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Carbon emissions from deforestation in the Brazilian Amazon Region

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Abstract. A simulation model based on satellite observations of monthly vegetation greenness from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to estimate monthly carbon fluxes in terrestrial ecosystems of Brazilian Amazon and *Cerrado* regions over the period 2000–2002. The NASA-CASA (Carnegie Ames Stanford Approach) model estimates of annual forest production were used for the first time as the basis to generate a prediction for the standing pool of carbon in above-ground biomass (AGB; $\mathrm{g\,C\,m^{-2}}$) for forested areas of the Brazilian Amazon region. Plot-level measurements of the residence time of carbon in wood in Amazon forest from Malhi et al. (2006) were interpolated by inverse distance weighting algorithms and used with CASA to generate a new regional map of AGB. Data from the Brazilian PRODES (Estimativa do Desflorestamento da Amazônia) project were used to map deforested areas. Results show that net primary production (NPP) sinks for carbon varied between 4.25 $\mathrm{Pg\,C\,yr^{-1}}$ (1 Pg=10^{15} g) and 4.34 Pg C for the region and were highest across the eastern and northern Amazon areas, whereas deforestation sources of CO_2 flux from decomposition of residual woody debris were higher and less seasonal in the central Amazon than in the eastern and southern areas. Increased woody debris from past deforestation events was predicted to alter the net ecosystem carbon balance of the Amazon region to generate annual CO_2 source fluxes at least two times higher than previously predicted by CASA modeling studies. Variations in climate, land cover, and forest burning were predicted to release carbon at rates of 0.5 to 1 $\mathrm{Pg\,C\,yr^{-1}}$ from the Brazilian Amazon. When direct deforestation emissions of CO_2 from forest burning of between 0.2 and 0.6 $\mathrm{Pg\,C\,yr^{-1}}$ in the Legal Amazon are overlooked in regional budgets, the year-to-year variations in this net biome flux may appear to be large, whereas our model results implies net biome fluxes had actually been relatively consistent from year to year during the period 2000–2002. This is the first study to use MODIS data to model all carbon pools (wood, leaf, root) dynamically in simulations of Amazon forest deforestation from clearing and burning of all kinds.

1 Introduction

Greenhouse gas emissions from tropical deforestation and land cover change are among the most uncertain components of the global carbon cycle. This missing information about global deforestation patterns and fluxes has significant implications for balancing the present-day carbon budget and predicting the future evolution of climate change. A number of studies have estimated carbon emissions from tropical deforestation (Houghton, 1999; Potter, 1999; Fearnside, 2000; McGuire et al., 2001; DeFries et al., 2002; Achard et al., 2004), but the estimates vary greatly and are difficult to compare due to differences in (land cover) data sources, estimated regional extents, and carbon computation methodologies.

A recent review of previous work on estimating carbon emissions from tropical deforestation by Ramankutty et al. (2007) pointed to the importance of considering land-cover dynamics following deforestation, including the fluxes from the decay of products and slash pools, and the fluxes from either newly established agricultural lands or regrowing forest. This review also suggested that accurate carbon-flux estimates should consider historical land-cover changes for at least the previous 20 years. Such results can be highly sensitive to estimates of the partitioning of cleared carbon into instantaneous burning vs. long-time scale dead woody pools. Accordingly, the main objective of our study was to understand the major controls on carbon cycling patterns and processes in the Amazon region, using NASA satellite data

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products to drive models of net ecosystem production (NEP) and tropical ecosystem disturbance, leading to detailed estimates of net biome production (NBP).

Inclusion of deforestation sources of CO_2 emission in the Amazon is a crucial step in developing a full carbon balance for the region. Previously, Potter et al. (2001) and VanderWerf et al. (2003) used the CASA model with inputs from satellite observations of global rainfall from the NASA Tropical Rainfall Monitoring Mission (TRMM) to account for the effects of fire on regional carbon stocks and ecosystem carbon fluxes. Annual carbon emissions from fires in the Legal Amazon were estimated to range from 0.2 to 0.5 Pg C yr^{-1}. In comparison, Potter et al. (2002) used the CASA model production and biomass predictions together with Landsat-derived mapping of burned areas for the Legal Amazon states to estimate total ecosystem source to range from 0.2 to 1.2 Pg C yr^{-1} for the period 1992–1993. The Carbon and Land-Use Change (CARLUC) model estimates the net flux caused by deforestation and forest re-growth (Hirsch et al., 2004). CARLUC predicted that the net flux to the atmosphere from the Legal Amazon area during the period from 1970 to 1998 reached a maximum of 0.35 Pg C yr^{-1} in 1990, with a cumulative release of 7 Pg C. The net flux is higher than predicted by an earlier study (Houghton et al., 2000) by a total of 1 Pg C over the period 1989–1998, mainly because CARLUC predicts relatively high mature forest carbon storage compared with the datasets used in earlier studies.

There are two broad categories of processes responsible for sources and sinks of carbon in tropical forest regions. The first category includes natural physiological processes – photosynthesis, decomposition, respiration, evapotranspiration – plant and soil processes that respond to environmental drivers, such as radiation, precipitation, temperature, and nutrients. The second broad category of processes falls under the heading of ecosystem disturbances, including both direct anthropogenic effects (e.g. deforestation and conversion to pasture), and natural or indirect anthropogenic effects (e.g. wildfire). The CASA model studies by Potter et al. (2009) addressed the first category of physiological processes controlling carbon balance of the Amazon region, whereas the CASA model studies in the present paper focused mainly on the second category of disturbances and how they change photosynthesis, decomposition, and respiration in converted forest ecosystems.

The Instituto Nacional de Pesquisas Espaciais (INPE) in Brazil currently analyzes more than 200 Landsat scenes each year to provide annual high-resolution mapping of deforestation as part of the PRODES (Estimativa do Desflorestamento da Amazônia) project (INPE, 2002). According to these data sets, deforestation rates in the Legal Amazon have remained roughly constant or increased intermittently over the past two decades (INPE, 2003). In this study, we combine PRODES deforestation data with the results of the CASA model's (Potter et al., 1993) predictions of forest biomass using 2000–2002 MODIS EVI inputs at 8 km spatial resolution. Having combined PRODES and CASA results, we can infer variability in region-wide NBP carbon fluxes from land cover change in the Brazilian Amazon and savanna ecosystems. As recommended by Ramankutty et al. (2007), our NASA-CASA modeling framework (Potter et al. 1999, 2003, and 2009) has been designed to estimate historical as well as current monthly patterns in plant carbon fixation, living biomass increments, nutrient allocation, litter fall and decomposition, long-term decay of slash pools, soil CO_2 respiration, and soil nutrient mineralization before, during, and after deforestation events in the tropics. To our knowledge, this is the first study to take full advantage of both Landsat and MODIS land cover products to make annual NBP estimates for the Amazon region.

This study examines the processes of tropical deforestation that include forest cutting and burning, primarily from anthropogenic fires, and the subsequent decay of residual forest biomass. The unique aspects of our methodology are in the combination of MODIS satellite images to first quantify and map standing forest biomass pools across the entire Amazon region in a manner consistent with forest age, tree production estimates, and soil properties, and second to simulate the loss of forest carbon to the atmosphere in a mechanistic manner that maps and tracks all the pools of wood and litter remaining for years following anthropogenic disturbance (i.e. deforestation). We have used MODIS EVI to model the carbon cycle in forested areas prior to deforestation, and then immediately reduce plant carbon uptake to observed levels in field-based studies of forest clearing. All model carbon pools (wood, leaf, and root) have been altered dynamically in the simulations of clearing and burning anywhere and everywhere that deforestation has been mapped out by PRODES results.

2 Background on CASA carbon modeling methods

The launch of NASA's Terra satellite platform in 1999 with the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on-board initiated a new era in remote sensing of the Earth system with promising implications for carbon cycle research. Direct input of satellite vegetation index "greenness" data from the MODIS sensor into ecosystem simulation models is now used to estimate spatial variability in monthly net primary production (NPP), biomass accumulation, and litter fall inputs to soil carbon pools. Global NPP of vegetation can be predicted using the relationship between leaf reflectance properties and the absorption of photosynthetically active radiation (PAR), assuming that net conversion efficiencies of PAR to plant carbon can be approximated for different ecosystems or are nearly constant across all ecosystems (Running and Nemani, 1988; Goetz and Prince, 1998).

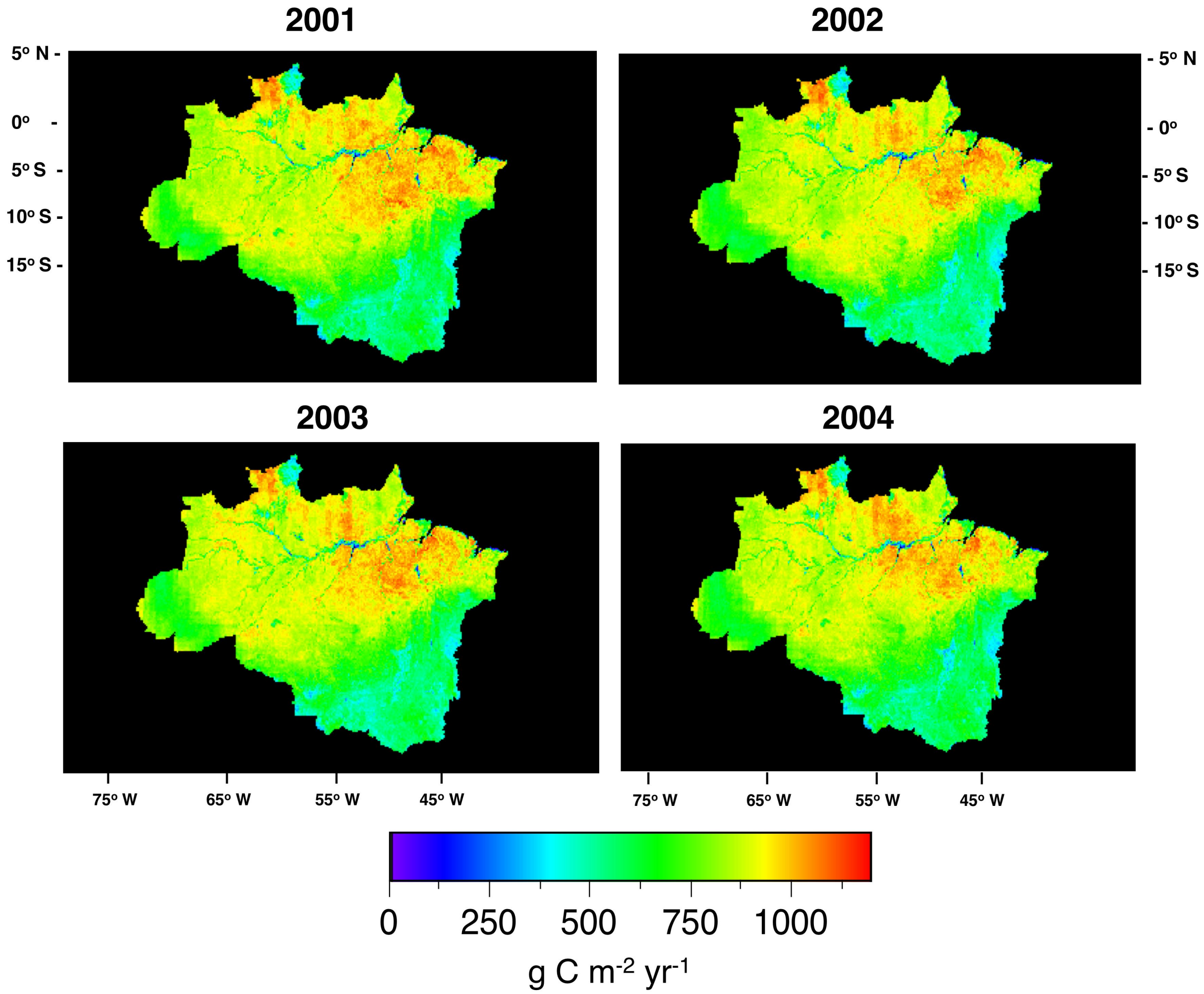

Fig. 1. Predicted annual NPP fluxes from the CASA model for the Legal Amazon over the years 2001–2004.

Operational MODIS algorithms generate the Enhanced Vegetation Index (EVI) (Huete et al., 2002) as global image coverages from 2000-present. EVI represents an optimized vegetation index, whereby the vegetation index isolines in red and near infra-red spectral bands are designed to approximate vegetation biophysical isolines derived from canopy radiative transfer theory and/or measured biophysical-optical relationships. EVI was developed to optimize the greenness signal, or area-averaged canopy photosynthetic capacity, with improved sensitivity in high biomass regions. The EVI has been found useful in estimating absorbed PAR related to chlorophyll contents in vegetated canopies (Zhang et al., 2005), and has been shown to be highly correlated with processes that depend on absorbed light, such as gross primary productivity (GPP) (Xiao et al., 2004; Rahman, 2005).

Potter et al. (2009) used MODIS EVI inputs to the CASA model (Fig. 1) to report that summed NPP fluxes for the Legal Amazon region of Brazil decreased gradually over the period of 2000–2004. NPP declined from 4.34 Pg C yr^{-1} (1 Pg=10^{15} g) in 2001 to a low of 4.25 Pg C yr^{-1} in 2002, and then remained relatively low at 4.26 Pg C yr^{-1} in 2004 (spatial patterns are shown in Fig. 2). Predicted NPP sinks for carbon were generally highest across the eastern and central Amazon areas. Annually summed net ecosystem production (NEP) across the Legal Amazon region varied from year to year over the period of 2000–2004, from a relatively low CO_2 emission source of -0.07 Pg C yr^{-1} in 2000 to a higher CO_2 emission source of -0.13 Pg C yr^{-1} in 2002, excluding emissions from biomass burning sources and decomposition fluxes from residual biomass in forest areas cleared over the preceding several years. Identifying and quantifying the missing process of deforestation-related disturbance is one of the main objectives of the present study.

CASA model predictions of NEP fluxes of CO_2 were found to match tower-based flux measurements from the LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia) program at the Tapajos National Forest in both seasonality and magnitude. LBA is an international research

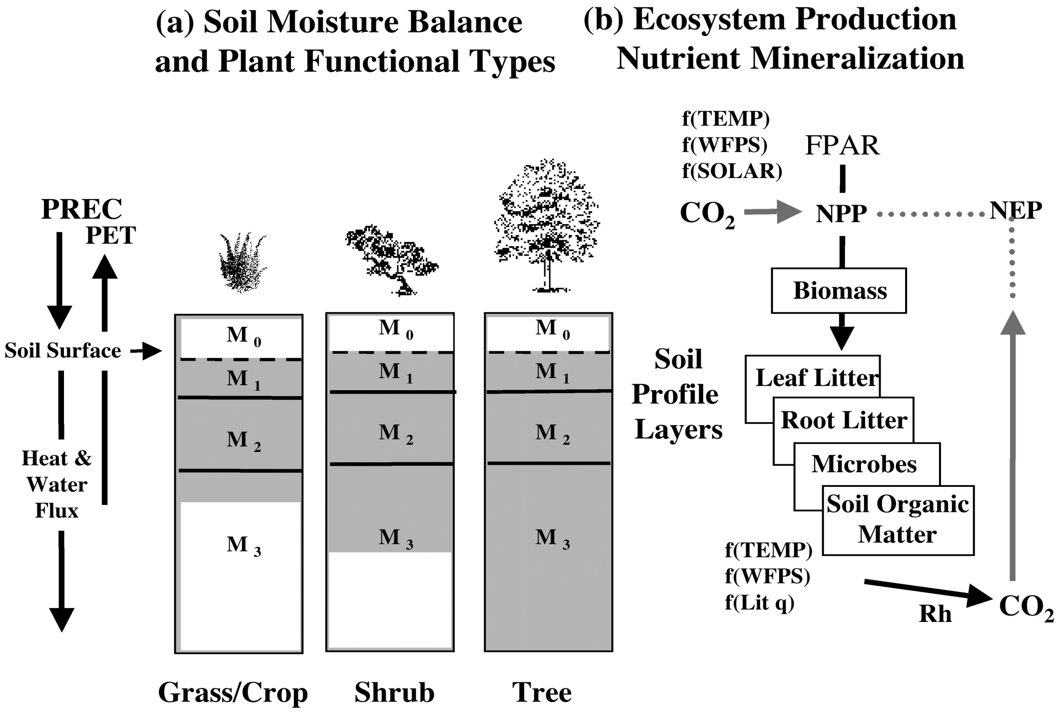

Fig. 2. Schematic representation of components in the NASA-CASA model. The soil profile component **(a)** is divided by depth into a surface ponded layer (M_0) above all other layers for wetlands only, a surface organic layer (M_1), topsoil (M_2), and subsoil to rooting depth (M_3), showing typical levels of soil water content (shaded) in three general vegetation types (DeFries et al., 1995). The production and decomposition component **(b)** shows separate pools for carbon cycling among pools of leaf litter, root litter, woody detritus, microbes, and soil organic matter, with dependence on litter quality (q). Other abbreviations include FPAR for the fraction absorbed of photosynthetically active radiation, TEMP for air temperature, WFPS for water fill pore space of the soil, and Rh for heterotrophic respiration.

initiative led by Brazil whose main science objectives include developing methods to quantify, understand, and model the processes controlling carbon cycling in the Amazon region.

3 Methods – model algorithms and data sets

As documented in Potter (1999), the monthly NPP flux, defined as net fixation of CO_2 by vegetation, is computed in NASA-CASA on the basis of light-use efficiency (Monteith, 1972). Monthly production of plant biomass is estimated as a product of time-varying surface solar irradiance, S_r, and EVI from the MODIS satellite, plus a constant light utilization efficiency term ($e_{\max}$) that is modified by time-varying stress scalar terms for temperature (T) and moisture (W) effects (Eq. 1).

$$NPP = S_r \, EVI \, e_{\max} T W \tag{1}$$

The $e_{\max}$ term is set uniformly at 0.39 g C MJ^{-1} PAR, a value that derives from calibration of predicted annual NPP to previous field estimates (Potter et al., 1993). This model calibration has been validated globally by comparing predicted annual NPP to more than 1900 field measurements of NPP (Zheng et al., 2003; Potter et al., 2007). Interannual NPP fluxes from the CASA model have been reported (Behrenfeld et al., 2001) and validated against multi-year estimates of NPP from field stations and tree rings (Malmström et al., 1997). Our NASA-CASA model has been validated (with r correlation values >0.75) against field-based measurements of monthly-to-annual NEP fluxes at multiple Amazon forest sites (Potter et al., 2009) and against atmospheric inverse model estimates of global NEP (Potter et al., 2003).

The T stress scalar is computed with reference to derivation of optimal temperatures (T_{opt}) for plant production. The T_{opt} setting can vary by latitude and longitude, with values in the middle thirties for tropical forests. The W stress scalar is estimated from monthly water deficits, based on a comparison of moisture supply (precipitation and stored soil water) to potential evapotranspiration (PET) demand using the method of Priestly and Taylor (1972). The Moderate Resolution Imaging Spectroradiometer (MODIS) 1 km land cover map (Friedl et al., 2002) aggregated to 8 km pixel resolution was used to specify the predominant land cover class for the W term in each pixel as either forest, savanna (*Cerrado*) crop, pasture, or other classes such as water or urban area. When moving the CASA model into deforestation simulations, a fractional land cover approach has been introduced in this study, whereby mixed 8 km land cover pixels are effectively represented.

Monthly mean surface air temperature and precipitation grids for model simulations over the years 2000–2002 came from NCEP reanalysis products (Kistler et al., 2001). Monthly mean inputs of solar radiation flux to the model were derived from top of the atmosphere shortwave radiation budget products of Laszlo et al. (1997 and 2006).

Carbon accumulation rates in forest biomass at the stand level are a function of both growth and mortality of trees. For the NASA-CASA model, Potter (1999) reported that these processes could be expressed in terms of the mean residence time (τ, in years) of carbon in the aboveground wood tissue pools. Tissue allocation ratios (α percent of NPP) were expressed in a similar manner, based on estimates from the global ecosystem literature. These default forest values for τ (40 years) and α (45%) together determine the model's estimation of potential accumulation rates of forest biomass in the Amazon. These potential accumulation rates of woody biomass are based on the assumption of forest growth to mature stand status, but are subject to validation and readjustment based on comparisons to field-based inventory measurements.

Evapotranspiration in NASA-CASA is connected to water content in the soil profile layers (Fig. 1), as estimated using the NASA-CASA algorithms described by Potter (1999). The soil model design includes three-layer (M_1–M_3) heat and moisture content computations: surface organic matter, topsoil, (0.3 m), and subsoil to rooting depth (1 to 10 m). These layers can differ in soil texture, moisture holding capacity, and carbon-nitrogen dynamics. Water balance in the soil is modeled as the difference between precipitation or volumetric percolation inputs, monthly estimates of PET, and the drainage output for each layer. Inputs from rainfall can recharge the soil layers to field capacity. Excess water percolates through to lower layers and may eventually leave the system as seepage and runoff.

Based on plant production as the primary carbon and nitrogen cycling source, the NASA-CASA model is designed to couple daily and seasonal patterns in soil nutrient mineralization and soil heterotrophic respiration (R_h) of CO_2 from soils worldwide. Net ecosystem production (NEP) can be computed as NPP minus R_h fluxes, excluding the effects of small-scale fires and other localized disturbances or vegetation regrowth patterns on carbon fluxes. The soil model uses a set of compartmentalized difference equations with a structure comparable to the CENTURY ecosystem model (Parton et al., 1992). First-order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fractions) at the soil surface. The model also simulates surface soil organic matter (SOM) fractions that presumably vary in age and chemical composition. Turnover of active (microbial biomass and labile substrates), slow (chemically protected), and passive (physically protected) fractions of the SOM are represented. Along with moisture availability and litter quality, the predicted soil temperature in the M_1layer controls SOM decomposition.

The soil carbon pools were initialized to represent storage and flux conditions in near steady state (i.e. an annual NEP flux less than 0.5% of annual NPP flux) with respect to mean land surface climate recorded for the period 1999–2000. This initialization protocol was found to be necessary to eliminate any notable discontinuities in predicted NEP fluxes during the transition to our model simulation years of interest prior to MODIS EVI availability. Initializing to near steady state does not, however, address the issue that some ecosystems are not in equilibrium with respect to net annual carbon fluxes, especially when they are recovering from past disturbances. For instance, it is openly acknowledged that the CASA modeling approach using 8 km satellite data inputs cannot capture all the carbon sink effects of cutting and burning of forests and regrowth from recent wood harvest activities (Turner, 2005), although impacts of major wildfires are detectable (Potter et al., 2005). We have assumed therefore that no significant impacts of disturbances in the Amazon could be detected using a few years of MODIS time series data and that we must instead capture these changes by inclusion of Landsat-based analysis of area deforested from PRODES.

Whereas previous versions of the CASA model (Potter et al., 1993 and 1999) used a normalized difference vegetation index (NDVI) to estimate FPAR, the current model version (Potter et al., 2009) instead has been calibrated to use MODIS EVI datasets as direct inputs to Eq. (1) above. In long-term (1982 to 2004) simulations, continuity between AVHRR and MODIS sensor data for inputs to NASA-CASA is an issue that must be addressed by recalibration of annual NPP results post 2000. NASA-CASA model predictions with 2001 monthly MODIS EVI inputs have been adjusted using the same set of field measurements of NPP (Olson et al., 1997; Potter et al., 2003; Zheng et al., 2003; and Potter et al., 2007). To best match predictions with previously measured NPP estimates at the global scale (R^2=0.91), the model e_{max} term for MODIS EVI inputs was reset to 0.55 g C MJ^{-1} PAR.

It is worth noting that vegetation index values from Landsat could not be used for previous CASA studies in the Amazon (nor for the present study) in place of MODIS EVI, because Landsat does not provide enough temporally frequent images to create a continuous seasonal cycle of ecosystem growth estimates in the CASA model.

4 Results – prediction of standing forest biomass carbon

The CASA model was modified for this study to use a new version of mean forest stand age (i.e. years since last disturbance) as the input setting for the model's τ variable for mean residence time of carbon in aboveground wood pools.

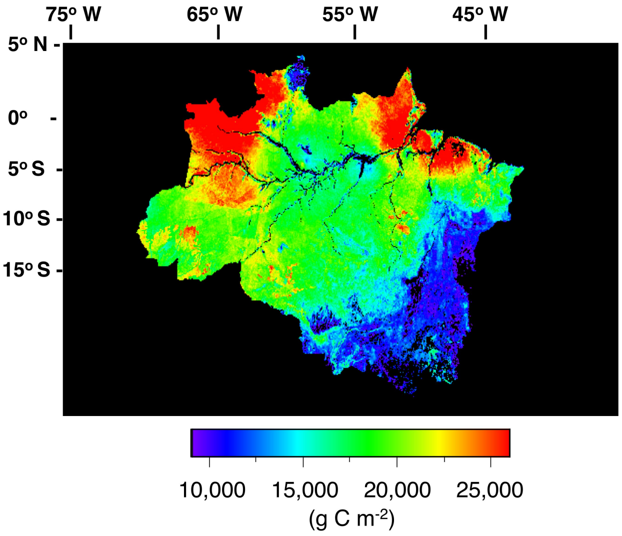

Fig. 3. Predicted aboveground wood biomass pools of carbon from the CASA model for the Legal Amazon, circa 2000.

The largest available database for forest age in the Amazon as reported by Baker et al. (2004a, b) from over 220 measurement plot locations across the region. We interpolated these measured forest age values by an inverse distance weighted algorithm (Malhi et al., 2006) to generate a gridded regional τ variable input layer at 8 km spatial resolution for forests in the Brazilian Amazon region.

The resulting prediction of standing wood biomass in Amazon forests (Fig. 3) reflects both MODIS EVI and the CASA model's climate-controlled patterns of production of new carbon by annual NPP fluxes, plus the estimated distribution of forest age, which is influenced by soil types (Malhi et al., 2006). Amazon forest biomass was reported by Malhi et al. (2006) to be highest in the moderately seasonal, slow growing forests of central Amazonia and the Guyanas (up to 350 Mg dry weight ha^{-1}) and declining to 200– 250 Mg dry weight ha^{-1} at the western, southern and eastern margins. When adjusted to units of carbon in standing forest biomass (50% by weight), the geographic patterns predicted by our CASA model (Fig. 3) closely match the range and geographic distribution reported by Malhi et al. (2006). The largest woody biomass pools (on a per ha basis) in our CASA model results were predicted in the remote northwestern regions in Amazonas state, north of Umarituba (2.2° N, 67.4° W) and in the northeastern regions in central Amapa state (1.6° N, 51.7° W), both locations where no biomass measurement plots were available for comparisons. More typical standing pools of wood carbon (compared to results of Malhi et al., 2006) were predicted by CASA model results at 160–180 Mg C ha^{-1} throughout the central Amazon region, although some relatively isolated areas were estimated at nearly 250 Mg C ha^{-1} in live wood pools.

Predicted totals of standing (live) wood and down (dead) wood debris (Pg C) from CASA indicated that the states of Amazonas and Pará still represent the largest pools of forest biomass in the Legal Amazon region, both in terms of standing live and down dead wood (Table 1). While these two states also occupy the largest land areas in the region, CASA's prediction of average wood carbon density was higher for the states of Amapa, Acre, and Rondonia (at 240, 194, and 193 Mg C ha^{-1}, respectively) than for Pará (at 185 Mg C ha^{-1}) and was nearly as high as for Amazonas (at 204 Mg C ha^{-1}).

The total aboveground biomass of intact Amazonian rainforests in 2000 was estimated by Malhi et al. (2006) to be 93±23 Pg C over a total area =5.76 10^6 km^2. The CASA model prediction for total abovegroundbiomass of intact rainforests in the Legal Amazon region (area =5.05 10^6 km^2) in 2000 was 90 Pg C. If the average wood carbon density from the CASA model were extrapolated to the entire Amazonian rainforest area considered by Malhi et al. (2006), the two estimates would still be within 10% of one another.

5 Results – deforestation simulations and regional carbon predictions

Having generated the most spatially detailed maps of standing forest biomass pools to date from MODIS satellite inputs in the Amazon, we next used the CASA model to simulate the net flux of carbon across the region before, during, and for several years after, deforestation of the fractional land mapped annually according to the PRODES outputs as newly cleared rainforest (example shown in Fig. 4). It is worth noting that annual deforestation maps derived from PRODES may include a small portion of deforested area from previous years in that some pixels were previously cloud-covered and therefore, deforestation was not recorded until that year but actually occurred in a previous year. For instance, we have estimated that only a small percentage (upper limit of 2% of the total area) mapped by PRODES as deforested land in the year 2000 may have been observed as cloud covered in previous years. Therefore, in our analysis we did not want to omit areas deforested and therefore used all of the classes for each year of deforestation, regardless of the number of years of previous clouds.

Starting in 2000, CASA was run twice with identical climate inputs – once with settings for undisturbed forest or savanna land cover (Potter et al., 2009) and then again with different settings for cleared and burned forest or savanna cover within every 8 km MODIS grid cell location. The area-weighted fluxes of carbon predicted as monthly NEP from both undisturbed and cleared forest or savanna land cover were combined to estimate the 8 km resolution net biome production (NBP) flux of CO$_2$ in states of the Legal Amazon.

Table 1. Predicted totals of standing (live) wood and down (dead) wood debris (Pg C) and net fluxes of carbon (Pg C yr^{-1}) from CASA model net biome production (NBP) estimates for states of the Brazilian Legal Amazon, from 2000–2002.

	Area (sq.km)	Wood Biomass	Down Wood Carbon	NBP 2000	NBP 2001	NBP 2002
Roraima	227,904	4.28	0.29	−0.016	−0.015	−0.018
Amapa	136,896	3.29	0.19	−0.007	−0.007	−0.003
Para	1,225,984	22.63	1.82	−0.059	−0.104	−0.121
Amazonas	1,553,088	31.56	1.89	−0.013	−0.063	−0.068
Maranhao	324,096	5.11	0.46	−0.021	−0.029	−0.098
Tocantins	277,056	2.92	0.29	0.000	−0.005	−0.009
Acre	152,640	2.95	0.23	0.005	−0.001	−0.002
Mato Grosso	911,104	12.52	1.15	−0.002	−0.034	−0.052
Rondonia	244,544	4.76	0.36	0.000	−0.022	−0.023
Legal Amazon Totals	5,053,312	90.04	6.69	−0.114	−0.279	−0.395

The model settings for a cleared and burned forest or savanna simulation were first applied in the month of September, 2000, at which time all CASA above-ground biomass (AGB) as leaf and wood was removed from these live carbon pools. According to published literature values (Hao and Liu, 1994; Kauffman et al., 1995; Guild et al., 1998; Graça et al., 1999; Sorrensen, 2000), 100% of the leaf carbon and 50% of the wood carbon per unit area in CASA predicted AGB was immediately transferred to the atmosphere as CO_2 emissions from biomass burning events, while the other 50% of AGB wood carbon was transferred to the decomposing down wood carbon pool of the model. Decomposition, CO_2 emission from R_h fluxes, and redistribution of residual carbon into soil pools of this augmented pool of down wood were simulated for the following four years. The model's land cover class for the cleared and burned forest or savanna area was immediately reset to pasture grassland and the observed 8 km MODIS EVI value for each monthly time step was subsequently adjusted by a multiplier factor of 0.25 to represent the typical reduction reported for leaf area index (LAI) in the transition of Amazon forest to pasture vegetation cover (Asner et al., 2003; Bohlman et al., 1998; Eduardo et al., 2005; McWIlliams et al., 1993; Ratana et al., 2005; Xavier and Vettorazzi, 2003).

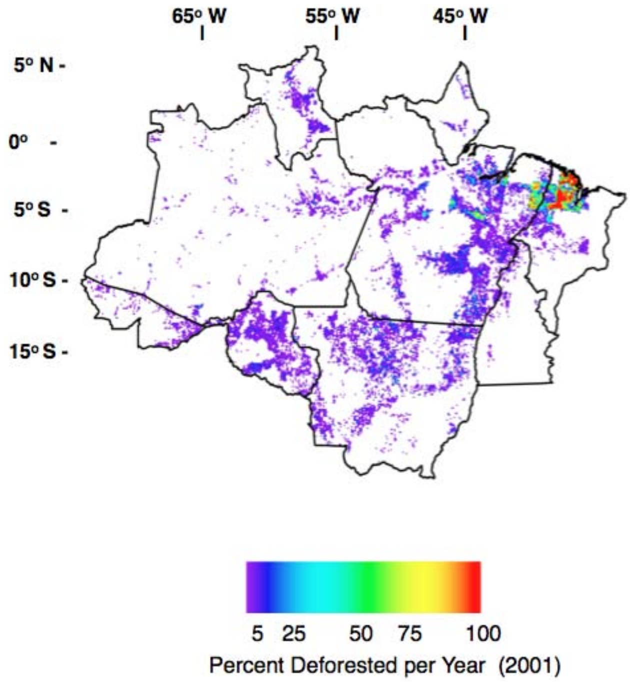

Fig. 4. Percent of land areas deforested, aggregated from the Brazilian PRODES (Estimativa do Desflorestamento da Amazônia) data into 8 km grid cells for the Legal Amazon in 2001.

Regrowth of secondary forest vegetation in the cleared area fractions from 2000 through 2002 was not considered in these relatively short-term clearing and burning simulations in the CASA model, although forested areas cleared prior to 2000 were treated in the model as MODIS-classified non-forest land cover types (as did Potter et al., 2009). Although we have intentionally reduced the observed EVI values to represent post-clearing (non-forest) EVI, the original MODIS forest EVI values may have represented a mixture of cover classes in each 8 km grid cell. However, because clearing of forest in the Amazon occurs on such small scales, there is essentially no detectable deforestation signal in the 8 km resolution EVI observations used to drive the CASA "before clearing" forest carbon simulations. Deforestation signals are observed only at Landsat (30 m) spatial resolutions, which leaves no other option but to modify the observed forest EVI value to typical non-forest classes.

CASA model deforestation simulations from general locations of three LBA-supported forest research sites show the immediate increase in CO_2 emissions from the transfer of live wood biomass into decomposing down wood debris (Fig. 5). Prior to the simulated deforestation event at each site, the outputs for monthly NPP and soil Rh fluxes of CO_2

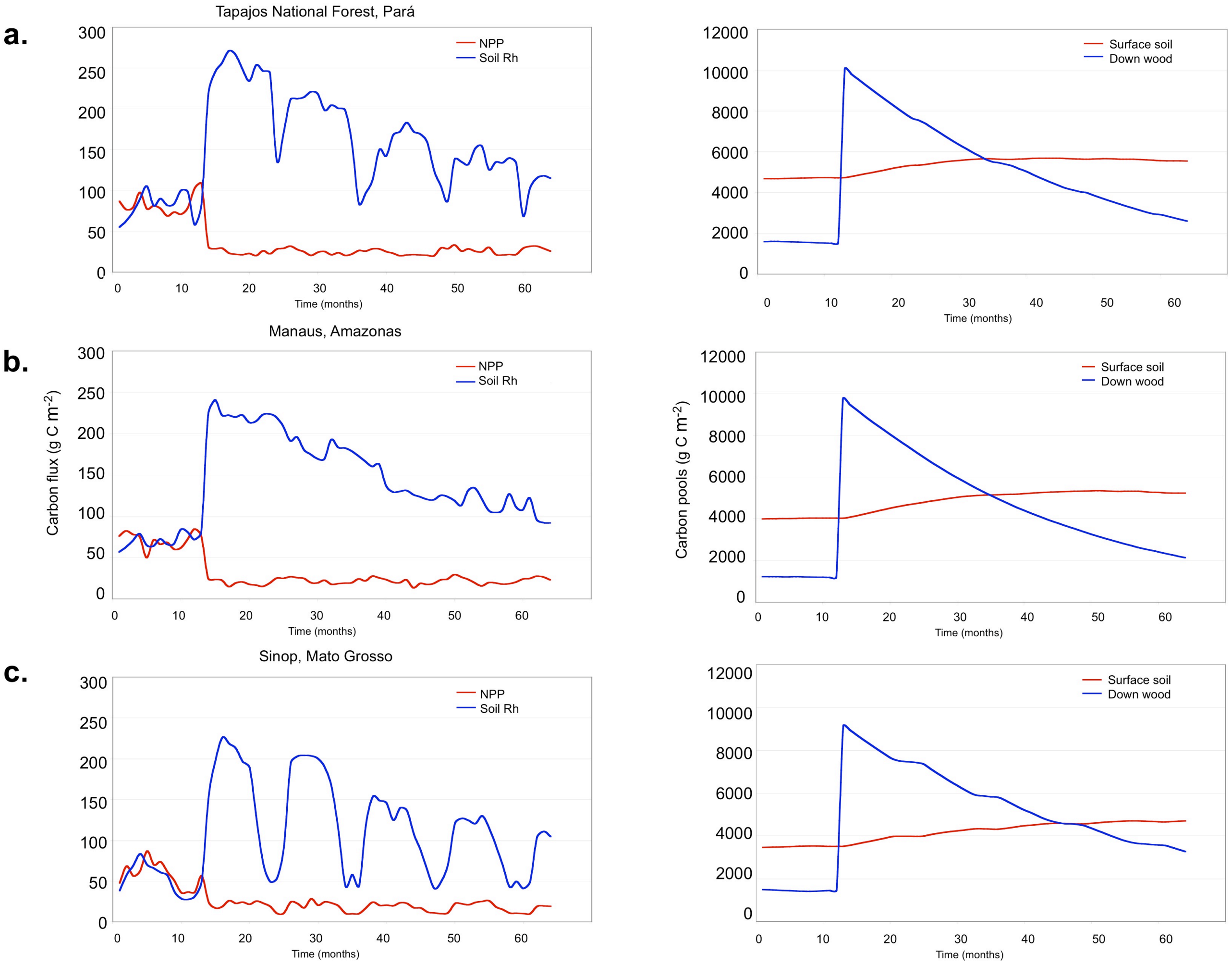

Fig. 5. CASA model simulation results for deforestation events at the locations of three LBA-supported forest research sites **(a)** Tapajos National Forest, Pará, **(b)** Manaus, Amazonas, and **(c)** Sinop, Mato Grosso. Carbon fluxes in primary forests are shown for each site during the first 10 months of the simulation results, after which time the deforestation event alters NEP fluxes (left panels) and down wood debris and soil carbon pools (right panels). These simulations cover a period of 72 months total for an extension of flux patterns beyond the three-year period of 2000–2002.

were approximately balanced when summed over an entire year of NEP fluxes. The model predictions for the forest site at Manaus, Amazonas were the least seasonal of the three sites, whereas the forest site at Sinop, Mato Grosso showed the seasonal effects of a longer dry period than the other two sites. This seasonal wet-dry cycle was readily observed in the elevated (by approximately 2.5 times, compared to primary forest) monthly soil Rh fluxes of CO_2 among the deforested sites, as well as in the yearly loss trends of carbon from the residual down wood debris left from the burning event. In all three cases, each site was predicted to release more than 50% of the carbon in the residual down wood debris in three years since the simulated disturbance events.

On a regional level, the predicted emissions of carbon to the atmosphere directly from burning of forest biomass were highest in 2000 through 2002 in the Legal Amazon states of Pará and Mato Grosso (Table 2), as well as in Rondonia (in 2000) and Maranhão (in 2001). The CASA model prediction for the entire region was a loss of between 0.23 and 0.66 Pg C directly to the atmosphere from forest biomass burning events, depending on the year (Fig. 6). The lower end of this range of total regional emissions was predicted for 2002, when areas deforested dropped considerably compared to previous years.

The predicted annual NBP fluxes from the CASA model (Fig. 7), which included emission sources of CO_2 from deforested areas, summed to be greatest for the states of Pará and Amazonas (Table 2). Although the total forested area in the state of Amazonas was predicted to experience lower annual carbon emissions directly from biomass burning events than did the states of Maranhão, Mato Grosso, or Rondonia individually, NEP fluxes across intact forests of the state

Table 2. Predicted totals of carbon emission flux (Pg C yr^{-1}) to the atmosphere directly from forest biomass burning for states of the Brazilian Legal Amazon, from 2000–2002.

	Area(sq.km)	Burn-C 2000	Burn-C 2001	Burn-C 2002
Roraima	227,904	0.007	0.010	0.003
Amapa	136,896	0.000	0.003	0.001
Para	1,225,986	0.201	0.255	0.079
Amazonas	1,553,088	0.027	0.012	0.009
Maranhao	324,096	0.029	0.287	0.012
Tocantins	277,056	0.012	0.002	0.002
Acre	152,640	0.023	0.004	0.008
Mato Grosso	911,104	0.173	0.058	0.083
Rondonia	244,544	0.114	0.028	0.031
Legal Amazon Totals	5,053,312	0.586	0.660	0.226

Amazonas were not as strongly positive as in these other states of the Legal Amazon during the years studied (Potter et al., 2009). This resulted in lower overall predicted carbon sink estimates from the CASA model for forested areas in the state of Amazonas, compared for instance to the state of Mato Grosso, which has higher annual deforestation rates but also has less than half of the standing forest biomass than does Amazonas (Table 1).

Based on CASA results shown in Figs. 4 and 7, specific locations of the Brazilian Legal Amazon predicted to have lost the greatest amounts of carbon due post-burning effects of deforestation in 2000–2002 were as follows:

- 50 km north and southwest of the city of Pinheiro (2.52° S, 45.08° W) in Maranhão
- 30–60 km north and northwest of the city of Paragominas (3.00° S, 47.36° W) in Pará
- 50 km northwest of the city of Tucurui (3.77° S, 49.68° W) in Pará
- 175 km along the Trans-Amazonian Highway BR-230 (centered at 3.58° S, 51.11° W) in Pará
- 40–100 km south of the city of Marabá (5.38° S, 49.12° W) in Pará
- 150 km along State Highway PA-279 (centered around 6.40° S, 51.64° W) in Pará
- 30 km along State Highway MT-328 (centered around 11.19° S, 56.92° W) in Mato Grosso
- 50 km south of the city of Sinop (11.87° S, 55.49° W) in Mato Grosso
- 50–120 km west and east of the city of Ariquemes (9.92° S, 63.04° W) in Rondonia
- 100 km southwest of the city of Boa Vista (2.82° N, 60.67° W) in Roraima

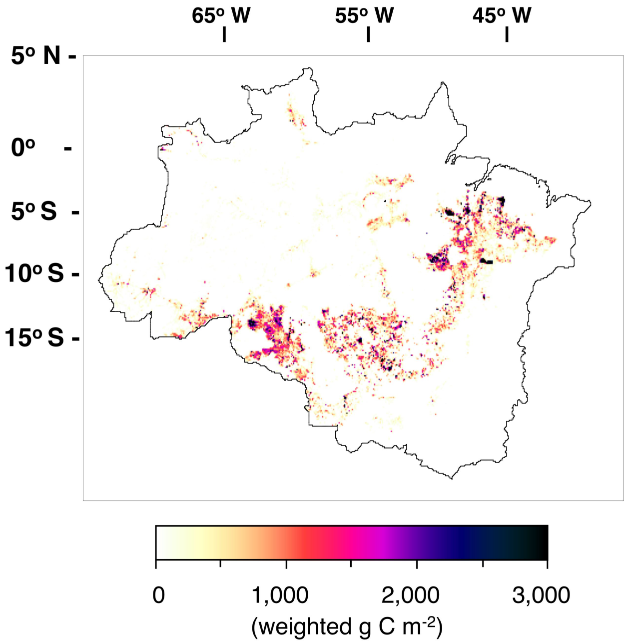

Fig. 6. Biomass burning fluxes of carbon for the Legal Amazon in 2001, based on weighted area values from PRODES deforestation mapping (Fig. 4) and CASA model aboveground wood biomass pools of carbon (Fig. 3).

In addition to the loss of between 0.23 and 0.66 Pg C directly to the atmosphere from forest biomass burning events each year, the CASA model predicts that between 0.28 and 0.4 Pg C per year was emitted from all land areas of the Legal Amazon (Table 1), the majority of which derived from decomposition of residual woody biomass from previous deforestation events. This net regional emission for the Brazilian Amazon can therefore total to between 0.5 and 1 Pg C per year.

6 Discussion

To address forest disturbance effects on tropical carbon cycles, it is necessary first to produce accurate maps of standing forest biomass across a given region. Estimates of aboveground biomass change from repeated censuses of permanent sample plots (Baker et al., 2004b; Lewis, 2006) can provide a valuable check on remote sensing methods to derive forest biomass. However, since the plot-based approaches involve the sampling of an area of approximately one hectare, concerns have been raised with respect to the validity of extrapolating results of such studies to estimate the carbon balance for the Amazon Basin as a whole (Saleska et al., 2003; Chambers and Silver, 2004; Wright et al., 2005). Central to the latter criticism is the notion that all forests studied are recovering either from some small-scale but regular disturbance (Chambers et al., 2004b) or from some severe,

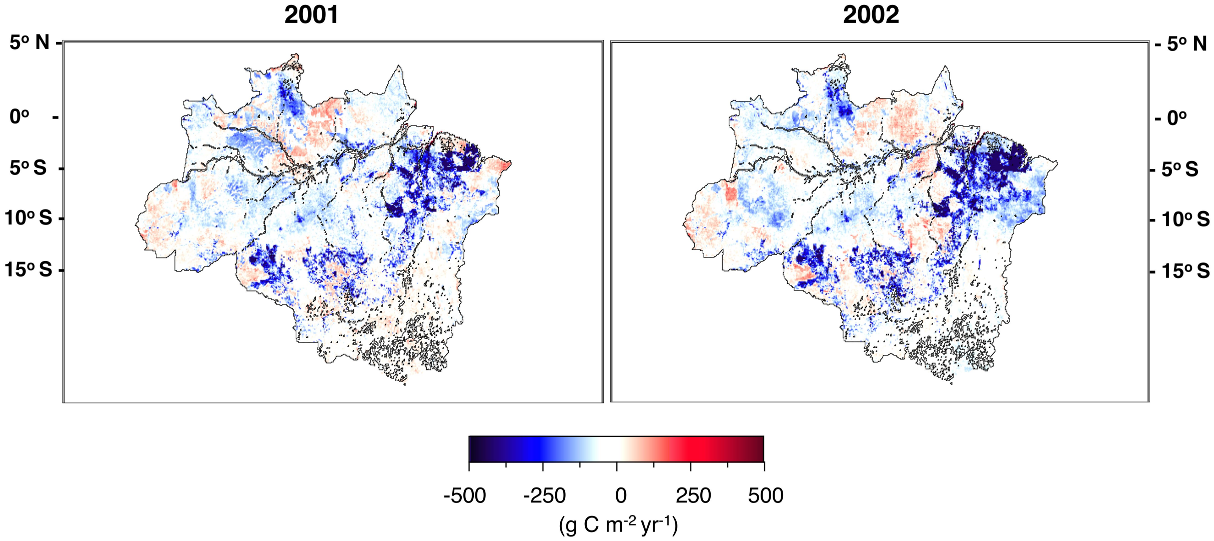

Fig. 7. Predicted annual NEP fluxes from the NASA-CASA model plus emission sources of CO_2 from down wood debris following deforestation in 2001 and 2002 over the Brazilian Amazon region, which combined represents estimates of annual NBP flux of carbon.

widespread mortality events (Wright, 2005), such as those that may have occurred in the great Amazon drought of 1926.

An advantage of combining ecosystem modeling with satellite observations for vegetation biomass estimation is to uniquely enhance the spatial resolution of physiological controls on CO_2 net flux from terrestrial systems. Using MODIS and Landsat land cover products, carbon models can identify numerous relatively small-scale patterns throughout the tropical zones where forest cover has been altered and where climate cycles such as ENSO (Zeng et al., 2008) have impacted stand productivity. Although plant biomass production and decomposition rates are simulated (rather than measured) using CASA, the land cover types, seasonal phenologies of green canopy cover, and extents of forest conversions are all observed directly from satellites in the modeling approach.

Prior to the MODIS era, uncertainties in biomass pools, deforestation rates, and rates of decomposition were estimated to account for 60%, 25%, and 15% of the uncertainty in flux estimates for the Amazon (as summarized in review by Houghton et al., 2000). With the combined use of MODIS and Landsat, as well as other satellite imagery into ecosystem biogeochemical models, uncertainty in the regional carbon balance of the Amazon appears to be narrowing. For example, Potter et al. (2001) used a version of the CASA model, together with Landsat-derived mapping of burned areas for the Legal Amazon (Alves, 1999), to estimate total NBP emission fluxes of 0.2 to 1.2 $\mathrm{Pg\,C\,yr^{-1}}$ for the region. More recently, van der Werf et al. (2003) used the CASA model with inputs of rainfall from the NASA Tropical Rainfall Monitoring Mission (TRMM) to calculate annual carbon emissions from fires in the Legal Amazon of 0.2 to 0.5 $\mathrm{Pg\,C\,yr^{-1}}$. The present study using our NASA-CASA model likewise estimated direct carbon emissions from forest burning at between 0.2 and 0.6 $\mathrm{Pg\,C\,yr^{-1}}$ in the Legal Amazon, for total NBP fluxes to the atmosphere of between 0.5 and 1 $\mathrm{Pg\,C\,yr^{-1}}$.

Deforestation for new types of land use in Brazil may have begun to affect regional emissions of carbon. For instance, adding in the conversion of forests from logging in the Amazon (which we have not included in our study), Asner et al. (2005) calculated a gross source of 0.08 $\mathrm{Pg\,C\,yr^{-1}}$ from decomposition of roundwood, residual stumps, branches, foliage, and roots left on site following wood harvest. The value is a gross flux because logged forests will presumably accumulate carbon as they regrow. Other conversions are underway, as a greater proportion of deforestation in Mato Grosso in recent years has been for soybean production rather than for pastures (Morton et al., 2006). This change in land use to crops can release more carbon more rapidly than conversions to pasture. Aboveground biomass and woody roots are removed rapidly and completely when the land is intensively cultivated, as opposed to grazed by livestock. Cultivation leaves little forest biomass for decomposition and delayed emissions. Our CASA model has been adapted to simulate these intensive cultivation effects on soil carbon cycles and will be applied in subsequent years for biogeochemical studies across Brazil.

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