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Deforestation in Brazilian Amazonia and Global Warming

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Abstract: Deforestation in Brazilian Amazonia makes a substantial contribution to global emissions of greenhouse gases because of the high rates of forest clearing and the high biomass per hectare of forest. Half of the dry weight of the trees is carbon, and this is released primarily as CO_2 or CH_4 when the felled trees are burned or when any unburned wood decays. Amazonia is not only important to global emissions because of the emissions today, but also because the region has a vast area of forest that remains uncleared. While some tropical forest regions of the world also have rapid clearing and high emissions today, this will not last long because the forest in these areas is coming to an end. The large unreleased carbon stock in Amazonia means that any policy changes that affect deforestation will have an important effect on future emissions. Uncertainty is still high regarding the magnitude of net emissions from Amazonia, including estimates of biomass and carbon stock, burning efficiency (and related trace-gas emissions), and the biomass and carbon dynamics of the landscape that replaces the forest. Substantial progress has been made in reducing the uncertainty surrounding these key components, but the additional information also serves to reveal the scale of our ignorance. Despite these uncertainties, it is clear that deforestation emissions are large and that the environmental gain from reduced deforestation and degradation (REDD) is therefore also large.

Key words: Carbon, environmental services, ecosystem services, greenhouse effect, rainforest, tropical forest.

Deforestation Emissions from Primary Forests

The stock of carbon in primary forests in Brazilian Amazonia is enormous, and avoiding the release of this carbon to the atmosphere therefore represents an important environmental service by avoiding the corresponding impacts of global warming. The term “primary” is used here to refer to forests that are present since European contact. They are not “virgin” in the sense of being uninfluenced by the indigenous people who have inhabited them for millennia, nor are they necessarily free of impact from selective logging and ground fires from recent human influence.

Estimates vary widely as to the amount of biomass and carbon stocked in Amazonian primary forests. However, because of known errors in some of the estimates, the range of genuine uncertainty is much less than the range of numbers that have been published and quoted. Part of this stems from an extremely low value for forest biomass estimated by Brown and Lugo (1984), who calculated that Amazonian forests have an average live biomass of only 155.1 Mg (megagrams

= tons) per hectare, including the roots. This is approximately half the magnitude of present-day estimates. This estimate and a subsequent revision (for above-ground biomass only) to 162 Mg ha^{-1} from the forest volume surveys by the Radar in Amazonia-Brazil Project (RADAMBRASIL) and 268 Mg ha^{-1} from forest volume surveys by the Food and Agriculture Organization of the United Nations (FAO) (Brown and Lugo, 1992a), then revised to 227 and 289 Mg ha^{-1}, respectively (Brown and Lugo, 1992b), were the subject of a colorful dispute, during which this author was accused of being "clearly alarmist" (Lugo and Brown, 1986) for defending higher values for biomass (see Brown and Lugo, 1992c; Fearnside, 1985, 1986, 1992, 1993). While Brown and Lugo themselves no longer use their very low biomass estimates of that period, the ghost of these numbers is still with us to this very day, especially the notorious 155.1 Mg ha^{-1} estimate. This is because many discussions of Amazonian biomass confine themselves to reporting a range of published values, from "X" to "Y" (e.g., Houghton, 2003a,b; Houghton *et al*., 2000, 2001). Readers unfamiliar with the details of the controversies usually assume that the "real" value lies in the middle of the range. This is the "Goldilocks fallacy," or assuming *a priori* that the middle value is "just right." Unfortunately, if the terms are defined in the same way there can only be one correct value for the average biomass of the Amazon forest. That value will depend on the quality and quantity of the underlying data and on the validity of the interpretation applied to these numbers. There is no substitute for understanding and evaluating the arguments involved.

The vast area of Amazonia, diverse types of forest in the region, and the high variability of biomass from one hectare to the next within any given forest type mean that a large number of sample plots is required to adequately represent the region's biomass. The principal sources of data are the RADAMBRASIL survey, with over 3000 one-hectare plots where trees were measured in the 1970s and early 1980s (Brazil, Projeto RADAMBRASIL, 1973-1983) and the 1356 ha of plots surveyed by the FAO (Heinsdijk, 1957, 1958; Glerum, 1960; Glerum and Smit, 1962). Estimates based on much smaller data bases will necessarily carry substantial uncertainty. Examples include the estimates by Saatchi *et al.* (2007), based on 280 plots in primary forests (approximately half of which were in Brazil), and the study of Malhi *et al.* (2006), which interpolated (followed by adjustments for the effects of various environmental variables) based on 226 plots of which 81 were in Brazil, these being heavily clustered in the Manaus, Belém and Santarém areas. One estimate (Achard *et al.*, 2002) was based on a mean of two values, one of which Brown (1997) was for a single plot located in the Tapajós National Forest in Pará (FAO, 1978) and made no claim to represent the whole of Amazonia (see Fearnside and Laurance, 2004). Houghton *et al.* (2000) derived an estimate interpolated from 56 plots, while Houghton *et al.* (2001) produced an estimate interpolated from 44 samples, of which only 25 were in Brazilian *terra firme* (upland) forests; these authors then averaged the resulting 192 Mg C ha^{-1} value with six other regional estimates to produce the 177

Mg C ha^{-1} average biomass carbon stock used by Ramankutty *et al.* (2007) in calculating emissions. This also applies to studies that have based calculations on the Houghton *et al.* (2000) estimate, such as Soares-Filho *et al.* (2004, 2006) and DeFries *et al.* (2002). An additional factor adding uncertainty to interpolation from the small number of samples used in the estimates by Houghton and coworkers is the effect of a pronounced clustering of sample locations, which both exacerbates the lack of coverage for most of the region and reveals the large uncertainty of estimates based on small sample areas, which display high variability among nearby locations. The present study uses 2860 of the RADAMBRASIL plots and includes the information in the RADAMBRASIL vegetation maps.

The placement of the RADAMBRASIL plots is highly non-random, with the samples heavily concentrated along rivers and roads. The concentration of samples near rivers means that riparian vegetation is proportionately more heavily sampled than the upland interfluves between the rivers. Simply converting the RADAMBRASIL volume estimates to biomass and interpolating between the locations will therefore over-emphasize the lower biomass riparian vegetation types and will tend to underestimate average biomass in the region (i.e., the "RADAMBRASIL" estimates in Houghton *et al.*, 2001). The computational ease of using geographical information system (GIS) software to interpolate between the sample points using Kriging techniques produces visually attractive maps but throws out the tremendous amount of labor that the RADAMBRASIL teams invested in classifying and mapping the vegetation.

Another approach is to use remote-sensing information to estimate biomass by associating a variety of parameters detected from space with the biomass measured at a series of reference points on the ground. This has been done by Saatchi *et al.* (2007) using 1 km resolution satellite-borne radar data, from which a number of characters were extracted and associated with published or otherwise available data from plots surveyed since 1990. The older, but much larger, data sets from the RADAMBRASIL and FAO surveys were not used for calibrating the satellite-borne radar results, nor were the vegetation maps that the RADAMBRASIL project derived from high-resolution airborne radar coupled with extensive field observations.

Using the RADAMBRASIL dataset requires considerable effort due to confusion regarding the vegetation types in the map legends. Among the 23 volumes into which the coverage of Brazilian Amazonia is divided, the map codes corresponding to different vegetation types change from one volume to another. The level of detail in the codes is not consistent throughout the survey, some volumes using four-letter codes and others simplified to three. In Brazilian Amazonia there are 145 vegetation types in the RADAMBRASIL data set. These can be translated into the 19 forest types used in 1:5,000,000-scale maps by the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) and 1:2,500,000-scale maps by the Brazilian Institute of Geography and Statistics (IBGE), using equivalences that change depending on the RADAMBRASIL volume.

There are many inconsistencies in reporting the vegetation type associated with each plot. All volumes are composed of a green-covered main volume plus a packet of 1:1,000,000-scale maps. From Volume 8 onward there is also a white-covered volume with plot-level data on wood volume by species and size class. The chapters in the green volumes up to Volume 18 also contain many small 250,000-scale maps showing plot locations and vegetation types. Approximately half of the 3000 plots have some sort of inconsistency, where the green volume text lists a given plot for one vegetation type, the white volume lists another, and/or the 1:1,000,000-scale vegetation map or the 1:250,000-scale location map shows a different vegetation type. Fearnside (1997a, 2000b,**c**) used only the 1500 points with no inconsistency in reporting the vegetation type. An ongoing effort to clarify these inconsistencies has expanded the number of usable plots.

The tree-by-tree data from the plots are not reported in the published RADAMBRASIL volumes. These data have apparently been digitized twice: once by FUNCATE (Foundation for Space Research, Applications and Technology, a firm in São José dos Campos, São Paulo, that did contract work for INPE in preparing the data for the deforestation emission estimates included in Brazil's national communication to the UN-FCCC). As far as can be determined, this data set has been lost. Repeated efforts by this author and by Carlos Nobre have been unsuccessful in obtaining the original tree-by-tree data used in Brazil's national communication. The national communication estimate of deforestation emissions (Brazil, MCT, 2004; FUNCATE, 2006) is based on a "personal communication" from 2000 that has never been released. In addition to rendering impossible any checking of the calculations, this official estimate ignores all the work done in the five years from 2000 to December 2004.

The RADAMBRASIL data have subsequently been digitized by IBGE. A large number of apparent typographical errors, together with inclusion of tree savannas, make extensive filtering and culling necessary in order to use the data. Work on this is underway. It is probable that similar errors apply to the version of the dataset used in the national communication, but there is no way to verify this.

Recent advances have been made by Nogueira *et al*. (2007, 2008a,b) in adjusting biomass estimates for the effect of variation in wood density between the arc of deforestation and the central Amazon area, where almost all previous data had originated. Part of this is due to regional differences in the frequency of species with different wood densities (Chave *et al*., 2006; Fearnside, 1997b), and part is due to geographical variation in wood density within the same species. Additional adjustments correct for differences in tree height between these parts of Amazonia (Nogueira *et al*., 2008c). Trees of the same species in the arc of deforestation are shorter for any given diameter than they are in central Amazonia, and they have lighter density wood and higher water content. These corrections have the effect of lowering biomass as compared to previous estimates.

The corrections do not resolve differences between these previous estimates, however, as all of them would decrease in parallel. For estimates based on tree-by-tree data (as opposed to estimates based on wood volume estimates by plot published by RADAMBRASIL), it is also necessary to make corrections for irregular and hollow trunks (Nogueira *et al*., 2006). In some cases, additional corrections are needed for wood density sample positioning within the trunk and/or for the way the wood samples are dried (Nogueira *et al.*, 2005).

Carbon Uptake by Standing Forest

Is standing forest absorbing a large amount of carbon? This question has long been a source of controversy, but much progress has been made in resolving it. The still-popular misconception that Amazonia is the “lungs of the world,” meaning that it is responsible for supplying the global atmosphere with oxygen, implies that a vast amount of carbon must be stocked away in the region, presumably in increasing biomass of the forest. The impossibility of such a mechanism supplying a significant amount of oxygen has always been clear because to do so would imply such a rapid increase in biomass that it would be obvious to casual observers. The forest trees are not several-fold larger today than they were a century ago. Although photosynthesis by the trees releases oxygen, approximately the same amount of oxygen is consumed by the forest through respiration of both plants and animals (which takes place 24 hours per day, unlike photosynthesis which is restricted to the daylight hours). In order to have a net release of oxygen, the carbon sequestered by photosynthesis must be stored away such that it cannot recombine with oxygen to produce carbon dioxide. This occurs, for example, with organic matter that falls to the bottom of the ocean and is buried in marine sediments.

Since carbon dioxide only makes up approximately 3% of the atmosphere, as compared to approximately 20% for oxygen, a much smaller emission or absorption would be necessary to have an appreciable effect on the concentration in the case of carbon dioxide. Imbalances in the uptake and release of carbon could affect atmospheric carbon dioxide concentrations over a time scale of a few years, although over a scale of centuries the balance must be approximately zero. A series of estimates from eddy-correlation measurements of vertical movement of CO_2 past sensors mounted on towers above the forest canopy has produced widely differing values for net carbon flux, often simply reported as a range, such as uptake of 1-6 Mg C ha^{-1} annually. Expressing it this way implies that there is an enormous disagreement in the scientific community over the general nature of the result. While there is some disagreement, it is much less than such a range implies. In large part, the wide range of results represents a progression of revisions of the numbers due to problems with the initial measurement methodology. The revisions resulted in a steady decrease in the estimated uptake by the forest, and numbers at the upper end of the range have been disqualified because much of the carbon dioxide measured as entering the forest during the day was, in fact, leaking away by flowing downhill near the ground at night, only to be released past the boundary layer in the morning from some downhill location away from the tower (Araújo *et al*., 2002; Kruijt *et al*., 2 004).

Corrected estimates extrapolated to all of Amazonia indicate substantial variation, with standing forests serving either as a source or a sink, the mean being a sink of 2.3 3.8 Mg C ha^{-1} annually (Ometto *et al*., 2005). The nocturnal and early-morning fluxes are especially important for the huge uncertainty in the overall balance. During El Niño years the forest loses carbon, and at the Santarém site the forest was found to be a small source even in non-El Niño years (Saleska *et al*., 2003), a result that is consistent with carbon stocks estimated from monitoring tree biomass and coarse woody debris in the same forest (Rice *et al*., 2004). This effect is also expected from modeling results (Tian *et al*., 1998, 2000). It was evident at the time of the early high estimates that something was wrong with the numbers because forest growth at the implied rate would be readily observable, and this contradicts tree measurement data from the large survey at the Biological Dynamics of Forest Fragments Project near Manaus (Fearnside, 2000a).

There is substantial variation with location in the amount of carbon uptake calculated. The maximum uptake rates were estimated from tree-growth measurements in Peru and Ecuador (Baker *et al*., 2004; Phillips *et al*., 1998, 2002, 2004); unfortunately, there are no towers at these sites for comparable eddy correlation measurements. A gradient in uptake rates declining from the Andes to the Atlantic has been attributed to a corresponding gradient in soil quality (Malhi *et al*., 2006).

Carbon Uptake by Secondary Forests

Shortly before the 1997 Kyoto Conference of the Parties, which produced the Kyoto Protocol, the Brazilian government announced that the country produces *zero* net emissions from Amazonian deforestation because "the carbon is re-absorbed" (*IstoÉ*, 1997). The claim that "the plantations [i.e., secondary forests] that replace the forest re-absorb the carbon that was thrown into the atmosphere by the burning" ignores the approximately two-thirds of the deforestation emission that comes from decomposition rather than burning (Fearnside, 1997a). Even so, the notion that the landscape in the area that is deforested each year absorbs this much carbon is still a gross exaggeration. Only 7.3% of the 1990 CO_2 emission will eventually be re-absorbed by the replacement landscape (Fearnside, 2000b, p. 235). This is based on the equilibrium composition of the landscape implied by transition probabilities among land uses in the 1980s and early 1990s (Fearnside, 1996a; Fearnside and Guimarães, 1996).

Estimates of carbon uptake and stock in secondary forests vary tremendously, and several of the most frequently used numbers for these important parameters are not based on any data whatsoever. This is the case for the estimates by Houghton *et al*. (2000, p. 303) and Ramankutty *et al*. (2007, p. 65), which assume that secondary forests will grow linearly to attain 70% of the original primary forest biomass carbon stock in 25 years. For example, considering primary forest biomass carbon of 196 Mg C ha^{-1} (above + below ground), which is the average of three estimates by Houghton *et al.* (2000), this secondary forest growth rate corresponds to 5.5 Mg C ha^{-1} annually. The corresponding figure for Ramankutty *et al.* (2007) would be 5.0 Mg C ha^{-1} annually, given their assumptions. These assumed growth rates are approximately double the growth rates that have been measured in secondary forests growing in abandoned pastures in Brazilian Amazonia. For abandoned pastures near Brasil Novo, Pará measured by Guimarães (1993) the mean annual accumulation to 20 years is 2.2 Mg C ha^{-1} annually, while for abandoned pastures near Paragominas, Pará, with a history of "moderate" use studied by Uhl *et al*. (1988) the accumulation by year 20 would average 2.6 Mg C ha^{-1} annually (see Fearnside and Guimarães, 1996). These values assume a carbon content of 45% for secondary forest biomass.

The growth rate assumed by Houghton *et al.* (2000), although not supported by any reference to data, has been used in such carbon-balance calculations and in global calculations by Achard *et al*. (2002, 2004), Houghton *et al*. (2003a) and Persson and Azar (2007). This is one of the reasons these studies underestimate greenhouse-gas emissions from Amazonian deforestation (Fearnside and Laurance, 2003, 2004; see also: Eva *et al*., 2003; Achard *et al*., 2004). Most important from a policy standpoint is the fact that this value for secondary forest growth is used in Brazil's national inventory of greenhouse-gas emissions (Brazil, MCT, 2004), leading this official estimate to includ an absorption of 34.9 million Mg C per annum from secondary forests in Amazonia, supposedly absorbing 23% of the gross emission from deforestation calculated in the report. This author's estimate for absorption by the landscape in 1990 is only 7.9 million Mg C per annum (Fearnside, 2000b). The much higher value in the official estimate is only partially due to the high value used for per-hectare uptake in secondary forest; even more important is the misleading decision of counting all of the Amazonian landscape's uptake in an estimated 8.23 million hectares of secondary forest (an area 5.4 times the annual deforestation rate in the inventory period), but not counting any of the emission from each year's clearing of a portion of these secondary forests. In addition, if the inherited uptake from the more rapid clearing of the 1980s is to be claimed, then the inherited emissions from this period would also have to be counted to have a fair estimate of the impact of deforestation; these emissions are quite substantial for the years in question (Fearnside, 1996b, 2000b). Selective mixing of elements from net committed emissions and annual balance calculations does not produce a valid result (see Fearnside, 2000b, 2003). "Net committed emissions" refers to the net result of the emissions and uptakes that occur in the area felled in a given year, such as the 13.8 x 10^3 km^2 of primary forest cleared in Brazilian Amazonia in 1990, extending from the moment of deforestation to the far-distant (theoretically infinite) future (Fearnside, 1997a); "annual balance," on the other hand, refers to the emissions and uptakes occurring in a single year (such as 1990) over the entire landscape (such as the 415 x 10^3 km^2 deforested by 1990) (Fearnside, 1996b). If trace gases are ignored, the two measures would be the same if (and only if) the deforestation rate were constant over an extended period of years preceding the year in question, which is not the case for the inventory period. As an indication of the magnitude of the omission of emissions from secondary forest clearing that would be needed to be included for the inclusion of the full landscape's secondary forest uptake to be valid, release from these stocks in 1990 totaled an estimated 25.8 million Mg of CO_2-equivalent carbon (Fearnside, 2000b).

A key aspect of secondary forests in Brazilian Amazonia is that the vast majority of them are growing in abandoned cattle pasture – they are not shifting-cultivation fallows. Under cattle pasture, the soil becomes compacted and depleted in nutrients and soil biota, with the result that secondary forests in abandoned pastures grow much more slowly than those in shifting cultivation (Fearnside, 1996a; Fearnside and Guimarães, 1996). Abandoned pastures also lack seed sources and other features that favor regeneration (Nepstad *et al*., 1991). Most published data on tropical secondary forests are based on abandoned agricultural fields, including all of the studies included in the pan-tropical review of secondary forests by Brown and Lugo (1990).

The percentage of the deforested landscape that is under secondary forests in Brazilian Amazonia varies in response to the economic forces that motivate pasture maintenance. A widely used value is 30% of the deforested area under secondary forest (Houghton *et al.*, 2000), based on an analysis by David Skole of Michigan State University of 1:500,000-scale LANDSAT-MSS images for 1986. This is a reasonable estimate for 1986, a period following rapid growth of Amazonian pastures for "ulterior" motives such as maintaining land-tenure claims for speculative profits during a period of hyperinflation (Fearnside, 1987, 2005a). It also fits with the pattern of behavior indicated by interviews with ranchers (Uhl *et al.*, 1988; see calculations in Fearnside, 1996a) and is close to the percentage (37%) calculated for 1990 from transition probabilities in the 313 x 10^3 km^2 deforested at that time excluding 5 x 10^3 km^2 of hydroelectric dams and 98 x 10^3 km^2 of pre-1970 clearing.

In recent years, however, the ranching economy has become increasingly driven by the profit of raising beef for sale (e.g., Margulis, 2003). This author traveled through ranching areas in northern Mato Grosso in 1986 and 2006; the contrast was evident – in 1986 large areas were in abandoned cattle pasture reverting to secondary forest, whereas the same areas were maintained as productive pasture stocked with cattle in 2006 (personal observation).

The intensity of use is a key factor in the rate of growth of secondary forest (e.g., Uhl *et al.*, 1988). A special case is presented by the large areas of secondary forests in the Superintendency of the Manaus Free-Trade Zone (SUFRAMA) Agriculture and Ranching District, located approximately 80 km north of Manaus. This area of ranches was heavily subsidized in the 1970s and early 1980s, but when the subsidies effectively came to an end in 1984 much of the cleared area was abandoned to secondary forest (Fearnside, 2002). One would expect the secondary forest to grow more vigorously under these circumstances than in typical abandoned pastures because the soil had not degraded

Table 1. Net committed emissions from Amazonian deforestation over the 1988-1994 Brazilian inventory period[(a)] *(Please see Table formate)*

	Emissions (million Mg gas/year)									
	CO_2	CH_4			N2O					
Forest biomass gross emission	819.40	1.56	–	2.23	0.04	–	0.05			
Committed uptake	-71.61									
Forest biomass net committed emission	747.80	1.56	–	2.23	0.04	–	0.05			
CO2 carbon equivalent (Million Mg C)	203.94–	10.61	–	15.19	2.90	–	4.25	217.46	–	223.39

(a) Average deforestation rate 15,228 km^2/year. Low and high values reflect range of emission factors, not uncertainty in biomass.

(b) Converted using 100-year global warming potentials from the IPCC AR4: per Mg of gas CO2=1, CH4=25, N2O=298.

to the point where pasture growth was reduced enough to force the rancher to suspend its use for grazing. In a part of the area, including one 1200 ha clearing, the land had not been used for pasture at all because the unusual rainfall during the burning season in 1983 prevented the ranch from burning the felled area (Fearnside *et al.*, 1993). Because of the large area of homogeneous secondary forest with known history on these ranches, there have been several studies of these secondary forests (e.g., Foody *et al.*, **1996 or 2006**; Lucas *et al.*, 1993, 2002). However, the growth rates from this area cannot be extrapolated to the vast areas of abandoned pastures where the soil is more degraded under more-typical circumstances.

Net Emissions from Amazonian Deforestation

Current values for emissions are summarized in **Table 1**. Even in years when the deforestation rate is lowest the emission from this source is several times the 69 million t C per annum that Brazil was emitting from fossil-fuel combustion and cement manufacture when these emissions were inventoried for 1994 (Brazil, MCT, 2004). The deforestation emissions in Table 1 are much higher than those reported in Brazil's national communication to the UN-FCCC (**Table 2**). The discrepancy is primarily due to various omitted components in the official biomass estimates, including belowground biomass and dead biomass (necromass), plus the exaggerated secondary forest uptake mentioned earlier. The discrepancy totals 115% if comparable biomass values are used (Table 2). Approximately one-third of this discrepancy remains unexplained.

The emissions summarized in Tables 1 and 2 include the effect of two trace gases:methane (CH_4) and nitrous oxide (N_2O). Other trace gases such as carbon monoxide (CO), nitrogen oxides (NOx) and non-methane hydrocarbons (NMHC) are not

Table 2. Comparison of deforestation emissions results with the official Brazilian estimate

Year	Deforestation rate (10^3 km^2/year)	Net emission (million tons CO_2-equivalent C/year)			
		Fearnside (e.g., Table 1 midpoint)	Brazilian national inventory[a]	Discrepancy (%)	
				Raw values	With comparable biomass[b]
1990	13.8	200.0			
1988-1994	15.2	220.4	116.9	90	115
2000	18.2	263.8			
2004	27.4	396.3			
2007	11.2	162.5			

(a) Brazil, MCT (2004), (b) Calculated using Fearnside value without the adjustments to biomass for new estimates of wood density and tree height that are included in the values in Table 1.

included, in accord with current IPCC practices. Particularly in the case of CO, which is an important product of biomass burning, an eventual agreement on the magnitude of its indirect effect would increase the global-warming impact attributed to deforestation (see discussion in Fearnside, 2000a). CH_4 and N_2O emissions are converted to CO_2-equivalents using the 100-year global-warming potentials (GWPs) from the Fourth Assessment Report (AR-4) of the Intergovernmental Panel on Climate Change (IPCC): 25 for CH_4 and 298 for N_2O (Forster *et al*., 2007). The 100-year GWP represents the cumulative radiative forcing of one ton of gas relative to one ton of CO_2 over a 100-year period with no discounting or other adjustment for time preference within this time horizon. Quantities of CO_2 can be converted to carbon by multiplying by 12 (the atomic weight of carbon) and dividing by 44 (the molecular weight of CO_2). One ton of carbon in the form of CH_4 has the impact of 9.1 tons of carbon in the form of CO_2. The IPCC's values for 100-year GWPs have changed: the 1995 Second Assessment Report, which is still used for calculations under the Kyoto Protocol through 2012, adopted values of 21 for CH_4 and 310 for N_2O; the 2001 Third Assessment Report GWPs were 23 for CH_4 and 310 for N_2O. Deforestation emits more trace gases relative to CO_2 than does burning fossil fuels, and these effects must be included to have fair comparisons between these two major sources of emissions. Trace-gas emissions increase (Table 1) the impact of Amazonian deforestation by 6.6-9.5% relative to the release of CO_2 alone (updated from Fearnside, 2000b based on 100-year global warming potentials from the IPCC's AR-4 and emission factors from Andreae and Merlet, 2001). The range of percentage values reflects the range of estimates for emission factors for each trace gas associated with each emission process (flaming combustion, smoldering combustion, etc.).

In addition to carbon from primary and secondary forest biomass (the source of the emissions in **Tables 1 and 2**), deforestation produces emissions from release of soil carbon (Fearnside and Barbosa, 1998). Additional anthropogenic emissions occur from various other types of land use and land-use change in Amazonia, including hydroelectric dams (Fearnside, 2005b; Kemenes *et al*., 2007), savanna clearing (Fearnside, 2000b), periodic burning of savannas (Barbosa and Fearnside, 2005), logging in areas that will not be cleared within a short period (approximately three years) (Asner *et al*., 2005; Fearnside, 1995), forest fires in areas that will not later be cleared (Alencar *et al*., 2006; Barbosa and Fearnside, 1999) and edge effects from the portion of the forest area near edges in the region that represents a net annual increase (Laurance *et al*., 1997, 2001; see discussion in Fearnside, 2000a). Implicitly included in the biomass estimates used for the deforestation emissions estimates are the losses to edge effects that are not net increases in the total edge area present, logging in areas that will later be cleared, and forest-fire effects in these same areas.

Potential Carbon Release from Climate Change

Global change is expected to result in substantial climate modification in Amazonia, although the various global climate models vary widely in the amount of change indicated for the region. Several models indicate that Amazonia will become significantly hotter and drier in the latter half of the present century. These include the Hadley Center model (HadCM3) from the United Kingdom, the Max Planck Institute model (ECHAM4) from Germany and the National Center for Atmospheric Research (NCAR) model (CCSM3) from the United States, the GCM2 model from Canada and the CCSR/NIES2 model from Japan. Of the 21 models considered by the Intergovernmental Panel on Climate Change (IPCC) in its 2007 Fourth Assessment Report (AR-4), some, such as the CSIRO model from Australia, show no change and only one, the Geophysical Fluid Dynamics Laboratory (GFDL) model from the United States, shows increased rainfall (Kundzewicz *et al*., 2007).

The Hadley Center model is the most catastrophic in its predictions for Amazonia, including virtually all of the forest in Brazilian Amazonia being killed by 2080 (Cox *et al*., 2000, 2004; see also White *et al*., 2000). The changes, however, should not be as great as the Hadley model indicates because the model substantially underestimates the rainfall in the present climate (Cândido *et al*., 2007). But two facts suggest that it is likely that the general nature of the change indicated would hold, namely a climate that is sufficiently hotter and drier to result in massive tree mortality. First is the fact that the Hadley Center model was the best of 21 models tested in representing the connection between increased temperature of water at the surface of the equatorial Pacific Ocean and droughts in Amazonia (Cox *et al*., 2004). High sea-surface temperature in the Pacific is the criterion for what is known as “El Niño-like conditions.” The IPCC’s AR-4 concluded that there is now general agreement among the models that continued global warming will produce more “El Niño-like conditions” (Meehl *et al*., 2007). However, the report notes that there is yet no agreement among the models on the next step: the connection between El Niño-like conditions and the modeled occurrence of El Niño itself, meaning the characteristic pattern of droughts and floods at different locations around the world. But this second step does not depend on the results of climate models because this connection is based instead on direct observations: whenever the water in the Pacific warms, we have drought and forest fires in Amazonia, especially in the northern portion. The El Niño fires of 2003, 1997/98, and 1982 are remembered by many people in the region. The second fact that justifies concern is that the heat and drought indicated by the Hadley model so greatly exceed the levels of tolerance of Amazonian trees that large-scale mortality could be expected even if the changes were more modest than those indicated by the Hadley model. In fact, the majority of 15 models studied by Salazar *et al*. (2007) indicate that the eastern portion of Amazonia would have a climate appropriate for savanna by 2100. A similar result is shown by an analysis of 23 models (Malhi *et al*., 2008). In other words, this is not a result that depends on the Hadley Center model proving to be correct.

El Niños provoked by warming in the Pacific are only part of the threat to Amazonia. Warming of the Atlantic, also a result of global warming (Trenberth and Shea, 2006), is projected to have impacts at least as great. While El Niño has effects concentrated in the northern part of Amazonia (Malhi and Wright, 2004), warming in the northern part of the tropical Atlantic has its impact in the southern part of Brazilian Amazonia, as occurred in the drought of 2005 (Fearnside, 2006; Marengo *et al*., 2008). Greatly reduced rainfall over the headwaters of the tributaries on the southern side of the Amazon River produced a dramatic drop in water levels, impeding boat traffic and isolating many communities. Fires burned large areas of standing forest in Acre, a virtually unprecedented event (Brown *et al.*, 2006; Vasconcelos and Brown, 2007). Recent simulation results with the Hadley model (Cox *et al.*, 2008) indicate a tremendous rise in the probability of events like the 2005 drought over the coming decades. The key change is an increase in the temperature gradient between warm water in the northern part of the tropical Atlantic and colder water in the southern part. Global warming differentially warms the northern end of this gradient, and the effect is greatly augmented by continued decrease in aerosol pollution in the industrial countries of North America and Europe. The stronger north-south temperature gradient in Atlantic sea-surface temperatures draws the intertropical convergence zone further north, resulting in dry air from the Hadley circulation descending in areas further into the southern portion of Amazonia. The Hadley circulation is a flow of air that rises near the equator and then splits and moves toward the poles at an altitude of about 1800 m (an altitude at which the air holds very little water); the air then falls to the ground at a point between approximately 15 and 30 degrees latitude, depending on the time of year, after which it returns to the equator in winds blowing near ground level. The descending dry air desiccates the area where this air flow falls to the ground, as occurred in southern and western Amazonia in the drought of 2005. In 2005 the annual probability of an event of this type occurring in this part of Amazonia was approximately 5%, meaning that it had an expected recurrence interval of one year in 20. The Hadley Center model simulation with "business as usual" (IS92a) emissions indicates this frequency of recurrence increasing to one year in two by 2025, and to nine years in ten by 2060 (Cox *et al.*, 2008). The atmospheric concentrations of CO_2 causing this would be 450 ppmv in 2025 and 610 ppmv in 2060. Increasing atmospheric CO_2 levels even than lower these two concentrations would therefore represent a severe threat to Amazonian forest.

The mechanisms by which forest mortality could occur under the predicted climate conditions have been the subject of a number of studies. Current climatic variability already endangers large areas of Amazon forest (Huytra *et al.*, 2005; Nepstad *et al.*, 2004). The microclimate near the edge of forest that abuts cattle pasture is hotter and drier than that in the interior of the forest. Trees near the forest edge have much higher mortality rates than those in the forest interior, and the largest trees are the most likely to die. This is shown by the Biological Dynamics of Forest Fragments Project (PDBFF) near Manaus, where over 65,000 trees have been monitored for over 25 years (Nascimento and Laurance, 2004). In a one-hectare plot near Santarém where plastic panels were installed to exclude 60% of the throughfall, the same result was found, with the large trees dying first (Nepstad *et al.*, 2007).

Forest fires occur under the hot, dry conditions that characterize both El Niño and droughts like the one in 2005 (e.g., Alencar *et al.*, 2006; Barbosa and Fearnside, 1999; Barlow *et al.*, 2003). These fires have a positive feedback relationship with tree mortality, killing trees by heating the bark at the base of the trunk, thereby leaving large quantities of dead wood in the forest that serves as fuel for the next fire (Alencar *et al.*, 2004; Cochrane, 2003; Cochrane *et al.*, 1999; Nepstad *et al.*, 1999, 2001). The effect of fire is not included in the Hadley Center model or in other global climate models, meaning that forest mortality could proceed more rapidly than they indicate. Direct loss of forest through deforestation is also not included in these models.

Conclusions

Deforestation in Brazilian Amazonia contributes substantial emissions of greenhouse gases to the atmosphere at current rates of clearing, and the large forest area and carbon stock remaining implies the potential for correspondingly large releases from future deforestation and/or from future climate change. Regrowth of vegetation in the deforested areas absorbs some of the carbon dioxide released by burning and decay of the original vegetation, but none of the trace gases such as methane and nitrous oxide are absorbed. Only about 7% of the CO_2-equivalent carbon emission from clearing the original forest is eventually reabsorbed. The role of Amazonian forest in avoiding global warming is primarily in preventing the release of carbon stocks through deforestation, as opposed to absorption of carbon by standing forest. Assessing the net impact of deforestation depends on the biomass stock in the forest, on the dynamics of the landscape that replaces the forest, and on the rate of growth of secondary forests. A number of estimates of this impact have understated the importance of Amazon deforestation in contributing to global warming either by underestimating the biomass of the original forest, overestimating the proportion of the replacement landscape that is occupied by secondary forest (or the area to be counted in indices of net emissions), or overestimating the growth rate of secondary forest. The value of averting deforestation also applies to averting levels of climate change that could threaten the forest by increased drought and temperature and through a positive feedback with forest fires. The large emissions from Amazonian deforestation imply substantial potential gain for the global climate from programs for reduced emissions from deforestation and degradation (REDD).

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