05
Feedbacks					
All Feedbacks	163	133	-207	0.16	-0.26
All Feedbacks, beta low	199	165	-135	0.62	0.27
All Feedbacks, beta high	127	102	-279	-0.30	-0.80

The above results presented as a percent of the central model result.

Scenario	**Total 1700-2000**	**Total 1850-2000**	**Total 2000-2100**	**Average 1980-1989**	**Average 1990-1999**
Land-Use History					
No Shifting Cultivation, Primary Land Priority	101%	100%	109%	101%	91%
No Shifting Cultivation, Secondary Land Priority	98%	97%	91%	100%	95%
Shifting Cultivation, Primary Land Priority	103%	103%	117%	106%	109%
Shifting Cultivation, Secondary Land Priority	99%	98%	86%	104%	103%
Carbon Density & NPP Assumptions					
C densities based on GCAM model (not crop or wetland)	109%	110%	116%	102%	98%
All forest C densities based on GCAM model (not soil)	106%	106%	104%	113%	119%
All forest C densities based on CASA model (not soil)	135%	136%	132%	162%	168%
Non-boreal forest C densities based on VEGAS model (not soil)	82%	83%	91%	74%	44%
Non-boreal forest C densities based on CESM model (not soil)	94%	96%	85%	110%	85%
Soil C densities based on CESM model for all ecosystems available	84%	80%	111%	74%	61%
Soil C densities based on CESM model for ecosystems with organic soils	92%	88%	114%	80%	67%
Harris et al. Vegetation and litter C densities for tropical forests	89%	88%	90%	84%	74%

Cropland And Pasture					
Cropland with grassland C values	70%	69%	127%	49%	18%
Pasture with grassland C values	89%	88%	107%	85%	79%
Land-Use Change Carbon Disturbance					
5% soil loss to atmosphere from cropland and pasture under LUC	100%	100%	98%	101%	101%
50% litter loss to atmosphere from all forest under LUC	100%	100%	100%	99%	101%
No soil loss from grassland and shrubland under LUC	98%	98%	96%	101%	104%
10% higher soil loss to atmosphere under LUC	109%	109%	106%	107%	100%
No soil loss to atmosphere under LUC	96%	96%	96%	96%	101%
Carbon Box Flow					
Forest NPP to veg flow 25% higher	99%	98%	106%	96%	91%
Forest NPP to veg flow 25% lower	102%	102%	90%	105%	111%
Forest NPP 100% to vegetation	95%	94%	114%	90%	76%
Pasture/grass/shrubland NPP to veg flow 25% higher	100%	100%	101%	100%	100%
Pasture/grass/shrubland NPP to veg flow 25% lower	100%	100%	99%	100%	100%
Crop NPP to litter flow 40%	102%	102%	107%	92%	87%
Other					
No wetlands	98%	93%	110%	85%	78%
Rapid tropical forest growth	99%	99%	104%	95%	90%
Slow forest growth	101%	102%	91%	104%	110%
No Forest Nitrogen Feedback	104%	105%	87%	123%	143%

3.2. NPP and Carbon Values for Sensitivity Tests

Above ground forest carbon density is not directly available from most ecosystem model outputs, instead only total vegetation carbon density (for forested and non-forested portions of the cell) by grid cell is provided. This means that forest carbon density must be inferred from model outputs, given that, in general, grid cells are generally partitioned between multiple ecosystem types. In the case of CASA, vegetation is internally represented as forested and herbaceous, in the case of VEGAS between four PFTs, and in the case of CESM between multiple ecosystem types.

The following procedure was used to infer forest carbon density for purposes of conducting sensitivity tests. In all cases, data is estimated using a pre-industrial equilibrium spin-up supplied by each modeling group, where vegetation has reached its equilibrium value. (For CASA the spin-up period is for 1946.)

For CASA, based on the percentage of tree-cover and vegetation-cover, grid cells were categorized into separate classes, separated by each 10% increments of forest cover. The forest carbon density was taken to be the average of the two bins with the highest fractional forest cover that included at least 10% of total forested cells, filtering by cells that were designated as forest cells in the CASA vegetation map. Density values were obtained for vegetation, litter, and NPP by dividing total carbon by the total tree-covered area of the cells used to obtain densities; the total soil carbon was divided by the total vegetation-covered area of the cells to obtain the density.

Forest carbon densities for CESM were processed in a similar fashion. In this case, the total carbon in forested cells estimated in this manner was greater than the total carbon in the original CESM output data in several regions. The largest bias was in the

USA, Africa, Latin America, and Southeast Asia. This could be because the forested portion of cells with a high forest cover in these regions had higher vegetation density than cells with lower fractional forest cover. The average carbon density values in these regions were reduced to be consistent with the total vegetation carbon in forested cells. The carbon density was set so that total forest vegetation carbon was equal to total above-ground vegetation carbon from the CESM data times the fraction of forest vegetation to total above ground vegetation in each region from the default G-CARBON dataset.

For VEGAS a similar process occurred, except that tree-cover and vegetation-cover grids were not available for the data. Vegetation type grids were used instead, and the same percent cover classes were created based on percent forest PFT, and percent vegetation of any type. The CASA vegetation map was used to filter out cells that are not forest cells in the CASA dataset. This was done because the VEGAS forest PFT category represents a broad range of woody vegetation, and we wanted to restrict our sensitivity test to areas that would be considered forest in the other datasets. To obtain forest vegetation carbon as comparable as possible to the other datasets, we also reduced the estimated value by the fraction of forest vegetation to total above ground vegetation in each region from the default G-CARBON dataset.

For a majority of regions, especially in tropical areas, the average non-boreal forest carbon densities from Carnegie-Ames-Stanford Approach (CASA) Project are higher than the values used in the G-CARBON core case (Potter, 2012). If CASA regional boreal and non-boreal forest NPP and C densities are used for forest in G-CARBON, the global cumulative emissions for the period 1700-2000 are 89 GtC higher than in the core case, an increase of 35%. If GCAM core model carbon densities are used for all ecosystems (except crops and wetlands), total emissions are 23 GtC (9%) higher. If only the GCAM boreal forest and non-boreal forest carbon density values are used, emissions are 14 GtC (5.6%) higher. If non-boreal forest C densities from the Vegetation-Global-Atmosphere-Soil (VEGAS) Terrestrial Carbon Cycle Model are used, 1700-2000 emissions are 16.4 GtC (6.5%) higher. For many regions, VEGAS non-boreal forest vegetation C densities are lower than the core values, but soil C is higher. Emissions from non-boreal forest are actually 19.8 GtC lower than in the core model; emissions from the croplands and pasture that these forests are converted to, however, are 16.8 GtC and 19.4 GtC higher respectively. Almost all of the increased emissions come from tropical areas. Vegetation C estimates from the Community Earth System Model (CESM) are very high in tropical areas, and very low in some non-tropical areas. CESM soil C estimates do not include organic C; for non-boreal forest, for most regions, these estimates are slightly lower than the core estimates used. If non-boreal forest NPP and carbon densities from CESM are used, 1700-2000 emissions are 20.4 GtC (8.1%) higher. The higher emissions are nearly all released from non-boreal forest, as 78% of forest vegetation goes directly to the atmosphere during LUC.

If CESM mineral soil C is used for all ecosystems, total emissions are 40.3 GtC (15.9%) lower. Cropland releases are 42.7 GtC lower (78% less) than emissions in the core model over this period. Secondary forest uptake is 15.8 GtC greater (44% higher) than in the core scenario. If CESM mineral soil C is used only for ecosystems with high organic C contents (boreal forest, tundra, all wetlands, and, indirectly, pasture), emissions are 21.3 GtC (8.4%) lower. Pasture takes up 12.4 more GtC than it does in the core run, an increase of 106%. Similarly, cropland releases 13.9 GtC (25%) less than in the core run. Because peat does not build, high latitude wetlands take up almost no carbon, whereas in the core run they take up 8.3 GtC over this period. Low latitude wetlands release 3.5 GtC. Oddly, secondary non-boreal forest uptake is 7.2 GtC (24%) higher than in the core run.

The assumptions used in the tropical forest sensitivity test are provided below:

	Vegetation Density (kgC/m^2)	
Region	**Harris et al. (2012)**	**Default Value**
Africa	9.3	16.6
Latin America	11.2	17.2
Southeast Asia	14.9	17.1
India	10.4	15.5

The Harris et al. values are smaller than the default values, resulting in lower estimates of LUC emissions. We note, however, that these values appear to be for all forests: if substantial areas of secondary forest are included, these values could be biased low in their use here as estimates of primary (undisturbed) forest carbon density. The Harris et al. (2012) values are similar to those derived by Baccini et al. (2012), except for their "Tropical Asia" value (11.6 kgC/m^2) which is lower than the values above.[1] Baccini et al. (2012) also show estimates for forests overall, and forest where "deforestation took place". In many cases these values are quite different, highlighting the issue of heterogeneity.

3.3. Alternative Land Use History

In addition to their four focal cases, which include the RCP 4.5 scenario dataset that is primarily used here, Hurtt et al. (2011) constructed 1660 complete harmonized land-use datasets; for their purposes, these were to test the effect of different assumptions about land-use practices on the frequency and magnitude of land-use transitions over the study period. Datasets with alternative parameters for inclusion/exclusion of shifting cultivation in tropical areas, and for priority given to primary or secondary land for land conversion, are used in this study to test the sensitivity of LUC emissions to these land-use factors. The four alternative land-use history datasets used here are:

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[1] See also: http://blogs.nature.com/news/2012/12/scientists-publish-consensus-statement-on-deforestation-emissions.html/

Land-Use History Dataset
No Shifting Cultivation, Primary Land Priority
No Shifting Cultivation, Secondary Land Priority
Shifting Cultivation, Primary Land Priority
Shifting Cultivation, Secondary Land Priority

Because primary and secondary land is differentiated only for non-boreal forest in these scenarios, only non-boreal forest area is affected in these scenarios. The four cases above allow comparison of the effects of each alternative assumption in isolation. Note that the Hurtt et al. (2011) focal case used as the core scenario in this work has parameters set between the extremes of these alternative scenarios; in the focal case, secondary land is prioritized in Eurasia and primary land is prioritized elsewhere.

The impact of alternative land-use practices on total forest area varies. If shifting cultivation does not occur, prioritizing primary land conversion in all regions has little effect on forest area from 1700-2000 relative to the focal case; prioritizing secondary land leaves 28.4 million km^2 more primary forest intact over this period. With shifting cultivation, if primary land is prioritized, 23.3 million km^2 more primary forest are lost from 1700-2000; if secondary land is prioritized 27.0 million km^2 primary forest are saved.

The net effects of these scenarios on global emissions for the period 1700-2000 are small. If shifting cultivation does not take place, prioritizing primary land conversion in all regions increases LUC carbon emissions over the focal case by 1.0%, and prioritizing secondary land decreases emissions by only 2.5%; with shifting cultivation, primary land priority increases global emissions by 2.7%, and secondary land priority decreases global emissions by only 1.4%.

This summary of small net emissions deviations, however, hides large disparities between the scenarios in the amount of carbon stored and released by each ecosystem. For instance, in the scenario with primary land priority and no shifting cultivation, net secondary forest area is nearly the same as in the focal case. With fewer gross transitions between this forest and agricultural land, however, this forest area takes up twice as much carbon. The lower number of gross transitions also causes cropland and pasture to inherit soil with higher carbon levels, and these areas stay in agricultural land-use for longer periods of time. As a result, cropland releases 26% more carbon; instead of sequestering carbon, pasture releases 8.9 GtC over the period.

The effects of these scenarios on future 2000-2100 net global emissions are much larger as compared to the historical timer period. With no shifting cultivation and primary land priority, net LUC carbon uptake is 9.4% greater; with secondary land priority, uptake is 8.6% lower. With shifting cultivation and primary land priority, net uptake is 16.8% higher; with secondary land priority it is 13.9% lower.

3.4. **Land-Use Change Carbon Disturbance**

The fate of carbon under LUC is not well-constrained. Some of the carbon initially held on sites that are cleared or harvested is released to the atmosphere immediately, and some is released gradually. In the G-CARBON core scenario, when an area used as cropland or pasture is changed to a different land-use, all of the soil carbon stays in the soil; for all other land-uses, 5% of the soil carbon is released to the atmosphere immediately. In a sensitivity experiment, if 5% of the soil carbon is immediately released from cropland and pasture when these land-uses change, over 1700-2000 an additional 0.5 GtC is released, an increase of 0.2% above the core scenario.

In the core scenario, for all land-uses when LUC occurs, 75% of the litter carbon is immediately released to the atmosphere and 25% stays as litter carbon. In a sensitivity experiment, forest litter carbon parameters were set so that when boreal or non-boreal forest is changed to another land-use, only 50% of the litter carbon goes to the atmosphere immediately. Over the period 1700-2000 this has a very small effect, causing 0.7 GtC less to be released, a decrease in emissions of 0.3% below the core run.

In a third sensitivity test, no grassland or shrubland soil carbon is immediately released during LUC. This has a slightly larger effect than the previous changes, causing the release of 4.7 GtC less from 1700-2000 than the core case, a decrease of 1.9%.

In a fourth test, for all land-uses, the immediate release of soil carbon during LUC is set 10% higher than the release for each corresponding land-use in the core scenario. This causes an additional release of 22.6 GtC over the period 1700-2000, an increase in emissions of 8.9%.

In a fifth test, for all land-uses, no C is immediately released from the soil to the atmosphere during LUC. 11.1 GtC less is released over 1700-2100, a decrease of 4.4%.

3.5. **Carbon Box Turnover-Time Sensitivities**

For non-boreal forest, the flow of carbon from NPP to vegetation are set for each region individually, in order to match turnover timescales in the literature. If each flow is increased by 25% of its value (e.g., a flow of 20% will increase to 25%), and timescales decreased in order to maintain the same equilibrium carbon contents, 1700-2000 emissions are 3.7 GtC (1.5%) lower; from 2000-2100 there is 3.9 GtC (5.8%) more uptake. If each flow is decreased by 25% of its value, 1700-2000 emissions are 3.9 GtC (1.5%) higher, and from 2000-2100 there is 6.7 GtC (10%) less uptake. If all flows from NPP to vegetation are set to be 100% (e.g., no NPP directly to litter), 1700-2000 emissions are 13 GtC (5.1%) lower, and from 2000-2100 there is 10 GtC (15%) more uptake.

When the same ±25% manipulations are performed on pasture, grassland, and shrubland of all regions simultaneously, resulting emissions changes are negligible.

If, for all regions, cropland flow from NPP to litter is reduced from 65% to 40%, and flow to soil is increased to 15% to 40%, 1700-2000 emissions are increased by 5.3 GtC (2.1%). From 2000-2100 5.2 GtC more (7.7%) is taken up.

3.6. **Other Forest Sensitivities**

If forest nitrogen fertilization is not included in the model, total emissions over 1700-2000 are 10.9 GtC (4.3%) higher. In this case, there is less carbon uptake over the period 2000-2100 as well; 9.2 less GtC of carbon (13.6%) is taken up.

Turnover timescales of forests are also highly uncertain. If the equilibrium carbon content is held steady, but the flows are adjusted so that the timescales of non-boreal forests of tropical regions are reduced by 17-33% (exact amounts depending on individual settings), total emissions over 1700-2000 are 2.9 GtC (1.2%) lower. Uptake over the period 2000-2100 is 2.6 GtC (3.9%) higher.

If the turnover timescales of all boreal and non-boreal forests are increased by 30%, total emissions over 1700-2000 are 3.5 GtC (1.4%) higher. Uptake over the period 2000-2100 is 6.0 GtC (8.9%) lower.

3.7. **Wetlands Sensitivity**

If wetlands are not included as an ecosystem (only the ecosystems of SAGE and MODIS are included), 1700-2000 emissions are 6 GtC (2.4%) lower, and from 2000-2100 there is 6.9 GtC (10%) more uptake.

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