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CHAPTER _

Greenhouse Gas Emissions from Land-Use Change in Brazil's Amazon Region

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I. Introduction

Deforestation in Brazilian Amazonia releases quantities of greenhouse gases that are significant both in terms of their present impact and in terms of the implied potential for long-term contribution to global warming from continued clearing of Brazil's vast area of remaining forest. The way in which emissions are calculated can have a great effect on the impact attributed to deforestation. Two important indices for expressing the global warming impact of deforestation are net committed emissions and the annual balance of net emissions (or, more simply, the annual balance).

Net committed emissions expresses the ultimate contribution of transforming the forested cover into a new one, using as the basis of comparison the mosaic of land uses that would result from an equilibrium condition created by projection of current trends. This includes emissions from decay or reburning of logs that are left unburned when forest is initially felled (committed emissions), and uptake of carbon from growing secondary forests on sites abandoned after use in agriculture and ranching (committed uptake) (Fearnside, 1997a).

Net committed emissions considers the emissions and uptakes that will occur as the landcover approaches a new equilibrium condition in a given deforested area. Here the area considered is the 13.8 X 10^3 km^2 of Brazil's Amazonian forest that was cut in 1990, the reference year for baseline inventories under the United Nations Framework Convention on Climate Change (UN-FCCC). The "prompt emissions" (emissions entering the atmosphere in the year of clearing) are considered along with the "delayed emissions" (emissions that will enter the atmosphere in future years), as well as the corresponding uptake as replacement vegetation regrows on the deforested sites. Not included are trace gas emissions from the burning and decomposition of secondary forest and pasture biomass in the replacement landcover, although both trace gas and carbon dioxide fluxes are included for emissions originating from remains of the original forest biomass, from loss of intact forest sources and sinks, and from soil carbon pools. Net committed emissions are calculated as the difference between the carbon stocks in the forest and the equilibrium replacement landcover, with trace gas fluxes estimated based on fractions of the biomass that burn or decompose following different pathways.

In contrast to net committed emissions, the annual balance considers releases and uptakes of greenhouse gases in a given year (Fearnside, 1996a). Annual balance considers the entire region (not just the part deforested in a single year), and considers the fluxes of gases entering and leaving the region both through prompt emissions in the newly deforested areas and through the "inherited" emissions and uptakes in the clearings of different ages throughout the landscape. Inherited emissions and uptakes are the fluxes occurring in the year in question that are the result of clearing activity in previous years, for example, from decomposition or reburning of the remaining biomass of the original forest. The annual balance also includes trace gases from secondary forest and pasture burning and decomposition.

The annual balance represents an instantaneous measure of the fluxes of greenhouse gases, of which carbon dioxide is one. Even though the present calculations are made on a yearly basis, they are termed "instantaneous" here to emphasize the fact that they do not include future consequences of deforestation and other actions taking place during the year in question.

The present paper updates previous estimates of net committed emissions (Fearnside, 1997a) and annual balance (Fearnside, 1996a). The present paper incorporates additional information on wood density (Fearnside, 1997b), below-ground biomass, *cerrado* biomass (Graça, 1997), soil carbon releases (Fearnside and Barbosa, 1998), burning efficiencies, charcoal formation and other factors.

II. Forest Biomass

The average biomass of the primary forests present in the Brazilian Amazon has been estimated based on analysis of published wood volume data from 2954 ha of forest inventory surveys distributed throughout the region (Fearnside, nd, updated from Fearnside, 1994). Average total biomass (including dead and below-ground components) is estimated to be 463 t ha^{-1} for all unlogged mature forests originally present in the Brazilian Legal Amazon. The average aboveground biomass is 354 t ha^{-1}, of which 28 t ha^{-1} is dead; below-ground biomass averages 109 t ha^{-1}. These estimates include wood density calculated separately for each forest type based on the volume of each species present and published basic density data for 274 species (Fearnside, 1997b). The total biomass estimates are disaggregated by state and forest type, allowing use of the data in conjunction with Brazil's LANDSAT-based deforestation estimates, which are reported on a state-by-state basis (Fearnside, 1993, 1997c).

The areas of protected and unprotected vegetation of each type in each state have been estimated (Fearnside and Ferraz, 1995). By multiplying the per-hectare biomass of each forest type by the unprotected area present in each state, one can estimate the biomass cleared if one assumes that clearing within each state is distributed among the different vegetation types in proportion to the unprotected area present. By weighting the biomass by the deforestation rate in each state, the average total pre-logging biomass in areas cleared in 1990 has been estimated to be 433 t ha^{-1}, or 6.5% lower than the average for forests present in the Legal Amazon as a whole (see Fearnside, 1997a). The difference is due to concentration of clearing activity along the southern and eastern edges of the forest, where per-hectare biomass is lower than in the areas of slower deforestation in the central and northern parts of the region.

The values for biomass from "unlogged" forest represent the best estimates for each forest type at the time it was surveyed (in the 1950s in the case of the Food and Agriculture Organization of the United Nations (FAO) forest inventories that comprise 10% of the data and in the early 1970s in the case of the RADAMBRASIL data covering the remaining 90%). FAO data are from Heinsdijk (1957, 1958a,b,c) and Glerum (1960); RADAMBRASIL data are from Brazil, Projeto RADAMBRASIL (1973-1983). There is some reason to believe that the survey teams avoided logged-over locations (Sombroek, 1992). In addition, logging damage was much less widespread at the time of the surveys than it is at present. Logging is progressing rapidly, with the fraction of areas cleared that are logged prior to felling increasing noticeably since the mid-1970s as road access has improved. In addition, logs and wood for charcoal and firewood are sometimes sold *after* the burn.

The biomass reduction due to logging in areas being felled is much higher than the average biomass reduction over the forest as a whole, as the areas being felled generally have the best road access. Much of the biomass reduction from logging will result in gas releases similar to those that would occur through felling: decay of the slash and the substantial number of non-commercial trees that are killed or damaged during the logging process; decay and/or burning of the scrap generated in the milling process, plus a slower decay of wood products made from the harvested timber (see Fearnside, 1995a). With adjustment for logging, areas cleared in 1990 had an average total biomass of 406 t ha^{-1}, of which 249 t ha^{-1} was aboveground live biomass, 59 t ha^{-1} was aboveground dead and 98 t ha^{-1} was below-ground.

III. Greenhouse Gas Emissions

A. Initial Burn

The burning efficiency (percentage of pre-burn aboveground carbon presumed emitted as gases) averaged 38.8% in the 10 available measurements in primary forest burns in Brazilian Amazonia (Table 1). Adjustments for the effect of logging on the diameter distribution of the biomass gives an efficiency of 39.4%.

Charcoal (char) formed in burning is one way that carbon can be transferred to a long-term pool from which it cannot enter the atmosphere. Charcoal in the soil is a very long-term pool, considered to be permanently sequestered in the analysis. The mean of the four available measurements of charcoal formation in primary forest burns in Brazilian Amazonia indicate 2.2% of aboveground carbon being converted to charcoal (Table 1).

Graphitic particulate carbon is another sink for carbon that is burned. A small amount of elemental carbon is formed as graphitic particulates in the smoke; over 80% of the elemental carbon formed remains on the site as charcoal (Kuhlbusch and Crutzen, 1995). Graphitic particulate carbon is calculated by emission factors from the amount of wood combusted. The amount of carbon entering this sink is only 1/13 the amount entering the charcoal sink.

The pre-1970 secondary forest must be considered separately from the primary forest, as these areas are not included in the deforestation rate estimate (13.8 X 10^{6} km^{2} y^{-1} in 1990). A rough estimate of clearing rate is 713 km^{2} y^{-1} (Fearnside, 1996a). Pre-1970 secondary forest is only relevant to the annual balance, not net committed emissions. The amounts of greenhouse gases contributed by clearing of pre-1970 forest are very small.

Greenhouse gas emissions and uptakes are tabulated for a net committed emissions calculation in a "low trace gas scenario" (Table 2) and a "high trace gas scenario" (Table 3). These two scenarios use high and low values appearing in the literature for the emissions factors for each gas in different types of burning (reviewed in Fearnside, 1997a). They do not reflect the doubt concerning forest biomass, deforestation rates, burning efficiency and other important factors.

The initial burn represents 270 X 10^{6} t of CO_2 gas, or 27% of the gross committed emission of 999 X 10^{6} t. Gross emission of a gas refers to all releases of the gas, but not uptakes. The initial burn contribution of CH_4 is 0.87-1.05 of 1.18-1.51 X 10^{6} t (70-74%), CO is 21-26 of 30-37 X 10^{6} t (68-70%) and N_2O is 0.05-0.14 of 0.07-0.18 X 10^{6} t (71-78%). For NO_x and NMHC, if considered apart from the loss of mature forest sources, represent, respectively, 0.66 of 0.81 X 10^{6} t (81%) and 0.58-1.10 of 0.63-1.26 X 10^{6} t (87-92%).

Table 1. Combustion and charcoal formation studies in Brazil

Location	State	Burn year	Pre-burn aboveground biomass		Burning efficiency	Net charcoal f	
			Dry weight (t ha^{-1})	Carbon (t ha^{-1})	% pre-burn C	(t C ha^{-1})	% of bio
Original forest (first burning)							
Manaus	Amazonas	1984	264.6	130.2	27.6	3.5	
Altamira	Para	1986	263.0	129.9	41.9	1.6	
Manaus	Amazonas	1990	368.5	181.7	28.3	3.4	
Jacunda	Para	1990	292.4	147.6	51.5		
Maraba	Para	1991	434.6	218.2	51.3		
Santa Barbara	Rondonia	1992	290.2	142.1	40.5		
Jamari	Rondonia	1992	361.2	178.9	56.1		
Manaus	Amazonas	1992	424.4	203.5	25.1		
Tomé Açu	Para	1993	214.2	96.2	21.9		
Nova Vida	Rondonia	1994	306.5	142.3	34.6	4.1	
Mean			321.9	157.0	39.	3.2	
Original forest remains (subsequent burnings)							
Apaiu	Roraima	1991	101.2	48.4	30.1	0.6	
Apaiu	Roraima	1993	96.3	46.1	13.2	0.3	
Mean			98.7	47.2	21.6	0.5	
Secondary forest (not including remains of original forest)							
Altamira	Para	1991	26.1	11.3	25.9	0.1	
Apiau	Roraima	1991	41.5	17.8	66.5	0.2	
Apiau	Roraima	1993	6.2	2.8	69.1	0.02	
Mean			24.6	10.7	53.6	0.1	
Pasture							
Apaiu	Roraima	1993	8.0	3.4	93.4	0.04	

B. Subsequent Burns

The burning behavior of ranchers can alter the amount of carbon passing into a long-term pool as charcoal. Ranchers reburn pastures at intervals of 2-3 years to combat invasion of inedible woody vegetation. Logs lying on the ground when these reburnings occur are often burned. Some charcoal formed in earlier burns can be expected to be combusted as well. Parameters for transformations of gross carbon stocks are given in Fearnside (1997a: 337-338), with changes in biomass, aboveground fraction, burning efficiency, charcoal formation and soil carbon release as specified elsewhere in the

Table 2. Net committed greenhouse gas emissions by source for 1990 clearing in the Legal Amazon: low trace gas scenario

Source	Area affected (10^3 km^2)	Emissions (million t of gas)					
		CO_2	CH_4	CO	N_2O	NO_x	NMHC
Forest							
Initial burn	13.8	270	0.87	20.90	0.05	0.66	0.55
Reburns	13.8	57	0.28	8.89	0.01	0.15	0.14
Termites aboveground	13.8	17	0.014				

decay							
Other aboveground decay	13.8	365					
Belowground decay	13.8	247					
Cattle (a)	6.1		0.010				
Pasture soil (a)	6.1				0.002		
Loss of intact forest sources and sinks (a)	7.3		0.0003			-0.01	-0.09
Soil carbon (top 8 m)	13.8	43					
Regrowth	13.8	-65					
Forest subtotal		934	1.18	29.79	0.07	0.81	0.63
Cerrado							
Initial burn	5.0	11	0.04	0.85	0.002	0.03	0.02
Reburns	5.0	1	0.01	0.18	0.01	0.003	0.003
Termites aboveground decay	5.0	0.1	0.0001				
Other aboveground decay	5.0	2					
Belowground decay	5.0	9					
Cattle (a)	5.0		0.008				
Pasture soil (a)	5.0				0.002		
Loss of intact *cerrado* sources and sinks (a) (b)	5.0		0.0002			-0.0004	-0.004
Soil carbon (top 8 m)	5.0	16					
Regrowth	5.0	-9					
Cerrado subtotal		31	0.05	1.03	0.004	0.03	0.02
Total for Legal Amazon		964	1.23	30.83	0.07	0.83	0.66

(a) Recurring effects (cattle methane, forest soil methane sink, pasture soil N_2O,) summed for 100-year period for consistency with IPCC 100-year horizon calculation.

(b) Intact *cerrado* source for NO_x and NMHC derived from the forest per hectare emission assuming emission is proportional to the tree leaf dry weight biomass in each ecosystem. *Cerrado* tree leaf biomass (dry season) = 0.756 t^{-1}ha (dos Santos, 1989: 194); forest (at Tucurui, Para) = 12.94 t ha^{-1} (Revilla Cardenas et al., 1982).

Table 3. Net committed greenhouse gas emissions by source for 1990 clearing in the Legal Amazon: high trace gas scenario

Source	Area affected (10^3 km^2)	Emissions (million t of gas)					
		CO_2	CH_4	CO	N_2O	NO_x	NMHC
Forest							
Initial burn	13.8	270	1.05	26.13	0.14	0.66	1.10
Reburns	13.8	57	0.44	11.32	0.03	0.15	0.25
Termites aboveground	13.8	17	0.014				

decay							
Other aboveground decay	13.8	365					
Belowground decay	13.8	247					
Cattle (a)	6.1		0.01				
Pasture soil (a)	6.1				0.002		
Loss of intact forest sources and sinks (a)	7.3		0.0003			-0.01	-0.09
Soil carbon (top 8 m)	13.8	43					
Regrowth	13.8	-65					
Forest subtotal		934	1.51	37.45	0.18	0.81	1.26
Cerrado							
Initial burn	5.0	11	0.04	1.07	0.006	0.027	0.04
Reburns	5.0	2	0.01	0.36	0.001	0.005	0.01
Termites aboveground decay	5.0	0.1	0.0001				
Other aboveground decay	5.0	2					
Belowground decay	5.0	15					
Cattle (a)	5.0		0.01				
Pasture soil (a)	5.0				0.002		
Loss of intact *cerrado* sources and sinks (a) (b)	5.0		0.0002			-0.0004	-0.004
Soil carbon (top 8 m)	5.0	16					
Regrowth	5.0	-9					
Cerrado subtotal		37	0.07	1.43	0.009	0.03	0.05
Total for Legal Amazon		971	1.88	38.87	0.18	0.84	1.31

(a) Recurring effects (cattle methane, forest soil methane sink, pasture soil N_2O, hydroelectric methane) summed for 100-year period for consistency with IPCC 100-year horizon calculation.

(b) Intact *Cerrado* source for NO_x and NMHC derived from the forest per hectare emission assuming emission is proportional to the tree leaf dry weight biomass in each ecosystem. *Cerrado* tree leaf biomass (dry season) = 0.756 t ha^{-1} (dos Santos, 1989: 194); Forest (at Tucuruí, Pará) = 12.94 t ha^{-1} (Revilla Cardenas et al., 1982).

present paper. A typical scenario of three reburnings over a 10-year period would raise the percentage of aboveground C converted to charcoal from 2.2% to 2.9%. Parameters for carbon emissions by different pathways as CO_2, CO and CH_4, and for other trace gas emissions are also given in Fearnside (1997a: 341-344). The calculations are carried out by a program known as "DEFOREST," contained in a series of approximately 150 interlinked spreadsheets.

C. Decay of Unburned Remains

Aboveground decay of unburned remains is calculated using the available studies listed in Fearnside, 1996a: 611). Decay makes a significant contribution to greenhouse gas emissions, and it is apparent that the focus of interest on biomass burning leads many to overlook the contributions of decay. The greenhouse gas emissions from deforestation that have been put forward by official Brazilian government sources (Borges, 1992; Silveira, 1992) are lower than those calculated in the present paper by a factor of three, mainly because they ignore the inherited emissions, in which decay plays a large role.

Bacterial decomposition and termite activity occur largely over the first decade. Termite emissions of methane from decay of unburned biomass (Martius et al., 1996) are substantially lower than previous estimates (Fearnside, 1991, 1992). This is mainly because estimates of the number of termites in deforested areas indicate that the populations are insufficient to consume the quantity of wood that had previously been assumed. Lower emissions of methane (0.002 g CH_4 per g of dry wood consumed) also contributes to lower emissions from this source, estimated to total only 0.014 X 10^6 t of CH_4 gas from original forest in cleared area in 1990 (Tables 2 and 3).

D. Soils

Conversion of natural forest to the replacement landcover will result in a new equilibrium of soil carbon stocks. Changes under cattle pasture are particularly important because of the dominance of pasture and secondary forest derived from pasture in the replacement landcover. Changes in the surface soil (0-20 cm depth under forest) are important because of higher concentrations of carbon in this layer and because the changes occur more quickly than in deeper layers. Compaction of the surface soil must be corrected for: one must consider the layer of soil in the replacement land use that is compacted from the 0-20 cm layer of forest soil (see Fearnside, 1980). The emission calculated here (43 X 10^6 t CO_2) considers the top 8 m of forest soil, but only considers emissions in the first 15 years (Fearnside and Barbosa, 1998). The 1-8 m layer contains a large stock of carbon (Nepstad et al., 1994; Trumbore et al., 1995); unfortunately, data on soil carbon in the 1-8 m layer are only available from one site (Paragominas, Para). The carbon stock in the deep soil may be drawn down to a new lower equilibrium level over a longer time period because the deep roots of trees in natural forest are a source of carbon inputs to this soil layer, and their replacement by pasture and other less deeply rooted types of vegetation can be expected to shift the balance between carbon inputs and oxidation in the deep soil layer. Transformation of forest to the equilibrium landcover results in emission of 8.5 t C ha^{-1} from the top 8 m of soil, 7.9 t C ha^{-1} of which is from the top 1 m (Fearnside and Barbosa, 1998).

E. Removal of Sources and Sinks in Pre-Clearing Landcover

1. Soil Sink for CH_4

The tropical forest soil provides a natural sink for methane, removing 0.0004 tons of carbon per hectare per year (Keller et al., 1986). Clearing the forest eliminates this sink, thereby having an effect equal to a source of the same magnitude.

2. Forest Sources of NO_x and NMHC

The leaves of the forest release 0.0131 t ha^{-1} y^{-1} of NO_x (Kaplan et al., 1988; see Keller et al., 1991) and 0.12 t ha^{-1} y^{-1} of non-methane hydrocarbons (NMHC) (Rasmussen and Khalil, 1988: 1420). No information is available on the releases of these gases from the replacement vegetation. Assuming no releases from farmland, productive and degraded cattle pasture, and releases from secondary forests the same as those from primary forests, the area cleared in 1990 implied loss of fluxes of 0.01 X 10^6 t y^{-1} of NO_x and 0.09 X 10^6 t y^{-1} of NMHC (Tables 2 and 3).

3. CH_4 Release by Termites

Termites in the mature forest release methane produced by bacteria that digest cellulose under anaerobic conditions in the insects' abdomens. These emissions will be lost when forest is cleared, but for a long time thereafter these emissions will be more than compensated for by termites that ingest the unburned biomass after clearing. In calculating emissions from termites in the forest, the item of interest is the absolute amount of biomass decaying annually (in t ha^{-1} y^{-1}), rather than the rate (fraction) of decomposition per year. For fine litter the amount can be known directly from data on litter fall rates, since all that falls decomposes and the level of the stock can be assumed to be in equilibrium. For coarse litter such data are unavailable, and the amount decomposing must be calculated from information on the stock and the rate of decomposition. Dead trees in a tropical forest can decay remarkably quickly. The decay constant (k) for decomposition of boles in Panama has been calculated to be 0.461 y^{-1} for trees >10 cm DBH, based on observation after a 10-year interval (Lang and Knight, 1979). Here, however, the lower decay rates measured in slash-and-burn fields are used for all coarse biomass. The amounts of fine and coarse litter are calculated from available studies (Fearnside, 1997a).

4. Possible Carbon Sink in Standing Forest

A possible sink of carbon in "undisturbed" standing forest is not considered in the present calculation. Eddy correlation work (studies of gas movements in air flows inside and immediately above the forest) at one site in Rondonia indicated an uptake of 1.0 ∀ 0.2 t C ha^{-1} y^{-1} (Grace et al., 1995). This would imply an annual uptake of 366 X 10^6 t C by the 358.5 X 10^6 ha of forest still standing in 1990 in the Brazilian Legal Amazon, and a loss of the annual uptake of 1.4 X 10^6 t C from the 1.38 X 10^6 ha cleared in 1990. Malhi et al. (1996, cited by Higuchi et al., 1997: 99) have estimated an uptake of 5.6 ∀ 1.6 t C ha^{-1} y^{-1} based on eddy correlation work near Manaus. Higuchi et al. (1997: 99) have estimated an uptake of 1.2 t C ha^{-1} y^{-1} in 3 ha of forest growth measurements over the 1986-1996 period near Manaus. On the other hand, forest growth measurements over intervals of 10-16 years in the 1980-1997 period in 32 one-ha plots >300 m from a forest edge at another site near Manaus indicate no net growth whatsoever (W.F. Laurance, personal communication, 1997; see also same data in 36 one-ha control plots >100 m from a forest edge in Laurance et al., 1997).

Research interest in a possible sink in standing forest is intense, and efforts in progress to evaluate data on basal area changes in long-term forest monitoring sites and to extend eddy correlation studies may well indicate the existence of a sink. Given the vast area of standing forest, even a small uptake per hectare would make a significant contribution to the global carbon balance. Large spatial coverage is needed in order to draw conclusions, as uptake at one site may be balanced by emissions at other sites. Time scale is undoubtedly also important: over the long term, "mature" forest cannot continue to grow in biomass, but imbalances over periods of years or decades are still important for understanding global carbon dynamics, including clarification of the "missing sink." An uptake would increase the impact of deforestation by eliminating part of the sink. For example, if the sink were 0.45 t C ha^{-1} y^{-1}, the 1.38 X 10^6 ha of deforestation in 1990 would eliminate an annual sink of 0.621 X 10^6 t C, while the annual loss for the 41.6 X 10^6 ha that had been lost through 1990 would total 18.72 X 10^6 t C. While the amount of sink loss in a single year's deforestation may appear modest compared to the emissions from forest biomass caused by the clearing, the fact that the sink represents an annual flux rather than a one-time emission means that it would have significant consequences over the long term if the sink can be assumed to have a duration of decades or more.

F. Hydroelectric Dams

One of the impacts of hydroelectric dams in Amazonia is emission of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). Existing hydroelectric dams in Brazilian Amazonia emitted about 0.27 X 10^6 t of methane and 37 X 10^6 t of carbon dioxide in 1990. The CO_2 flux in 1990 included part of the large peak of release from above-water decay of trees left standing in the Balbina reservoir (closed in 1987) and the Samuel reservoir (closed in 1988). Most CO_2 release occurs in the first decade after closing. The methane emissions represent an essentially permanent addition to gas fluxes from the region, rather than a one-time release. The total area of reservoirs planned in the region is about 20 times the area existing in 1990, implying a potential annual methane release of about 5.2 X 10^6 t. About 40% of this estimated release is from underwater decay of forest biomass, which is the most uncertain of the components in the calculation. Methane is also released from open water, macrophyte beds, and above-water decay of forest biomass (Fearnside, 1995b, 1997d).

G. Logging

In a typical situation, forests accessible by land or river transportation are logged, reducing their biomass both by the removal of timber and by killing or damaging many unharvested trees. This logged-over forest is later cleared for agriculture or cattle ranching.

The effect of logging is not as straightforward as it might appear. By removing the trunks of large trees, the burning efficiency will increase, as will the average decay rate of the unburned biomass. This is because small-diameter branches burn better and decay more quickly than do large trunks. These changes will partially compensate for the reduction in emissions from lower biomass. In calculations where discounting or time preference weighting gives emphasis to short-term releases, the effect of logging on the impact of deforestation when the logged areas are subsequently cleared will be further reduced, since the large logs removed would have been slow to decay had they been left to be cut in the deforestation process.

IV. Uptake by Replacement Vegetation

A. The Replacement Landcover

A Markov matrix of annual transition probabilities was constructed to estimate landcover composition in 1990 and to project future changes, assuming behavior of farmers and ranchers remains unchanged. Transition probabilities for small farmers are derived from satellite studies of government settlement areas (Moran et al., 1994; Skole et al., 1994). Probabilities for ranchers are derived from typical behavior elicited in interview surveys by Uhl et al. (1988). Six land uses are considered, which, when divided to reflect age structure, results in a matrix of 98 rows and columns.

The estimated 1990 landcover in deforested areas was 5.4% farmland, 44.8% productive pasture, 2.2% degraded pasture, 2.1% 'young' (1970 or later) secondary forest derived from agriculture, and 28.1% 'young' secondary forest derived from pasture, and 17.4% 'old' (pre-1970) secondary forest. This landcover would eventually approach an equilibrium of 4.0% farmland, 43.8% productive pasture, 5.2% degraded pasture, 2.0% secondary forest derived from agriculture, and 44.9% secondary forest derived from pasture. An insignificant amount is regenerated 'forest' (defined as secondary forest over 100 years old). Average total biomass (dry matter, including below-ground and dead components) was 43.5 t ha^{-1} in 1990 in the 410 X 10^3 km^2 deforested by that year for uses other than hydroelectric dams. At equilibrium, average biomass would be 28.5 t ha^{-1} over all deforested areas (excluding dams) (Fearnside, 1996b). Official sources have recently claimed a massive C uptake in "crops" resulting in zero net emissions from deforestation (*ISTOÉ*, 1997). Such a claim is completely at variance with the results presented here.

Better quantification of carbon sinks such as secondary forests is important for both scientific and diplomatic reasons. From a scientific standpoint, better assessments of carbon flows to these sinks are needed in order to have better estimates of net emissions, and, consequently, better estimates of such quantities as the "missing sink." On the diplomatic side, scientists who work on global warming are frequently criticized for spending almost all of their time and money in measuring carbon emissions rather than sinks, with the implication that it is therefore unsurprising that researchers conclude that carbon emissions are a major problem. Thorough investigation of all possible sinks would preclude use of such arguments by those in search of excuses for refusing to take global warming seriously.

B. Secondary Forest Growth Rates

The growth rate of secondary forests is critical in determining the uptake over the replacement landcover. Most discussions of uptake by secondary forests have assumed that these will grow at the rapid rates that characterize shifting cultivation fallows (e.g. Lugo and Brown, 1981, 1982). In Brazilian Amazonia, however, most deforestation is for cattle pasture, shifting cultivation playing a relative minor role (Fearnside, 1993). Secondary forests on degraded pastures grow much more slowly than on sites where only annual crops have been planted following the initial forest felling.

Brown and Lugo (1990) have reviewed the available data on growth of tropical secondary forests. The available information is virtually all from shifting cultivation fallows. Brown and Lugo (1990: 17) trace a freehand graph from available data for secondary forest stands ranging in age from 1 to 80 years, including biomass for wood (twigs, branches and stems: 13 data points), leaves (10 data points), and roots (12 data points). This has been used to estimate growth rate and the root/shoot ratio for shifting cultivation fallows of different ages. Secondary forests on abandoned pastures grow more slowly (Guimarães, 1993; Uhl et al., 1988). This information on growth rate of secondary vegetation of different origins has been used to calculate uptakes in the landscape in 1990 (Fearnside and Guimarães, 1996).

Table 4. 1990 annual balance of net emissions by source in the originally forested area of the Brazilian Legal Amazon (a): low trace gas scenario

Source	Emissions (million t of gas)						Sink (million t of carbon)	
	CO_2	CH_4	CO	N_2O	NO_x	NMHC	Charcoal carbon	Graphite carbon
Original forest biomass								
Initial burn	269.97	0.87	20.96	0.05	0.66	0.66	3.52	0.20
Reburns	65.95	0.32	10.21	0.01	0.51	0.16	1.05	0.08
Termites aboveground decay	14.60	0.02						
Other aboveground decay	357.08							
Belowground decay	321.55							
Secondary forest biomass								
Burning (b)	52.06	0.17	4.03	0.010	0.06	0.11	0.25	0.04
Termites above ground decay	0.98	0.001						
Other aboveground decay	21.29							
Belowground decay	23.60							
Termites in secondary forest		0.003						
Pre-1970 secondary forest biomass								
Initial burning	5.34	0.017	0.419	0.001	0.013	0.012	0.069	0.004
Reburnings	0.85	0.004	0.135	0.0002	0.007	0.002	0.014	0.001
Termites aboveground decay	0.21	0.0002						
Other aboveground biomass	5.21							
Belowground decay	3.03							
Termites in pre-1970 stands		0.0035						
Pasture burning	(c)	0.07	1.69	0.004	0.12	0.05	0.08	0.02
Hydroelectric dams								
Forest biomass	35.75	0.12						
Water		0.11						
Macrophytes		0.04						

Table 4. continued

Source	Emissions (million t of gas)						Sink (million t of gas)	
	CO_2	CH_4	CO	N_2O	NO_x	NMHC	Charcoal carbon	Graphite carbon
Other sources								
Cattle		0.31						
Pasture soil				0.07				
Loss of intact forest sources and sinks		0.02			-4.24	-0.46		
Loss of natural forest termites		-0.03						
Soil carbon (top 8 m)	56.65							
Total emissions	1233.40	2.04	37.37	0.16	-2.87	0.45	4.98	0.34
Uptake	-28.98							
Net emissions	1204.12	2.04	37.37	0.16	-2.87	0.45	4.98	0.34

(a) Deforestation in originally forested area in 1990 was 1,381,800 ha.

(b) Secondary forest burning includes both initial and subsequent burns for secondary forest from both agriculture and pasture, and for degraded pasture that is cut and recuperated.

(c) CO_2 from maintenance burning of pasture is not counted, as this is re-assimilated annually as the pastures regrow, making the net flux equal to zero. The gross flux in 1990 from this source is estimated at 22 million t of CO_2 gas.

V. Annual Balance of Net Emissions

The sources of emissions and uptakes of greenhouse gases for the annual balance in 1990 are presented in Table 4 for the low trace gas scenario, and in Table 5 for the high trace gas scenario. Considering only CO_2, 1218-1233 X 10^6 t of gas were emitted (gross emission) by deforestation (not including logging emissions). Deducting the uptake of 29 X 10^6 t of CO_2 gas yields a net emission of 1189-1204 X 10^6 t of CO_2, or 324-328 X 10^6 t of carbon. Adding effects of trace gases using the IPCC Second Assessment Report SAR global warming potentials for a 100-year time horizon, the impacts increase to 353-359 X 10^6 t of CO_2-equivalent carbon. Consideration of more indirect effects of trace gases would raise these values substantially: the IPCC SAR recognizes some indirect effects for CH_4 but none for CO, which is an important component of emissions from biomass burning. Logging added 224 X 10^6 t of CO_2 gas, plus trace gases that raised the impact to 228-229 X 10^6 t of CO_2 gas equivalent (63 X 10^6 t CO_2 = equivalent C).

In terms of carbon dioxide from the original forest biomass only, 27% of the emission (before deducting uptakes) in the annual balance was from prompt emissions from deforestation in that year, and 73% was from inherited emissions from decay and reburning of unburned biomass left from clearing in previous years. Because of higher inherited emissions in the areas cleared in the years of faster deforestation preceding 1990, the annual balance is higher than the net committed emissions by 27-29% if only CO_2 is considered and by 29-32% if the CO_2 equivalents of other gases are also included. Net committed emissions would be equal to the annual balance that would prevail were deforestation to proceed at a constant rate over a long period.

Table 5. 1990 annual balance of net emissions by source in the originally forested area of the Brazilian Legal Amazon (a): high trace gas scenario

Source	Emissions (million t of gas)						Sink (million t of carbon)	
	CO_2	CH_4	CO	N_2O	NO_x	NMHC	Charcoal carbon	Graphite carbon
Original forest biomass								
Initial burn	269.97	1.05	26.13	0.05	0.66	1.10	3.52	0.24
Reburns	64.95	0.51	12.99	0.1	0.51	0.31	1.05	0.12
Termites aboveground decay	16.02	0.02						
Other aboveground decay	357.09							
Belowground decay	321.53							
Secondary forest biomass								
Burning (b)	40.24	0.16	3.89	0.008	0.04	0.16	0.23	0.04
Termites above ground decay	0.93	0.0007						
Other aboveground decay	20.25							
Belowground decay	22.49							
Termites in secondary forest		0.003						
Pre-1970 secondary forest biomass								
Initial burning	5.34	0.021	0.516	0.001	0.013	0.022	0.069	0.005
Reburnings	0.85	0.007	0.170	0.001	0.007	0.004	0.014	0.002
Termites aboveground decay	0.23	0.0002						
Other aboveground biomass	5.31							
Belowground decay	3.03							
Termites in pre-1970 stands		0.0027						

Pasture burning	(c)	0.08	2.02	0.004	0.11	0.08	0.08	0.02
Hydroelectric dams								
Forest biomass	35.75	0.12						
Water		0.11						
Macrophytes		0.04						

Table 5. continued

Source	Emissions (million t of gas)						Sink (million t of carbon)	
	CO_2	CH_4	CO	N_2O	NO_x	NMHC	Charcoal carbon	Graphite carbon
Other sources								
Cattle		0.29						
Pasture soil				0.07				
Loss of intact forest sources and sinks		0.02			-4.06	-0.44		
Loss of natural forest termites		-0.03						
Soil carbon (top 8 m)	54.43							
Total emissions	1218.37	2.39	45.72	0.25	-2.71	1.23	4.96	0.42
Uptake	-28.98							
Net emissions	1189.39	2.39	45.72	0.25	-2.31	1.23	4.96	0.42

(a) Deforestation in originally forested area in 1990 was 1,381,800 ha.

(b) Secondary forest burning includes both initial and subsequent burns for secondary forest from both agriculture and pasture, and for degraded pasture that is cut and recuperated.

(c) CO_2 from maintenance burning of pasture is not counted, as this is re-assimilated annually as the pastures regrow, making the net flux equal to zero. The gross flux in 1990 from this source is estimated at 21 million t of CO_2 gas.

Table 6. Comparison of methods of calculating the 1990 global warming impact of deforestation in originally forested areas of Brazilian Amazonia in millions of tons of CO_2-equivalent carbon

Gases included	Net committed emissions	Annual balance

	(Deforestation only)	Deforestation only	Logging	Deforestation + logging
Low trace gas scenario				
CO_2 only	255	328	61	390
CO_2, CH_4, N_2O	267	353	62	415
High trace gas scenario				
CO_2 only	255	324	61	386
CO_2, CH_4, N_2O	278	359	63	422

Net committed emissions and the annual balance are compared in Table 6 for the low and high trace gas scenarios, both considering only CO_2 equivalents using the IPCC Second Assessment Report SAR 100-year integration global warming potentials. The emissions from logging are also tabulated. Inclusion of trace gases (using the IPCC SAR 100-year global warming potentials) raises the impact of net committed emissions by 5-9%, and of the annual balance by 8-11%. Trace gas impacts are likely to increase when the IPCC reaches agreement on additional indirect effects. For example, if the impact of CO calculated using the global warming potential of 2 that was adopted in the 1990 IPCC report (Shine et al., 1990: 60), but dropped in subsequent reports pending agreement, the annual balance would be increased by the equivalent of 75-92 X 10^6 t of CO_2 gas, while inclusion of the additional effect of CO on extending the atmospheric lifetime of CH_4 due to removal of OH radicals (Shine et al., 1990: 59) would further increase this impact.

VI. Conclusions

1. In 1990, the year for baseline inventories under the United Nations Framework Convention on Climate Change, land-use changes in Brazil's 5 X 10^6 km^2 Legal Amazon Region included 13.8 X 10^3 km^2 of deforestation, approximately 5 X 10^3 km^2 of clearing in *cerrado,* the central Brazilian scrubland that originally occupied about 20% of the Legal Amazon (savanna), 7 X 10^2 km^2 in "old" (pre-1970) and 19 X 10^3 km^2 in "young" (1970+) secondary forests; burning of 40 X 10^3 km^2 of productive pasture (33% of the area present), and regrowth in 121 X 10^3 km^2 of "young" secondary forests. No new hydroelectric flooding occurred in 1990, but decomposition continued in 4.8 X 10^3 km^2 of reservoirs already in place. Logging at 24.6 X 10^6 m^3 was assumed — the 1988 official rate.

2. Unlogged original forests in Brazilian Amazonia are estimated to have an average total biomass of 463 metric tons per hectare (t ha^{-1}), including below-ground and dead components. Adjustment for the spatial distribution of clearing and for logging indicates an average total biomass cleared in 1990 of 406 t ha^{-1} in original forest areas, 309 t ha^{-1} of which is aboveground (exposed to the initial burn). In addition to emissions from the initial burn, the remains from clearing in previous years emitted gases through decay and combustion in reburns. More rapid deforestation in the years preceding 1990 make these inherited emissions greater than they would have been had deforestation rates been constant at their 1990 levels.

3. Estimated net committed emissions (the net amounts of greenhouse gases that will ultimately be emitted as a result of the clearing done in a given year) from deforestation (not including logging emissions or the clearing of *cerrado* totaled 934 X 10^6 t CO_2, 1.3-1.5 X 10^6 t CH_4, 30-37 X 10^6 t CO, and 0.07-0.18 X 10^6 t N_2O. These emissions are equivalent to 267-278 X 10^6 t of CO_2-equivalent carbon, using IPCC SAR 100-year GWPs. CO_2 emissions include 270 X 10^6 t of gas from the initial burn, 628 X 10^6 t from decay, 57 X 10^6 t from subsequent burns of primary forest biomass, and 43 X 10^6 t C from soil carbon in the top 8 m. The replacement landcover eventually stores 65 X 10^6 C, or 6.5% of the gross emission. The ranges of emissions given above are for low- and high-trace gas scenarios, reflecting the range of emission factors appearing in the literature for different burning and decomposition processes. These scenarios do not reflect the uncertainty of values for deforestation rate, forest biomass, logging intensity and other inputs to the calculation. Some carbon enters sinks though conversion to charcoal (5.0 X 10^6 t C) and graphitic particulate carbon (0.42 X 10^6 t C).

4. The annual balance of net emissions in 1990 (net fluxes in a single year over the entire region) included 1189-1204 X 10^6 t CO_2, 2.1-2.4 X 10^6 t CH_4, 37.4-45.7 X 10^6 t CO, and 0.16-0.25 X 10^6 t N_2O. CO_2 emissions include 270 X 10^6 t of gas from the initial burn, 693-695 X 10^6 t from decay, 65-66 X 10^6 t from subsequent burns of primary forest biomass, and 46-58 X 10^6 t from burning of secondary forest biomass of all ages, 54-57 X 10^6 t CO_2 from net release of soil carbon to 8 m depth (first 15 years only), 224 X 10^6 t from logging and 36 H 10^6 t from hydroelectric reservoirs. Secondary forest regrowth in 1990 removed 29.0 X 10^6 t of CO_2 gas (only 2.4% of the gross emission, excluding hydroelectric and pasture emissions). Pastures release through burning (and assimilate in growth) 21-22 X 10^6 t of CO_2 gas, not counted in the calculations. The effect of deforestation on the annual balance is a net emission equivalent to 353-359 X 10^6 t of CO_2-equivalent carbon, while logging adds 62 X 10^6 t of CO_2-equivalent carbon.

5. The net committed emissions and annual balance of net emissions from land-use change in Brazilian Amazonia in 1990 were both dominated by deforestation. Because deforestation rates declined in the three years immediately preceding 1990, the annual balance from deforestation (i.e., excluding logging) is higher than the net committed emissions.

6. These results indicate that deforestation in Brazilian Amazonia makes a substantial contribution to global warming, and points to the high priority that should be placed on improving the estimates of these emissions and of the uncertainties they contain. Changes in management in the deforested landcover can only compensate for a small fraction of this impact. Therefore, any policy changes that reduce the rate of deforestation would have the greatest potential for reducing the net emission of greenhouse gases from Amazonia.

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