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Fire-related carbon emissions from land use transitions in southern Amazonia

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[1] Various land-use transitions in the tropics contribute to atmospheric carbon emissions, including forest conversion for small-scale farming, cattle ranching, and production of commodities such as soya and palm oil. These transitions involve fire as an effective and inexpensive means for clearing. We applied the DECAF (DEforestation CArbon Fluxes) model to Mato Grosso, Brazil to estimate fire emissions from various land-use transitions during 2001–2005. Fires associated with deforestation contributed 67 Tg C/yr (17 and 50 Tg C/yr from conversion to cropland and pasture, respectively), while conversion of savannas and existing cattle pasture to cropland contributed 17 Tg C/yr and pasture maintenance fires 6 Tg C/yr. Large clearings (>100 ha/yr) contributed 67% of emissions but comprised only 10% of deforestation events. From a policy perspective, results imply that intensification of agricultural production on already-cleared land and policies to discourage large clearings would reduce the major sources of emissions from fires in this region. **Citation:** DeFries, R. S., D. C. Morton, G. R. van der Werf, L. Giglio, G. J. Collatz, J. T. Randerson, R. A. Houghton, P. K. Kasibhatla, and Y. Shimabukuro (2008), Fire-related carbon emissions from land use transitions in southern Amazonia, *Geophys. Res. Lett.*, *35*, L22705, doi:10.1029/2008GL035689.

1. Introduction

[2] Carbon emitted to the atmosphere from land use change is one of the most uncertain components of the global carbon budget. Deforestation in the tropics has been the predominant source of land use emissions during the last few decades. Pan-tropical estimates of net flux from deforestation range from 0.6 to 1.9 PgC/yr for the 1980s, 0.9 to 2.2 PgC/yr for the 1990s [*Denman et al.*, 2007], and 1.5 PgC/yr for the current decade [*Canadell et al.*, 2007]. In comparison, fossil fuel and cement production emitted 5.4, 6.4, and 7.2 PgC/yr for the 1980s, 1990s, and 2000–05 respectively [*Denman et al.*, 2007].

[3] The need to reduce uncertainties in carbon fluxes from deforestation arises from several factors. First, some atmospheric measurements suggest that tropical forests are a net sink of carbon from the atmosphere [*Stephens et al.*, 2007]. Because the net carbon flux from tropical forests is the difference between flux from undisturbed forest and emissions from land use change, improved estimates of carbon fluxes from deforestation are central to understanding whether tropical forests will continue to be a sink for atmospheric carbon into the future. Second, policy attention is focusing on carbon credits to developing countries for averted deforestation in the post-Kyoto commitment period [*Gullison et al.*, 2007]. Accurate estimates at a national scale are a prerequisite to implementation of any policy addressing averted deforestation. Third, capital-intensive, mechanized clearing for commodity production in response to international markets is an increasingly strong driver of tropical deforestation. Relative to previous decades, a greater portion of deforestation in this decade is driven by large-scale, commodity production, including soya in Latin America [*Morton et al.*, 2006] and palm oil in Southeast Asia [*Langner et al.*, 2007]. The ability to estimate carbon fluxes from different land use actors, e.g. large-scale mechanized producers and small-scale farmers for local consumption, underlies development of effective policies to reduce emissions and abilities to project emissions in the future. Quantifying the fire-emitted component is also important for air quality and climate forcing agents other than CO_2 (e.g., aerosols, tropospheric ozone, and methane).

[4] The current method to estimate carbon emissions from deforestation tracks changes in carbon pools following deforestation [*Ramankutty et al.*, 2007]. Area deforested is derived either from national-scale assessments [*Food and Agriculture Organization of the United Nations*, 2006; *Houghton and Hackler*, 2001] or satellite analysis [*Achard et al.*, 2002; *DeFries et al.*, 2002]. The method accounts for carbon that initially enters the atmosphere through burning and subsequently through decomposition of remaining forest biomass left to decay on site. Resulting estimates of annual carbon flux are consequently highly sensitive to the partitioning of cleared carbon into instantaneous burning vs. long-term decomposition pools and the rates of regrowth following abandonment.

[5] Evidence from fire frequency and field observations strongly suggest that the partitioning between instantaneous burning and decomposition pools varies with post-clearing land use. For example, deforested land that is subsequently used for mechanized cropland initially exhibits a higher

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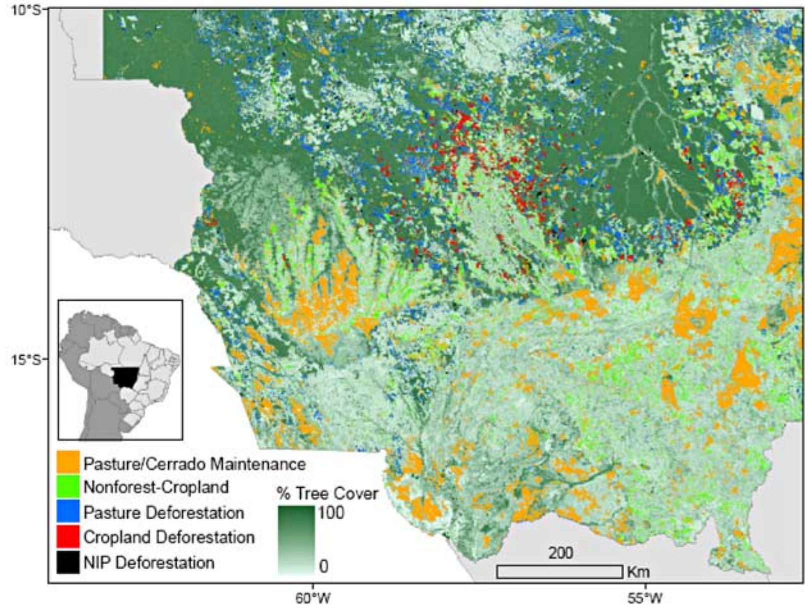

Figure 1. Location of study area and transition types (NIP, not in production).

number of fires and biomass removal through combustion than forest clearing for cattle ranching in the state of Mato Grosso, Brazil (4.6 vs. 1.7 fire days per deforested area) [*Morton et al.*, 2008a].

[6] We use the DECAF model with satellite-derived inputs on deforested area, fire activity, and post-clearing land use [*van der Werf et al.*, 2008] to estimate carbon fluxes from deforestation for 2001 to 2005 in a study area in the southern Amazon. The study area covers most of the Brazilian state of Mato Grosso, which contributed approximately 40% of all area deforested in the Brazilian Amazon during this period (Instituto Nacional de Pesquisas Espaciais, PRODES digital, 2007, available at http://www.obt.inpe.br/prodes/prodes_1988_2007.htm). The objectives of the analysis are to: 1) quantify the relative contributions of different land use transitions to fire emissions in the study area; 2) compare the absolute value of emissions estimated with the DECAF model with two alternate approaches, a coarse-scale global fire emissions database and a spatially-aggregated bookkeeping approach; and 3) assess implications for policies to reduce carbon emissions from deforestation.

[7] This study considers gross emissions from fires used for land conversion. For a full carbon accounting of net fluxes in tropical forests from land use change, several additional components are needed including respiration from remaining slash and soil, carbon uptake from regrowth, emissions from accidental forest fires, and forest damage from unsustainable logging. In addition to fluxes associated with land use, responses of tropical forests to changing atmospheric chemistry and climate are elements of a full carbon accounting [*Mahli et al.*, 2007].

2. Data and Methods

2.1. Study Area

[8] The study area corresponds to the portion of the state of Mato Grosso, Brazil in the southern Amazon that falls within the MODIS tile h12v10 (Figure 1). Tropical forest covers the northern portion of the state and woodland savanna (Cerrado) predominates in the southern portion. The only large tracts of remaining forest exist within indigenous reserves. We chose this study area because it is currently undergoing rapid expansion for agricultural production. Mechanized cropland, in particular cultivation of soya, has altered the dynamics of deforestation since the beginning of this decade [*Morton et al.*, 2006]. Fire, an inexpensive and effective mode for forest clearing, is the primary means for deforestation. Fire activity for clearing may continue for several years as debris is piled and burned multiple times, leading to estimates of nearly 100% combustion completeness for cropland deforestation and 50–90% for pasture deforestation [*Morton et al.*, 2008a]. Fire is also used in the study area for maintaining pasture and removing remnant trees and shrubs in the process of converting pasture to mechanized cropland.

2.2. DECAF Model

[9] We use the DECAF model to estimate fire emissions from multiple types of land cover transitions. The model was adapted from the biogeochemical CASA (Carnegie-Ames-Stanford Approach) model with a fire module following *van der Werf et al.* [2003]. The model and input data sets are described by *van der Werf et al.* [2008]. Land cover transitions and characteristic fire use are determined from MODIS surface reflectance, active fire observations and Landsat analysis [*Morton et al.*, 2008a, 2008b, 2006]. In brief, the DECAF model differs from previous approaches to estimate carbon emissions from deforestation by including 1) estimates of combustion completeness for deforested areas using satellite-based measures of fire frequency and post-clearing land use, 2) land use transitions in addition to deforestation that involve fire (conversion of non-forest and pasture maintenance fires), and 3) high-resolution (250 m) treatment of landscape heterogeneity based on time series of MODIS NDVI.

Table 1. Carbon Emissions for Land Use Transition Types

Land Use Transition Type	2001	2002	2003	2004	2005	Annual Average
Forest to Crop[a]						
area (km^2)	1468	1594	2518	1267	375	1444
new emissions (TgC/yr)	18	15	25	13	4	15 (13–15)[b]
carryover emissions[c] (TgC/yr)		1	3	4	1	2 (2–3)
emissions per area (MgC/ha)						116 (104–125)
Forest to Pasture[a]						
area (km^2)	4782	6565	5923	5678	3577	5305
new emissions (TgC/yr)	45	46	45	44	29	42 (26–46)
carryover emissions (TgC/yr)		7	7	9	9	8 (5–6)
emissions per area (MgC/ha)						94 (58–98)
Forest Clearing Not in Production[a]						
area (km^2)	365	592	435	637	1077	621
new emissions (TgC/yr)	1	1	1	2	2	1 (0–3)
carryover emissions (TgC/yr)		2	2	2	3	2 (0–1)
emissions per area (MgC/ha)						48 (0–64)
Pasture to Crop[d]						
area (km^2)	3026	2467	2672	3832	2315	2862
new emissions (TgC/yr)	6	6	9	12	7	8 (8–8)
emissions per area (MgC/ha)						28
Cerrado to Crop[d]						
area (km^2)	4522	4547	4243	3829	4278	4284
new emissions (TgC/yr)	7	8	9	9	12	9 (9–9)
emissions per area (MgC/ha)						21
Total[e]						
area deforested[f] (km^2)	6615	8751	8877	7582	5028	7371
area nonforest to crop (km^2)	7548	7014	6915	7611	6592	7146
deforestation emissions (Tg C/yr)	63	71	82	73	48	67 (46–73)
nonforest emissions (Tg C/yr)	13	14	18	21	19	17 (17–17)
total emissions (Tg C/yr)	76	85	100	94	67	84 (63–90)[g]

[a]Deforestation transition type. Includes deforestation events of all sizes. Figure 3 provides relative contributions by size category.
[b]Numbers in parentheses are high and low estimates based on varying assumptions of combustion timing and completeness.
[c]Emissions from deforestation fires that continue after the initial year when deforestation is identified.
[d]Nonforest to crop transition.
[e]Pasture maintenance and grassland fires (unrelated to land transitions) contributed an additional 6 Tg C/yr.
[f]Includes both new and carryover emissions.
[g]Conservatively assumes no carryover emissions from deforestation prior to 2001. If carryover emissions from years prior to 2001 are assumed to be the 2002–05 average, then annual average would be 87 Tg C/yr.

2.3. Method to Compare DECAF With Other Emission Estimates

[10] We compare the carbon emission from land use transitions to estimates using two other approaches. First, the Global Fire Emissions Database (GFEDv2) is a publicly-available database of monthly fire emissions at a one by one degree spatial resolution [*van der Werf et al.*, 2006]. Comparison between GFED and DECAF highlights differences in the two approaches regarding 1) approaches to estimate combustion completeness, and 2) use of Landsat-derived deforestation area in DECAF and MODIS-derived burned area in GFED. Because GFED does not distinguish between deforestation and maintenance fires, we compare the sum of the emissions from both fire types.

[11] The second method for comparison with DECAF is derived with the bookkeeping approach that tracks carbon through initial loss, storage, decay, and regrowth using region-specific response curves [*Houghton and Hackler*, 2001]. The bookkeeping approach is not spatially-explicit at a per-grid cell scale. To compare with DECAF, we use the area and average above and below ground biomass for each land use transition type from DECAF. The comparison therefore indicates differences resulting from different partitioning of burning and decay and different spatial representations in the two approaches, and not to cleared area or biomass. Because the bookkeeping approach does not estimate maintenance fires, we compare only deforestation fires during the study period. We do not include the heterotrophic respiration component in the comparison; if both initial fire and respiration components were included, the two approaches would lead to similar estimates on a multi-decade time scale. *Van der Werf et al.* [2008] estimate that fire emissions are 4.7 and 2.8 times higher than respiration for conversion to cropland and pasture, respectively, in the 2000–05 time period.

3. Results and Discussion

[12] Pasture maintenance and grassland fires in Cerrado contributed the largest burned area in the study domain for 2001 to 2005 (averaging 16141 km^2/yr or 53% of all burned area), but carbon emissions averaged only 6 Tg C/yr (7% of all fire emissions). This result is expected considering the relatively low biomass in these land cover types. Three transition types were associated with deforestation (forest to crop, forest to pasture, and forest clearing not in production).

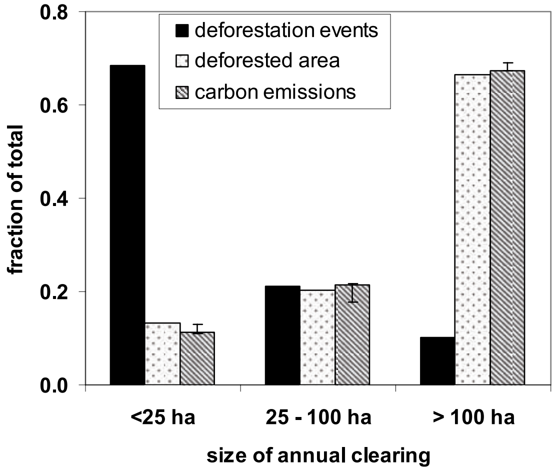

Figure 2. Mean annual fraction of total deforestation events, deforestation area, and carbon emissions from all deforestation transitions from annual clearings less than 25 ha, 25 to 100 ha, and greater than 100 ha for 2001 to 2005.

These transition types contributed 20, 72, and 8% of deforested area and 24, 71, and 5% of the estimated 67 Tg C/yr from deforestation fires respectively (calculated from annual averages in Table 1). Higher combustion completeness, determined by satellite-derived fire frequency and post-clearing land use, generates higher per-area emissions for forest to crop transitions than for other transition types (Table 1). In addition, nonforest conversions to cropland (including pasture to cropland and Cerrado to cropland) contributed a smaller but substantial portion of total fire emissions (17 Tg C/yr). These land use transitions associated with agricultural intensification are not generally included in current estimates of carbon emissions from deforestation.

[13] Partitioning the emissions according to size of annual clearings (based on data from Instituto Nacional de Pesquisas Espaciais (PRODES digital, 2007, available at http://www.obt.inpe.br/prodes/prodes_1988_2007.htm)) rather than transition type reveals that small clearings (<25 ha annual clearing size) constitute close to 70% of the total number of deforestation events (Figure 2). In contrast, the total deforested area in small clearings (annual average 946 of total 7371 km^2) and contributions to fire emissions (9 of total 67 Tg C/yr) are relatively small at 13 and 11% respectively. On the other hand, large clearings (>100 ha annual clearing size) comprised only 10% of deforestation events but approximately 67% of emissions. This finding is particularly relevant to the use of moderate resolution satellite data (e.g., MODIS) for monitoring deforestation and identifying the relative contributions of different land use actors to fire emissions. Policies to reduce emissions from small clearings, though they are prevalent on the landscape, would only address a minor component of fire emissions in this study area.

[14] Comparison of DECAF and bookkeeping methods with GFED indicates differences among approaches (Figure 3). Individual years do not agree to the same extent as the aggregated result. The bookkeeping approach assumes all fire emissions occur in the year when deforestation is first identified, whereas DECAF spreads emissions over multiple years as fires continue to be observed at that location. GFED, on the other hand, does not distinguish between initial fires and lower biomass fires in subsequent years following initial deforestation. In comparison with the bookkeeping approach, DECAF estimates are higher, largely due to the higher combustion completeness. Neither GFED nor the bookkeeping approach varies emission estimates according to land use transition types, so that years with relatively high forest to crop conversion (for example, 2003) are likely underestimated.

[15] Production of soya, beef, biofuels, and other commodities is likely to continue and even accelerate in the future with expansion of enabling infrastructure and pursuit of economic development goals in the tropics. This reality has sparked debate about intensification of production as a strategy to conserve land [*Green et al.*, 2005]. Conversion of pasture to cropland intensifies production, but potentially leads to more deforestation as additional forest is cleared to replace the pasture displaced by cropland [*Fearnside*, 2001]. It is not feasible to know to what extent this displacement has actually occurred over large areas. Using the per-area fire emissions from DECAF (Table 1), we estimate a carbon savings of 19% of deforestation fire emissions (13 of 67 Tg C/yr, the difference between actual forest to crop emissions and emissions if same area emitted at the pasture to crop rate per area) if the forest area that had been converted to cropland between 2001 and 2005 had instead occurred on land previously cleared for pasture. The carbon savings would be 9% of deforestation fire emissions if half of the pasture area lost to cropland were replaced by

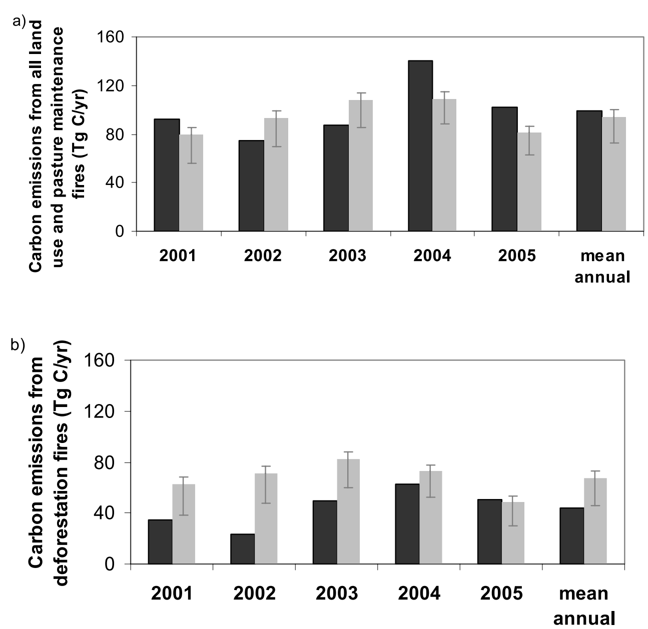

Figure 3. (a) Comparison of emission estimates for deforestation and pasture maintenance fires from GFEDv2 (black) and DECAF (gray) over study domain and (b) comparison of bookkeeping approach (black) and DECAF (gray) for burned flux for 2001 to 2005 for all deforestation transitions combined (forest to crop, forest to pasture, and forest not in production).

new forest clearing (6 Tg C/yr, same as above but if half the area also emitted at the forest to pasture rate).

4. Conclusions

[16] The main advantages of the DECAF modeling approach are that 1) the full suite of land use transition types involving fire are included in estimating carbon emissions, and 2) fire emissions can be partitioned according to the type of land use transition. Understanding contributions to atmospheric fire emissions from different land use actors is fundamental to devising effective policies for reducing greenhouse gas emissions, improving air quality, and projecting future emissions.

[17] In the study area, the results indicate that policies to encourage intensification of already-cleared lands result in emission savings even if some displaced pasture leads to new clearing. In addition, the relatively small contribution to emissions from clearings less than 25 ha (Figure 2) suggests that policies aimed at these landholders would reduce less than 10% of total fire emissions despite the ubiquity of small clearings. This study area is not typical of many other places in the tropics where clearing may result mainly from small-scale farmers and less capital-intensive activities. Similar analyses are needed in other locations to examine the relative contributions from different land use actors and determine effective policy strategies.

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