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# CONTRIBUTION TO THE GREENHOUSE EFFECT FROM DEFORESTATION IN BRAZILIAN AMAZONIA

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subject to government decisions. Separate discussions have been published treating deforestation's causes in Brazil (Fearnside, 1987a), its meager benefits (Fearnside, 1985a, 1986a), heavy environmental costs (Fearnside, 1985b, 1988), and irrationality from the perspective of the long-term interests of the country (Fearnside, 1989a,b). Measures that would help slow forest loss in Brazilian Amazonia have been reviewed both from the perspective of what the Brazilian government could do (Fearnside, 1989c) and that of possible contributions from other countries (Fearnside, 1989d). Potential impact on other countries makes Amazonian deforestation a focus of worldwide concern (Fearnside, 1989g).

The present and potential contributions to the greenhouse effect from deforestation in the Brazilian Amazon are uncertain because of the small amount and low reliability of data on several key components in the calculation. Brazilian Amazonia's great size and heterogeneity, combined with the relative paucity of data, make these uncertainties a weak point in global carbon budget calculations.

The present contribution of deforestation is a function of the annual rate at which forests are being cleared, biomass of the forests, partioning of biomass in above and below ground compartments, carbon content of the vegetation, fraction of aboveground carbon transferred to long-term pools such as charcoal, completeness of burning, reburning practices (including transformations to and from charcoal pools), rate of decomposition of unburned biomass, carbon stocks in replacement vegetation, and carbon stocks in soil under original and replacement vegetations. The ratio of gases released by deforestation affects contribution to the greenhouse effect. Calculation of potential release also requires knowing the total area for each vegetation type present. All of these quantities are uncertain. The uncertainty of the overall result depends both on the uncertainty of each factor and on the sensitivity of the result to changes in that factor. Many uncertainties have multiplicative effects, rapidly degrading the reliability of the calculated releases (Robinson, 1989). Despite these limitations, it is essential that the best estimate possible be made from the available data. Where measurements are missing for needed quantities, such as the biomass of certain vegetation types, then guesses or assumptions based on similar vegetation elsewhere must be used. Use of such low-reliability values is preferable to extrapolating to the region from the few existing high-reliability biomass measurements: it is better to be approximately right than to be precisely wrong. Despite disagreements and conflicting data on such vital factors as forest biomass and deforestation rates, the conclusion remains inescapable that Amazonian deforestation makes a significant contribution to the greenhouse effect. More fundamental than disagreements about the magnitude of deforestation and biomass is lack of consensus over how the results should be interpreted in terms of policy changes.

ABSTRACT

Examination of the often contradictory estimates of the rate and extent of deforestation in Brazilian Amazonia leads to a "best estimate" of the cumulative area of forest cleared through 1988 as 345 X $10^3$ km$^2$ (including old clearings), or 8.2% of the 4 X $10^6$ km$^2$ forested portion of Brazil's 5 X $10^6$ km$^2$ Legal Amazon region. Recent (post-1960) clearing of primary and old secondary forest totaled 268 X $10^3$ km$^2$ ,or 6.4%. Including clearing in the _cerrado_ increases the total of recent clearing to 460 X $10^3$ km$^2$ , or 9.6% of the area originally under forest and _cerrado_. Forest loss in 1988 was proceeding at 20 X $10^3$ km$^2$ / year; inclusion of estimated _cerrado_ loss raises the total to 39 X $10^{\cancel{8}}$ km$^2$ / year, an area almost the size of Holland.
3

Mean dry weight biomass (above and below ground) is estimated at 211 metric tons (MT)/ha for forest areas being cleared in 1988 and 247 MT/ha for the region's forest as a whole (carbon content of biomass is 50%). Pasture biomass averages 10.7 MT/ha. Soil release of carbon (C) from converting forest to pasture is 3.92 MT/ha from the top 20 cm. Were all of the forest and _cerrado_ areas converted to pasture, 51 billion metric tons (gigatons = GT) of C would be released. The annual rate of forest and _cerrado_ loss in 1988 was releasing 270 X $10^6$ MT of carbon on conversion to cattle pasture. Considering the quantities of carbon dioxide and methane released -- and the relatively greater impact of methane carbon on the greenhouse effect -- the release of carbon in these two forms at 1988 clearing rates totals from 262 to 282 million metric tons, depending on assumptions regarding methane release from burning and from termites. This is almost three times the annual carbon release from Brazil's use of fossil fuels, but brings little benefit to the country.

## I.) INTRODUCTION

The greenhouse effect is the sum of heat-absorbing actions of various gases emitted from a variety of human activities and natural processes in different parts of the world. Although carbon dioxide emissions from industrialized countries represent the largest single factor, other sources of greenhouse gases, such as tropical deforestation, also make significant contributions. Policies designed to control global warming must be based on an adequate understanding of the nature and magnitude of the gas sources, the cost and effectiveness of possible policy changes, and the benefits that are being derived from activities that now release greenhouse gases. The Brazilian Amazon, with the largest remaining area of tropical forest, is of central importance not only because deforestation in this region contributes a substantial amount of carbon to the atmosphere, but also because controlling deforestation is amply justified from the perspective of Brazil's own interests, independent of the question of global warming. Slowing forest loss is possible because the process of deforestation in Brazil is largely driven by factors that are

## II.) DEFORESTATION RATES

### A.) AVAILABLE ESTIMATES

### 1.) Types of Data Sources

Controversy surrounds the existing estimates of the extent and rate of deforestation in Brazilian Amazonia. Other estimates have produced values substantially higher or lower than the ones derived in the present paper, which estimates that through 1988 8.2% of the originally forested portion of the Brazilian Amazon had been cleared (including old clearings), with new clearing in the forest (virgin + old secondary forest) area expanding at 20 X $10^3$ km$^2$/year.

Much of the literature on the contribution of tropical deforestation to global warming has been based on the deforestation estimates of the Food and Agriculture Organization of the United Nations (FAO) for 1980 (Lanly, 1982). This survey is both out of date and unlikely to represent the true extent of deforestation even for the period it covers. The information it reports was obtained by a questionnaire sent to the government of each country, rather than from independent monitoring methods such as remote sensing. In the case of Brazil, the task of responding was given to the Superintendency for Development of the Amazon (SUDAM), the agency responsible for subsidizing and promoting large cattle ranches in the region. Much of the information available at the time (reviewed in Fearnside, 1982) is not reflected in the report.

Data on deforestation are now available from a variety of satellites. Some of the conflicting values presented for the extent and rate deforestation are due to differences in the sensors and interpretation techniques used. The LANDSAT satellites of the US National Aeronautics and Space Agency (NASA) are the source of much valuable information on deforestation. This satellite is designed for monitoring land resources, and is well suited to measuring deforested areas. Its main limitations are the high cost of images for a large area such as Amazonia, and the difficulty of obtaining cloud-free images because of relatively infrequent coverage (once every nine days with two satellites in operation). From the time the first LANDSAT satellite was launched in 1972 until 1982 all data were collected by the Multispectral Scanner (MSS) with a resolution of 80 m (that is, with the image made up of picture elements or pixels each corresponding to an area measuring 80 m X 80 m). Since 1982 data from the Thematic Mapper (TM), with a resolution of 30 m, are also available. Data may be analyzed either by computer-aided interpretation of digital tapes, or by manual interpretation of paper images. Digital interpretation has the advantage of eliminating inconsistency among cartographers in their judgement as to what is to be counted as deforestation. Smaller clearings can also be included using digital

methods. On the other hand, manual interpretation of paper images allows greater opportunity for the application of common sense in distinguishing, for example, between cattle pastures and spectrally-similar patches of "natural" grassland: pasture is usually in rectangular blocks whereas "natural" grassland (which may owe its presence in part to burning by indigenous peoples) has irregular curved edges.

In the case of photographic interpretation, the scale of images used can greatly affect the reliability of the resulting estimates. Paper images can be obtained at scales ranging from 1:100,000 to 1:1,000,000; most deforestation estimates use either 1:250,000 or 1:500,000 scale.

The Advanced Very High Resolution Radiometer (AVHRR) sensor carried by the US National Aeronautics and Space Administration (NOAA) weather satellites, provides a means of monitoring deforestation that is cheaper but coarser than LANDSAT. Images are obtained daily, making cloud-free coverage much more likely than for LANDSAT. Data can be obtained at a resolution of 1.1 km by special request; if no special request is made, data are recorded at 3.4 km resolution. Deforested areas can be measured using a normalized difference relationship between the first two of the five spectral channels recorded by the sensor (0.55-0.68 um and 0.73-1.1 µm) (Tucker *et al.*, 1984). Pixels containing fires can be located and counted using the third and fourth channels (3.5-3.9 um and 10.5-11.5 µm) (Setzer *et al.*, 1988). The area of the fires, which may be much smaller than the 120 ha pixel size of 1.1 km resolution AVHRR data, cannot be reliably estimated.

The French satellite SPOT, with a resolution of 10 m, produces images sufficiently detailed to detect even the smallest clearings. However, the high cost of the images make them impractical for monitoring large areas. Coverage of the Brazilian Amazon would cost approximately US$3 million. SPOT data are important for calibrating other remote sensing tools, but no data are available covering sufficiently large areas for direct use in estimating deforestation in the Brazilian Amazon.

Problems in interpreting the available data include data from different studies referring to overlapping but different geographical areas. Many studies only cover a portion of a political unit, such as a state, making it hard to use the results in conjunction with available state-level data. Interpreting study results by vegetation type, such as forest and *cerrado* (the central Brazilian scrub savannah), is often hampered by inconsistencies among the definitions of the vegetation types by different studies, and by frequent lack of explanation of the criteria used. Most data in Brazil refer to the "Legal Amazon," a 5 X $10^6$ km$^2$ administrative region to which special tax incentives and development programs apply. The Legal Amazon covers all or part of nine states; depending on the definitions of forest, approximately 70-80% of the region is forest, while the remainder is savannah such as the _cerrado_ (Figure 1). Because data have only been available for the area of clearing, but not for the original area of the vegetation under consideration, percentages have invariably been expressed using the areas of political units as denominators. This practice understates the relative extent of clearing, since humid savannahs are included in the denominators but not in the numerators. Many calculations also include water surfaces in the denominators. The distortion from using the areas of political units is unfortunate, but at least has allowed more-or-less consistent values to be compared between years. Recently, however, a much larger bias of this type has been introduced by a study of 1988 images that excluded the _cerrado_ from the numerator while continuing to divide by the area of political units.

An examination of some of the problems affecting different satellites and interpretation techniques will make clear why widely different conclusions are reached. Despite the difficulties, it is essential that the most reliable information be identified for each location.

## 2.) AVHRR Burning Estimates

One study that has received widespread public attention estimated areas burning using the thermal infra-red bands of the AVHRR sensor on the NOAA-9 weather satellite. The study, conducted at Brazil's Institute for Space Research (INPE), concluded that 204,000 km$^2$ burned in 1987 in the Brazilian Legal Amazon, of which 80,000 km$^2$ represented deforestation in the region's forested portion (Setzer _et al._, 1988). Most of the difference between 204,000 km$^2$ (20 million ha) and 80,000 km$^2$ (8 million ha) represents burning of the _cerrado_ and of cattle pasture or other land uses. The value for the total area burned is too high, in part because 427,331 km$^2$ in the states of Goiás and Maranhão outside the Legal Amazon were included.

The 80,000 km$^2$ 1987 value for clearing in the forest area is too high for two reasons. One is lack of an objective method for estimating the share of burning that represents deforestation. The 40% correction factor used to calculate the deforestation value was derived by Pereira (1987: 142). By comparing an AVHRR thermal infra-red estimate of area burning with a reference value for deforestation in the same year, Pereira estimated that 67,000 km$^2$ was burning in the portion of the Legal Amazon covered by the 1985 AVHRR image he used. The reference value (27,000 km$^2$) for deforestation in forest areas of the Legal Amazon in that year was taken from a newspaper report of an interview given by Carlos Marx Ribeiro Carneiro (Marcos da Costa Pereira, personal communication, 1987). It should be noted that the statement of Carlos Marx Ribeiro Carneiro, who had coordinated IBDF's LANDSAT study of 1980 deforestation, may have been referring to the entire Legal Amazon rather than forest only since the estimate he had coordinated

earlier used this larger administrative unit (Brazil, IBDF, 1983a).

The second reason for overestimation of burned areas is saturation of the AVHRR sensor when even a relatively small fire is present within one of the 120 ha picture elements or pixels. Theoretical calculations indicate that a fire of only 30 m$^2$ is sufficient to make the whole of the 1,200,000 m$^2$ pixel in which it is located appear as though it were on fire (Robinson, nd). The constant correction factor of 0.7 used to adjust for partially burning pixels is insufficient. The correction factor was derived by Pereira (1987: 142) by comparison of 1985 AVHRR and LANDSAT-TM results for an area in northern Mato Grosso. However, the sharp dependence of sensor saturation on fire temperature makes deriving a constant correction factor difficult. The relationship is nonlinear: a tiny increase in fire temperature results in a tremendous increase in the percentage of overestimation from partially burning pixels. Fire temperature varies greatly depending on weather and fuel load conditions.

Even if it were possible to obtain an accurate measurement of the area of the flame front, translating this into area burned would be difficult. The NOAA satellites pass over Amazonia daily at about 14:00 h, and the measurements capture only what is burning at the instant the image is taken. Since fires start at one side of a felled area and move across it over the course of about half a day, the area burned is larger (by a highly variable amount) than that which is burning at any given instant. Estimating the area of fires is also hampered to a variable degree by thick clouds of smoke that blanket the region at the height of the burning season.

Overestimation due to saturation of the sensor is indicated by a discrepancy for Rondônia between the thermal infra-red measurement of burning and another AVHRR measurement in the same state and year using reflected light from deforested areas. The area registered as burning in Rondônia (18.7% of the state: Setzer _et al._, 1988: 28) -- equivalent to approximately 40% deforestation since each hectare is burned once every 2-3 years -- is much higher than the cumulative deforested area through the same year (15.1%) measured by Jean-Paul Malingreau (personal communication, 1988; see Fearnside, 1989e). Some of this discrepancy may be explained by fires in neighboring portions of Bolivia having been inadvertently included in the Rondônia estimate (A.W. Setzer, personal communication, 1989), but insufficient correction for saturated pixels is the likely cause of much of the overestimation by roughly a factor of two. Possible overestimation in the AVHRR deforestation estimate would only increase further the discrepancy with the burning results from the AVHRR thermal infra-red band: as will be explained later, a corrected AVHRR clearing estimate for 1987 indicates only 32,282 km$^2$ (13.3% of the state) deforested by that year. A LANDSAT study for the same year reports 22,913 km$^2$ cleared (Brazil, IBDF, 1989).

The INPE researchers have made an AVHRR thermal infra-red estimate of burning in 1988 indicating 121,000 km$^2$ total in the Legal Amazon, 48,000 km$^2$ (40%) of which is attributed to new deforestation in the forest area (Setzer *et al.*, in preparation). The 1988 estimate does not include areas outside the Brazilian Legal Amazon, but uses the same subjective correction factors as the 1987 estimate to adjust for burning that is not new forest clearing (0.4) and for partially burning pixels (0.7). The method is therefore likely to produce unreliable area values for the same reasons that affected the 1987 burning estimate. This limitation does not affect other uses of the same images, as for estimating the number of fires and for pinpointing the location of burning (including identifying violators of Brazil's environmental laws).

### 2.) The World Bank Estimate

The International Bank for Reconstruction and Development (World Bank) published a report estimating that 598,972 km$^2$ (11.7%) of the Legal Amazon had been cleared by 1988 (Mahar, 1989; see Table 1). The estimate was derived from data presented in Fearnside (1986c), where LANDSAT surveys of clearing through 1980 are summarized (Brazil, IBDF, 1983a; Tardin *et al.*, 1980). Exponential projections within each state were made by the World Bank, with the apparent exception of the value for the state of Par . Data from more recent satellite measurements have shown that deforestation has not proceeded so quickly as it would have had the trends to 1980 continued unaltered. Over half the difference between the World Bank estimate and the linear projection estimate from the most recent data in each state is accounted for by the state of Amazonas (Fearnside, 1989e). Amazonas, by far the largest state in Amazonia, weighs heavily in the regional total. The 6.8% indicated as deforested by 1988 (Mahar, 1989) is much higher than what is apparent on INPE's mosaic of 1986 images (Brazil, INPE, 1988). The 0.8% measured by INPE (Brazil, INPE, 1989a,b) appears to be the most reasonable value for the state of Amazonas.

### 3.) The INPE/Our Nature Program Estimate

On 6 April 1989, the day of President Jos' Sarney's announcement of the *Nossa Natureza* ("Our Nature") package of environmental programs, Brazil's Institute for Space Research (INPE) released a new estimate of deforestation through 1988 (Brazil, INPE, 1989a). The study concluded that only 5.12% of Brazil's Legal Amazon had been deforested -- substantially lower than the 8.0% indicated by linear projection from the most recent satellite data available in each state (Fearnside, 1989e). The INPE study used LANDSAT-TM images at a scale of 1:1,000,000 to locate the most heavily deforested areas, and used 101 images at 1:250,000 to measure deforestation in these locations (numbers from Roberto Pereira da Cunha, personal communication, 20 April 1989). The 133 images at 1:1,000,000 not analyzed at 1:250,000 had no deforestation apparent and were considered to be completely intact -- measurements were not made on 1:1,000,000 images (R.P. da Cunha, personal communication, 20 April 1989). Most of the images are from 1988 (R.P. da Cunha, personal communication, 20 April 1989), but a list of images with their dates is not included. Previous studies have invariably been forced to use a substantial (but highly variable) number of images from years prior to the nominal year of the estimate because of Amazonia's notorious cloud cover.

A second edition of the INPE report on the study was released on 2 May 1989 (Brazil, INPE, 1989b). The revised edition contains important differences for interpreting the results. The 1988 measurements were originally presented as representing alteration of the "vegetation cover" (Brazil, INPE, 1989a: 37), which was amended to "forest cover" in the second edition (Brazil, INPE, 1989b: 28). Because a significant part of the Legal Amazon is *cerrado* or other nonforest vegetation, the restriction of the measured alteration to forested area makes the 5.12% of the Legal Amazon deforestation figure meaningless, since the numerator and denominator refer to different areas. It also makes plotting the absolute deforestation figures misleading when presented with data from previous LANDSAT studies, all of which represent alteration of both forest and *cerrado* rather than only forest. Obtaining a valid time series for the forested portion of the Legal Amazon should be an important priority, but this will require re-analysis of the images used in previous studies.

The revelation that the INPE/Our Nature Program values for alteration of "vegetation cover" were really referring to "forest cover" makes it indispensible to have information on the area of forest and *cerrado* originally present in each state. Otherwise the deforested area values cannot be interpreted in terms of percentages. Valid comparisons are also not possible with the data from previous studies for establishing trends (although gross inconsistencies, such as decreasing deforested area, can be spotted). Unfortunately, the original areas of forest and *cerrado* are not included in the INPE reports. The distinction between forest and *cerrado* is not so simple as it might seem: no maps exist (at scales more detailed than a gross sketch) that classify the region into "forest" or "*cerrado*." Rather, the continuous gradations between vegetation types is broken into many finer categories -- and assignment of intermediate categories to the "forest" or "*cerrado*" groups is somewhat arbitrary. The inconsistencies in such classification among past studies have been one of the impediments to obtaining usable estimates of clearing in the forest area, rather than for the whole Legal Amazon.

The INPE/Our Nature Program estimate delineated forest from savannah by tracing with an erasable crayon onto the original 1:250,000 scale LANDSAT-TM images, using 1:1,000,000 scale vegetation maps from the side-looking airborne radar (SLAR) surveys done by the RADAM project (Brazil, Projeto RADAMBRASIL, 1973-1983). The line was drawn freehand, using as a reference the latitude and longitude coordinates printed on the images. When the LANDSAT images were subsequently needed for display in a public exhibition, the line was erased, thus making and exact recuperation of the criteria used impossible (Carlos Alfonso Nobre, personal communication, 29 August 1989). The INPE report contains a small map (scale approximately 1:5,000,000) presenting what is described as the limit used between forest and savannah (Brazil, INPE, 1989b: 5). The map was actually drawn from information in maps made by the Brazilian Institute for Geography and Statistics (IBGE) rather than the RADAM maps used in the study, but the team leader states that it approximately represents the forest and savannah areas that were used. In the absence of another alternative then, the map published in the report must be taken as the baseline for the original areas of forest and savannah (Figure 1). Some divergences from reality are apparent, such as the shape and location of the Humaitá savannahs in the southern part of the state of Amazonas. The forest and savannah areas represented on the map were measured gravimetrically to a precision of 645 km$^2$. The uncertainty associated with the map itself is not known but probably large. Table 2 presents the areas obtained for forest and savannah in each state, standardized for the area of the state that was used in the source for the deforestation estimates presented in the same table. Relative to other classifications, the criterion used in the INPE/Our Nature Program study appears to be broad in defining forest and restrictive in defining savannah. Of the Legal Amazon, 18% is classified as savannah (including both cerrado and humid savannah) and 82% as forest according to the INPE map (Figure 1). However, some doubt is cast on this by statements from INPE personnel to the effect that the criterion minimized the area classified as forest by assigning to the savannah category all vegetation not specifically containing the word "forest" in its RADAM mapping unit definition (i.e. the "transition zone"), and by assigning to savannah the long intrusions of riparian forest along rivers (Carlos Alfonso Nobre, personal communication, 19 August 1989).

The percentage values given in the INPE/Our Nature Program report are misleading because of the treatment of savannah. However, this is not the only problem in interpreting the results. Problems and doubts differ with each of the Legal Amazon's nine states. It is important to evaluate these, in order to make use of as much information from the study as possible.

## B.) DATA FROM AMAZONIAN STATES

### 1.) Acre

The INPE study claims that only km$^2$ (or 3.6%) of the state of Acre had been deforested by 1988. This is inconsistent with the 8,133 km$^2$ (5.3%) that a study by the Brazilian Institute of Forestry Development (IBDF) showed as deforested by 1987: it implies that 2,623 km$^2$ of forest had reappeared. The IBDF study of 1987 images also used LANDSAT-TM, so differences in characteristics of the sensor probably do not explain this discrepancy. One possible explanation suggested by the head of the INPE team might be a difference in interpreting the approximately 30,000 km$^2$ bamboo area in Acre (R.P. da Cunha, personal communication, 20 April 1989). However, all of Acre was originally classified as forest in the INPE report. Another explanation offered by the INPE group is differences in the scale of images used for the different estimates (R.P. da Cunha, public statement, 29 August 1989). This interpretation is apparently based on the mistaken belief that studies prior to the INPE/Our Nature Program estimate were all done with images at a scale of 1:500,000. Actually, only the studies of 1975 and 1978 deforestation used images at this scale; later studies used the same 1:250,000 scale used in the INPE/Our Nature Program estimate. In any case, a difference of almost 60% is difficult to explain by this factor alone. In general, more detailed mapping should result in higher, rather than lower, values for deforestation because smaller clearings are missed on the less detailed maps.

Another IBDF deforestation estimate, this one for 1980, is passed over in the INPE report, although included as a stray point on the graph of increasing deforestation in the state. The curve is not drawn through the point indicating the 4,625 km$^2$ (cited as 4,627 km$^2$ on the INPE graph) that IBDF's study of 1980 LANDSAT images had shown as deforested (Brazil, IBDF, 1982a). Instead, the curve is shown as a straight line from the 1978 value, thereby hiding the unrealistic implication that only 885 km$^2$ had been cleared in Acre over the 1980-1988 period - something obviously false to anyone who had visited the area during those years of explosive deforestation.

### 2.) Amapá

Amapá has long been one of the political units with the lowest rate of increase in deforested area (e.g. Fearnside, 1982). The INPE/Our Nature Program study shows somewhat more clearing than would have occurred by continuation of the 1975-1978 trend, and represents the best data available for Amapá. Prior to the INPE report, the most recent data are from 1978 (Brazil, IBDF, 1983c). The usually heavy cloud cover in Amapá has discouraged LANDSAT measurements, while AVHRR measurements have omitted this state because areas north of the equator are not included on the AVHRR scene that covers most of Amazonia.

### 3.) Amazonas

Amazonas has very little deforestation so far. Most is concentrated either in the Manaus area or near Boca do Acre. The INPE/Our Nature Program estimate of 0.8% deforested by 1988 is the best available for this state, which has no other satellite measurement since 1978. Linear projection from 1978 would imply

0.3% deforested. In 1989, IBAMA initiated a project in collaboration with SUDAM technicians to interpret LANDSAT-TM images from Amazonas for 1987, but results are not yet available.

### 4.) Maranhão

Maranhão is the most heavily deforested state, if old (pre-1960) deforestation is considered. The INPE/Our Nature Program measurement of 60.7% (including old secondary forest) is the best available for 1988. .

### 5.) Mato Grosso

In the case of the state of Mato Grosso, INPE reports 62,216 km$^2$ of forest as cleared by 1988. The graph of deforested area is shown rising gently from a level of 59,183 km$^2$ in 1983, citing IBDF for the latter figure (NB: the implication of slow deforestation is invalid, since the INPE/Our Nature Program value refers only to forest while the previous estimates are for all vegetation types). How the value attributed to IBDF for 1983 was derived is unclear, since the 1983 LANDSAT images in Mato Grosso interpreted by that agency (Brazil, IBDF, 1985) cover only the western half of the state where the World Bank-financed POLONOROESTE Project paid for interpretation, and found only 24,281 km$^2$ deforested there. An estimate for the entire state using the IBDF estimate for the western half and a linear projection from the state-wide deforestation rate in the 1978-1980 period for the eastern portion (data from Brazil, IBDF, 1982b), calculates 89,903 km$^2$ as cleared by 1983 (Fearnside, 1989e). These figures would imply that the deforested area shrank by 27,687 km$^2$ between 1983 and 1988, but omission of *cerrado* from the INPE/Our Nature Program estimate can explain the apparent decrease. The location of fires during this period detected by AVHRR thermal infra-red images (Setzer *et al.*, 1988) shows Mato Grosso as one of the principal *foci* of deforestation in Amazonia.

If *cerrado* were cleared in the same proportion as forest, then the total cleared area in the state would be 103,400 km$^2$, or 12.9% of the 802,408 km$^2$ area used in the INPE/Our Nature Program estimate as the area of the state in the Legal Amazon. This area refers to that in effect from creation of the Legal Amazon in 1953 to dismembering the former state of Mato Grosso in 1977 into Mato Grosso do Sul and the present state of Mato Grosso. The Legal Amazon currently encompasses the entire present state of Mato Grosso (881,001 km$^2$), and this larger area has been used by all other deforestation estimates using images from 1980 onwards (beginning with Brazil, IBDF, 1983a). Adjusting the INPE/Our Nature Program results proportionately for the larger state area would bring the total clearing to 113,538 km$^2$ (12.9%) for all vegetation types. The additional area added to the Legal Amazon in Mato Grosso is virtually all *cerrado* vegetation.

The likelihood that only 59,183 km$^2$ had been deforested in Mato Grosso by 1983 (the IBAMA estimate cited by the INPE/Our Nature Program report) is low if the 1980 estimate of 52,786 km$^2$ by Tardin *et al.* (1980) is correct, since the implied average deforestation rate of 2,132 km$^2$/year in the 1980-1983 period is improbable, given that the corresponding deforestation rate for the 1978-1980 period was 11,208 km$^2$/year.

Mato Grosso is one of the most difficult states to interpret because of the complex of fingers and islands of forest that forms the border between forest and *cerrado* vegetation in this state. A study of AVHRR imagery from 1985 provides some evidence that the area of forest cleared is less than that derived from linear projections, but, like the INPE/Our Nature Program study, interpretation is made difficult by lack of reporting of criteria used to define original vegetation types and their respective areas. The study measured 56,646 km$^2$ deforested in the "phytogeographically Amazonian" portion of Mato Grosso (Malingreau and Tucker, 1988: 53). If one assumes that "phytogeographically Amazonian" refers to forest as mapped in the INPE/Our Nature Program report, then 9.9% of the forest in Mato Grosso was deforested by 1985; if clearing in *cerrado* was proportional to that in forest, then a total of 87,148 km$^2$ (9.9% of the area of the state) had been cleared by that year. This implies that cleared area had declined by 2,755 km$^2$ between 1983 and 1985 if the 1983 estimate is correct. If one assumes that the 1983 estimate is not correct, then linear projection from the 1980 and 1985 data would yield a 1988 clearing figure of 107,765 km$^2$ of the area originally under either forest or *cerrado* (the clearing would represent 12.2% of the state); 70,074 km$^2$ of this clearing is in the forested portion of the state.

Because available data for Mato Grosso are conflicting, it should be borne in mind that the value used for deforestation in this state is highly uncertain. Obtaining a time series for clearing measurements with consistently applied criteria for vegetation classification is particularly urgent for this state. The clearing values for 1988 in Mato Grosso may well change as better information becomes available.

### 6.) Pará

In Pará, the INPE report claims that only 88,741 km$^2$ of forest had been cleared by 1988. An estimate made by IBDF technicians working in SUDAM using 1986 LANDSAT-TM images had found that 114,770 km$^2$ of the state (all vegetation types) had been cleared by 1986. Adjusting the 1988 forest clearing value, assuming the same proportion of clearing in other vegetation types, would increase the total to 93,767 km$^2$ (7.5% of the state). The discrepancy between a value of 88 and 114 X 10$^3$ km$^2$ is explained by INPE as being due to "very old deforestation" having been included in the IBDF study but not in the INPE study (Brazil, INPE, 1989a: 46). However, both studies used LANDSAT-TM imagery, counting as "deforested" the areas that appeared bare in the images. In the IBDF study, black and white images of LANDSAT-TM bands 3, 4 and 5 were used at a scale of 1:250,000. In the INPE study the areas selected for examination at the 1:250,000 scale were analyzed in the same way, with the exception of the Zona Bragantina, where a false color composite of the same three bands was used (Brazil, INPE, 1989a: 11 and R.P. da Cunha, personal communication, 20 April 1989). The technique used by IBDF is not capable of distinguishing between old secondary forest and virgin forest, as is made plain by the wide discrepancy between INPE's earlier results using the same technique with LANDSAT-MSS images from 1975 and older cleared areas known to exist in Pará's Zona Bragantina -- these are larger than the area indicated by INPE (Tardin *et al.*, 1980) as cleared by 1975 in the entire Legal Amazon (see Fearnside, 1982). INPE's decision to discard the IBDF 1986 estimate as overstating deforestation is therefore questionable -- if anything, the IBDF estimate underestimates deforestation. INPE's graph for Pará (Brazil, INPE, 1989a: 46) shows an estimate of 120,563 km$^2$ for 1988 deforestation including old clearings, but uses the lower value of 88,741 km$^2$ as the "real value for 1988" (amended to "value obtained for 1988" in the second edition of the report). The lower value is used in computing the 5% deforestation overall total for the Legal Amazon. Exclusion of older deforestation from this total is inconsistent with President Sarney's presentation of the 5% value as the total cleared "since Cabral discovered Brazil."

### 7.) *Rondônia*

In Rondônia, the INPE/Our Nature Program report indicates 30,046 km$^2$ of forest was cleared by 1988. Adjusting this for proportional clearing in savannah would yield a total of 31,016 km$^2$ and adjusting for different values used for the area of the state would bring total clearing to 31,623 km$^2$ (13.0% of the state). The adjustment for savannah assumes that only 25% of savannah area indicated on the INPE map (Figure 1) is exposed to clearing: the remainder is located in two Amerindian reserves (NB: although some illegal clearing has occurred in Amerindian reserves in Rondônia, it has so far been in forested areas). The *cerrado* clearing (989 km$^2$ adjusted for state area) is conservative given the widespread conversion of this vegetation type to pasture and soybean cultivation near Vilhena in eastern Rondônia.

The INPE/Our Nature Program estimate for Rondônia is inconsistent with information derived from the AVHRR sensor on the NOAA-9 satellite. Although better correction factors may eventually resolve the discrepancy, no adequate explanation is currently available. AVHRR indicated 39,600 km$^2$ (15.1% of the state) as cleared by 1987 (J.P. Malingreau, personal communication, 1988). An AVHRR image from 1985 had indicated 27,658 km$^2$ (11.3% of the 243,044 km$^2$ state area)(1) (Malingreau and Tucker, 1988). A linear projection from the 1985 and 1987 AVHRR estimates would yield a deforested area of 41,521 km$^2$ (17.1% of the state) by 1988 (Fearnside, 1989e).

The AVHRR sensor's much coarser resolution than LANDSAT makes it less reliable. It may be, therefore, that the difference in results is explained by differences between the two sensors. INPE bolsters its claim of lower deforestation in Rondônia by citing an estimate for 1986 of 22,913 km$^2$ made by the Brazilian Institute for Environment and Renewable Natural Resources (IBAMA).(3) The head of the INPE team states that the 1986 value was supplied in a telex from Fernando Cesar Mesquita, director of IBAMA (R.P. da Cunha, personal communication, 20 April 1989). A subsequent IBAMA report indicates that the 22,913 km$^2$ deforestation value refers to 1987 rather than 1986 LANDSAT images (Brazil, IBDF, 1989), thereby increasing even further the discrepancy with previous results.

The data on deforestation in Rondônia are confusing, to say the least. Part of the discrepancy between the various existing studies may be due to over or under estimation inherent in the technique used for each study. AVHRR 1.1 km resolution data have been reported to *under*estimate deforestation by 2-18% when applied to Rondônia, but uncertainties in the adjustments made for comparing LANDSAT-TM to AVHRR images from different years led the authors of the study to conclude that a correction factor of 1.0 (*i.e.* leaving results unchanged) was appropriate (Woodwell *et al.*, 1986: 252). This group continued to find good agreement between LANDSAT and AVHRR in Rondônia (Woodwell *et al.*, 1987), but now believes that AVHRR is *over*estimating deforestation (I. Foster Brown, personal communication, 1989). Other published AVHRR estimates for Rondônia have assumed that a correction factor is unnecessary (Malingreau and Tucker, 1988; Tucker *et al.*, 1984). Comparison of 10 meter resolution data from the SPOT satellite with a simulated AVHRR image produced by degrading the SPOT data to the 1.1 km resolution of AVHRR has resulted in a value of 18% as the correction factor for overestimation by AVHRR under the conditions prevailing in Rondônia (David Skole, INPA seminar, 1989). Overestimation by AVHRR would be greater in Rondônia than in areas such as Mato Grosso where large ranches dominate deforestation. The long narrow strips of clearing that characterize the "fish bone" pattern of small-farmer settlements in Rondônia would introduce bias because of a predominance of sub-pixel width clearings that are sufficiently large to trigger the entire pixel.

LANDSAT studies such as those available for Rondônia for 1975, 1978, 1980, 1983, 1987 and 1988 images would also produce biased results, but in the opposite direction. All of these studies used manual interpretation of paper photographic products, rather than computer aided analysis of digital tapes. Small clearings are underestimated using manual methods, with greater error at larger map scales. The studies with images from 1975 and 1978 used 1:500,000 images, while the later studies used 1:250,000 images.

Legal Amazon (i.e., in "Tocantins/Goiás"). If one uses the sum of these two forest types (100,629 km$^2$) as the forest area for Tocantins/Goiás, then the percentage represented by the 20,279 km$^2$ that the INPE study found deforested falls to 20.2%. Proportional clearing in the cerrado, assumed to occupy the remaining 169,282 km$^2$ of Tocantins/Goiás, would be 34,114 km$^2$. These lower numbers are used in the present estimate (Table 2).

That doubt could exist as to whether a state is 20% or 63% deforested indicates the low reliability of the estimates. Fortunately, Tocantins/Goiás weighs little in the total for Amazonia because of its small geographical area and because its vegetation has a low average biomass. For all states, the cerrado clearing values are less certain than the forest clearing values.

### C.) A BEST ESTIMATE FOR DEFORESTATION

The areas and percentages deforested by 1988 indicated by various studies are presented in Table 1. If one uses clearing data from the INPE LANDSAT study with corrections for area of states and for clearing in old secondary forest (assumed to be proportional to that registered for primary forest), then recently cleared area in the forested portion of the Legal Amazon is 267,969 km$^2$ or 6.4% of the forest (Table 2). In the case of Acre, the result of linear projection from 1987 data is used in preference to the INPE result because of unexplained discrepancy between results from the INPE study and the previous IBDF study for that state (see Table 6).

No direct measurement exists of clearing by 1988 in the savannah areas. An approximation of cerrado area cleared can be obtained by assuming that cerrado within each state is cleared at a rate proportional to the fraction of forest that is cleared (Table 2). This procedure can be expected to yield a conservative estimate for clearing in cerrado because, in general, these savannahs have been cleared more rapidly than forest areas -- simply because cerrado is located along the southern fringe of the region, where entry of population and conversion to agriculture and ranching are concentrated. Cerrado is also easier to clear than forest, and on large ranches in Mato Grosso is often cleared using two bulldozers with a chain dragged between them -- a technique that cannot be used in forest. The cerrado in Mato Grosso also suffers from the market for charcoal created by Brazil's iron and steel industry in the Central-South part of the country.

Partially compensating for heavy pressure on cerrado is the clearing behavior of farmers and ranchers with properties astride the irregular boundary between forest and cerrado. LANDSAT imagery shows that within each property, clearing takes place first in the forest (Dicks, 1982).

The assumption that clearing in forest and savannah portions of each state is equal in proportion to the areas present is far from ideal, but is better than alternative assumptions. One alternative assumption is that clearing in the cerrado portion of each state continued (since the previous available deforestation rate data) at the same rate observed for vegetation of all types in that state. In Mato Grosso, the assumption of proportionately equal clearing rates probably underestimates cerrado clearing, but in the remaining three states the opposite is likely. In Rondônia, most of the savannah is spared by being located in an Amerindian reservation. All of the savannah in Roraima and over half the savannah in Pará is humid savannah rather than dry cerrado: these humid savannah areas are often used for cattle or buffalo grazing without being cleared. The carbon release calculations assume that no carbon is released by humid savannahs, nor from the portion of Rondônia's savannahs located in Amerindian reserves. Conversion of cerrado to pasture is assumed to be taking place in all the savannah regions of Maranhão, Mato Grosso and Tocantins/Goiás, and in one-third of the savannah in Pará (corresponding to areas in the southern part of the state).

The estimates for cerrado clearing are much less reliable than the forest clearing values. Fortunately, the low biomass of cerrado vegetation means that clearing in these areas contributes very little to total carbon emissions, and the poor reliability of cerrado estimates therefore have little impact on the reliability of calculations of greenhouse gas contributions from the entire Legal Amazon.

By the "best estimate" calculation outlined above, the cleared area in the Legal Amazon totals 353 X 10$^6$ km$^2$, 268 X 10$^6$ km$^2$ (76%) of which is forest (Table 2). Of the original vegetation cover, 7.4% of the total and 6.4% of the forest had been cleared by 1988. These values do not include "old clearings" (clearings made prior to 1960, which the INPE/Our Nature Program measurements registered as 31,822 km$^2$ in Pará and 60,724 km$^2$ in Maranhão). These older secondary forests were not detected in the earlier LANDSAT-MSS studies (see Fearnside, 1982), and so cannot be used in the present study for the purpose of establishing trends by comparison with older data. The INPE study's area values for old secondary forest have been included in the biomass and carbon release calculations by considering old secondary forest as a separate vegetation type. The area that has lost its original forest cover, including the old secondary forest area, is an area the size of Sweden: 345 X 10$^6$ km$^2$, or 8.2% of the original forest area.

The above values for the Legal Amazon can be compared with the result of linear projections in all nine states from the most recent satellite data available prior to the INPE/Our Nature Program estimate. Such projections would indicate 399,765 km$^2$ cleared by 1988, or 8.0% of the region (Fearnside, 1989e). Were the clearing figures from the INPE/Our Nature Program estimate used for all nine states, with corrections made for the proportion of

No information is available to correct for biases in the manual methods used. The resolution of the sensors also varies: estimates for 1983 and earlier used the multispectral scanner (MSS) with 80 m resolution, while the more recent estimates used the thematic mapper (TM) with 30 m resolution.

If one uses only LANDSAT data, the trend in deforestation rates in Rondônia is consistent except for an improbably high jump from 1987 to 1988. LANDSAT studies have found 1,217 km$^2$ (0.5% of the state) cleared by 1975 and 4,185 km$^2$ (1.7% of the state) cleared by 1978 (Tardin *et al.*, 1980); 7,579 km$^2$ (3.1% of the state) cleared by 1980 (Brazil, IBDF, 1983a); 13,955 km$^2$ (5.7% of the state) cleared by 1983 (Brazil, IBDF, 1985); 22,913 km$^2$ (9.4% of the state) cleared by 1987 (Brazil, IBDF, 1989), and 31,623 km$^2$ (13.0% of the state) cleared by 1988 (Brazil, INPE, 1989a,b corrected for savannah clearing and state area; see Table 2). These clearing estimates imply rates of deforestation climbing from less than 243 km$^2$/year(4) in 1970-1975 to 989 km$^2$/year in 1975-1978, to 1,697 km$^2$/year in 1978-1980, to 2,125 km$^2$/year in 1980-1983, to 2,167 km$^2$/year for 1983-1987, followed by a tremendous jump to 8,437 km$^2$/year for 1987-1988.

If one uses results from AVHRR corrected by a factor of 18% to adjust for overestimation and with an additional correction for *cerrado* clearing to make the values comparable to the LANDSAT studies (all LANDSAT studies included *cerrado* with the exception of that for 1988; AVHRR studies excluded *cerrado*), the deforested area in Rondônia reached 9,973 km$^2$ (4.1% of the state) by 1982 (calculated from Woodwell *et al.*, 1984: 252), 24,195 km$^2$ (10.0% of the state) by 1985 (calculated from Malingreau and Tucker, 1988), and 32,280 km$^2$ (13.3% of the state) by 1987 (calculated from Malingreau, personal communication, 1988). A linear projection to 1988 would indicate 36,323 km$^2$ (14.9% of the state) as deforested. The implied clearing rates would indicate a drop from the LANDSAT-based rate of 1,697 km$^2$/year for 1978-1980 to 1,197 km$^2$/year for 1980-1982, followed by a jump to 4,741 km$^2$/year for 1982-1985, falling to 4,042 km$^2$/year for 1985-1987.

More information will be needed to evaluate the 9,898 km$^2$ discrepancy between the INPE estimate for Rondônia (adjusted for savannah and state area) and the uncorrected AVHRR-based estimate, or the 4,700 km$^2$ discrepancy with the corrected AVHRR-based estimate. The discrepancy with uncorrected AVHRR is 31.3%, falling to 14.9% when the corrected AVHRR value is used. Although the difference is substantial for this state, Rondônia's relatively small area (about 5% of the Legal Amazon) means that the discrepancy weighs little in the total for the Amazon region. The present study will use the more conservative INPE value (with the adjustments for savannah and for state area).

### 3.) Roraima

INPE's estimate for forest clearing by 1988 in Roraima is 2,187 km$^2$. The previous estimates for Roraima shown in the INPE report's graph of the growth of deforested area (Brazil, INPE, 1989a: 48) omit the estimate for 1981 LANDSAT images(2) made by IBDF (Brazil, IBDF, 1983b). Taking into account the 1,170 km$^2$ indicated by the IBDF estimate, it appears improbable that only 1,017 km$^2$ were cleared over the seven year period between 1981 and 1988. This was the period during which the National Institute for Colonization and Agrarian Reform (INCRA) established Apiaú, São Luis and other official colonization projects that are clearly visible on the 1986 images in INPE's mosaic of the northern region (Brazil, INPE, 1988). Nevertheless, the present study uses the INPE/Our Nature Program value for clearing by 1988 in Roraima.

### 9.) Tocantins/Goiás

Tocantins/Goiás(5) is the political unit where results are least satisfactory for estimating *cerrado* clearing rates based on the INPE measurements of forest clearing. This state has only a narrow sliver of forest along its northwestern edge. The INPE/Our Nature Program study indicates a high percentage (63.3%) of the forest has been cleared; by assuming that the same percentage applies to the *cerrado*, a large area ($171 \times 10^3$ km$^2$) is estimated to have been cleared. Continuation of the previous trend would imply only 9% cleared. The extensive deforestation apparent to any visitor to Tocantins makes the higher figure likely to be correct, but the low level of certainty should be borne in mind. Any error in INPE's mapping of original vegetation would produce a large effect on clearing percentage values for forest in this case, and thereby affect the *cerrado* cleared area estimate. As will be explained later, estimates of the original area present are unreliable, despite being the best available. Because *cerrado* is the original vegetation type for a large proportion of Tocantins/Goiás, uncertainty in drawing the *cerrado*/forest boundary has its greatest effect on the total for the Legal Amazon in the values for savannah clearing. By assuming clearing in the Tocantins/Goiás *cerrado* proportional to that indicated by the INPE study for the forest, this would contribute 80,730 km$^2$ to the *cerrado* clearing total. However, a more conservative assumption is made in the present estimate.

The assumption used in the current "best estimate" is that the INPE map does not reflect the criteria really used in the deforestation estimate for the Tocantins/Goiás area. IBGE data (reproduced in Benchimol, 1989: 56) indicate that the entire states of Tocantins and Goiás jointly contain 31,916 km$^2$ of Amazonian *terra firme* humid forest, plus 68,573 km$^2$ of "sub-humid forest of the interior". The value for *terra firme* forest area is almost exactly the same as that indicated by the INPE map (32,056 km$^2$), and can be considered identical given the wide margin of error for the forest area estimates. The sub-humid forest is also likely to be located in the portion of this two-state area that is within the

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The estimates for *cerrado* clearing are much less reliable than the forest clearing values. Fortunately, the low biomass of *cerrado* vegetation means that clearing in these areas contributes very little to total carbon emissions, and the poor reliability of *cerrado* estimates therefore have little impact on the reliability of calculations of greenhouse gas contributions from the entire Legal Amazon.

By the "best estimate" calculation outlined above, the cleared area in the Legal Amazon totals 353 X 10$^6$ km$^2$, 268 X 10$^6$ km$^2$ (76%) of which is forest (Table 2). Of the original vegetation cover, 7.4% of the total and 6.4% of the forest had been cleared by 1988. These values do not include "old clearings" (clearings made prior to 1960, which the INPE/Our Nature Program measurements registered as 31,822 km$^2$ in Pará and 60,724 km$^2$ in Maranhão). These older secondary forests were not detected in the earlier LANDSAT-MSS studies (see Fearnside, 1982), and so cannot be used in the present study for the purpose of establishing trends by comparison with older data. The INPE study's area values for old secondary forest have been included in the biomass and carbon release calculations by considering old secondary forest as a separate vegetation type. The area that has lost its original forest cover, including the old secondary forest area, is an area the size of Sweden: 345 X 10$^6$ km$^2$, or 8.2% of the original forest area.

The above values for the Legal Amazon can be compared with the result of linear projections in all nine states from the most recent satellite data available prior to the INPE/Our Nature Program estimate. Such projections would indicate 399,765 km$^2$ cleared by 1988, or 8.0% of the region (Fearnside, 1989e). Were the clearing figures from the INPE/Our Nature Program estimate used for all nine states, with corrections made for the proportion of the area in forest, the total area cleared would be 572,917 $km^2$ or 11.5% of the Legal Amazon using the areas of the political units used in the report. Like the "best estimate" calculation, the assumption of proportional cerrado clearing in each state, especially Tocantins/Goiás, leads to the substantial increase in total cleared area when the cerrado is included. More reliable would be comparison of forest areas only: if the forest to savannah proportions of the INPE/Our Nature Program hold, then the "best estimate" value of 267,969 $km^2$ (6.4% of the forest) would be compared to a value from linear projections of 399,765 $km^2$ (8.4% of the forest) and the INPE/Our Nature Program's 251,430 $km^2$ (6.0% of the forest).

The average rate of deforestation can be conservatively estimated by assuming constant rates since the last available satellite measurement of cleared area (Table 6). This procedure underestimates the current rate of deforestation, because the calculation averages deforestation over the period between the last two available satellite measurements while all evidence indicates that areas cleared have, in general, been increasing every year. An exception to this trend may be clearing in 1989, when the number of fires registered on AVHRR thermal infra-red imagery interpreted at INPE was less than in the previous two years. The amount of smoke and observable fire was noticeably less during the 1989 dry season, lending support to the conclusion of lower deforestation that year. An important reason for reduced burning is that substantially more rain than usual fell during the dry season in much of the region (for example, at the INPA research station in Ouro Preto do Oeste, Rondônia, the amount of rain registered during the first three months of the dry season was four times greater in 1989 than in 1988). Some reduction in burning may also be due to a campaign by IBAMA to fine those who burn without a newly-required burning permit. These reasons give little grounds to expect that the 1989 reduction indicates that the trend to increased clearing has changed. The deterrent effect of the fines is likely to diminish in the future since none of the money owed by the fined landowners had been collected five months after the repression campaign began.

The rate of deforestation has been climbing steadily in the decade following the inauguration of the Transamazon Highway in 1970, the event that marks the beginning of the current era of rapid development in the Brazilian Amazon. The increasing rate of clearing renders obsolete the many greenhouse effect calculations that have been based on deforestation estimates for 1980 or earlier. The rapid increase in felling dramatizes the urgency of strong and swift government policy changes to slow the process -- by removing the motives for deforestation.

## III.) RELEASE OF GREENHOUSE GASES

### A.) AVAILABLE ESTIMATES

Calculating the potential contribution of deforestation to the greenhouse effect requires comparison of carbon stocks present before and after clearing. Estimates of potential emissions have been evolving as better information becomes available. An estimate (Fearnside, 1985c) based on a seven-category classification of vegetation by Braga (1979) and biomass for dense forest based on the mean results from existing studies where direct measurements were made, concluded that conversion of the Legal Amazon to cattle pasture would release 62 billion metric tons (gigatons = GT) of carbon. The biomass for the "upland dense forest" category used was 361.5 MT/ha dry weight total biomass, including live above ground (251.7 MT/ha), below ground (86.3 MT/ha) and litter and dead above ground biomass (23.6 MT/ha). This biomass value from direct measurements is higher by a factor of two than the 155.1 MT/ha value for total biomass derived by Brown and Lugo (1984) from FAO forest volume surveys for "tropical American undisturbed productive broadleafed forests" -- a value that has been used in recent global carbon balance calculations (e.g. Detwiler and Hall, 1988).

The Brown and Lugo (1984) forest volume estimate of 155.1 MT/ha is lower than biomass values derived using the same methodology for 15 of 16 locations for which volume information is given in the FAO reports, making it unlikely that a mean value this low applies to dense forests in Brazilian Amazonia (Fearnside, 1986b). Revising the estimate, principally by incorporating FAO wood volume information into the dense forest mean and by using values for pasture biomass based on monitoring over an annual cycle at Altamira (Pará) and Ouro Preto do Oeste (Rondônia) (Fearnside, 1989f), yields an estimate of 49.7 GT as the potential release from conversion to cattle pasture (Fearnside, 1987b). The biomass calculations in the present paper yield an intermediate value of 51 GT (Tables 3 and 5).

### B.) LAND USE TRANSFORMATIONS

The cattle pastures that replace forest last only about a decade before they cease to be productive. The vegetation that succeeds cattle pasture has a higher biomass than pasture, thus reducing somewhat the net release of carbon. However, degradation of soil under pasture, combined with rainfall changes expected should the scale of deforestation greatly expand, are likely to make low-biomass dysclimaxes, including grassy formations, the dominant land cover in a deforested Amazon (Fearnside, nd).

The rate of deforestation, together with the biomass of forest being cleared, affects the current (as opposed to potential) contribution of deforestation to the greenhouse effect. The rate of clearing was calculated for each state (Table 6), but must also be apportioned between various forest types within each state. This is done by assuming that within each state, each forest type is cleared in proportion to which it occurs.

The areas of different forest types present and the biomass of each forest type are both uncertain quantities. In Table 3, the values listed have been derived from a variety of sources, and have varying degrees of uncertainty. The area figures presented in Table 3 have been rounded off after carbon release calculations were made.

The factor most heavily influencing the total biomass present is the dense forest of the state of Amazonas. This has both the largest area and the highest biomass per hectare of any forest type. It also happens to be the unit where the largest number of direct biomass measurements have been made. This area represents approximately 37% of the total potential carbon release from conversion of the Legal Amazon to cattle pasture.

## C.) THE FATE OF CARBON STOCKS

### 1.) Biomass Carbon

Char formed in burning is one way that carbon can be transferred to a long-term pool where it cannot enter the atmosphere. A burn of forest being converted to cattle pasture near Manaus resulted in 3.6% of above-ground carbon being converted to char (Fearnside et al., nd-a). This is substantially lower than the 20% assumed by Seiler and Crutzen (1980) when they identified charcoal formation as a potentially important carbon sink. Using these higher rates of charcoal formation in global carbon cycle modeling tends to result in tropical deforestation appearing to be less important for the greenhouse effect than would be the case with lower rates of transfer to long-term pools (e.g. Goudriaan and Ketner, 1984).

The burning behavior of ranchers can alter the amount of carbon passing into a long-term pool as charcoal. Carbon budget calculations generally assume that forest is only burned once, and that all unburned biomass subsequently decomposes (e.g. Bogdonoff et al., 1985). This is not the typical pattern in cattle pastures that dominate land use in deforested areas in the Brazilian Amazon. Ranchers reburn pastures at intervals of 2-4 years to combat invasion of inedible woody vegetation. Logs lying on the ground when these reburnings occur are often burned. Some char formed in earlier burns can be expected to be combusted as well. A typical scenario of three reburnings over a ten-year period would raise the percentage of above-ground C converted to charcoal from 3.6% to 4.6%, given the assumptions outlined in Figure 2 and Table 4.

The remaining carbon would be released through combustion and decay; the relative importance of each affects the gases released. A one-burn-only scenario would release 27.5% of the pre-burn above-ground carbon through combustion and 68.9% through decay, whereas the scenario with three reburnings would release 40.6% through

combustion and 54.8% through decay. Both combustion and decay release methane, 20 times more potent per ton of carbon in provoking the greenhouse effect than is carbon dioxide (Blake and Rowland, 1988). Measurements of emission ratios of $CH_4$ to $CO_2$ (expressed as percent volume) indicate values ranging from 0.5-2.3% with a geometric mean of 1.1% for samples collected from the ground near burning forest in the Brazilian Amazon (Greenberg et al., 1984) and ranging from 0.3-2.0% with a geometric mean of 0.8% when sampled from aircraft (Crutzen et al., 1985: 242). The amount of methane released is heavily dependent on the ratio of smoldering to flaming combustion, smoldering releases substantially more $CH_4$. Aircraft sampling over fires (mostly from virgin forest clearing) indicates that a substantial fraction of combustion is in smoldering form (Andreae et al., 1988). Logs consumed by reburning of cattle pastures are virtually all burned through smoldering rather than flaming combustion (personal observation).

Termites are the major agent of decay for unburned wood (Uhl and Saldarriaga, nd). No measurements exist of the fraction the biomass ingested by Amazonian termites, and termite researchers refuse to offer a guess more precise than that "most" of the above-ground post-burn biomass is ingested (Adelmar Bandeira, personal communication, 1989). The calculations in the present paper assume that 75% of the above-ground biomass and none of the below-ground biomass is ingested. A lively controversy surrounds the question of how much methane is produced by termites (Collins and Wood, 1984; Fraser et al., 1986; Rasmussen and Khalil, 1983; Zimmerman et al., 1982, 1984). Support for substantial emission potential from termites in deforested areas in the Amazon is provided by high population densities in fields in Par where forest biomass remains present (Bandeira and Torres, 1985), and high methane emissions from termite mounds near Manaus (Goreau and Mello, 1987). The billions of metric tons of wood that these insects would devour as Amazonia is deforested cannot help producing substantial contributions of methane regardless of which production rates prove to be correct.

The release of different greenhouse gases can be calculated based on available information from laboratory and field measurements. Low and high methane release scenarios are shown in Tables 8-10, using a range of available values for release from combustion and from termites.

In the low methane scenario, 1550 g $CO_2$ per kg of fuel burned is produced in mixed flaming and smoldering burns (i.e. initial burns) and 1400 g $CO_2$/kg fuel in smoldering burns (i.e. in reburns) (both values calculated by Kaufman et al., from Ward, 1986). Mixed combustion produces 5 g CH4/kg fuel (calculated by Kaufman et al., nd from Ward, 1986). Smoldering combustion produces 7 g $CH_4$/kg fuel (calculated by Kaufman et al., from Greenberg et al., 1974). The carbon content of the fuel is assumed to be equal to that in the biomass being cleared (0.50). Termites in the low methane scenario release 0.2% of the carbon injected as methane carbon (Seiler *et al.*, 1984 cited by Fraser *et al.*, 1986). The transformations in the low methane scenario are summarized in Figure 3.

In the high methane scenario, mixed and smoldering burns release the same quantities of carbon dioxide as in the low methane scenario. Methane is produced at a rate of 6 g/kg fuel in mixed burns and 11 g/kg fuel in smoldering burns (calculated by Kaufman *et al.*, nd from Ward, 1986). Termites release 7.8 X $10^{-3}$ molecules of $CH_4$/molecule of $CO_2$ (Goreau and Mello, 1987), or 7.9 g $CH_4$ carbon/kg fuel carbon, assuming that all carbon is released either as $CO_2$ or $CH_4$. The methane release from termites in the high methane scenario is that measured in termite mound emissions near Manaus -- a value slightly lower than the emissions of the temperate zone species that led Zimmerman *et al.* (1982) to postulate massive global emissions from termites.

The effect of methane is to raise the impact of net carbon release from Amazonian deforestation by 8-16%, depending on whether the low or high methane scenario is used. The effect is slightly lower (7-15%) if gross carbon release is considered since the uptake of carbon by the replacement vegetation in the net release calculation only affects $CO_2$ because $CH_4$ does not enter photosynthetic reactions.

Carbon monoxide (CO) is also produced by burning (Tables 8-10). This gas contributes indirectly to the greenhouse effect by impeding natural cleaning processes in the atmosphere that remove a number of greenhouse gases, including methane. Methane removes hydroxyl radicals ($OH^-$), which react with $CH_4$ and other gases, including various cloroflourocarbons (CFCs) that provoke stratospheric ozone depletion, in addition to the greenhouse effect.

For mixed flaming and smoldering combustion in the low release scenario 120 g CO result per kg of fuel (calculated by Kaufman *et al.*, nd. from Greenberg *et al.*, 1984), while in the high release scenario the equivalent figure is 150 g (calculated by Kaufman *et al.*, nd. from Crutzen *et al.*, 1985). Assuming 50% fuel carbon, these values are equivalent to 0.096 and 0.12 kg CO carbon per kg of fuel carbon.

For smoldering combustion in the low release scenario, 220 g CO is released per kg of fuel (Ward, 1986 cited by Kaufman *et al.*, nd), while in the high release scenario the equivalent figure is 280 g (calculated by Kaufman *et al.*, nd from Greenberg *et al.*, 1984 and Ward, 1986). Assuming fuel carbon content as above, these values are equivalent to 0.176 and 0.224 kg CO carbon per kg of fuel carbon, respectively. Complete clearing of the Brazilian Legal Amazon would release 5-8 GT of CO (Table 10).

One can calculate by difference the amount of carbon that must be released in other forms, such as non-methane hydrocarbons (NMHCs) and graphitic carbon (soot). From the carbon release from forest in Table 5, one can calculate a gross release from biomass of 105.59 MT/ha, while the equivalent gross carbon release in the form of $CO_2$, $CH_4$ and CO totals 103.13 MT/ha (from Table 8), implying a difference of 2.46 MT/ha (2.3%) that is presumed to represent release in other forms. However, uncertainties such as the carbon content of fuel used in deriving the gas emission relationships make this number unreliable.

Burning also releases nitrous oxide ($N_2O$), which contributes both to the greenhouse effect and to the degradation of stratospheric ozone. The mass of $N_2O$ is calculated by the ratio of this gas to $CO_2$, multiplying by a factor of 2 X $10^{-4}$ (Cofer *et al.*, 1988 cited by Kaufman *et al.*, nd). The quantities are not tremendous -- 10 X $10^6$ MT of gas from complete clearing of the Legal Amazon (Table 10). Nitrous oxide, however, is very long-lived and so would continue its impact much longer than other gases. The long life of $N_2O$ allows it to reach the stratosphere, permitting even these small quantities of the gas to have a greater impact on stratospheric ozone than any counterbalancing from the tropospheric ozone that is also produced by burning (indirectly as a consequence of $OH_-$ depeletion caused by CO release). Only burning releases of $N_2O$ are considered here. This gas is also released from soils in greater quantities in cattle pasture than in forest (observations in the dry season near Manaus by Goreau *et al.*, 1987; see also Goreau and Mello, 1988). Burning in non-tropical environments has been found to stimulate $N_2O$ release from soils (Anderson *et al.*, nd. cited by Kaufman *et al.*, nd). Ignoring soil releases makes the nitrous oxide releases in Table 10 conservative. Ignoring greenhouse contributions from both CO and $N_2O$ in calculating $CO_2$ equivalent greenhouse contribution means that the true effect of deforestation is higher than that implied by the equivalents presented in Table 8.

## 2.) Soil Carbon

Soil carbon in pasture is taken to be that in a profile equivalent to what is compacted from a 20 cm profile in the forest. It would not be fair to compare the amount of carbon in the top meter of pasture soil to the top meter in forest soil, since soil under pasture undergoes compaction when exposed to sun, rain and trampling of cattle. As the pores are crushed and soil bulk density increases, the amount of carbon in the top meter may increase as an artifact of including a greater weight of soil in the profile. The carbon in the top 20 cm of soil decreases from 0.91% to 0.56% by weight (see Fearnside, 1985c), based on soil carbon under forest and 10 and 11 year-old pastures at Paragominas (Pará) sampled by Falesi (1976: 31 and 42). Considering the soil density as 0.56 $g/cm^3$ under forest at Paragominas (Hecht, 1981: 95), the layer compacted from the top 20 cm of forest soil releases

3.92 MT/ha of carbon.

The 3.92 MT/ha release from the top 20 cm of soil represents 38% of the pre-conversion carbon present in this layer. This is higher than the 20% of pre-conversion carbon in the top 40 cm of soil that Detwiler (1986) concluded is released, on average, from conversion to pasture (based on a literature review). The difference is not so great as it might seem: since carbon release is greatest nearest the surface, considering soil to 40 cm would thereby reduce the percentage released. One factor acting to compensate for any overestimation possibly caused by using a higher percentage of soil carbon release is the low bias introduced by having considered only the top 20 cm. If soil to one m depth is considered (the usual practice), then the release would be increased to 9.33 MT/ha. The calculation to one m depth considers that the top 20 cm of soil contains 42% of the carbon in a one m profile (based on samples near Manaus: Fearnside, 1987b). Brown and Lugo (1982: 183) have used a similar relationship to estimate carbon stocks to a depth of one m from samples of the top 20 cm, considering 45% of the carbon in a one m profile to be located in the top 20 cm.

Conversion of all forest and cerrado in the Legal Amazon to cattle pasture would release 1.9 GT of carbon from the top 20 cm of soil -- about 4% of the total released from converting the region to pasture. Were the soil considered to a depth of one m, and the assumption made that the proportion of carbon released remains constant with depth, the soil release would be 4.5 GT, or 8% of the total. Considering soil to one m would add 0.014 GT/year to the 0.010 GT/year release from the top 20 cm, given the 1988 rate and distribution of clearing.

Release of soil carbon would be expected when forest is converted to pasture because soil temperatures increase when forest cover is removed, thus shifting the balance between organic carbon formation and degradation to a lower equilibrium level (Cunningham, 1963; Nye and Greenland, 1960). A number of studies have found lower carbon stocks under pasture than forest (reviewed in Fearnside, 1980). Lugo et al. (1986), however, have found increases in carbon storage in pasture soils in Puerto Rico, especially in drier sites, and suggest that tropical pastures may be a carbon sink. The present study treats soils as a source of carbon when forests are converted to pasture. All carbon released from soils is assumed to be in the form of $CO_2$.

### D.) GLOBAL CONTRIBUTION OF TROPICAL DEFORESTATION

Global carbon emissions from deforestation are uncertain, in part because of the uncertainty associated with Brazil's large contribution to the total. One estimate places the global annual total at 1.67 GT, of which 0.80 GT are ascribed to Brazil (Goldemberg, 1989). The Brazilian contribution of more than double the current estimate of 0.27 GT is probably due to using the AVHRR thermal infra-red burning estimates from 1987 (Setzer et al., 1988) as the rate of deforestation. The global total implies that 0.87 GT of carbon are released annually from non-Brazilian deforestation, and that the global total using the current estimate for Brazil would be 1.14 GT. Brazil's present contribution to the global total from deforestation would be 24%. Assuming a 5 GT/year global total release from fossil fuels, deforestation in the Brazilian Amazon contributes 4.4% of the combined total from fossil fuels and deforestation. Using the fossil fuel release as the standard of comparison, as is the usual practice, Brazil's annual rate of deforestation in Amazonia represents 5.4% (Table 7). Using emission estimates for individual gases produces a similar result, since the loss of some carbon in forms not contributing to the greenhouse effect is compensated for by the greater impact of carbon in the form of methane. Using $CO_2$ equivalent carbon release of 0.262-0.282 GT (for the low and high methane scenarios in Table 8), the contribution represents 5.2-5.7% of the global fossil fuel total.

## IV.) DISCUSSION AND CONCLUSIONS

Deforestation in Brazilian Amazonia already makes a significant contribution to the greenhouse effect, and continuation of deforestation trends could lead to an even greater potential contribution to this global problem. Uncertainties concerning clearing rate, biomass and other factors do not change the basic conclusion regarding the significance of deforestation. This can be seen by examining a series of hypothetical examples (Table 7): were the average biomass of 210.7 MT/ha found to be incorrect, biomass values from other sources would result in contributions that, expressed as percentages of a 5 GT global total fossil fuel release, range from 2.8% to 4.6% if only the forest is considered, or 3.3% to 5.1% if the entire Legal Amazon is considered. The conclusion that the effect is significant is therefore quite robust.

Brazil emits 100 X $10^6$ MT of carbon annually from burning fossil fuels (Goldemberg, 1989). This contribution to the greenhouse effect is balanced against the benefits of the country's industry and transportation powered by oil and coal, all domestic use of natural gas, etc. In contrast, each year's clearing of forest and cerrado in the Brazilian Amazon is now contributing to the atmosphere 270 X $10^6$ MT of carbon -- almost three times as much as Brazil's use of fossil fuels (Table 5). The benefits of deforestation, however, are minimal: it leaves in its wake only destroyed rain forests and degraded cattle pastures.

The contrast between costs and benefits of biomass burning and fossil fuel combustion are also tremendous on a per-capita basis. Brazil's 140 X $10^6$ population emits 714 kg of carbon/person/year from fossil fuels. A single rancher who clears

2,000 ha of forest (with an average biomass of 210.7 MT/ha, see Table 3) is emitting as much carbon as a city of 280,000 people burning fossil fuels (calculation patterned after Brown, 1988). Even a small farmer who clear's one hectare per year is releasing 100 MT of carbon, the equivalent of 140 people in Brazil's cities. The gulf between the costs and benefits of deforestation compared to fossil fuel use makes slowing forest loss an obvious place for Brazil to start reducing its contribution to global warming.

More important than the question of whether 5% or 8% of the Legal Amazon has been deforested is the conclusion that is drawn from the estimate. President Sarney concluded from the INPE study, in his speech unveiling the Our Nature Program, that the data show that deforestation during his administration was "infinitesimal." Unfortunately, this assertion was incorrect regardless of which estimate is used. By the present estimate, 58,116 km$^2$ (18.2% of the total for clearing of original vegetation) had taken place during President Sarney's Administration (March 1985- April 1989). All the estimates, including the INPE/Our Nature Program estimate, indicate that deforestation is still raging out of control, and that the government must take strong steps to slow the process. To be effective, these steps must go beyond trying to enforce a prohibition of deforestation to addressing the root causes of rapid clearing, including land speculation, establishment of land tenure, fiscal incentives, and migration to Amazonia for lack of acceptable employment alternatives (Fearnside, 1987a, 1989c). Unfortunately, many of the basic causes of deforestation have not been included in the Our Nature Program.

Immediate action is needed to reduce emissions of greenhouse gases in order to minimize the global warming that continuation of current trends would provoke. While research and monitoring efforts must be fortified and continued, ample scientific evidence is already in hand to justify strong measures by governments throughout the world. Reducing fossil fuel burning and slowing the rate of tropical deforestation are areas that can be readily identified as targets for such measures. Governments must not wait for the availability of more research results nor for the appearance of observable temperature changes before taking action, or the opportunity will be lost to avert the most damaging impacts of the greenhouse effect.(6)

## V.) NOTES

(1) INPE uses an area of 238,739 km$^2$ for Rondônia (Brazil, INPE, 1989a,b).

(2) The IBDF report uses 1982 as the nominal year for the estimate, but most images are from 1981 (see Fearnside, 1989e).

(3) IBAMA was created in January 1989, and incorporates the former Brazilian Institute for Forestry Development (IBDF). From January to April 1989, IBAMA was known as IBRNRN.

(4) This deforestation rate assumes that there was no clearing prior to 1970 -- an assumption that, while clearly false, makes the upsurge of deforestation appear less explosive in the early 1970s than it really was (see Fearnside, 1986c).

(5) The term "Tocantins/Goiás" is used by INPE (Brazil, INPE, 1989a,b) to refer to portions of the states of Tocantins and Goiás north of 13° S. latitude -- the limit of the "Legal Amazon" in this area. Tocantins was created by Brazil's October 1987 constitution from the northern half of the former state of Goiás. The border between Tocantins and the present state of Goiás is an irregular line zig-zagging along the 13th parallel, leaving a small part of Tocantins out of the Legal Amazon and a small part of Goiás inside this administrative unit.

(6) Studies on burning in Altamira were funded by National Science Foundation grants GS-422869 (1974-1976) and ATM-86-0921 (1986-1988), and in Manaus by World Wildlife Fund-US grant US-331 (1983-1985). Alberto Setzer made useful comments on an earlier version of the discussion of deforestation.

## VI.) LITERATURE CITED

Anderson, I.C., J.S. Levine, M. Poth and P.J. Riggan. nd. Enhanced

# TABLE 1

| State | Area of recent (post 1960) clearing (km2): Fearnside 1989e | Brazil, INPE, 1989a(a) as reported | Brazil, INPE, 1989b with corrections(b) | Mahar, 1989 | Current best estimate | Area of original primary forest cleared (km2)(d) (recent + old clearings)(d) | Percentage of political unit (c): Fearnside 1989e | Brazil, INPE, 1989a(a) as reported | Brazil, INPE, 1989b with corrections (b) | Mahar, 1989 | Best estimate for comparison with political unit percentages | RECENT CLEARING BEST ESTIMATE: Percentage of forest (primary+ old secondary)+ cerrado recently cleared | TOTAL CLEARING BEST ESTIMATE: Percentage of origin primary forest cleared ( |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acre | 8,634 | 5,510 | 5,510 | 19,500 | 8,634 | 8,634 | 5.7 | 3.6 | 3.6 | 12.8 | 5.7 | 5.7 | 5.7 |
| Amapá | 231 | 842 | 842 | 572 | 842 | 842 | 0.2 | 0.2 | 0.6 | 0.4 | 0.6 | 0.8 | 0.8 |
| Amazonas | 5,150 | 12,837 | 12,837 | 105,790 | 12,837 | 12,837 | 0.3 | 0.8 | 0.8 | 6.8 | 0.8 | 0.8 | 0.8 |
| Maranhao | 24,019 | 23,771 | 54,803 | 50,670 | 54,803 | 84,495 | 9.3 | 9.1 | 21.1 | 19.7 | 21.1 | 21.1 | 60.7 |
| Mato Grosso | 151,766 | 67,216 | 201,493 | [illegible] | 201,493 | 67,216 | [illegible] | [illegible] | 22.9 | 23.0 | 22.9 | 24.9 | 11.7 |
| Pará | 148,111 | 88,741 | 92,922<br>(e) | 120,000 | 92,922 | 118,150<br>(e) | 12.1 | 7.1 | 7.5 | 9.6 | 7.5 | 7.7 | 10.0 |
| Rondônia | 41,521 | 30,046 | 31,623 | 58,000 | 31,623 | 30,634 | 17.1 | 12.6 | 13.0 | 23.7 | 13.0 | 13.0 | 14.2 |
| Roraima | 3,565 | 2,187 | 2,187 | 3,270 | 2,187 | 2,187 | 1.6 | 1.0 | 1.0 | 1.4 | 1.0 | 1.3 | 1.3 |
| Tocantins/Goiás | 16,768 | 20,279 | 170,700 | 33,120 | 54,393 | 20,279 | 5.9 | 7.5 | 63.2 | 11.6 | 20.2 | 20.2 | 20.2 |
| Legal Amazon (forest+cerrado) | 399,765 | 251,429 | 572,917 | 598,922 | 459,734 | | 8.0 | 5.1 | 11.5 | 12.0 | 9.2 | 9.6 | |
| Legal Amazon (forest only) | | 251,429 | 295,432 | | 267,969 | 345,274 | | | 7.0 | | 6.4 | | 8.2 |

(a) Areas and percentages as reported in Brazil, INPE, 1989a. The second version of the report (Brazil, INPE, 1989b) indicates that the areas refer only to forest clearing while the denominators used in calculating the percentages refer to the areas of political units, including savannah vegetation. Unless otherwise specified, all other values in the table refer to clearing forest (both primary and old secondary) and cerrado (but not humid savannah). All values in the table refer to recent clearing identifiable by traditional techniques for satellite image interpretation (see text). Areas adjusted for state area in Rondônia and Mato Grosso, and for clearing in old secondary forest in Pará and Maranhao.

(b) Areas for clearing forest (primary and old secondary) + cerrado estimated assuming that cerrado is cleared in the same proportion reported for forest clearing within each state. In the case of Rondônia, approximately 75% of The cerrado area indicated on the INPE map is inside Amerindian reserves and is assumed to be protected from clearing.

(c) All percentages calculated using the areas of political units used by the cited publications.

(d) Old (pre-1960) clearing only included for Pará and Maranhão, as reported by Brazil, INPE, 1989b.

Denominator is original area of tropical terra firme (upland) primary forest (humid and subhumid), and does not include cerrado and humid savannah.

(e) Adjusted for state area.

## TABLE 2: ORIGINAL VEGETATION AND BEST ESTIMATE OF AREAS RECENTLY CLEARED IN THE BRAZILIAN LEGAL AMAZON FROM 1960 THROUGH 1988

| State | Original Vegetation (km2)(a): Forest | Cerrado | Humid savannah | Total original vegetation | Recently cleared area (km2): Forest | Cerrado (b) | Total | Percent recently cleared: Of forest | Of forest + cerrado | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| Acre | 152,589 | 0 | 0 | 152,589 | 8,634 | 0 | 8,634 | 5.7 | 5.7 | (d) |
| Amapá | 99,525 | 0 | 42,834 | 142,359 | 842 | 0 | 842 | 0.8 | 0.8 | (e) |
| Amazonas | 1,562,488 | 0 | 5,465 | 1,567,953 | 12,837 | 0 | 12,837 | 0.8 | 0.8 | (e) |
| Maranhao | 139,215 | 121,017 | 0 | 260,232 | 34,140 | 20,664 | 54,803 | 24.5 | 21.1 | (e) |
| Mato Grosso | 572,669 | 235,345 | 72,987 | (c)<br>881,001 | 67,216 | 134,277 | 201,493 | 11.7 | 24.9 | (e) |
| Pará | 1,180,004 | 22,276 | 44,553 | 1,246,833 | 91,200 | 1,722 | 92,922 | 7.7 | 7.7 | (e) |
| Rondônia | 215,259 | 27,785 | 0 | 243,044 | 30,634 | (f)<br>989 | 31,623 | 14.2 | 13.0 | (e) |
| Roraima | 173,282 | 0 | 51,735 | 225,017 | 2,187 | 0 | 2,187 | 1.3 | 1.3 | (e) |
| Tocantins/ Goiás | 100,629 | 169,282 | 0 | 269,911 | 20,279 | 34,114 | 54,393 | 20.2 | 20.2 | (e) |
| Legal Amazon | 4,195,660 | 575,705 | 217,574 | 4,988,939 | 267,969 | 191,765 | 459,734 | 6.4 | 9.5 | |

(a) Original vegetation in accord with the INPE map (Figure 1), with the savannah areas apportioned between humid savannah and cerrado in their approximate proportions in the savannah areas shown for each state. The forest in Tocantins/Goiás has been increased by 68,573 km2 presumed to have been included in the INPE survey but not in the map of original vegetation. "Forest" includes both primary (virgin) forest and "old secondary forests" (from clearings prior to 1960 in Pará and Maranhão). Totals are areas of political units, including water surfaces, as in the INPE and IBDF reports (making the percentages underestimates). The area of Tocantins/Goiás is that used by Brazil, INPE, 1989a,b; it is at variance with the 235,793 km2 used in previous INPE reports (e.g. Tardin et al., 1980) for the same geographical area.

(b) Cerrado clearing, which was not measured in the INPE study (Brazil, INPE, 1989b), has been estimated assuming that this vegetation type is cleared in the same proportion as the forest within each state, the exceptions of Rondônia (where proportionality is assumed excluding cerrado areas in Amerindian reservations) and Mato Grosso (where data exist for cerrado clearing in the western part of the state in 1983, and the ratio of cerrado to forest clearing observed there is assumed to apply to the entire state through 1988).

(c) Pantanal (Mato Grosso humid savannah) area from IBGE data reproduced in Benchimol (1989: 56). The remainder of the savannah area in Mato Grosso shown in Figure 1 (with correction for state area) is considered cerrado.

(d) Linear projection from the last two years of available satellite data (see Fearnside, 1989e).

(e) Brazil, INPE, 1989b, with corrections for state area and cerrado clearing (see text).

(f) Rondônia cerrado clearing assumes that 6,946 km2 of cerrado (25% of the 27,785 km2 of cerrado in the state according to the INPE map) is exposed to clearing. The remainder is in an Amerindian reserve.

TABLE 3: APPROXIMATE BIOMASS AND FOREST AREA BY STATE

| State | Forest type | Approximate area (Km2 X 103) | Approximate Biomass (MT/ha) | Area source | Biomass source |
|---|---|---|---|---|---|
| Acre | Bamboo | 30 | 20 | W.G. Sombroek, pers. comm. 1989 | |
| | Other low biomass | 31 | 209 | (25% of remainder) | |
| | Dense | 92 | 418 | (75% of remainder) | |
| Amapá | Mangrove | 1 | 200 | Braga, 1979 | guess |
| | Dense | 99 | 354 | remainder | Jordan and Russell, 1983 for Jari |
| Amazonas | Flooded | 30 | 216 | | |
| | Jurua/Purus | 400 | 149 | | |
| | Western Amazonas | 200 | 119 | guess | Commercial volume 100 m3/h.. (W.G. Sombroek, pers. comm., 1989). |
| | Bamboo | 30 | 20 | | |
| | Other low biomass | 226 | 232 | 25% of forest on fragile soils (W.G. Sombroek, pers. comm., 1989) | assumed 50% of dense forest |
| | Dense | 677 | 464 | | Mean from four locations around Manaus: Fazenda Dimona (327.7 MT/ha) (Fearnside et al., nd-a); Fazenda Porto Alegre (Fearnside et al., nd-a) Reserva Ducke and environs (367.5 MT/ha see Fearnside, 1987b (Klinge and Rodrigues, 1974 Reserva Egler (507.5 MT/ha) (Klinge et al., 1975). |
| Maranhao | Old secondary | 61 | 100 | Brazil, INPE, 1989a,b | guess |
| | Other | 78 | 175. | | guess based on 144.7 m3/ha trunk volume for forests Grande Carajas region Brazil, SEPLAN/CODEBAR/SUDAM, 1986 |
| Mato Grosso | Northern | 100 | 143 | guess | Based on 120 m3/ha merchantable bole found by Jaime Antonio Ubially and Edezio Cardoso Carvalho (W.G. Sombroek, pers. comm., 1989) |
| | Transition | 473 | 83 | guess | Based on 70 m3/ha merchantable bole found by Jaime Antonio Ubially and Edezio Cardoso Carvalho (W.G. Sombroek, pers. comm., 1989). |
| Pará | Old secondary | 32 | 100 | Brazil, INPE, 1989a,b | guess |
| | Central | 465 | 226 | guess | FAO forest volume surveys |
| | West | 249 | 356 | guess | (mean of 16 localities: see review in Fearnside1986b, 1987b). Tucurui reservoir area: |
| | North | 158 | 354 | guess | (Cardenas et al., 1982). Jari Project: |
| | Vine/low biomass | 277 | 175 | guess | Jordan and Russell, 1983 Assumed 25% of dense forest |
| Rondônia | Dense (Samuel) | 215 | 418. | Brazil, INPE, 1989a,b | 300 MT/ha above ground biomass for Samuel reservoir: (Martinell et al., nd) |
| Roraima | Montane | 26 | 266 | Braga, 1979 | Seiler and Crutzen, 1980 for montane forest in general |
| | Other | 147 | 119 | remaining forest | Assumed same as western Amazon |
| Tocantins/ Goiás | Transition | 101 | 83 | Assumed all forest reported in Brazil, INPE, 1989a,b | Assumed same as transition forest in Mato Grosso |
| Legal Amazon | All forests | 4,196 | 247 (mean weighted by area present)<br>211 (mean weighted by clearing rate) | | |
| | Cerrado | 576 | 70.70 | | |

TABLE 3 p.

Table 4, P. 1

### ᴀʙʟᴇ 4: LIST OF PARAMETERS FOR CARBON TRANSFORMATIONS

| arameter | Value | Units | Source | Comment |
|---|---|---|---|---|
| otal biomass | 210.67 | MT/ha dry weight | Table 2 | Weighted mean for areas being cleared in 1988 |
| rbon content biomass | 0.5 | fraction of dry weight | Brown and Lugo, 1984 | |
| ove ground action | 0.761 | | Klinge et al., 1975 | Near Manaus, Amazonas |
| ar C fraction initial burn | 0.036 | | Fearnside et al., nd-a | Near Manaus, Amazonas |
| action of char biomass llowing initial rn | 0.89 | | preliminary data from Fearnside et al., nd-b | Near Altamira, Para |
| posed to soil ar c transfer action during rst interval | 0.3 | | guess | First interval = 4 years |
| action surviving cay in first terval | 0.41 | | Calculated from Uhl and Saldariagga, nd (a) | |
| nbustion ficiency in rst reburn | 0.275 | fraction of C released | Assumed equal to initial burn | |
| action converted char in st reburn | 0.036 | | Assumed equal to initial burn | |
| ar C. nbustion fraction first reburn | 0.2 | | guess | |
| ction surviving ay in second erval | 0.57 | | Calculated from Uhl and Saldariagga, nd (b) | Second interval = 3 years |
| bustion iciency in ond reburn | 0.275 | fraction of C released | Assumed equal to initial burn | |
| ction of C verted to char second reburn | 0.036 | | Assumed equal to initial burn | |
| ction of char biomass after first reburn | 0.89 | | Assumed equal to initial burn | |
| Exposed to soil char C transfer fraction during second interval | 0.3 | | guess | |
| Char C combusted fraction in second reburn | 0.2 | | guess | |
| Fraction of char on biomass after second reburn | 0.89 | | Assumed equal to initial burn | |
| Exposed to soil char C transfer fraction during third interval | 0.3 | | guess | |
| Fraction surviving decay in third interval | 0.77 | | Calculated from Uhl and Saldarriaga, nd (b) | Third interval = 3 years |
| Combustion efficiency in third reburn | 0.275 | fraction of wood C released | Assumed equal to initial burn | |
| raction of C o char in hird reburn | 0.036 | | Assumed equal to initial burn | |
| har C ombustion raction in hird reburn | 0.2 | | guess | |
| oil C elease | 3.92 | MT/ha | Fearnside, 1985c, 1987b | Top 20 cm |
| eplacement egetation iomass | 10.67 | MT/ha | Fearnside et al., nd-c; Fearnside, 1989f | Pasture: average biomass throughout year at Ouro Preto do Oeste, Rondon |

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a) Uhl and Saldarriaga (nd) report an average of 97.3 MT of above ground dry weight biomass remaining 3-4 years after clearing a Venezuelan forest whose original above-ground biomass was believed to be 290 MT/ha based on estimates in the area by Stark and Spratt (1977). Assuming the combustion efficiency (0.275) and charcoal formation fraction (0.036) measured in Brazil (Fearnside et al., nd-a), the post-burn above-ground biomass exposed to decay in Venezuela would be reduced to 200 MT/ha. Loss to decay over the 3.5 year interval (using the midpoints of the range of site ages) would therefore be 51%. Loss in a 4-year interval following the initial burn would be 59%.

) Uhl and Saldarriaga (nd) report average biomass as 56 MT/ha for 6-7 year-old sites; 45.3 MT/ha for 8-10 year old sites, 22.7 MT/ha for 12-20 year old sites and 7 MT/ha for 30-40 year old sites. Assuming a linear decline in wood mass within each age interval (and using midpoints of age ranges as the limits of the intervals), the loss per year as a percentage of the wood mass at the beginning of each interval would be 14.7% for 0-3.5 years, 14.2% for 3.5-6.5 years, 7.6% for 6.5-9 years, 7.2% for 9-16 years and 3.6% for 16-35 years. These loss rates have been used to calculate loss values for the intervals used in the present calculation (0-4 years, 4-7 year and 7-10 years).

## TABLE 5: APPROXIMATE CARBON RELEASE FROM CLEARING IN THE BRAZILIAN LEGAL AMAZON

| | Carbon release if all converted to pasture (GT) | Carbon release at current rate of clearing (GT/year) |
|---|---|---|
| Forest biomass | 47.3 | 0.196 |
| Cerrado biomass | 1.9 | 0.059 |
| Soil (top 20 cm) | 1.9 | 0.015 |
| Total | 51.0 | 0.270 |

## TABLE 6: AVERAGE CLEARING RATES IN THE BRAZILIAN LEGAL AMAZON

| STATE | Last previous data | | | Clearing total by 1988 (km2) | Average clearing rate in 1988 (km2/year) | | |
|---|---|---|---|---|---|---|---|
| | Year | Source | Clearing total (km2) | | Forest | Cerrado | Total |
| Acre | 1987 | IBDF | 8,133 | 8,634 | 501 | 0 | 501 |
| Amapá | 1978 | Tardin et al., 1980 | 171 | 842 | 67 | 0 | 67 |
| Amazonas | 1978 | Tardin et al., 1980 | 1,791 | 12,837 | 1,105 | 0 | 1,105 |
| Maranhão | 1980 | IBDF, 1983a | 10,671 | 54,803 | 3,437 (a) | 2,080 | 5,517 |
| Mato Grosso | 1980 | IBDF, 1982b | 52,786 | 201,493 | 5,580 | 13,008 | 18,588 |
| Pará | 1986 | IBDF/SUDAM | 85,203 (a) | 92,922 | 3,788 | 72 | 3,860 |
| Rondônia | 1987 | IBDF, 1989 | 22,913 | 31,623 | 3,916 (b) | 126 | 4,042 |
| Roraima | 1981 | IDBF, 1983b | 1,170 | 2,187 | 145 | 0 | 145 |
| Tocantins/Goiás | 1980 | IBDF, 1983a | 9,120 | 54,393 | 1,759 | 2,959 | 4,718 |
| Legal Amazon | | | | 459,734 | 20,298 | 18,245 | 38,543 |

(a) Pará and Maranhão clearing include reclearing in the area of old (pre-1960) secondary forest. Old secondary forest zones total 31,822 km2 in Pará and 60,724 km2 in Maranhão; of these an estimated 2,255 km2 and 2,459 km2 were cleared by 1986 and 1988 respectively in Pará and 10,369 km2 by 1988 in Maranhão. Estimates in these states for years prior to 1986 had been unable to distinguish the old secondary forest from virgin forest, and the clearing in the old secondary forest region is therefore included without correction. For 1986 and 1988 in Pará and for 1988 in Maranhão the clearing within the old secondary forest area is assumed to have occurred in the same proportion as that in virgin forest.

(b) Rondônia clearing rate assumed to follow the trend from the 1985-1987 period shown by AVHRR. Uncorrected deforestation values: ~~for 1989~~ 27,658 km2 by 1985 (Malingreau and Tucker, 1988); 36,900 km2 by 1987 (Jean-Paul Malingreau, personal communication, 1988); Corrected for cerrado and 18% adjustment for pixel size effect: 24,195 km2 by 1985 and 32,280 km2 by 1987.

## TABLE 7:

## CARBON RELEASE FROM THE PRESENT RATE OF CLEARING IN THE BRAZILIAN LEGAL AMAZON GIVEN DIFFERENT ASSUMPTIONS CONCERNING AVERAGE FOREST BIOMASS

| Average Forest Biomass (MT/ha) | Biomass carbon release (a) (MT/ha) | Carbon release | | | |
|---|---|---|---|---|---|
| | | From forest clearing (b) | | Total from Legal Amazon (c) (GT/year) | % of 5 GT global fossil fuel release |
| | | (GT/year) | % of 5 GT global fossil fuel release | | |
| 262.60 (d) | 120.1 | 0.252 | 5.0 | 0.318 | 6.4 |
| 252.00 | 115.2 | 0.242 | 4.8 | 0.308 | 6.2 |
| 225.00 | 102.9 | 0.217 | 4.3 | 0.283 | 5.7 |
| 210.67 | 96.3 | 0.203 | 4.1 | 0.270 | 5.4 |
| 200.00 | 91.5 | 0.194 | 3.9 | 0.260 | 5.2 |
| 174.00 | 79.6 | 0.169 | 3.4 | 0.236 | 4.7 |
| 155.10 (e) | 70.9 | 0.152 | 3.0 | 0.218 | 4.4 |

(a) Assumes that the replacement vegetation is cattle pasture (10.67 MT/ha) dry weight biomass; see Fearnside, 1987: 79); carbon content of vegetation 0.50 (after Brown and Lugo, 1982, 1984).

(b) Includes 3.92 MT/ha carbon release from the top 20 cm of soil.

(c) Includes release from cerrado (average biomass 70.7 MT/ha) and for soils assumed equal to forest release. Cerrado carbon release at current clearing rate is 0.059 GT/year (exclusive of soil release).

(d) Value derived from FAO forest volume estimates and from available direct measurements (Fearnside, 1987).

(e) Value derived from FAO forest volume estimates for tropical American productive closed broadleaf forests (Brown and Lugo, 1984).

TABLE 8: CARBON RELEASES IN THE BRAZILIAN LEGAL AMAZON(a)

LOW METHANE SCENARIO

| | Complete clearing of Legal Amazon (GT) | | | | Annual net release in 1988 (GT/year) | | | | Carbon monoxide C | | Gross release per hectare (MT C/ha cleared) for complete clearing of the Legal Amazon | | | Gross release per hectare (MT C/ha cleare for clearing in 1988 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Carbon dioxide C | Methane C | Total C | CO2 equivalent C | Carbon dioxide C | Methane C | Total C | CO2 equivalent C | Total clearing (GT) | Annual release (GT/year) | CH4 | CO2 | CO | CH4 | CO2 | CO |
| Forest | 45.40 | 0.19 | 45.59 | 49.16 | 0.187 | 0.001 | 0.188 | 0.203 | 1.97 | 0.008 | 0.45 | 113.54 | 4.71 | 0.38 | 97.58 | 4.02 |
| Cerrado | 1.73 | 0.01 | 1.74 | 1.88 | 0.054 | 0.000 | 0.054 | 0.059 | 0.08 | 0.002 | 0.13 | 35.35 | 1.35 | 0.13 | 35.35 | 1.35 |
| Total | 47.13 | 0.20 | 47.32 | 51.03 | 0.241 | 0.001 | 0.242 | 0.262 | 2.05 | 0.011 | | | | | | |

HIGH METHANE SCENARIO

| | Complete clearing of Legal Amazon | | | | Annual net release from 1988 clearing rate | | | | Carbon monoxide C | | Gross release per hectare (MT C/ha cleared) for complete clearing of the Legal Amazon | | | Gross release per hectare (MT C/ha clear for clearing in 1988 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Carbon dioxide C | Methane C | Total C | CO2 equivalent C | Carbon dioxide C | Methane C | Total C | CO2 equivalent C | Total clearing (GT) | Annual release (GT/year) | CH4 | CO2 | CO | CH4 | CO2 | CO |
| Forest | 45.25 | 0.39 | 45.64 | 52.97 | 0.187 | 0.002 | 0.188 | 0.227 | 2.49 | 0.010 | 0.92 | 113.18 | 5.93 | 0.79 | 97.27 | 5.07 |
| Cerrado | 1.72 | 0.02 | 1.74 | 2.03 | 0.055 | 0.000 | 0.055 | 0.055 | 0.10 | 0.003 | 0.26 | 35.25 | 1.70 | 0.26 | 35.25 | 1.70 |
| Total | 46.97 | 0.40 | 47.37 | 55.00 | 0.242 | 0.002 | 0.243 | 0.282 | 2.59 | 0.013 | | | | | | |

(a) Net release from biomass and soils. Gross releases would increase CO2 carbon by 5.34 MT/ha, but would not affect other ga
For the low and high methane scenarios respectively, gross release of CO2 equivalent carbon would be 53.58 and 57.54 GT f clearing the Legal Amazon, or
0.283 and 0.341 GT/year for annual release in 1988.

TABLE 9: GREENHOUSE GAS EMISSIONS FROM DEFORESTATION OF THE BRAZILIAN LEGAL AMAZON (MT/ha)

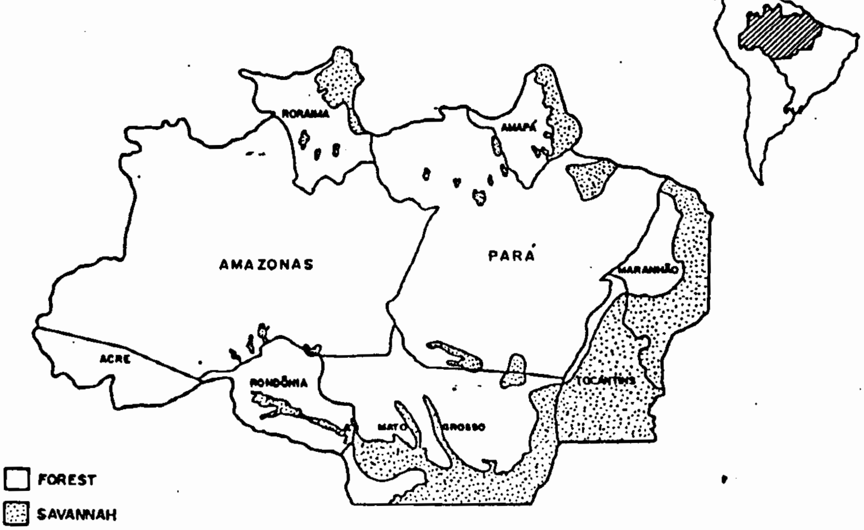
| | | | $CH_4$ | $CO_2$ | CO | $N_2O$ |
|---|---|---|---|---|---|---|
| LOW METHANE SCENARIO | | | | | | |
| | FOREST | | | | | |
| | | Burning | 0.44 | 115.45 | 11.77 | 0.02 |
| | | Total | 0.60 | 454.16 | 11.77 | 0.02 |
| | CERRADO | | | | | |
| | | Burning | 0.12 | 33.10 | 3.37 | 0.01 |
| | | Total | 0.17 | 141.41 | 3.37 | 0.01 |
| HIGH METHANE SCENARIO | | | | | | |
| | FOREST | | | | | |
| | | Burning | 0.59 | 115.45 | 14.83 | 0.02 |
| | | Total | 1.23 | 452.73 | 14.83 | 0.02 |
| | CERRADO | | | | | |
| | | Burning | 0.17 | 33.10 | 4.25 | 0.01 |
| | | Total | 0.35 | 140.99 | 4.25 | 0.01 |

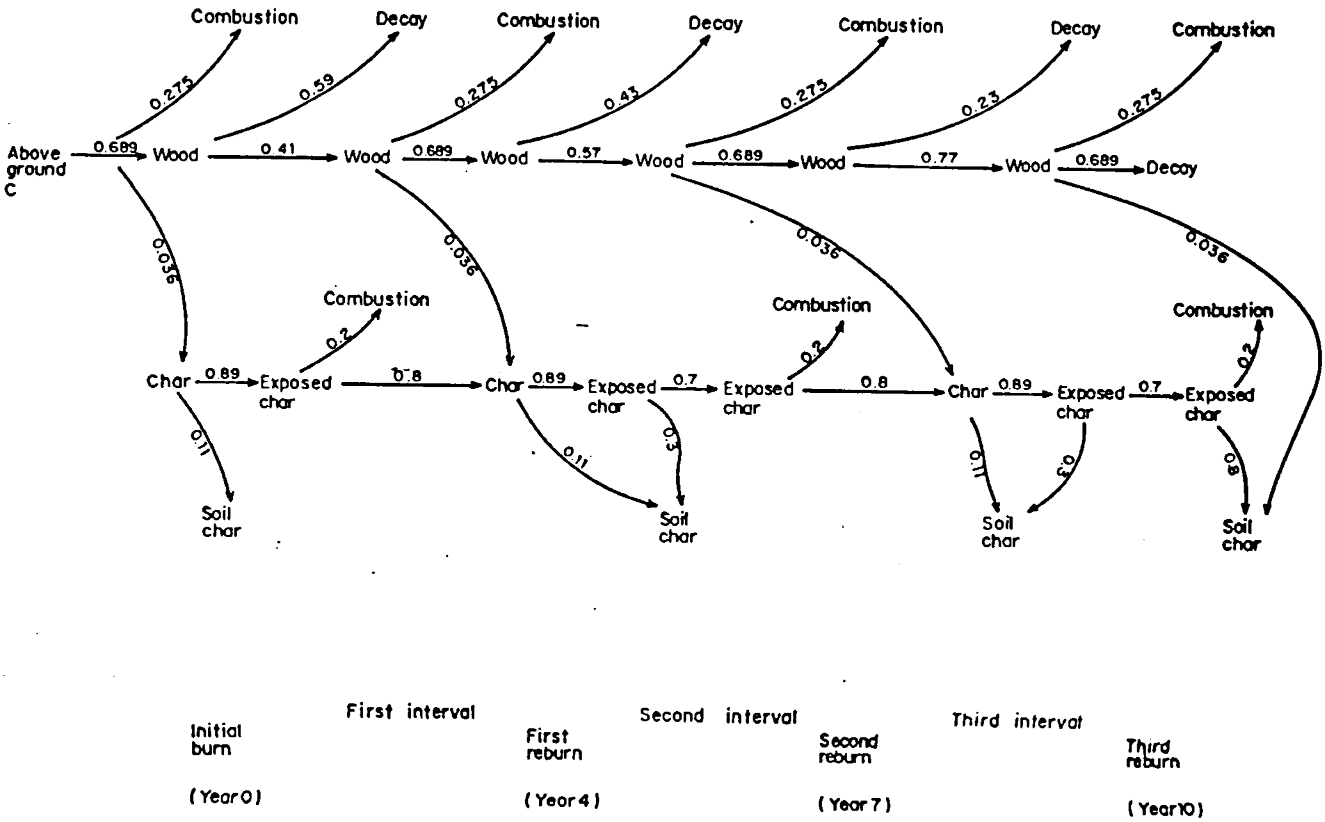
(a) Calculated using average biomass for forests in the Legal Amazon.

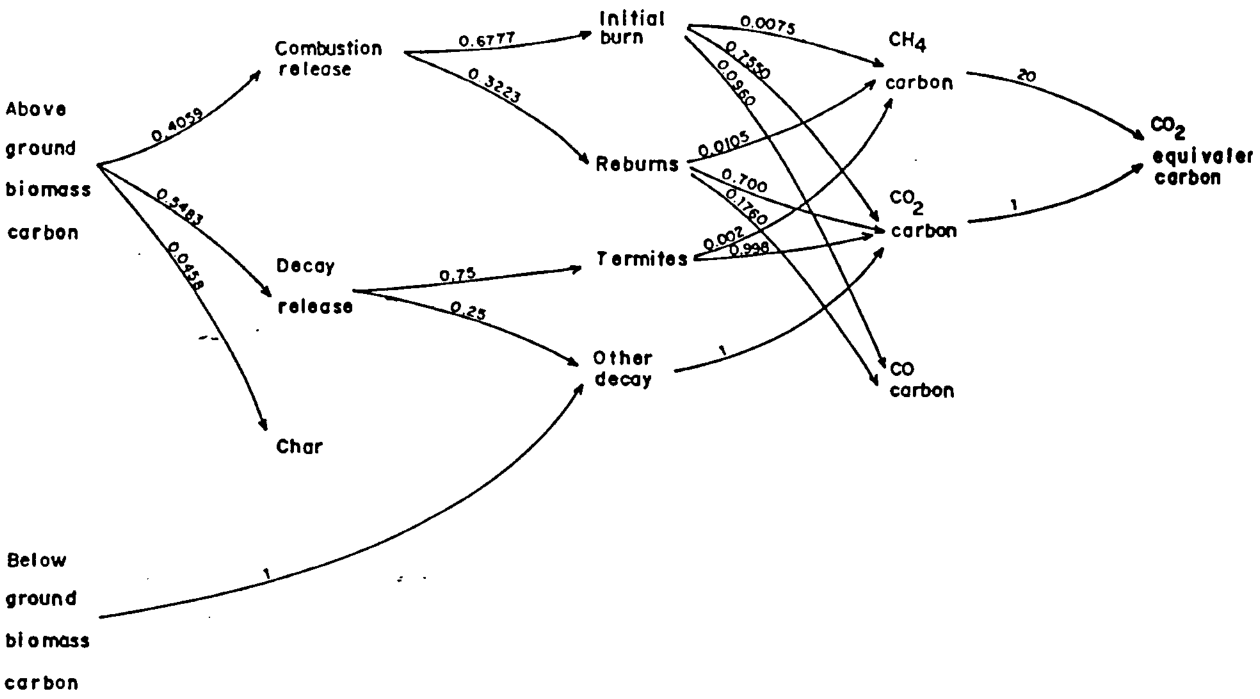
TABLE 10: GREENHOUSE GAS EMISSIONS FROM COMPLETE DEFORESTATION OF THE BRAZILIAN LEGAL AMAZON (GT OF GAS)

| | | $CH_4$ | $CO_2$ | CO | $N_2O$ |
|---|---|---|---|---|---|
| LOW METHANE SCENARIO | FOREST | 0.25 | 190.55 | 4.94 | 0.01 |
| | CERRADO | 0.01 | 8.14 | 0.19 | 0.00 |
| | TOTAL | 0.26 | 198.69 | 5.13 | 0.01 |
| HIGH METHANE SCENARIO | FOREST | 0.51 | 189.95 | 6.22 | 0.01 |
| | CERRADO | 0.15 | 59.16 | 1.78 | 0.00 |
| | TOTAL | 0.66 | 249.11 | 8.01 | 0.01 |

LEGAL AMAZON




Above ground C
0.689
Wood
0.41
Wood
0.689
Wood
0.57
Wood
0.689
Wood
0.77
Wood
0.689
Decay
Combustion
0.275
Decay
0.59
Combustion
0.275
Decay
0.43
Combustion
0.275
Decay
0.23
Combustion
0.275
0.036
0.036
0.036
0.036
Char
0.89
Exposed char
Combustion
0.2
0.8
Char
0.89
Exposed char
0.7
Exposed char
Combustion
0.2
0.8
Char
0.89
Exposed char
0.7
Exposed char
Combustion
0.2
0.11
Soil char
0.11
0.3
Soil char
0.11
0.3
Soil char
0.8
Soil char
Initial burn
(Year 0)
First interval
First reburn
(Year 4)
Second interval
Second reburn
(Year 7)
Third interval
Third reburn
(Year 10)


Above ground biomass carbon
0.4059
0.5483
0.0458
Combustion release
Decay release
Char
0.6777
0.3223
0.75
0.25
Initial burn
Reburns
Termites
Other decay
0.0075
0.7550
0.0960
0.0105
0.700
0.1760
0.002
0.998
1
CH4 carbon
CO2 carbon
CO carbon
20
1
CO2 equivalet carbon
Below ground biomass carbon
1

**Fearnside, P.M. 1987.** **Summary of Progress in Quantifying the Potential Contribution of Amazonian Deforestation to the Global Carbon Problem. Proceedings of the Workshop on Biogeochemistry of Tropical Rainforests: Problems for Research.**

This article reviews previous estimates of the contribution of Legal Amazon forests to atmospheric carbon. Accurate information of the impacts from complete deforestation is necessary to give decision makers the information they need to judge whether taking action to contain deforestation is worth the financial and political cost. Consequently, this paper focuses on clarifying and addressing the latest information on carbon releases and sinks from the Legal Amazon.

Most of the Legal Amazon forest is dense tropical forest. According to Fearnside, previous estimates of the biomass contained in dense tropical forests by Lugo and Brown (among others) have been too low. Fearnside's measurements show much higher levels of dense forest biomass, producing higher carbon releases from deforestation than previously anticipated. The reliability of estimating the biomass levels of dense tropical forest will have the greatest impact on final estimates of carbon released from the Legal Amazon forests.

According to Fearnside, the timber volumes method for estimating biomass is not adequate. It results in biomass values that are too low. Direct measurements show twice the amount of biomass than estimates using the timber volume method.

Fearnside uses measurements in 19 localities within Legal Amazon to determine a total volume of biomass for Legal Amazon. The average biomass from his calculations is 254.5 metric tons/ha. This gives a total carbon store (using 0.45 coefficient for conversion of biomass to carbon) of 45.34 G tons carbon or 50.38 G tons of carbon using Brown and Lugo's 0.50 conversion rate. Data presently being collected by the World Wildlife Fund, INPA and Rankin should improve the accuracy of these figures. There are an additional 64.54 G tons of carbon in the soil.

Pasture biomass estimates produced by Fearnside are also higher, and estimates of the total biomass released from pastures declines very little (3.4%) from previous estimates. Using the higher biomass to carbon coefficient of 0.50, non-natural vegetation, such as secondary forests, contain higher amounts of carbon.

Fearnside discusses potential carbon sinks in the region that have been identified as additional absorbers of carbon. In previous studies charcoal produced from burning has been over-estimated as a sink. Pasture charcoal is negligible in the short-term. Carbon fixing by regeneration of secondary forests has also been over-estimated in the past by claiming that secondary forests store 50% of the original carbon levels. Fearnside's revised estimate has complete regeneration by secondary forests storing carbon at only 15% of that of the original forest.

$CO_2$ fertilization is discounted by Fearnside as a inadequate carbon sink. Plants are often limited in their growth by the lack of other nutrients, water and sunlight. Additional $CO_2$ in the atmosphere will only increase growth and carbon uptake a minimal amount. Climate changes from greenhouse gas concentrations could also alter the environment to reduce growth rates of plants. Finally, carbon deposited as litter and buried in sediments is not an important sink of carbon in the Legal Amazon. Most carbon in the rivers is from the Andes, not from the forests. Carbon is in a dissolved, not particulate state, and is in small concentrations compared to the amount of carbon released from deforestation. Much of the carbon washed away from burn sites, etc. would remain exposed to oxidation.

Fearnside concludes by claiming that 49.7 G tons C is the best present estimate of the longterm release of carbon from converting the Legal Amazon to cattle pasture, an amount 20% lower than his previous estimate.

**Fearnside, P.M. 1986.** **"Brazil's Amazon Forest and the Global Carbon Problem: Reply to Lugo and Brown". Interciencia 11(2): 58-64.**

ABSTRACT:

Fearnside rebuts arguments made by Lugo and Brown (Interciencia 11(2): 57-58) which question the validity of his 1985 literature review and calculations on the contribution of tropical deforestation to the global carbon problem (Interciencia 10 (4): 179-186). Lugo and Brown maintain that Fearnside's article exaggerates the carbon dioxide contribution of tropical deforestation due to the author's citation of old literature, his factual mistakes, and his preconceived bias.

Fearnside maintains that his review of old and new literature has been thorough, and that his analysis was conservative. He admits some factual errors were present in his article, but denies that they significantly alter his findings, and he denies that he was biased.

In response to the alleged factual errors, Fearnside: (1) admits that above-ground biomass figures were mistakenly labeled total biomass in the text, but maintains his calculations were correct save for one minor error which decreased released carbon; (2) admits some biomass figures may be high but denies better information is available in some cases, and denies the resulting error could reach the magnitude Lugo and Brown suggest; (3) claims that reliable values for the area of secondary forest are difficult to obtain; (4) disputes Lugo and Brown's claim that he has overestimated the carbon loss following conversion to pasture; and (5) disputes that his rates of carbon release due to land use change are unacceptable.

In regard to the allegations of unsubstantiated bias, Fearnside feels his analysis was conservative, and specifically responds that: (1) recovery rates for degraded pastures are low; (2) no evidence exists to indicate that natural forests have a role in the carbon cycle; and (3) he has not assumed delayed effects will cause all carbon in the Amazon vegetation to become airborne.