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GLOBAL WARMING AND TROPICAL LAND-USE CHANGE: GREENHOUSE GAS EMISSIONS FROM BIOMASS BURNING, DECOMPOSITION AND SOILS IN FOREST CONVERSION, SHIFTING CULTIVATION AND SECONDARY VEGETATION

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Abstract. Tropical forest conversion, shifting cultivation and clearing of secondary vegetation make significant contributions to global emissions of greenhouse gases today, and have the potential for large additional emissions in future decades. Globally, an estimated 3.1 $\times$ 10^9 t of biomass carbon of these types is exposed to burning annually, of which 1.1 $\times$ 10^9 t is emitted to the atmosphere through combustion and 49 $\times$ 10^6 t is converted to charcoal (including 26-31 $\times$ 10^6 t C of black carbon). The amount of biomass exposed to burning includes aboveground remains that failed to burn or decompose from clearing in previous years, and therefore exceeds the 1.9 $\times$ 10^9 t of aboveground biomass carbon cleared on average each year. Above- and belowground carbon emitted annually through decomposition processes totals 2.1 $\times$ 10^9 t C. A total gross emission (including decomposition of unburned aboveground biomass and of belowground biomass) of 3.41 $\times$ 10^9 t C $year^{-1}$ results from clearing primary (nonfallow) and secondary (fallow) vegetation in the tropics. Adjustment for trace gas emissions using IPCC Second Assessment Report 100-year integration global warming potentials makes this equivalent to 3.39 $\times$ 10^9 t of CO_2-equivalent carbon under a low trace gas scenario and 3.83 $\times$ 10^9 t under a high trace gas scenario. Of these totals, 1.06 $\times$ 10^9 t (31%) is the result of biomass burning under the low trace gas scenario and 1.50 $\times$ 10^9 t (39%) under the high trace gas scenario. The net emissions from all clearing of natural vegetation and of secondary forests (including both biomass and soil fluxes) is 2.0 $\times$ 10^9 t C, equivalent to 2.0-2.4 $\times$ 10^9 t of CO_2-equivalent carbon. Adding emissions of 0.4 $\times$ 10^9 t C from land-use category changes other than deforestation brings the total for land-use change (not considering uptake of intact forest, recurrent burning of savannas or fires in intact forests) to 2.4 $\times$ 10^9 t C, equivalent to 2.4-2.9 $\times$ 10^9 t of CO_2-equivalent carbon. The total net emission of carbon from the tropical land uses considered here (2.4 $\times$ 10^9 t C $year^{-1}$) calculated for the 1981-1990 period is 50% higher than the 1.6 $\times$ 10^9 t C $year^{-1}$ value used by the Intergovernmental Panel on Climate Change. The inferred (= "missing") sink in the global carbon budget is larger than previously thought. However, about half of the additional source suggested here may be offset by a possible sink in uptake by Amazonian forests. Both alterations indicate that continued deforestation would produce greater impact on global carbon emissions. The total net emission of carbon calculated here indicates a major global warming impact from tropical land uses, equivalent to approximately 29% of the total anthropogenic emission from fossil fuels and land-use change.

1. Introduction

Deforestation in the tropics contributes significant quantities of gases and particulate matter to the atmosphere. Avoidance of greenhouse gas emissions from deforestation, including those from burning, represents a major argument for taking steps to reduce rates of forest loss. More reliable quantification of the impact of deforestation on global warming is a prerequisite for assessing the value of avoiding these impacts, and hence the potential for future monetary flows to sustain this environmental service of the forest (Fearnside, 1996a). The objective of the present paper is to interpret available information on the use of fire in forest conversion, shifting cultivation and secondary forest to arrive at improved estimates of biomass burned and greenhouse gas (GHG) emissions from tropical land-use change. In addition to emissions from burning, gases are also released by decay of biomass and from soils.

The amounts of biomass exposed to burning and the fate of this material represent major areas of uncertainty in our understanding of atmospheric chemistry, including the historical and likely future changes in gas concentrations affecting global warming. Improved estimates of flux from terrestrial biota would yield by far the greatest dividends of any area of research related to increasing the reliability of the global carbon budget (Yearsley and Lettenmaier, 1987). Errors in individual parameters in biomass burning calculations propagate multiplicatively, resulting in wide margins of uncertainty for global emissions estimates (Robinson, 1989).

One must know how much biomass is present in tropical areas, how much of this is exposed to burning each year, how much of this amount burns, how much of the biomass that burns is apportioned between flaming and smoldering combustion processes, and how much carbon is left as charcoal or converted to soot. The amount of biomass burned affects emissions not only by releasing gases directly during combustion, but also by determining how much is not burned, and thereby how much passes through different decay pathways. Termite-mediated decay following tropical deforestation releases methane (CH_4), but the amount (7.34×10^{-5} t CH_4 per ton of aboveground biomass carbon oxidized through decay) is substantially less than had been thought because termite populations are unable to increase fast enough to consume most of the biomass that becomes available to them (Martius et al., 1996).

Biomass is usefully classified into different categories for the purpose of assessing biomass burning. Conversion of tropical forests is one such category. Biomass is also burned when clearing shifting cultivation fallows and other types of secondary succession, such as woody invaders in cattle pastures. Recurrent burning (without clearing) of cerrado (central Brazilian scrub savanna) and other types of savanna are processes not considered in the current paper. Also not considered is burning of crop residues and "weeds" (both herbaceous and small-diameter woody vegetation that is cut and burned prior to planting fields from which a crop had been harvested less than six months previously). Other sources not considered are emissions from logging, burning in intact forests (as in the Great Roraima Fire of 1997-1998), and manufacture of charcoal and burning of firewood and charcoal. It should be noted that emissions from biomass removed for firewood and charcoal are implicitly included by using forest biomass estimates that have not been reduced to reflect removal of these products: the carbon emission from deforestation is therefore overestimated by an amount equal to the underestimate from firewood and charcoal combustion, although there would be some difference in the trace gas components of the emission. Adjustment for any fossil fuel substitution effect (particularly for charcoal) has not been included.

An additional factor not considered is "biomass collapse" on the edges of forest fragments (Laurance et al., 1997). In the case of biomass collapse at forest edges, this is not believed to affect overall emissions from tropical land-use change by anything approaching the 22-149 $\times$ 10^6 t C $year^{-1}$ suggested by Laurance et al. (1998), although a small adjustment of the trace gas emissions would be desirable to account for a somewhat higher proportion of aboveground carbon passing through decay (rather than burning) pathways. The effect of biomass collapse at edges is not so great because the vast majority of deforestation is advancing from already deforested areas: areas being deforested in any given year were forest edges in the preceding years, and the biomass present at the time of clearing had therefore already been reduced by the biomass collapse effect. To the extent that the perimeter of edges in the region remains constant, the emission not considered in the present analysis from biomass collapse along these edges in a given year will be exactly compensated by the overestimate of deforestation emissions that results from having considered forest biomass without an adjustment for the collapse effect in the preceding years.

"Secondary forests," "secondary succession," "second growth," and "fallow forests" are all terms used to refer to woody vegetation that grows on "abandoned" agricultural or ranching land. This vegetation is usually cleared again, either for a short (1-2 year) cropping period in a shifting cultivation cycle or for a land use that maintains land without tree cover for longer periods, such as pasture, perennial crops, and irrigated agriculture or rainfed agriculture with higher inputs. The term "secondary forests" (florestas secundárias in Portuguese, for example) causes considerable confusion because it is used with other meanings in some parts of the world, both in English and in other languages. In Indonesia, lightly logged forest is referred to as "secondary forest" (hutan sekunder), while what are called "secondary forests" outside of Southeast Asia are known as "successional forests" (hutan sukesi) in Indonesia.

The distinction between biomass burning releases and deforestation must be emphasized. Only a portion of the biomass felled during deforestation is burned. However, almost all of the carbon remaining in the unburned biomass enters the atmosphere later as greenhouse gases when the material decomposes. This is the principal explanation of my estimates for emissions from Brazilian deforestation (Fearnside, 1996b, 1997a) being triple Brazil's official values for these emissions (Borges, 1992). The emission from decomposition, as well as that from burns subsequent to the initial one, have been ignored in Brazil's official numbers, although this is expected to change with completion of the national inventory based on the IPCC methodology (IPCC, 1997).

In Brazilian Amazonia virtually all cleared area is burned, and this is true in most other countries where tropical deforestation takes place. However, some systems exist where the cleared area is larger than the area burned. In the chitemene system in Zambia, in which wood from the surrounding area is added to the downed wood on the site to be burned and cultivated (see Allan, 1965), the area cleared may be 5-20 times the area cultivated (Ruthenberg, 1971, p. 23). In this case, the average aboveground biomass present in the area cleared provides a good indication of the amount exposed to burning, as the burning merely takes place at a different location.

Areas burned can be greater than areas cleared when fire escapes from pastures and agricultural fields into surrounding forests. In Brazilian Amazonia this is occurring with increasing frequency, especially when slash left by selective logging increases flammability of the forest (Uhl and Buschbacher, 1985; Uhl and Kauffman, 1990). In tropical moist forests, fires of this type generally do not reach the crown. Fires burn the ground layer and kill some large trees, thus generating emissions through decay as well as through combustion. Many large fires on the island of Borneo at the time of the 1982-1983 El Niño drought originated from agricultural burning by small farmers (Malingreau et al., 1985), while clearing for silviculture and oilpalm plantations were major ignition sources during the 1997 El Niño there (Runyan, 1998). In the 1997-1998 Great Roraima Fire, small farmers in government-sponsored settlements were major sources (Barbosa, 1998). Mega-El Niño events have already provoked widespread conflagrations in Amazonia four times over the past 2000 years (Meggers, 1994). Climatic changes provoked by Amazonian deforestation could greatly increase damage caused by fire escaping into the remaining standing forest in Brazil (Fearnside, 1995a).

Fire escaping from agricultural fields of squatters into adjacent silvicultural plantations has been an irritating but tolerable problem in Brazil's incipient Amazonian plantations of *Eucalyptus* and *Pinus*, burning about 0.4% per year of the area in these species (Fearnside and Rankin, 1985, p. 124). Brazil's silvicultural plantations are likely to expand greatly over the coming decades, especially in Amazonia (Fearnside, 1998).

Several types of forest loss can occur without burning. Along the eastern base of the Andes, rainfall is too heavy and constant to allow burning, and indigenous shifting cultivators employ a slash-and-mulch system in which the vegetation is left to rot instead (Rudel and Horowitz, 1993, p. 47). Hydroelectric dams destroy forests without burning and, in the case of Amazonian dams, without cutting of trees except for small areas around intakes to the power stations. Emissions from Amazonian reservoirs are significant today, and Brazil's plans to flood as much as 3% of its Amazonian forest imply much larger potential emissions from this source in the future (Fearnside, 1995b, 1997b).

2. Biomass Exposed to Burning

2.1. Forest Conversion

Tropical deforestation releases carbon dioxide, methane and other gases that contribute to the global greenhouse effect (e.g., Houghton et al., 1996). As the calculations to be developed in this paper will show, Brazil plays a significant role in current global emissions from biomass burning and from other processes initiated by deforestation. The relative importance of Brazilian contributions to these emissions is likely to increase substantially over the coming decades because vast areas of Amazonian forest remain standing and at risk of deforestation, while many areas of active deforestation in other parts of the tropics are nearing the end of their forest reserves. The FAO survey of forest resources in 1990 indicated that 41% of all remaining forest classified as "tropical rain forest" is in Brazil (FAO, 1993).

Primary forest in Brazil's 5×10^6 km^2 Legal Amazon region was converted to ranching, agriculture, hydroelectric dams and other uses at a rate of 20×10^3 km^2 $year^{-1}$ during the 1978-1988 period (Fearnside, 1993a), 19×10^3 km^2 $year^{-1}$ for 1988-1989, 14×10^3 km^2 $year^{-1}$ for 1989-1990, 11×10^3 km^2 $year^{-1}$ for 1990-1991 (Fearnside, 1993b), 14×10^3 km^2 $year^{-1}$ for 1991-1992 and 15×10^3 km^2 $year^{-1}$ for 1992-1994 (Brazil, INPE, 1996), 29×10^3 km^2 for 1995, 18×10^3 km^2 for 1996, 13×10^3 km^2 for 1997, and a preliminary estimate of 17×10^3 km^2 for 1998 (Brazil, INPE, 1998, 1999). The 1990 deforestation rate implied a contribution from clearing in forest areas in Brazilian

Amazonia of 0.251 × 10^9 t of net committed emissions of carbon in the form of CO_2 (Fearnside, 1997b). "Net committed emissions" refers to the long-term net result of converting a given area of forest (such as the 14 × 10^3 km^2 cleared in 1990) to the equilibrium landscape that will eventually replace it. In contrast, "annual balance of net emissions," or "annual balance," refers to the balance in only a single year but covers an entire landscape (such as Brazil's 5 × 10^6 km^2 Legal Amazon region), which includes a mosaic of patches cleared in different years.

Estimates of Amazon forest biomass loading vary tremendously, but, because a number of published estimates contain known errors, the range of true scientific uncertainty is much smaller than the range of biomass estimate values appearing in the literature. "Biomass loading" (also known as "biomass density") refers to biomass per unit of area, (i.e., t ha^{-1}). Because of the high biomass loading and vast area of dense upland forests of Amazonia, differences in the values used for their biomass loadings have a great effect on the conclusions drawn from calculations of release of CO_2 and other greenhouse gases. Current best estimates indicate average aboveground (live + dead) biomass loading of 354 t ha^{-1} for unlogged forest present in Brazil's Legal Amazon region in 1990, and 317 t ha^{-1} for areas felled in 1990, after adjustment for the location of clearings within the region and for removal of biomass by logging (Fearnside, 1994, pp. 116-117, nd); available information on belowground components brings the total average biomass loading to 463 and 415 t ha^{-1}, respectively, but estimates of belowground biomass loading are likely to increase (Fearnside, nd, updated from Fearnside, 1994).

A key portion of the global carbon balance is the net emission from tropical land-use change, especially deforestation. The Intergovernmental Panel on Climate Change (IPCC) has so far used a value of 1.6 × 10^9 t C $year^{-1}$ to represent this flux in all of its assessments from the first report in 1990 through the current Second Assessment Report (Watson et al., 1990, p. 17; 1992, p. 33; Houghton et al., 1995, p. 18; Schimel et al., 1996, p. 78). The current paper will present information indicating that this number should be revised upward.

The FAO assessment of forest resources in tropical countries in 1990 (FAO, 1993) is the most comprehensive survey available of changes in forest areas on a global basis. The report contains annual deforestation data by country and forest zone (FAO, 1993, Annex 1, Table 8), but the biomass loading data given (FAO, 1993, Annex 1, Table 3) are only for "natural forest" (not broken down by forest zone). The biomass loading data refer to the mean for all of the forest cover of natural forest (i.e., weighted by the area of each type present in the country, rather than weighted by the area of each type deforested annually in each country). A small adjustment is necessary for these numbers to reflect biomass loading at the time the forests are cut (i.e., at the age at which secondary forests are cleared, and after last-minute logging and firewood removal).

The mean value given by FAO (1993) for the biomass loading of forests present can misrepresent biomass exposed to burning and consequent emissions when clearing is concentrated in certain vegetation types within a country. In the case of Brazil, the high clearing rate in cerrado relative to the much higher-biomass "tropical rain forests" of Amazonia means that Brazilian emissions would be exaggerated by applying the FAO mean. Cerrado is classified by FAO (1993, p. 27) as "moist deciduous forest" but is considered not to be forest in Brazilian deforestation studies since 1988 (see Fearnside, 1990a). Cerrado, like all vegetation types, needs to be included in land-use change surveys if reliable emissions estimates are to be had. Biomass and clearing information need to be disaggregated sufficiently to allow weighting by the type of vegetation being cleared.

The FAO biomass loading estimates refer to live aboveground biomass loading of trees ≥10 cm DBH. Unfortunately, correction for the omitted smaller trees involves additional uncertainty because different minima were used for some of the forests: "for forests of smaller stature, such as those in the dry tropical zones or degraded forests, the minimum diameter could be smaller than 5 cm" (FAO, 1993, p. 14).

Another doubt regarding biomass loading estimates is the methodology used to derive stand volume from original measurements. In the case of Brazil, the 0.70 form factor used by the FAO and RADAMBRASIL surveys to convert the original diameter and height measurements into stand volume underestimated volume by almost 16%: this low bias subsequently was passed on to biomass loading estimates based directly on these surveys, such as those of Brown et al. (1989) and Brown and Lugo (1992) that use the same data and methodology employed in the FAO report (see: Fearnside, 1992a, 1993c; Fearnside et al., 1993). The FAO (1993) report does not allow assessment of the extent to which this kind of problem affects estimates for countries other than Brazil, as methodology is not specified by country. Some of the other tropical countries have local volume tables and equations based on harvested trees. In truth, the level of uncertainty of the FAO biomass loading estimates from many of these countries is very large: "the compilation of the VOB [volume over bark] data base by the FAO required much educated guesswork to produce estimates on a tropic-wide basis. This approach is, therefore, of unknown reliability ..." (Brown, 1997, p. 2).

Table I presents the FAO survey results for annual rates of tropical deforestation over the 1981-1990 period, together with alternative information for Brazil. The biomass of Brazilian cerrado is derived in Table II, while Table III derives biomass for Brazilian ecosystems other than Amazonian forest and cerrado. These "other ecosystems" include the pantanal wetlands, the remains of Atlantic forest and araucaria forest, the caatinga (Northeastern Brazilian thorny scrub), and those portions of the country's cerradão (high cerrado) and mangrove formations located outside the Legal Amazon region.

[Tables I, II and III here]

In order to calculate the net carbon emission to the atmosphere one must know the carbon loading of the landscape that replaces forest following deforestation. This landscape is assumed to be the landscape that was present in nonforested areas in 1990. The biomass of the nonforested landscape is derived for each continent in Table IV. The short-fallow biomass loading in this landscape refers to half the amount that will be present per hectare when these fallows are later burned.

[Table IV here]

In order to derive soil carbon estimates one must calculate how much soil carbon levels have changed from their original levels. This requires knowing the fraction of the landscape that is maintained under active agriculture (derived in Table V). Estimates of soil carbon losses are then derived in Table VI for the top meter of soil.

[Tables V and VI here]

Estimates of the biomass cleared in tropical countries and their carbon emissions are presented in Table VII. The biomass loading estimates in Table VII include a series of corrections for omitted components and, in the case of Brazil, for form factor. It should be noted that, in the case of Brazil, the calculations given in Table VII based on the FAO biomass loading estimates, including correction for omissions, imply values for aboveground and total biomass loading in Amazonian forests approximately 10% lower than those calculated from available forest volume surveys (Fearnside, 1994, nd).

[Table VII here]

The total stock of carbon in tropical forests can be calculated (Table VIII). The foregoing information on the replacement landscape when deforested (Table IV) and on soil carbon changes (Table VI) can then be used to calculate the potential net committed emission for tropical deforestation (Table VIII).

[Table VIII here]

In addition to carbon release as biomass lost through deforestation (that is, from transformations from forested categories to nonforested ones), carbon releases also occur due to category changes within forest and nonforest groups. These are derived in Table IX, based on the areas undergoing these transitions on each continent in the FAO Forest Resources Survey. These calculations only capture changes that cross the defining limits of the FAO land-use categories. For example, if a forest is thinned through logging from 50% crown cover to 30% crown cover, it will pass the 40% crown cover limit that distinguishes "closed" from "open" forest, but if it is thinned from 90% crown cover to 50% crown cover no change will be detected. No estimate of these within-category thinning losses is available on a global basis.

[Table IX here]

2.2. Shifting Cultivation

In shifting cultivation, woody secondary vegetation is cut and burned at each cycle to prepare land for planting. This burning (and decomposition of biomass that does not burn) will release both CO_2 and trace gases. If the shifting cultivation system is in equilibrium, the same amount of CO_2 carbon that is released will be reincorporated into the secondary forest biomass regrowing in the fallow areas that make up the system, while trace gas emissions will represent a net addition to the atmosphere. However, shifting cultivation systems are rarely in equilibrium; the deviations from equilibrium tend to result in a net emission of carbon (in addition to trace gases). These changes include the tendency to abandon the shifting cultivation system by installing some other land use (such as cattle pasture) at the completion of the cropping period, and, if the area does remain under shifting cultivation, the fallow period is often shortened and/or the soils degraded such that vegetation grows back progressively more slowly in the same fallow period.

The fallow period is an important factor affecting the amount of biomass that will be present at the time a successional stand is cut in shifting cultivation. Houghton et al. (1987, p. 135) assumed fallow periods in tropical moist forest areas to be 10 years in Latin America, 13 years in Africa and 15 years in Asia. Hao and Ward (1993, p. 20,659) assumed fallows of 15 years in closed forest areas and 9 years in open forest areas. However, indications exist that average fallow periods are, in reality, shorter than these assumptions indicate, making the biomass present at the time of clearing and the consequent emissions less than these authors have calculated but, on the other hand, if one considers cutting primary forest for long-fallow shifting cultivation to be "deforestation" (unlike the definition used for presentation of deforestation statistics by FAO, 1996, pp. 89-90), the shorter fallow period will make the carbon stock in fallow vegetation less, thereby increasing the net global warming impact of tropical deforestation that replaces original forest with a landscape that includes long-fallow shifting cultivation areas.

The tendency in shifting cultivation areas throughout the tropics has been for fallow periods to shorten as population pressures increase (e.g., Nye and Greenland, 1960, UNESCO/UNEP/FAO, 1978, Vermeer, 1970). Even without population pressure effects, fallow periods shorten as migration from densely populated areas where shifting cultivation is not practiced dilutes the population of traditional shifting cultivators. Long before population density could increase to the point where farmers would be obliged to shorten their fallow periods, the recently arrived colonists on Brazil's Transamazon Highway cleared secondary succession with such frequency that the benefits of fallow were largely forgone and sustainability of the system as practiced in the 1970s was unlikely (Fearnside 1984a). Fallows of 2 years or less were frequent, some land in this age group being cleared in over 70% of cases where such vegetation was available for clearing.

Over the succeeding two decades, behavior patterns on the Transamazon Highway shifted to longer fallows. Moran et al. (1994) used LANDSAT-TM imagery to measure land-use patterns in the Transamazon Highway colonization project in 1985 and 1991 in areas centered at km 23 and km 46 west of Altamira, Para. These data can be used to derive a Markov matrix of transition probabilities, indicating that secondary succession in abandoned farmland was cleared at a mean age of 6.7 years (Fearnside, 1996b). Traditional farmers along the nearby Xingu River appear to use a somewhat longer fallow period, although variability is too high for firm conclusions: fields derived from secondary forest had been cleared from stands with a mean age of 8.6 years (SD = 6.6, n = 17) (da Silva, 1991; Silva-Forsberg and Fearnside, 1997). For fallow derived from farmland in Brazilian Amazonia, the average age (measured from the time of abandonment) is estimated to be 5.2 years (Fearnside, 1996b, p. 26).

Short average fallow periods have been reported for some of the parts of the world where traditional shifting cultivation is most prominent. In Sarawak, where 282×10^3 ha of shifting cultivation fallow is cleared annually, average fallow period is only 7 years (Uhlig et al., 1993). In India, where 1000×10^3 ha of shifting cultivation fallow is cleared annually, the average fallow period is only 4.3 years (Joshi, 1991, p. 188).

Unfortunately, the FAO Forest Resources Assessment information on shifting cultivation and fallow forests does not allow disaggregation by country. The need for national level studies is obvious. All information must be capable of disaggregation by country to permit substitution of better data where available. This is hampered by inconsistency in forest definitions.

Substantial inroads into fallow forest stands would appear to be likely in many parts of the tropics, but in Brazilian Amazonia an expansion of secondary forest was underway at this time (Moran et al., 1994). This was not because of shifting cultivation, but rather due to degrading cattle pastures (Fearnside, 1996b).

The area and biomass of secondary forest exposed to burning are calculated in Table X. FAO defines "short fallow" as a shifting cultivation system where over one-third of the area is occupied by the cropping phase (FAO, 1996, p. 106).

[Table X here]

One problem with global estimates of shifting cultivation emissions is that they often implicitly consider all fallows to be part of shifting cultivation cycles, or the alternation of cropping periods on the order of 2 years under rainfed annual crops with periods under woody fallow vegetation. In Brazil, especially, most fallows do not fit this description, but rather are regeneration in former cattle pastures. The time woody second growth derived from pastures is allowed to regrow before being cut is less than the periods that many authors have assumed for shifting cultivation. The average period under secondary succession (measured from the time of last burning) is estimated at 6.2 years in abandoned cattle pastures in Brazilian Amazonia (Fearnside, 1996b, p. 26). In addition, this vegetation regrows more slowly than that in shifting cultivation fallows, leading to lower biomass present at the time it is cut (Fearnside and Guimarães, 1996). Comparing growth rates from the two existing studies in abandoned cattle pastures representative of Brazilian Amazonia--"moderately" used pastures at Paragominas studied by Uhl et al. (1988) and pastures near Altamira studied by Guimarães (1993)--with existing studies on shifting cultivation fallows (reviewed by Brown and Lugo, 1990), abandoned pasture fallows had 22% less biomass accumulation by age 6.2 years (Fearnside and Guimarães, 1996, p. 41).

2.3. Secondary Vegetation

Much secondary vegetation is not part of shifting cultivation systems and, for the reasons described earlier, conclusions on carbon balance will be misleading if an assumption is made that the fallow will be allowed to regenerate. In the carbon balance analysis by Houghton (1991), secondary vegetation (fallow forests) cut as "permanent deforestation" represented one of the major sources of carbon emissions.

Some biomass burning estimates have included components for the initial forest clearing for shifting cultivation, but here this is considered under a more general category of initial forest clearing independent of purpose. This is because of the great difficulty inherent in any system of classification that depends on the intent of clearing. In fact, studies of shifting cultivation in various parts of the world have concluded that the role of this activity as a source of deforestation as been exaggerated (McNeely et al., 1992). A large part of the problem is that slash-and-burn agriculture identical to that used in the initial phase of traditional shifting cultivation is the normal activity of most recent immigrants who enter tropical forests from other areas, labeled "shifted cultivators" by Myers (1991).

The FAO (1993) data set presents changes in "forest" area by climatic zone. The data reflect the mean net annual change over a 10-year period (1981-1990). The "forest" category is defined by >10% crown cover, and includes both mature or primary forests and secondary or successional ones; those forests with >40% crown cover are classed as "dense." There is some inconsistency in the data, however, as the Brazilian figures for tropical rain forest are derived from Brazil's own studies for the Legal Amazon (see Fearnside, 1993b), and these studies used different criteria to define deforestation: only clearing of original forest was considered to constitute deforestation, while secondary forests were considered to have already been deforested. Fortunately, more detailed estimates for Brazilian Amazonia are available, separating the biomass burned into different categories (Fearnside, 1996b, 1997a).

The forest cover changes from the FAO data set provide an important component of biomass burning, but do not capture all of this activity. Biomass burning occurs in four distinct processes: clearing of natural forest for rainfed annual crops, clearing of natural forest for other nonforest land uses, clearing of fallows (successional vegetation) for rainfed annual crops (i.e., including shifting cultivation), and clearing of fallows for other nonforest land uses. The FAO forest cover information reflects net changes, thereby missing any cycling on time scales more rapid than 10 years between the fallow and nonforest categories that is not apparent as a change at the end of the 10-year observation period (such as shifting cultivation activity during the initial years of the 10-year period). Despite the approximations that these features of the data necessitate, it is still possible to arrive at more reliable estimates of the amounts of biomass exposed to burning in different processes than has been possible in the past.

One problem is that some wood is removed for use as firewood at the time either a primary forest or a fallow area is cleared. This must not be double-counted in accounting for the burning for agriculture and also for firewood. The same is true of wood removed from standing forest or fallow stands before the time of clearing: the biomass loading value must be adjusted for this degradation effect. Flint and Richards (1993) have estimated degradation ratios for forests in 13 tropical Asian countries.

3. CHARACTERISTICS OF BURNING

3.1. Burning Efficiency

Burn quality varies tremendously over short distances within any given clearing. In one study of a 200-ha burn near Manaus (Amazonas), a visual assessment of 200 sampling stations classed burns into five categories: 22.0% of the points were classed as "excellent" (at least some trunks burned to ash), 45.5% were classed as "good" (burned vines and thick branches), 17.0% were "medium" (burned leaves and thin branches), 12.0% were "poor" (only leaves burned), and 3.5% were classed as "none" (not even dry leaves on the ground burned) (Fearnside et al., 1993).

Great variability in burn quality exists among farmers and among years. In a study among colonists on the Transamazon Highway near Altamira, burns were classified on a six-level scale: "none" (no burn attempted); "0" (burn attempted but did not burn); "1" (bad burn: only leaves and small twigs combusted); "2" (patchy burn: a mixture of class 1 and 3 burns); "3" (good burn: burned some wood as well as leaves and twigs); "4" (overburned: large logs burned completely to ashes) (Fearnside, 1986, 1989). Burn quality is a critical factor affecting soil fertility and agricultural productivity on the Transamazon Highway: a good burn is necessary to remove the physical encumbrance of downed vegetation, to deposit nutrients in the form of ashes, to reduce competition from weeds, and to reduce the acidity of the soil. Burn quality is significantly associated with raising soil pH, lowering the concentration of toxic aluminum ions, and raising the levels of soil phosphorus (Fearnside, 1986, pp. 188-191). Poor soil with a good burn often produces a greater agricultural yield than good soil with a poor burn.

The quality of the burn depends partly on luck in having little or no rain during the period when the cut vegetation is drying, and partly on the skill of the farmer in judging when to set the fire. The range of behavior is very great: of 138 virgin burns performed by Transamazon Highway colonists, an average of 44 days elapsed between felling and burning with a standard deviation of 65 (CV = 148%). The quality of the burn could be correctly predicted in 74% of 247 cases from meteorological factors (Fearnside, 1986, p. 186, 1989). Very high variability of rainfall and other meteorological parameters in the area guarantees high variability in burn quality from year to year (Fearnside, 1984b).

"Burning efficiency" refers to the percentage of the carbon exposed to burning that is released (i.e., is not left behind as unburned wood or converted to black carbon in charcoal or soot). This is also known as the "volatilization fraction," and as "combustion efficiency" (but the latter term is also used to refer to the fraction of the carbon emitted from a burn that is in the form of CO_2). Burning efficiency, which is calculated from pre- and post-burn stocks in terms of carbon, is similar but not identical to percentage biomass losses calculated from quantities expressed in terms of dry matter.

The range of burning efficiencies used in global biomass burning calculations has been very great. Wong (1978) assumed 75% as the average for tropical deforestation, while Seiler and Crutzen (1980, p. 234) assumed 25%. Bogdonoff et al. (1985, p. 347) assumed an efficiency of 25%. Crutzen and Andreae (1990) calculated emissions from tropical deforestation burning using an efficiency of 40% over the course of a sequence of the initial burn and subsequent reburns, based on Fearnside (1991). Additional studies refined these estimates to 33.2% from initial burning when adjusted for the effect of removal of trunks by logging, and 42.0% total from the full sequence of burns (Fearnside, 1997a). Almost all (91.0%) of the carbon in the original forest biomass is released by the end of the first decade, and of biomass carbon remaining after the initial burn, almost all (90.0%) is released over the course of the succeeding decade: 61.7% through decay and 12.5% through combustion in reburns (Barbosa and Fearnside, 1996). Initial burns studied by Kauffman et al. (1995) had higher efficiencies than those of the studies included in the Fearnside (1997a) and Barbosa and Fearnside (1996) estimates (Fearnside, 1996a, Fearnside et al., 1993), as well as a similar study near Ariquemes, Rondonia (Graça, 1997, Graça et al., 1999).

Two additional estimates are available, one finding a burning efficiency of 25.1% in an experimental burn near Manaus (Carvalho Jr. et al., 1995) and one finding an efficiency of 21.9% for an experimental burn near Tomé-Açu, Para (Araujo, 1995, Araujo et al., 1997). However, the methodology used in these cases makes interpretation somewhat difficult, as it does not yield an estimate of the central or mean value. For trunks and branches >10 cm in diameter, a maximum of 5 mm was found to be removed from the surface at Manaus and 3 mm at Tomé-Açu. The reductions in volume and biomass loading corresponding to these maximum removals were then calculated for all biomass in this diameter range (which accounts for most of the biomass present). In the Manaus study, biomass smaller than 10 cm in diameter was simply considered to be completely consumed in the fire, while in the Tomé-Açu study a weight was measured for this component after the burn. Given that these procedures make estimates of burning efficiency maximum values (i.e., overestimates of the mean), it is notable that the values obtained are lower than any of the eight other studies now available of initial burns in original forest, which indicate burning efficiencies range from 27.6% to 56.1%. The average percentage loss of the initial carbon stock in these eight studies was 42.2% (burning efficiency). Considering the full sequence of burning (the initial burn plus three reburns over the succeeding decade) would raise the total efficiency to 54.5%. Considering all ten available studies, the burning efficiency of 38.8% would be raised to 51.8% by a full sequence of burning. Combustion and charcoal formation studies in Brazil are summarized in Table XI.

[Table XI here]

The percentage of biomass in trunks, as opposed to vines and other finer material, appears to have a strong influence on the proportion of biomass combusted. Finer material burns much more thoroughly: in the study near Manaus (Fearnside et al., 1993), 100% of the leaves burned, 75.8% of the vines, 49.1% of the branches, and 20.9% of the trunks. In a study of burns near Altamira (Para), where a higher percentage of the forest biomass is composed of vines, a higher percentage of the biomass disappeared in the burn than was the case at Manaus (Fearnside et al., 1999) (Table XI).

Secondary vegetation, with a larger quantity of branches and thin trunks, can be expected to burn better than "virgin" forest, where many thick trunks remain practically intact after burning. Although the relation of diameter to completeness of burning is very strong (Fearnside et al., 1993), poor burns can be more frequent in secondary than in "virgin" forest clearings. For example, in 247 "virgin" forest burns studied among Transamazon Highway colonists, 76 (30.8%) were "bad" burns, whereas in 54 secondary forest burns, 31 (57.4%) were classified as "bad" (Fearnside, 1989).

3.2. Charcoal Formation

A small portion of the carbon in the wood that is exposed to burning is converted to elemental form in charcoal or in graphitic particulates (soot). Blackened material, more correctly termed "char," covers a range of different degrees of carbonization, and grades into brown-colored and then unaltered wood in the interior of a trunk left after a burn. "Charcoal" in the studies done in Brazilian Amazonia (Table XI) was removed using a blunt machete, striking each piece at a 45° angle with a "medium" amount of force. This was sufficient to remove char that was definitely black in color, while leaving the brownish-colored (i.e., partially charred) wood. Charcoal so removed, or picked up from the ground, constitutes the operational definition of this pool.

Following a burn in either primary or secondary forest, farmers may cut unburned branches and small trunks and pile them in mounds (known in Brazil as <u>coivaras</u>), which can be burned in a second burn prior to planting (Fearnside, 1990b, p. 111). These reburn piles are made by small farmers in preparing fields for planting certain annual crops (see Fearnside, 1990b). The high labor demand for cutting and carrying material to the reburn piles, especially when burn quality is poor, restricts this practice to only a portion of clearings made by small farmers. Reburning does not affect the much larger areas that are cleared for planting cattle pastures on larger properties in Brazilian Amazonia; only about 30% of clearing is done by small farmers with properties under 100 ha in area (Fearnside, 1993b). Araujo (1995, p. 70) conducted experimental reburns in cut primary forest in Tomé-Açu. Because relatively little biomass left after a primary forest burn is of diameter small enough for the pieces to be easily carried to the piles, the increase in emission from reburning is not great: in the Tomé-Açu experiment, 93.2% of the emission came from the initial burn and 6.8% from the reburn (Araujo, 1995, p. 95).

Accurate quantification of charcoal formation is important because it represents one of the only ways in which carbon can be removed from the cycle such that it cannot recombine with oxygen to form CO_2. If researchers studying GHG emissions ignore sinks of carbon, even if small, they leave themselves open to accusations of bias in exaggerating the impact of deforestation on global change.

Seiler and Crutzen (1980) were the first to point out the potential importance of charcoal formation to the global carbon cycle. The charcoal formation rate they estimated for tropical deforestation was 15-23% with respect to carbon exposed to burning (or 20-30% of post-burn C) subsequently revised by Crutzen and Andreae (1990, p. 1672) to 5% of exposed carbon. These values are higher than those reported in Table XI: the four existing studies of the initial burn of original forest have a mean charcoal formation equal to 2.2% of pre-burn biomass carbon.

Burns subsequent to the first one can affect charcoal in both directions: forming additional charcoal and consuming some of the charcoal present on the site from previous burns. The net result is only a slight addition to charcoal formed in the initial burn. Pasture burns are done every 2-3 years in cattle pasture that is being maintained for grazing. For original forest remains in pastures burned in Roraima, simulation results indicate only a small amount of carbon (4.1 t C ha^{-1} or 3.3% of the pre-deforestation aboveground carbon stock) is transformed into charcoal by the initial burn plus three reburns over 10 years of use as pasture (Barbosa and Fearnside (1996) based on charcoal formation from Fearnside et al. (1993) and Barbosa (1994)). Using the charcoal formation measurements and burning efficiencies included in Table XI, charcoal formation from the full sequence of burns totals 2.8%.

Because high-biomass forests tend to have a high proportion of the biomass in the form of large trunks that burn poorly, one might expect that charcoal formation would be more predictable if expressed as a percentage of "transformed carbon" rather than as a percentage of pre-burn biomass carbon. "Transformed carbon" refers to carbon either emitted or converted to charcoal and soot. Although the amount of data is insufficient for a firm answer, the existing studies do not bear out the expected reduction in variability from considering charcoal formation in terms of transformed carbon (Table XI).

Charcoal contains organic carbon as well as inert "black carbon." Kuhlbusch and Crutzen (1995) have pointed out the great potential source of divergence in measurements of black carbon depending on the methodology adopted. Black carbon is measured as the amount that remains unoxidized when a sample is heated in pure oxygen. Results are sensitive to the temperature to which the heating is done, for which there is no universally agreed standard (340^{o}C was adopted by Kuhlbusch and Crutzen (1995)). Lowering the temperature from 340^{o}C to 300^{o}C increases the final result for black carbon by a factor of two. The relationship is not known between resistance to oxidation at high temperatures and resistance to decay in the ground. Considering measurements made on temperate deciduous wood residues for total carbon and for black carbon determined at 340^{o}C, Kuhlbusch and Crutzen (1995) calculated that for the 2.7% charcoal formation found in the 1984 burn near Manaus (Fearnside et al., 1993 and Table XI), black carbon represents 1.4-1.7% of the carbon exposed to burning. The corresponding range for the 2.2% mean charcoal formation of the four initial burn studies reported in Table XI would be 1.1-1.4% black carbon formation. For the full sequence of burns (2.8% charcoal formation), the black carbon formation would be 1.4-1.8%.

3.3. Flaming versus Smoldering

The proportion of combustion occurring in flaming versus smoldering mode is critical to the amounts of trace gases emitted from biomass burning. Flaming combustion emits a higher proportion of CO_2 than smoldering combustion, which emits substantial quantities of CH_4, CO, NO_x and N_2O.

The initial burn is primarily flaming and is hotter than the subsequent burns. In the initial burn the twigs and small branches burn quickly, whereas remains of the original forest exposed to subsequent burns no longer have this fine fuel component, being dominated by the remaining large trunks. Trunks lying in cattle pastures may smolder for weeks and finally be converted completely to ash. Sampling from aircraft over deforestation fires in Brazil indicates the predominance of gases characteristic of flaming combustion (Andreae et al., 1988). The calculations in the present paper assume all initial burns are flaming and all combustion of original forest remains in subsequent burns is smoldering.

When burning is done in a two-step process, with material remaining from the first phase being heaped into reburn piles (coivaras) for burning a few days later, combustion in these reburn piles appears to be similar to that in the first phase. However, burning efficiency is higher: the one existing study of burning efficiency in reburn piles found 97.2% efficiency for an experimental burn in primary forest near Tomé-Açu, Para (Araujo, 1995). Measurements of temperatures during burning of reburn piles in Thailand indicate elevation of temperature similar to that found in burning "heavy fuel" (large logs) at heights ranging from 1 cm below the surface to 2 m above the surface, but warming was greater from 2-3 cm below the surface (Zinke et al., 1978, p. 144). "Moderate" fuels (smaller branches and leaves) produced less warming at all heights.

The flaming nature of most second growth burns is apparent. The small diameter of the fuel leads to quicker drying and more rapid burning. In a burn in 8-9-year-old second growth studied in Costa Rica by Ewel et al. (1981), high temperatures of 600°C were noted above the soil, but heating declined rapidly with depth below the soil surface. Burning of heavier trunks appears to be associated with greater heating at depth in the soil. The degree of soil heating is important to determining soil fertility changes and gas releases from the soil, including release of soil carbon stocks (Fearnside, 1986, pp. 188-192).

4. Emissions from Biomass Burning

Seiler and Crutzen (1980, p. 233), in their pioneering work on biomass burning, estimated that in 1980, 3.08×10^9 t C were exposed to burning in the tropics (excluding savannas, firewood and agricultural wastes), of which 0.93×10^9 t C were from deforestation. Hao et al. (1990, pp. 447, 456) estimated 1.58×10^9 t C and 0.68×10^9 t C, respectively, for these quantities in 1980, and Crutzen and Andreae (1990) revised these numbers to $2.7\text{-}6.8 \times 10^9$ t C and $0.5\text{-}1.4 \times 10^9$ t C for 1989. The present analysis indicates average annual values for 1981-1990 of 3.1×10^9 t C exposed to burning from clearing of primary and secondary tropical ecosystems (Table XII).

[Table XII here]

Crutzen and Andreae (1990) suggest a range of $500\text{-}1000 \times 10^6$ t C for the annual release in 1989 from burning of shifting cultivation fallows, based on ranges for 1980 of $400\text{-}1100 \times 10^6$ t C derived by Seiler and Crutzen (1980) and $500\text{-}700 \times 10^6$ t C derived by Hao et al. (1990). The amount of biomass carbon estimated to be exposed to burning in 1989 was $1000\text{-}2000 \times 10^6$ t in shifting cultivation fallows and $500\text{-}1400 \times 10^6$ t in permanent deforestation, or $1500\text{-}3400 \times 10^6$ t C from the two sources (Crutzen and Andreae, 1990, p. 1671). The estimates derived in the present review suggest that for the 1981-1990 period the average annual amount of biomass carbon exposed to burning in secondary forests not cleared permanently was 555 $\times$ 10^6 t, producing a gross emission of 299 $\times$ 10^6 t C (Table XII). The total amount of fallow aboveground carbon cleared annually (i.e., exposed to burning) for either shifting cultivation or permanent clearing is estimated to be 0.59 $\times$ 10^9 t C (Table X, considering carbon content = 45%). Of 3.14 $\times$ 10^9 t C exposed to burning annually (excluding recurrent burning of savannas), 1.50 + 1.06 = 2.56 $\times$ 10^9 t C is the result of deforestation of original forest or permanent clearing of long-fallow secondary forest (Table XII).

The average annual total gross emission from the types of burning considered here was 1127 $\times$ 10^6 t C over the 1981-1990 (Table XII). Of this, 828 $\times$ 10^6 t C (73%) was from tropical deforestation and clearing of cerrado and other natural ecosystems and cutting secondary vegetation for permanent clearings, while 299 $\times$ 10^6 t C (27%) was from clearing of secondary vegetation for shifting cultivation.

Table XIII presents calculated emissions of gases from tropical forest conversion and permanent clearing of secondary vegetation, and for cutting as part of shifting cultivation cycles. These are based on the area of secondary succession cleared, average age and average aboveground biomass loading. Carbon content of secondary vegetation is 0.45, or about 10% lower than the 0.50 carbon content that characterizes primary forest wood (Fearnside et al., 1993; Guimarães, 1993; Higuchi and Carvalho Jr., 1994). The values in Table XIII represent a "low trace gas scenario," in that values for emission factors have been used at the low end of the range of values appearing in the literature. The higher values are applied in Table XIV, as a "high trace gas scenario."

[Tables XIII and XIV here]

The impact of trace gases such as CH_4 and N_2O can be converted to CO_2-equivalent carbon using IPCC Second Assessment Report 100-year integration global warming potentials (GWPs) (Schimel et al., 1996, p. 121). The burning component of gross emissions ranges from 1.06 $\times$ 10^9 t CO_2-equivalent C in the low trace gas scenario to 1.50 $\times$ 10^9 t CO_2-equivalent C in the high trace gas scenario. This range of values reflects only uncertainty associated with trace gas emission factors--not the large and poorly quantified margins of uncertainty that apply to deforestation estimates, areas in some land uses (such as shifting cultivation), forest biomass loading and burning efficiency.

The average annual total gross emission (including decomposition emissions both from unburned aboveground biomass and from belowground biomass and carbon emission from the top meter of soil) can be calculated for the 1981-1990 period.

Total average emissions, calculated as net committed emissions using the parameters estimated for Brazil (Fearnside, 1997a), indicates 11.97 × 10^9 t of CO_2 gas, 12-14 × 10^6 t of CH_4, 313-366 × 10^6 t of CO, 0.69-5.8 × 10^6 t of N_2O and 8.8 × 10^6 t of NO_x. Adjustments for trace gas emissions make this equivalent to 3.39-3.83 × 10^9 t of CO_2-equivalent carbon. Biomass burning accounts for 31-39% of this total (Tables XIII and XIV).

It should be noted that IPCC SAR global warming potentials do not recognize any effect of carbon monoxide (CO), including the molecule of CO_2 that forms when each molecule of CO is oxidized to CO_2 after an average of only three months (Schimel et al., 1996, p. 92). In addition to its impact as a source of CO_2, CO increases global warming by removing OH radicals from the atmosphere, thereby extending the average lifetime of the CH_4 that these radicals would otherwise remove (Shine et al., 1990). The 0.134-0.157 × 10^9 t C released in the form of CO (Tables XIII and XIV) represents an omission in the calculated effect of deforestation as CO_2-equivalent carbon. If CO_2 resulting from oxidation of CO were counted, CO would have a GWP of 1.57 on a mass basis, and the impact of tropical land-use change would increase by 0.057-0.067 × 10^9 t of CO_2-equivalent carbon, or 2.4-2.8%.

5. Global Carbon Balance

Biomass burning is only one means by which GHG emissions occur from land-use change. Decay is the principal pathway for the remainder of carbon flows from the landscape to the atmosphere. The data considered here imply substantial differences from the global carbon balance currently used by the IPCC. Net annual carbon release from tropical land-use change in the 1981-1990 period is calculated in Table XV, using the values for areas undergoing land-use change (based on FAO, 1993) and other parameters from the current analysis. The average 1981-1990 annual emission from these sources totaled 2.4 × 10^9 t C $year^{-1}$, or 0.8 × 10^9 t C (50%) greater than the 1.6 × 10^9 t C value used by the IPCC (Schimel et al., 1996, p. 79). Among the implications of this is that the IPCC Second Assessment Report estimate of 1.3 × 10^9 t C $year^{-1}$ (IPCC, 1996, p. 20) for the "inferred sink" (formerly called the "missing sink") is too low, and should be at least 1.3 + 0.8 = 2.1 × 10^9 t C $year^{-1}$.

[Table XV here]

Part of the additional emission calculated above may be offset by uptake by intact Amazonian forest over the 1981-1990 period. Over much longer time periods (centuries, for example), such an uptake would not be possible, as its accumulated effect would result in obvious changes in the size and density of trees (which have not occurred). However, it is entirely possible that uptake could occur over shorter time scales due to temporary imbalances in the age structure of forest trees, for example as a result of past disturbances by El Niño events or other causes of elevated mortality. A process-based model of undisturbed ecosystems in the Amazon Basin, including savannas and forests (not necessarily defined as above), indicates wide interannual variations in net carbon flux from the vegetation and soil, ranging from emissions of 0.2 $\times 10^9$ t C in El Niño years to a sink of up to 0.7 $\times 10^9$ t C in other years, with the mean annual flux simulated over the 1980-1994 period being an uptake of 0.2 $\times 10^9$ t C (Tian et al., 1998). Whether tropical forests are currently taking up carbon on a time scale of a decade (i.e., 1981-1990), and if so how much, are matters of controversy (Table XVI). One approach is to estimate changes in carbon stocks based on tree growth and mortality in permanent sample plots (Phillips et al., 1998). While uptake may be occurring, only limited confidence can be placed in these estimates. A key argument for the existence of an uptake is the fact that more sites show uptakes than losses of carbon (Phillips et al., 1998, p. 439). However, this observation does not justify a conclusion that uptake is occurring on average because this is the same pattern that one would expect under conditions of complete equilibrium: losses would occur through death of a few large trees, leading to relatively substantial declines in biomass in the minority of plots where these events occur, while the majority of plots would show modest biomass increases as the smaller trees slowly grow in size. One would expect that the smaller the area monitored at any given site, the greater the probability that a biomass increase would be found. It is also important to realize that interannual variability is great due to El Niño events and other factors. Both high spatial and temporal variability indicate that many observations would be needed over substantial time periods to establish the magnitude of carbon fluxes from Amazonia and other tropical regions with confidence. Results from Amazonia dominate global estimates of carbon uptake by intact tropical forests (Phillips et al., 1998). The largest and longest-running series of observations available in Amazonia is the 17-year data set of the INPA/Smithsonian Institution "Biological Dynamics of Forest Fragments Project" (BDFFP) near Manaus, with observations on the oldest plots beginning in 1980. As of 1997 these plots had not shown any indication of a change in average biomass for the 36 one-hectare plots located $\geq$100 m from a forest edge (Laurance et al., 1997). The region-wide analysis (Phillips et al., 1998) that includes the BDFFP results does not weight the values for each of the 40 Amazonian sites (composed of a total of 97 plots) by either the area surveyed or by the number of years of observation. In general, smaller data sets are available for the sites showing biomass increases, such as the 3 ha monitored by the INPA/UK Department for International Development (DfID) "Biomass and Forest Nutrients" (BIONTE) project near Manaus (Table XVI).

[Table XVI here]

The micrometeorological technique of eddy correlation allows measurements of gas fluxes using instruments mounted on towers in the forest canopy; existing studies employing this technique indicate greater uptake from Amazon forests than do studies based on observations of tree growth and mortality in permanant plots. Additional micrometeorological studies are planned under the "Large-Scale Atmosphere Biosphere Experiment" (LBA) to confirm the generality of the results obtained at the two Amazonian sites where eddy correlation work has been done (Table XVI).

The estimate by Phillips et al. (1998) based on tree growth and mortality in permanent sample plots at 40 sites in Amazonia covers a much wider range of locations and integrates annual fluctuations over much longer periods than do the available eddy correlation studies. The permanent sample plots indicate that Amazonian forests have been absorbing an average of 0.62 ±0.37 t C ha^{-1} $year^{-1}$ over the past two decades. Using the areas of Brazil's Amazon forest and of tropical rain forests, moist deciduous forests and hill and montane forests in the countries comprising "other South America" from Table VIII, this represents an annual uptake of 0.38×10^{9} t C $year^{-1}$. If confirmed, a 0.38×10^{9} t C $year^{-1}$ sink would lower the global "inferred sink" to $2.1 - 0.4 = 1.7 \times 10^{9}$ t C $year^{-1}$. Tropical forests in Neotropical areas outside of Amazonia absorb carbon at lower rates, while those in the Paleotropics (Asia, Africa and Oceania) show no net change in carbon stocks according to available permanent plot data; Phillips et al. (1998) estimate that the Neotropical forests outside of Amazonia absorb 0.18×10^{9} t C $year^{-1}$, which would lower the inferred sink calculated above to 1.5×10^{9} t C $year^{-1}$.

With increased global warming, tropical forests are expected to become net sources of carbon as increases in respiration outstrip increases in photosynthesis (Grace et al., nd). In Costa Rica, tree growth records indicate that intact forests are already a net source of carbon, a result explained by increased nocturnal respiration due to warmer nights (Beardsley, 1998, Clark et al., 1998).

The carbon emissions from tropical land-use change calculated in the present paper indicate a substantial contribution to global warming. If one considers the average annual fossil fuel emission of 6.0×10^{9} t C over the 1981-1990 period (Watson et al., 1992, p. 29), the 2.4×10^{9} t C land-use change emission calculated here represents 29% of the combined total. Brazil is the largest single contributor to land-use change emissions, with 23% of the tropical land-use total; Brazil's 0.462×10^{9} t C annual emission from forest clearing (Table VII), plus 0.094×10^{9} t C from category changes (a proportional share of this emission: Table XV), together represent 6.6% of the global total from fossil fuels and land-use change.

6. Conclusions

Biomass burning and decomposition and soil carbon release from tropical forest conversion, shifting cultivation and secondary vegetation currently emit substantial amounts of greenhouse gases; these forests have the potential for large additional emissions. An estimated 3.1×10^9 t of biomass carbon is exposed to these forms of burning each year in tropical countries, of which 1.1×10^9 t C is emitted through combustion and 49×10^6 t C is converted to charcoal. Of the carbon converted to charcoal, $26\text{-}31 \times 10^6$ t C would represent black carbon as defined by resistance to oxidation at 340°C. Carbon emitted annually through decomposition processes totals 2.1×10^9 t C. The total gross emission (including burning and decomposition emissions both from aboveground and from belowground biomass and from the top meter of soil is 3.4×10^9 t of carbon, of which 3.3×10^9 t is in the form of CO_2. Adjustments for trace gas emissions using IPCC Second Assessment Report 100-year integration global warming potentials make this equivalent to $3.4\text{-}3.8 \times 10^9$ t of CO_2-equivalent carbon, of which $1.06\text{-}1.50 \times 10^9$ t (31-39%) is the result of biomass burning. The data used in the current analysis imply an average annual net carbon flux to the atmosphere of 2.4×10^9 t C year^{-1} from tropical land-use change, or 0.8×10^9 t C year^{-1} (50%) more than the value of 1.6×10^9 t C year^{-1} used by the IPCC Second Assessment Report. The inferred or "missing" carbon sink would therefore be 62% larger than the one used by the IPCC. However, a possible sink in uptake by Amazonian forests may be offsetting about half of the additional source suggested here. Considering 0.8×10^9 t C year^{-1} of additional emission by tropical land-use change, and a -0.4×10^9 t C year^{-1} uptake by Amazonian forests, the 1.3×10^9 t C year^{-1} IPCC inferred sink would rise to 1.7×10^9 t C year^{-1}, an increase of 31%.

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TABLE I
Tropical deforestation rates for 1981-1990 (10^3 ha $year^{-1}$)[a]

Region[b]	All forests	Tropical rain forests	Moist deciduous forest	Dry deciduous forest	Very dry forest	Desert	Hill and montane forest	Ex re fo co 19 ha
Africa	4,099.9	471.0	2,235.9	767.2	316.6	12.4	247.7	
Central America and the Caribbean	1,198.4	275.8	280.1	29.6	16.3	34.5	562.1	
Brazil (FAO: includes cerrado and caatinga)[c]	3,670.9	1,012.6	1,705.9	312.6	0.0	0.0	639.9	
Brazil (this study: includes cerrado and caatinga)[d]	4,126.7	1,988.2	1,705.9	312.6	0.0	0.0	120.0	
Other South America	2,533.4	636.7	1,199.5	254.9	7.4	4.8	417.5	

Asia	3,791.1	2,070.8	654.4	466.4	1.5	27.8	567.2	
Oceania	113.0	91.2	2.2	1.3	0.0	0.6	16.9	
Tropics total (FAO)	15,406.7	4,558.1	6,078.0	1,832.0	341.8	80.1	2,451.3	1,
Tropics total (this study)	15,862.5	5,533.7	6,078.0	1,832.0	341.8	80.1	1,931.4	1,

[a] All data from FAO (1993) except for Brazil as indicated. Column headings are FAO categories. Except last column, values are rates of forest cover loss and include permanent clearing of long-fallow seconda forests but not clearing of long-fallow secondary forests that are allowed to recover.

[b] Unlike FAO usage, regions are defined geographically: Guyana, Suriname and French Guiana considered So America; Belize is considered Central America.

[c] According to FAO (1993, p. 27) classification, in Brazil "tropical rain forests" refers to most of the Amazon region, except for the states of Maranhão, Tocantins and most of Para. Cerrado (central Brazilia savanna), lavrado (Roraima savanna) and Atlantic forest are classified as "moist deciduous forests;" caa is "dry deciduous forest," while forests in Rio Grande do Sul, Santa Catarina and Parana are "hill and m forests."

[d] Value listed for "tropical rain forests" in Brazil used in this study is from Fearnside (1999) updated
Fearnside (1997a); this refers to annual clearing rate of all forest types in the Legal Amazon over the
1990 period. Values for "moist deciduous forest" and "dry deciduous forest" are taken from FAO (1993) a
represent cerrado and caatinga, respectively, in all of Brazil. Value listed for "hill and montane fore
assumed, and refers to forests outside the Legal Amazon classed as "other closed forest" (cerradao, Atla
forests and araucaria forest), as well as "wetlands/mangrove" (pantanal, gallery forests and mangroves)
Table III). Extent (10^3 ha) in early 1990s of Brazilian vegetation types: Amazonian forests: 337,720 in
(Fearnside and Ferraz, 1995); Atlantic forest: 10,000 in 1991 (Fundacao SOS Mata Atlantica, 1992); arauc
forest: 2,546 in 1988 (Fearnside et al., 1996, based on Brazil, IBGE & IBDF, 1988); cerrado: 126,000 in
(Brazil, CIMA, 1991a); caatinga and other semi-arid: 155,000 in 1991 (Brazil, CIMA, 1991a); pantanal ori
area: 14,000 (Brazil, CIMA, 1991b); mangroves outside the Legal Amazon in 1988: 937.3 (Fearnside et al.,
p. 236), with 708.6 in the Legal Amazon (Fearnside and Ferraz, 1995, based on Brazil, IBGE & IBDF, 1988)

TABLE II
Biomass of Brazilian cerrado

Description	IBAMA vegetation code[a]	Area (10^6 ha) in "cerrado domain"[b]	Area (10^6 ha) in Amazonia[c]	Total area (10^6 ha)	Aboveground biomass loading (t ha^{-1})	Belowground biomass loading (t ha^{-1})	Root/shoot ratio
Cerradao	SN	16.9	0.2	17.1	91.7[d]	45.9	0.5[e]
Cerrado (sensu stricto)							
Cerrado aberto	Sa	54.0[f]	0.2	54.2	12.9[d]	33.6	2.6[g]

2

Cerrado denso	Sd	54.0[f]	0.0	54.0	23.1[d]	67.1	2.9[g]
Campos de cerrado							
Campo cerrado	Sp (?)	7.9[f]	2.5	10.3	8.6[h]	66.4	7.7[i]
Campo sujo	Sp	7.9[f]		7.9	4.5[h]	34.7	7.7[g]
Campo limpo	Sg	7.9[f]	1.5	9.4	4.4[h]	24.6	5.6[g]
Totals							
Cerrado (sensu stricto)		108.0	0.2	108.2	18.0	50.3	2.8

3

Campos de cerrado	23.6	4.0	27.6	5.0	35.8	7.2
Cerradao + cerrado sensu stricto	124.9	0.4	125.3	28.1	49.7	1.8
All cerrados	131.6	4.2	135.8	15.4	47.4	3.1

[a] Brazil, IBGE & IBDF (1988).

[b] Dias (1996, p. 19) based on Azevedo and Adamoli (1988).

[c] States of Amapa, Amazonas and Roraima only (cerrado vegetation in other Amazonian states is consic the "cerrado domain"; areas from Fearnside and Ferraz (1995).

[d] Graça (1997, p. 66), based on RADAMBRASIL data.

[e] Assumption.

[f] Area assumed to be equally distributed among cerrado variants in this category.

[g] de Castro and Kauffman (1998, p. 280).

[h] Kauffman et al. (1994, p. 523).

[i] Assumed equal to campo sujo (Sp).

TABLE III
Brazilian ecosystems other than cerrado and Amazonian forest

	Area (10^6 ha)[a]	Proportion of "other ecosystems"	Adjusted area for FAO data (10^6 ha)	Biomass C (t ha^{-1})[a]	Biomass C stock (10^9 t C)	Root/ shoot ratio [a]	Abovegrou nd C loading (t ha^{-1})	Abo gro sto t (
Other closed forest	16.4	0.27	18.0	60	1.08	0.23	48.8	
Degraded woodlands	33.0	0.53	36.2	20	0.72	1.6	7.7	
Wetlands/mangrove	12.4	0.20	13.6	30	0.41	0.75	17.1	
Total (for "other ecosystems" present)	61.8	1.00	67.8	33	2.21	0.59	20.5	
Total (for "other ecosystems" cleared)				30	0.01	0.69	17.6	

[a] Based on Shroeder and Winjum (1995). Note that "cerradao" is considered "other closed forest" anc woodlands".

[b] "Degraded woodlands" is FAO (1993) estimate for "dry deciduous forest" (caatinga). The 639.0 × 10 montane forest must be largely in Amazonia.

TABLE IV
Biomass of 1990 non-forested landscape

Land cover	Area (10^6 ha)[a]			Proportion of non-forested landscape			Total biomass (t ha^{-1})[b]	Biomass stock (10^9 t		
	Africa	Latin America	Asia	Africa	Latin America	Asia		Africa	Latin America	Asia
Short fallow	80.1	23.5	46.5	0.137	0.065	0.150	22.6	1.8	0.5	
Shrubs	57.5	89.0	13.5	0.098	0.247	0.044	62.4	3.6	5.6	
Other land cover	444.0	242.9	234.0	0.759	0.674	0.754	19.5	8.7	4.7	
Plantations	3.0	2.2	15.9	0.005	0.006	0.051	81.3	0.2	0.2	
Water	0.6	2.8	0.7	0.001	0.008	0.002	0	0.0	0.0	
Total	585.2	360.3	310.6	1.0	1.0	1.0		14.3	11.0	
Average biomass (t ha^{-1})								24.4	30.5	

[a] FAO (1996, pp. 137, 139, 141).

[b] Aboveground live biomass loading from FAO (1995, p. 37). For corrections for aboveground dead, litter and belowground, see Table VII, note c. Short-fallow and plantation biomass have been divid by 2 to represent the average in a landscape with equilibrium age structure.

TABLE V
Areas under active agriculture 1980-1990 from FAO data[a]

Continent	Year	Areas of land-cover categories (10^6 ha)					Percent "defores area und secondar forest
		"Other land cover" (mostly agriculture)	Short fallow[b]	Fragmented forest[c]	Area under active agriculture or pasture[d]	Area under short-fallow secondary forest[e]	
Africa	1980	431.45	69.75	116.82	532.35	46.73	
	1990	444.00	80.05	121.67	551.53	53.63	
	1980-1990 average	437.73	74.90	119.25	541.94	50.18	
	Annual change	1.26	1.03	0.48	1.92	0.69	
Asia	1980	219.98	41.26	17.61	245.34	27.64	
	1990	234.02	46.45	18.53	261.70	31.12	
	1980-1990 average	227.00	43.86	18.07	253.52	29.38	
	Annual change	1.40	0.52	0.09	1.64	0.35	
Latin	1980	191.83	18.29	40.63	224.95	12.25	

America						
	1990	242.89	23.46	36.49	274.96	15.72
	1980-1990 average	217.36	20.88	38.56	249.96	13.99
	Annual change	5.11	0.52	-0.41	5.00	0.35

[a] FAO (1996, pp. 137, 139, 141).

[b] "Short fallow" includes both cropped and fallow areas; "long fallow" shifting cultivation is considered to be forest by FAO (1996).

[c] FAO (1996, p. 21) considers two-thirds of "fragmented forest" to be deforested.

[d] "Active agriculture or pasture" is considered to be 100% of "other land cover" area, 33% of "short fallow" area (see note e), and 67% of "fragmented forest" area (see note c).

[e] "Short fallow" considered to have 2-year cropping period and 4-year average fallow period (Table X note d), making 33% of the area active agriculture and 67% secondary forest.

[f] "Deforested area" here is land under active cultivation or pasture and under short-fallow secondar forest. Other land uses normally included as deforestation, such as tree crops, silvicultural plantations, and hydroelectric dams, are not included.

TABLE VI
Soil carbon losses from deforestation

Location	Average organic carbon loading in top meter of soil (t C ha^{-1})[a]	Average change on conversion to active agriculture (t C ha^{-1})[b]	Average change relative to forest if under short-fallow secondary forest (t C ha^{-1})[c]	Average percent of "deforested" area under secondary forest[d]	Average organic carbon change in top m of soil per ha of deforestation (t C ha^{-1})
Africa	68	-12.6	-9.2	8.5	-12.3
Asia	87	-16.1	-11.8	10.4	-15.7
Central America	99	-18.4	-13.4	5.3	-18.1
Brazil	94	-12.3	-9.1	30.2	-11.4
Other South America	83	-15.4	-11.3	5.3	-15.2

[a] Sombroek et al. (1993, p. 420), except for Brazil (Fearnside and Barbosa, 1998, p. 160); Amazon region assumed to represent all of Brazil.

[b] Assumes 35% reduction in the 0-30 cm layer, this being the

midpoint of the 20-50% range reported by Sombroek et al. (1993, p. 421). Assumes no reduction below 30-cm depth; 0-30-cm layer contains 53.0% of 0-1 m C stock, based on average of 24 FAO soil groups (Sombroek et al., 1993, p. 418).

[c] For Brazil, average secondary forest age is 3.87 years; for other locations the average age of short-fallow secondary forest is 2 years (half the 4-year average age at cutting: Table X). Recovery is assumed to take 15 years (the assumption of R. A. Houghton et al. (1983), except that full recovery is assumed rather than only 75% of the forest soil C stock).

[d] Value for Brazil represents landscape in Amazonia in 1990 (Fearnside, 1996b, p. 29); values for other locations calculated in Table IV.

TABLE VII

Biomass cleared annually in natural ecosystems in tropical countries and their carbon emissions[a]

Location	Average aboveground live biomass loading reported for all forests (t ha^{-1})	Aboveground live biomass reported presumed cleared (10^9 t yr^{-1})	Belowground biomass presumed cleared[b] (10^9 t yr^{-1})	Other aboveground live biomass presumed cleared[c] (10^9 t yr^{-1})	Aboveground dead presumed cleared (10^9 t yr^{-1})	Total biomass presumed cleared (above + below, live + dead) (10^9 t yr^{-1})	Carbon in biomass presumed cleared[d] (10^9 t yr^{-1})	Carbon in charcoal (10^6 t C)	Carbon in replacement landscape[e] (10^9 t yr^{-1})	Net committed emissions from biomass (10^9 t C yr^{-1})	Soil carbon release[f] (10^9 t C)	Net comm emis from + bi (10^9 yr^{-1})
Africa	133.0	0.471	0.200	0.123	0.051	0.846	0.423	-9.20	-0.045	0.368	0.051	
Central America and the Caribbean	97.3	0.117	0.049	0.031	0.013	0.209	0.105	-2.28	-0.016	0.086	0.022	
BRAZIL												
Amazonian forest[g]	189.4	0.377	0.194	0.119	0.118	0.807	0.404	-8.74	-0.025	0.369	0.023	
Cerrado[h]	15.4	0.022	0.081			0.103	0.051	-0.31	-0.008	0.043	0.014	
Other ecosystems[i]	35.3	0.015	0.010			0.026	0.013	-0.22	-0.002	0.011	0.003	
Other South America	200.2	0.422	0.179	0.111	0.046	0.757	0.379	-8.25	-0.035	0.336	0.038	
Asia	179.4	0.706	0.299	0.185	0.077	1.267	0.634	-13.80	-0.043	0.577	0.059	
Oceania	191.0	0.022	0.009	0.006	0.002	0.039	0.019	-0.42	-0.001	0.018	0.002	
Tropics total[j]	166.1	2.152	1.022	0.574	0.306	4.054	2.027	-43.22	-0.176	1.808	0.212	

[a] Includes permanent clearing of long-fallow secondary forest, but does not include long-fallow shifting cultivation fallows cleared recover.

[b] Belowground percentage assumed same as Amazonian forest, or 33.6% of aboveground live biomass (Fearnside, 1994).

[c] FAO biomass data refer only to aboveground portions of live trees ≥10 cm DBH (Brown, 1997, p. 4). Corrections for omitted componen countries (from Fearnside, 1994): vines = +5.3%, other non-tree components = +0.2% and trees <10 cm DBH = +12.0%. Additional correc Brazilian data: +15.6% for form factor, +3.6% for trees 30.0-31.8 cm DBH, -6.6% for hollow trees, -0.9% for bark, and +2.4% for palm

[d] Carbon content of original biomass 0.50 (FAO, 1993, Fearnside et al., 1993).

[e] Replacement landscape in cleared areas derived in Table IV as the non-forested landscape present in 1990 for all areas except Brazi replacement landscape biomass in cleared forest assumed to be the 28.5 t ha^{-1} equilibrium landscape biomass in Brazilian Amazonia (Fe Carbon content of replacement landscape biomass 0.45 (Fearnside, 1996b).

[f] Soil carbon release to 1-m depth occurring in the first 15 years; assumed same as transformation to the replacement landscape in Br
7.9 t C ha^{-1} (Fearnside and Barbosa, 1998).

[g] Amazonian forest values for Brazil based on Fearnside (1999) updated from Fearnside (1997b: i.e., not based on FAO, 1993). Values
the Legal Amazon cleared in 1990 (aboveground biomass 308.5 t ha^{-1}, total biomass 406.0 t ha^{-1}).

[h] Cerrado is both inside and outside the Legal Amazon. The values given as "reported" include dead and all aboveground components.
to be cleared over the 1980-1990 period at the 2×10^6 ha annual rate that prevailed over the 1970-1985 period (Klink et al., 1994).
biomass assumed equal to the area-weighted average for cerrado in the Legal Amazon derived by Graça (1997). Assumed root/shoot rati
Shroeder and Winjum (1995), and replacement vegetation is pasture with biomass of 11.7 t ha^{-1}. (Fearnside, 1989); carbon concentratio
is assumed to be 0.50, and in pasture, 0.45.

[i] See Table III. Replacement vegetation and release of soil C assumed to be as for cerrado clearing.

[j] Biomass per ha value does not include cerrado.

TABLE VIII
Carbon stocks in natural ecosystems in tropical countries and their potential carbon emissions

Location	Extent of remaining forest cover in 1990 reported by FAO (1993) (10^3 ha)	Average aboveground live biomass loading reported by FAO (1993) for all forests (t ha^{-1})	Aboveground dead & other aboveground live biomass loading[a] (t ha^{-1})	Belowground biomass[b] (t ha^{-1})	Total biomass (t ha^{-1})	Total biomass stock (10^9 t)	Carbon stock in biomass[c] (10^9 t)	Replacement landscape average total biomass loading[d] (t ha^{-1})	Potential carbon stock in replacement landscape[d] (10^9 t)	Potential carbon in charcoal (10^6 t C)	Potential net committed emission from biomass (10^9 t C)	Soil carbon release (t C ha^{-1})	Po nt l so ca or re as (1 t
Africa	527,587	133.0	42.6	48.7	224.3	118.3	59.2	24.4	5.8	12.3	53.4	12.3	
Central America and the Caribbean	73,838	97.3	36.0	41.2	174.6	12.9	6.4	30.5	1.0	1.3	5.4	18.1	
Brazil[f]													
Amazonian forest[g]	358,475	246.4	78.1	109.1	433.6	155.4	77.7	30.5	4.9	15.4	72.8	11.4	
Cerrado[h]	155,600	28.1	---	49.7	77.8	12.1	6.1	10.7	0.7	0.6	5.3	1.5	
Other ecosystems[i]	67,787	41.0	---	24.3	65.2	4.4	2.2	10.7	0.3	0.4	1.9	1.5	
Other South America	282,979	200.2	61.7	70.6	332.5	94.1	47.0	29.6	3.8	9.8	43.3	15.2	
Asia	274,595	179.4	69.0	79.0	327.4	89.9	44.9	24.9	3.1	9.1	41.9	15.7	
Oceania	36,000	191.0	70.7	80.9	342.7	12.3	6.2	24.9	0.4	1.3	5.8	15.7	
Tropics total	1,553,474	166.1	43.5	55.8	265.4	412.3	206.1	26.8	20.1	50.1	229.6	14.2	2

[a] See Table VII, note c for corrections for components omitted from FAO (1993) biomass data.

[b] Belowground biomass in categories other than cerrado and "other ecosystems" is assumed same as Amazonian forest, or 33.6% of aboveg (Fearnside, 1994).

[c] Carbon content of original biomass 0.50 (FAO, 1993; Fearnside et al., 1993).

[d] Replacement landscape biomass derived in Table IV, except for Brazil, which is assumed to be 28.5 t ha^{-1}: the equilibrium landscape Amazonia (Fearnside, 1996b). Carbon content of replacement landscape biomass 0.45 (Fearnside, 1996b).

[e] Soil carbon release to 1-m depth.

[f] Amazonian forest values for Brazil are for forests in the Legal Amazon based on Fearnside (1999, updated from 1997b) (i.e., not bas

[g] Remaining area of Amazon forest in Brazil based on INPE definition of forest: calculated as difference between original area of 4 ×
1996) and 415 × 10^3 km^2 lost to either clearing or hydroelectric dams by 1990 (Fearnside, 1993b).

[h] Cerrado area from Stone et al. (1994), which differs from the area calculated in Table II. Biomass given as "reported" includes de
live components. Cerrado biomass averages for all Brazil are derived in Table II; values used are for cerradao + cerrado sensu stri

[i] Area of "other ecosystems" is difference between cerrado area and 223,387 × 10^3 ha as the area of vegetation in Brazil other than Ar
FAO (1993); this agrees well with total of 61.8 × 10^6 ha from Stone et al. (1994) for "other closed forest", "degraded woodlands" (mo
"wetlands/mangroves." Proportions of this category of each of these vegetation types are 0.27, 0.53 and 0.20, respectively, based o
Biomass carbon loadings and root/shoot ratios adopted for these vegetation types are those used by Shroeder and Winjum (1995). Abo
as "reported" includes all aboveground live and dead components. Soil carbon and replacement landscape values are assumed same as f

TABLE IX
Biomass stock change due to category transformations other than deforestation (1981-1990)

Land cover	Biomass loading (t ha^{-1})		Area change due to transformations other than deforestation (10^6 ha)			Biomass stock change due to transformations other than deforestation (10^9 t)			
	Aboveground live[a]	Total[b]	Africa	Latin America	Asia	Africa	Latin America	Asia	All tropics
Net transformations among forest categories									
Closed forest	225.0	403.7	-9.31	-8.55	-7.02	-3.76	-3.45	-2.83	-10.04
Open forest	90.0	161.5	-0.29	2.12	0.69	-0.05	0.34	0.11	0.41
Fragmented forest	59.0	105.8	7.87	3.06	2.67	0.83	0.32	0.28	1.44
Long fallow[c]	41.5	66.4	1.73	3.37	3.66	0.11	0.22	0.24	0.58
Forest subtotal					0.00	-2.86	-2.56	-2.20	-7.61
Net transformations among nonforest categories									
Short fallow[c]	15.0	28.8	0.01	-3.61	-1.77	0.00	-0.10	-0.05	-0.15
Shrubs	40.0	52.0	-0.92	-14.48	-2.34	-0.05	-0.75	-0.12	-0.92
Other land cover	7.0	9.1	1.08	17.30	3.68	0.01	0.16	0.03	0.20
Water	0.0	0.0	-0.40	0.59	0.20	0.00	0.00	0.00	0.00
Plantations[c]	56.5	73.5	0.23	0.20	0.23	0.02	0.01	0.02	0.05
Nonforest subtotal					0.00	-0.02	-0.68	-0.12	-0.83
Total (forest + nonforest)[d]					0.00	-2.88	-3.25	-2.32	-8.44

[a] Aboveground live biomass loading from FAO (1996, p. 136).

[b] Closed, open and fragmented forest corrected for other aboveground live components (26.18%) (Fearnside, 1994, nd). Root/shoot ratio = 0.34 with respect to corrected aboveground live biomass;

dead aboveground biomass is 8.6% for these forests (Fearnside, 1994, nd); see Table VII, note c. Short and long fallow have 2.6 t ha^{-1} of dead aboveground biomass loading excluding fine litter, plus 2.9 t ha^{-1} of fine litter (values for secondary forests following pastures with "moderate" use at Paragominas (Uhl et al., 1988). Short and long fallow have root/shoot ratio of 0.42 (Fearnside and Guimaraes, 1996, p. 37, based on Brown and Lugo, 1990). All other "nonforest" categories assumed to have root/shoot ratio of 0.3; dead aboveground biomass is ignored for shrubs, other land cover and plantations.

[c] FAO (1996, p. 136) value has been divided by 2 to represent average value of equilibrium age structure.

[d] Note that all area and stock values are given per decade, and must be divided by 10 to obtain annual values. Stock values refer to biomass (not carbon): C content of closed forest, open forest and fragmented forest is 0.50; all other categories have C content of 0.45.

TABLE X

Secondary forest biomass exposed to fire annually in shifting cultivation and permanent clearing

Land cover	Area present in 1990 (10^6 ha)	Average fallow period (year)	Area cleared per year in shifting cultivation (10^6 ha yr^{-1})	Area cleared per year in land use conversion (10^6 ha yr^{-1})	Total area cleared per year (10^6 ha yr^{-1})	Aboveground biomass loading at time of clearing (t ha^{-1})	Aboveground biomass stock cleared in shifting cultivation fallows allowed to recover (10^9 t)	Aboveground biomass stock cleared in shifting cultivation fallows cleared permanently (10^9 t)	Abov ounc biom stoc clea in a secc ry fore (10^9
Long fallow	60.8	12.5[a]	4.2	0.5[b]	4.8	90.5[c]	0.38	0.05	[illegible]
Short fallow	150.0	4.0[d]	24.9	0.8[e]	25.6	34.3[f]	0.85	0.03	[illegible]
Total (all shifting cultivation)	210.8	6.5	29.1	1.3	30.4	43.1	1.23	0.08	1

[a] Assumes cropped period of 2 years and secondary forest growth rates from Brown and Lugo (1990).

[b] Transitions to shrubs, short fallow, other land cover and plantations; note that these transitions from long fallow are considered deforestation, following FAO (1996).

[c] Aboveground live biomass (including leaves) from FAO (1996, p. 136). These biomass values are assumed to apply to biomass at time of cutting.

[d] Assumes cropped period of 2 years and maximum fallow period allowed under FAO (1995, p. 106) definition of "short fallow" as cropping period >33% of total cycle length.

[e] Transitions to shrubs, other land cover and plantations.

[f] Assumes growth rate of secondary forest aboveground live biomass (including leaves) from Brown anc

Lugo (1990; see Fearnside and Guimaraes, 1996, p. 37) = 26.6 t ha^{-1}; dead aboveground biomass = 2.6 t ha^{-1}; and fine litter = 4.9 t ha^{-1} (Uhl et al., 1988; see Fearnside and Guimaraes, 1996, p. 41); for comparison, FAO (1996, p. 136) value is 30 t ha^{-1}.

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TABLE XI
Combustion and charcoal formation studies in the Brazilian Amazon

Vegetation	Location	State	Burn year	Pre-burn aboveground biomass loading dry weight (t ha^{-1})	Pre-burn aboveground carbon loading (t ha^{-1})		Post-burn aboveground carbon loading (t ha^{-1})			Burning efficiency (% of pre-burn C released)	Trans-formation efficiency (% of pre-burn biomass C released or converted to charcoal)	Net charcoal formation			Source
					In biomass	In charcoal	In biomass	In charcoal	Presumed released			Net charcoal C formation (t ha^{-1})	% of pre-burn biomass carbon	% of trans-formed carbon	
Original forest (first burning)	Manaus	Amazonas	1984	264.6	130.2	0	90.8	3.5	35.9	27.6	30.3	3.5	2.7	8.9	Fearnside e 1993
	Altamira	Para	1986	262.9	129.8	0	73.8	1.6	54.4	41.9	43.2	1.6	1.3	2.9	Fearnside e 1999
	Manaus	Amazonas	1990	368.5	181.7	0	126.8	3.4	51.5	28.3	30.2	3.4	1.8	6.1	Fearnside e nd-a
	Jacunda	Para	1990	292.4	147.6	0	70.0[a]	1.6[a]	76.0	51.5					Kauffman et
	Maraba	Para	1991	434.6	218.2	0	104.0	2.28	111.9	51.3					Kauffman et
	Santa Barbara	Rondonia	1992	290.2	142.1	0	81.4	3.1	57.6	40.5					Kauffman et
	Jamari	Rondonia	1992	361.2	178.9	0	77.1	1.5	100.3	56.1					Kauffman et
	Manaus	Amazonas	1992	424.4	203.5	0			51.1	25.1					Carvalho Jr 1995
	Tomé-Açu	Para	1993	214.2	96.2	0			21.1	21.9					Araujo, 19
	Nova Vida	Rondonia	1994	306.5	142.3	0	89.0	4.1	49.2	34.6	37.5	4.1	2.9	7.7	Graça et al updated fro 1997
	Mean			321.9	157.0	0	89.1	2.6	60.9	38.8[b]	40.5[b,c]	3.2[b,c]	2.2[b,c]	5.5[b,c]	
Original forest remains (second burning)	Apaiu	Roraima	1991	101.2	48.4	0.4	33.1	1.0	14.7	30.1	31.6	0.6	1.3	6.6	Fearnside e nd-b
	Apaiu	Rorai	1993	96.3	46.1	1.9	40.1	2.3	6.2	13.2	14.1	0.3	0.7	35.0	Barbosa and

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		ma													Fearnside,
	Mean			98.7	47.2	1.2	36.6	1.6	10.4	21.6[b]	22.9[b]	0.5[b]	1.0[b]	15.1[b]	
Secondary forest (not including remains of original forest)	Altamira	Para	1991	26.1	11.3	0.003	8.2	0.1	2.9	25.9	27.0	0.1	1.1	4.1	Guimarães, 50
	Apaiu	Roraima	1993	41.5	17.8	0	5.3	0.2	11.9	66.5	67.7	0.2	1.2	1.7	Fearnside e nd-b
	Apaiu	Roraima	1993	6.2	2.8	0	0.9	0.01	1.9	69.1	69.9	0.02	0.8	1.1	Barbosa and Fearnside,
	Mean			24.6	10.7	0.0	4.8	0.1	5.6	53.8[b]	54.8[b]	0.1[b]	1.0[b]	2.3[b]	
Pasture grass	Apaiu	Roraima	1993	8.0	3.4	0.0	0.2	0.04	3.2	93.4	94.6	0.04	1.1	1.2	Barbosa and Fearnside,

[a] Post-burn "biomass" includes charcoal clinging to biomass pieces; "charcoal" is charcoal on ground + ash [reported together as "ash"].

[b] Means calculated from mean values of pre- and post-burn carbon.

[c] Charcoal mean only for Fearnside et al. (1993, 1999, nd-a,b) and Graça et al. (1999) studies.

TABLE XII
Biomass carbon transformed by burning in tropical deforestation and in clearin
and cerrado[a]

Type of biomass	Biomass carbon exposed to burning[b] (10^9 t C)	Burning efficiency (% of exposed biomass C)	Biomass carbon burned (10^9 t C)
Original forest or long-fallow secondary forest cleared permanently (first burning)	1.497	38.8	0.581
Remains of original forest or long-fallow secondary forest cleared permanently (subsequent burnings)[c]	1.052	21.6	0.228
Clearing of cerrado and "other ecosystems" in Brazil[d]	0.019	75.0	0.014
Secondary forest in short- and long-fallow shifting cultivation allowed to recover[e]	0.555	53.8	0.299
Short-fallow secondary forest permanently cleared	0.012	53.8	0.006
Total	3.135	36.0	1.127

[a] Annual amounts at 1981-1990 deforestation rates (Table I), considering adjusted FAO biomass es
for studies of burning and charcoal formation (Table XI).

[b] For remains of original forest exposed to subsequent burns, the pattern in Brazilian pastures i
period of 10 years, with burns assumed to occur in years 3, 6 and 9. Decay as in Fearnside (199
18.4% $year^{-1}$ for years 5-7; 8.5% $year^{-1}$ for year 8 onwards.

[c] Biomass exposed is sum of that exposed to three reburns (0.88, 0.39 and 0.19 X 10^9 t C); burnin
are for each reburn.

[d] See Table VII, note i. Note that this refers only to clearing, not to recurrent burning, of c
that assumed by Seiler and Crutzen (1980); charcoal formation assumed same as original (tropica

[e] Not including remains of original forest. Biomass loading from Table X, with carbon content o

TABLE XIII

Emissions of greenhouse gases from tropical forest conversion, shifting cultivation and secondary vegetation: Low trace gas scenario

Oxidation process	Emission factors (t gas emitted per t carbon oxidized by the process)				
	CO_2	CH_4	CO	N_2O	NO_x
Flaming combustion	3.1[a]	0.0100[a]	0.24[a]	0.0006[b]	0.0079[a]
Smoldering combustion	2.8[a]	0.0140[a]	0.44[a]	0.0006[b]	0.0079[a]
Decay[c]	3.8[d]	0.0001[e]	0	0	0

Biomass type	Oxidation mode	Carbon transformed (10^9 t C)	Emissions of gases (10^9 t of gas)					
			CO_2	CH_4	CO	N_2O	NO_x	Total
Original (nonfallow) forest and long fallow secondary forest permanently cleared	Initial burn[f]	0.581	1.80	0.006	0.139	0.00036	0.0046	
	Subsequent burns[f]	0.230	0.64	0.003	0.100	0.00014	0.0018	
	Aboveground decay	0.646	2.48	0.00007	0	0	0	
	Belowground decay	0.465	1.71	0	0	0	0	
	Soil C in top 1 m	0.195	0.71					
Short- and long-fallow secondary forest cut for temporary cropping and short fallow permanently cleared[g]	Initial burn[f]	0.305	0.95	0.00305	0.073	0.00019	0.0024	
	Subsequent burns[f]	0	0	0	0	0	0	
	Aboveground decay	0.262	1.01	0.000028	0	0	0	
	Belowground decay	0.238	0.87	0	0	0	0	
Cerrado and "other ecosystems" in Brazil	Burning	0.014	0.04	0	0	0	0	
	Decay	0.050	0.18	0	0	0	0	
	Soil C in top 1 m	0.017	0.06	0	0	0	0	
Category changes other than deforestation and permanent clearing of short fallow	Decay	0.413	1.51					

Burning subtotal	1.13	3.43	0.012	0.313	0.00069	0.0088	
Decay subtotal	2.07	7.77	0.0001	0	0	0	
Soils subtotal	0.21	0.78	0	0	0	0	
Total gross emission	3.41	11.97	0.012	0.313	0.00069	0.0088	
Uptake[h]	-0.99	-3.61					
Total net emission	2.43	8.35	0.012	0.313	0.00069	0.0088	
Net emission as carbon (10^9 t C)		2.28	0.009	0.134			2.43
Global warming potential[i]		1	21	0	310	0	
Burning gross emission as CO_2-equivalent carbon (10^9 t C)		0.93	0.069	0	0.058	0	1.06
Decay gross emission as CO_2-equivalent carbon (10^9 t C)		2.12	0.00056	0	0	0	2.12
Total gross emission from biomass as CO_2-equivalent carbon (10^9 t C)		3.05	0.070	0	0.058	0	3.18
Total gross emission as CO_2-equivalent carbon (10^9 t C)		3.26	0.070	0	0.058	0	3.39
Total net emission as CO_2-equivalent carbon (10^9 t C)		2.28	0.070	0	0.058	0	2.41

[a] Kaufman et al. (1990: from Ward, 1986); assumes 48% C in experimental fuel, see Fearnside (1997a); assumes 50% C in original forest biomass (Fearnside et al., 1993).

[b] 0.0002 t gas per t CO_2 emitted from burn: Cofer et al. (1988) cited by Kaufman et al. (1990).

[c] Assumed all C not released as methane is CO_2.

[d] Aboveground decay 2.97% via termites (Martius et al., 1996); belowground decay assumed not termite-mediated; termite-mediated decay emits 0.022 t CH_4 carbon per t C released through termites (Martius et al., 1993, 1996); other decay emits 100% CO_2; belowground biomass of original forest is 16% of total biomass (live + dead) (Fearnside, 1997a).

[e] Martius et al. (1993, 1996).

[f] Initial burn assumed to be 100% flaming combustion and subsequent burns 100% smoldering combustion.

[g] Shifting cultivation only for secondary succession burning and decay not counted in FAO estimates of changes in total forest cover area.

[h] Uptake from shifting cultivation fallows = 2.89 X 10^9 t CO_2 gas; uptake from replacement landscape formation in permanently deforested areas = -0.65 X 10^9 t CO_2 gas; uptake from replacement landscape (assumed to be "other land uses") in short-fallow areas cleared permanently = -0.081 $\times$ 10^9 t CO_2 gas.

[i] IPCC Second Assessment Report 100-yr integration (Schimel et al., 1996, p. 121).

TABLE XIV
Emissions of greenhouse gases from tropical forest conversion, shifting cultivation and secondary vegetation: High trace gas scenario

Oxidation process			Emission factors (t gas emitted per t carbon oxidized by the process)					
			CO_2	CH_4	CO	N_2O	NO_x	
Flaming combustion			3.1[a]	0.0120[a]	0.3[b]	0.0052[c]	0.0079[a]	
Smoldering combustion			2.8[a]	0.0140[a]	0.44[a]	0.0052[c]	0.0079[a]	
Decay[d]			3.8[e]	0.00011[f]	0	0	0	
Biomass type	Oxidation mode	Carbon transformed (10^9 t C)	Emissions of gases (10^9 t of gas)					
			CO_2	CH_4	CO	N_2O	NO_x	Total
Original (nonfallow) forest and long-fallow secondary forest permanently cleared	Initial burn[g]	0.581	1.80	0.007	0.174	0.0030	0.0046	
	Subsequent burns[g]	0.228	0.64	0.003	0.100	0.0012	0.0018	
	Aboveground decay	0.646	2.48	0.00007	0	0	0	
	Belowground decay	0.465	1.71	0	0	0	0	
	Soil C in top 1 m	0.195	0.71					
Short- and long-fallow secondary forest cut for temporary cropping and short fallow permanently cleared[h]	Initial burn[g]	0.305	0.95	0.00366	0.092	0.0016	0.00241	
	Subsequent burns[g]	0	0	0	0	0	0	
	Aboveground decay	0.262	1.01	0.000028	0	0	0	
	Belowground decay	0.238	0.87	0	0	0	0	
Cerrado and "other ecosystems" in Brazil	Burning	0.014	0.04	0	0	0	0	
	Decay	0.050	0.18	0	0	0	0	
	Soil C in top 1 m	0.017	0.06	0	0	0	0	
Category changes other than deforestation and permanent clearing of short fallow	Decay	0.413	1.51					
Burning subtotal		1.13	3.43	0.014	0.366	0.0058	0.0088	
Decay subtotal		2.07	7.77	0.0001	0	0	0	

Soils subtotal	0.21	0.78					
Total gross emission	3.41	11.97	0.014	0.366	0.0058	0.0088	
Uptake[i]	-0.99	-3.61					
Total net emission	2.43	8.35	0.014	0.366	0.0058	0.0088	
Net emission as carbon (10^9 t C)		2.28	0.010	0.157			2.45
Global warming potential[j]		1	21	0	310	0	
Burning gross emission as CO_2-equivalent carbon (10^9 t C)		0.93	0.079	0	0.489	0	1.50
Decay gross emission as CO_2-equivalent carbon (10^9 t C)		2.12	0.00056	0	0	0	2.12
Total gross emission from biomass as CO_2-equivalent carbon (10^9 t C)		3.05	0.080	0	0.489	0	3.62
Total gross emission as CO_2-equivalent carbon (10^9 t C)		3.26	0.080	0	0.489	0	3.83
Total net emission as CO_2-equivalent carbon (10^9 t C)		2.28	0.080	0	0.489	0	2.85

[a] Kaufman et al. (1990, from Ward, 1986); assumes 48% C in experimental fuel, see Fearnside (1997a); assumes 50% C in original forest biomass (Fearnside et al., 1993).

[b] Kaufman et al. (1990), from Crutzen et al. (1985).

[c] Calculated by Keller et al. (1991, p. 146) from Andreae et al. (1988).

[d] Aboveground decay 2.97% via termites (Martius et al., 1996); belowground decay assumed not termite-mediated; termite-mediated decay emits 0.022 t CH_4 carbon per t C released through termites (Martius et al., 1993, 1996); other decay emits 100% CO_2; belowground biomass of original forest is 16% of total biomass (live + dead) (Fearnside, nd).

[e] Assumed all C not released as methane is CO_2.

[f] Martius et al. (1993, 1996).

[g] Initial burn assumed to be 100% flaming combustion and subsequent burns 100% smoldering combustion.

[h] Shifting cultivation only for secondary succession burning and decay not counted in FAO estimates of changes in total forest cover area.

[i] Uptake from shifting cultivation fallows = -2.89×10^9 t CO_2 gas; uptake from replacement landscape formation in permanently deforested areas = -0.65×10^9 t CO_2 gas. Uptake from replacement landscape (assumed to be "other land cover") in short-fallow areas permanently cleared = -0.081×10^9 t CO_2 gas.

[j] IPCC Second Assessment Report 100-yr integration (Schimel et al., 1996, p. 121).

TABLE XV
Annual carbon accounting for tropical land-use change by process

Process	Area affected annually (10^6 ha)	Biomass C loading (t C ha^{-1})	Biomass C stock (10^9 t C)	Replacement landscape C loading (t C ha^{-1})	Replacement landscape C stock (10^9 t C)	Charcoal formed (10^9 t C)	Net emissions (10^9 t C)
Clearing natural vegetation and long fallow cleared permanently	15.9[a]	127.8	2.027	11.1[b]	-0.176	-0.0432	1.808[c]
Short fallow cleared permanently	0.8[d]	10.9	0.008	4.1[e]	-0.003	-0.0001	0.005[f,g]
Long fallow allowed to recover	4.2[d]	28.9[g]	0.122	28.9[h]	-0.122	-0.0017	-0.002[f,g]
Short fallow allowed to recover	24.9[d]	10.9[g]	0.272	10.9[h]	-0.272	-0.0039	-0.004[f,g]
Category changes other than deforestation and permanent clearing of short fallow	2.6[i]						0.413[i]
Soils emissions	15.9[a]						0.212[c]
Total net emissions							2.432

[a] Table I.

[b] Table IV; carbon content = 0.45.

[c] Table VII.

[d] Table X.

[e] Replacement landscape for short fallow cleared permanently assumed to be "other land cover" (see Table IX).

[f] Table XII.

[g] Biomass C loading refers to average over cycle, not biomass at time of clearing (see Table X); root/shoot ratio = 0.42, carbon content = 0.45.

[h] Full recovery assumed.

[i] Table IX.

TABLE XVI
Estimates of carbon uptake by Amazonian forests

Location	Method	Flux (t C ha^{-1} $year^{-1}$)		Extrapolated flux (10^{9} t C $year^{-1}$)		Source
		Mean	Range	Brazilian Legal Amazon forests[a]	All Amazon Basin forests[b]	
40 sites	Tree growth in permanent plots	-0.62	±0.37	-0.22	-0.38[c]	Phillips et al., 1998.
Jaru, Rondonia	Eddy correlation	-1.0	±0.2	-0.37	-0.63[d]	Grace et al., 1995.
Manaus, Amazonas (ZF-2 tower)	Eddy correlation	-5.9		-2.12	-3.66	Malhi et al., 1998.
Manaus, Amazonas (BIONTE)	Tree growth in permanent plots	-1.2		-0.43	-0.74	Higuchi et al., 1997, p. 99.
Manaus, Amazonas (BDFFP)	Tree growth in permanent plots	0		0.00	0.00	36 one-ha control plots •100 m f (Laurance et al., 1997).

[a] Area of forest remaining in 1990 based on Brazil, INPE (1996): 358.5 X 10^{6} ha.

[b] Area of forest in Brazilian Amazonia (note a) plus areas classified by FAO (1993, Table 7c) as tropical rainforest, moist deciduous forest and l Bolivia, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname and Venezuela: 620.5 × 10^{6} ha.

[c] Phillips et al. (1998, pp. 779-780) extrapolated a value of -0.44 ±0.26 × 10^{9} t C $year^{-1}$ using an area of 711.6 × 10^{6} ha (which included Braziliar "moist deciduous forest" by FAO (1993, p. 27)).

[d] Grace et al. (1995, p. 780) extrapolated a value of -0.56 × 10^{9} t C $year^{-1}$ using an area of 500 × 10^{6} ha for "the rain forests of the Amazon Basir