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Abstract

This paper provides an estimate of the amount of carbon emissions that resulted from large scale deforestation in the Brazilian Amazon during the aggressive development period 1970 - 1985.

The estimate is derived by combining a dynamic carbon model with a municipality level data set describing natural vegetation cover and land uses in 316 municipalities in Legal Amazonia.

The results show average carbon emissions from Legal Amazonia of 168 million tons per year during the period 1970-1985, or about 95 tC per hectare cleared. This is lower than other estimates found in the literature because we take into account the uneven spatial distribution of clearing.

The agressive development policies implied rapid economic growth in the region. On average, there was generated GDP of approximately $44 per ton carbon emítted.

JEL classification: Q23, Q28, R12, R14.

Keywords: Amazon deforestation, carbon emissions.

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1. Introduction

Deforestation has costs at both local and international levels, and one of the biggest international concerns seems to be its contribution to global warming through the release of the carbon that used to be stored in the biomass of the forests. Since Brazil contains vast amounts of forest and has been deforesting rapidly in the name of development, it is perceived as one of the main contributors to global warming. Deforestation in the Brazilian Amazon alone has been estimated to account for 1 to 9% of total CO_2 emissions (Schroeder & Winjum 1994; World Bank 1991; Brown & Lugo 1992).

It has been argued that a reduction in tropical deforestation rates would be a relatively cheap way of curbing global CO_2 emissions compared to the cost of reducing fossil fuel consumption in the industrialized world (Nordhaus 1991; Schneider 1993; Kolk 1996; FACE 1993). To assess whether this is a reasonable argument one would need better estimates of carbon emissions from deforestation as well as better estimates of the benefits of deforestation. This paper attempts to provide such estimates for the Brazilian Amazon by the use of detailed municipality level data for the period 1970—1985. This period was characterized by the implementation of unusually aggressive development policies in the region, resulting in rapid deforestation as well as rapid economic growth.

The remainder of the paper is organized as follows. Section 2 describes the carbon emissions model and the parameter values used for simulations. Section 3 describes the data on original vegetation cover and changes in land use and summarizes the estimated age structure of deforested land. Section 4 summarizes deforestation measures and the calculated carbon emissions and compares these to the economic activity generated by the agressive policies. Section 5 discusses factors contributing to uncertainty in the carbon estimates and makes several sensitivity analyses. Section 6 concludes.

2. The carbon emission model

A typical dense forest of the Brazilian Amazon contains a biomass of about 350 tons per hectare with a dry weight carbon content of approximately 50%, i.e. about 175 tC/ha. Typical agricultural land, on the other hand, contains less than 10 tC/ha. Thus, when forests are converted to agricultural land uses, massive amounts of carbon is released to the atmosphere, thus contributing to the increasing concentration of CO_2 in our atmosphere.

Houghton *et al* (1983) has developed a carbon emissions model that keeps track of the carbon that was originally stored in the biomass of the forest when the forest is converted to agricultural land use through slash-and-burn methods.

Various versions of this model has been used by Schroeder & Winjum (1994a, 1994b) and Reis (1996) to calculate carbon emissions from changes in land use in Brazil.

The carbon model has two important parts. First, a set of equilibrium values for the carbon content in different types of forests and in different types of land uses. Second, a set of response functions that indicate how carbon is decomposed and recomposed after changes in land use. The model is a bookkeeping type of model, and is thus purely mechanical. The parameters used to run the model are compiled from the literature.

2.1. Carbon contents

Table 1 presents central[1] estimates of carbon contents in different vegetation types and for different land uses in the Amazon[2]. The dry weight carbon content is everywhere assumed to be 50% of biomass (Fearnside *et al* 1993; Brown & Lugo 1984).

Aboveground estimates of carbon content is taken from Reis (1996) which is based on Bohrer's (1993) survey. Belowground carbon content is assumed to be 17% of above ground carbon content for dense forest, seasonal forest, and campinarana (Reis 1996; Brown & Lugo 1992; Schroeder & Winjum 1994; Fearnside 1992b). For savanna and ecological transition (cerrado woodland) belowground carbon content is assumed to be 160% of aboveground carbon content (Schroeder & Winjum 1994a; Singh & Joshi 1979). For wetlands this ratio is assumed to be 75% (Schroeder & Winjum 1994a; Cannell 1982).

Reis (1996) assumes that all secondary vegetation is identical and reaches a modest climax carbon content of 43.9 tC/ha after 40 years. This is a very conservative estimate which results in a worst case scenario for carbon emissions. In this paper we allow for different kinds of secondary vegetation and more realistic climax values. Following Houghton et *al* (1983), we assume that secondary vegetation in dense forest, seasonal forest, and campinarana areas reaches 75% of the original carbon content after 50 years. Secondary vegetation in savanna, wetlands, and ecological transition areas is assumed to reach 100% of original carbon content after 50 years (Houghton *et al* 1983).

For agropastoral land use (crops and planted pasture) it is assumed, according to Sanchez *et al* (1989), that belowground carbon content is 18% of aboveground carbon content.

Table 1: Carbon contents for different vegetation types and land uses

Vegetation type/ land use	Aboye-ground[a] (tC/ha)	Below-ground (tC/ha)	Total (tC/ha)
Primary vegetation:			
Dense forest (62.5%)	150.0	25.5	175.5
Seasonal forest (6.1%)	93.0	15.8	108.8
Savannas (15.4%)	37.5	60.0	97.5
Ecological transition (7.3%)	65.0	104.0	169.0
Wetlands (2.5%)	57.5	43.1	100.6
Campinarana (5.4%)	60.0	10.2	70.2
Secondary vegetation: (climax)			
Dense forest	112.5	19.1	131.6
Seasonal forest	69.7	11.9	81.6
Savannas	37.5	60.0	97.5
Ecological transition	65.0	104.0	169.0
Wetlands	57.5	43.1	100.6
Campinarana	45.0	7.7	52.7
Agropastoral land use	5.0	0.9	5.9

Source: Reis (1996) + assumptions in text.

a: Including litter.

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[1] Reis (1996, Table 3), in contrast, presents worst case numbers in the sense that carbon contents for natural vegetation are from the upper end of the range found in the literature, while carbon contents for agropastoral land and secondary forests are in the low end.

[2] Carbon contents vary greatly from plot to plot and from region to region. This has resulted in a vide variation in estimate of average carbon contents. See Brown & Lugo (1984), Fearnside **(1986,** 1987), Brown *et al* (1989), Brown & Lugo (1992), and Fearnside (1992) for a debate about biomass content in the Brazilian Amazon.

2.2 Carbon Dynamics

Typical slash-and-burn agriculture in the Amazon involves three phases: i) land clearing and forest burning, ii) agropastoral use of land, iii) soil exhaustion, land abandonment, and the recomposition of secondary vegetation. Figure 1 illustrates the carbon cycle of vegetation in this pattern of agricultural settlement.

Carbon emissions from deforestation can usefully be divided into the three phases identified for slash-and-burn agriculture. Evidence from Seiler and Crutzen (1980), Fearnside (1992), Fearnside et *al* (1993), Carvalho Jr. *et al* (1994), and Houghton *et al* (1991) suggests that about 30% of aboveground carbon is released in the first phase of forest burning, while belowground carbon is released in this phase. In the second phase, the remaining aboveground carbon plus belowground carbon is slowly decomposed. It is assumed that the decomposition follows an exponential decay function:

$$cav_{v,i} \quad = \quad 0.7\,.\,cav_{v,0}\;.\,e^{-r_v^{\cdot i}}$$

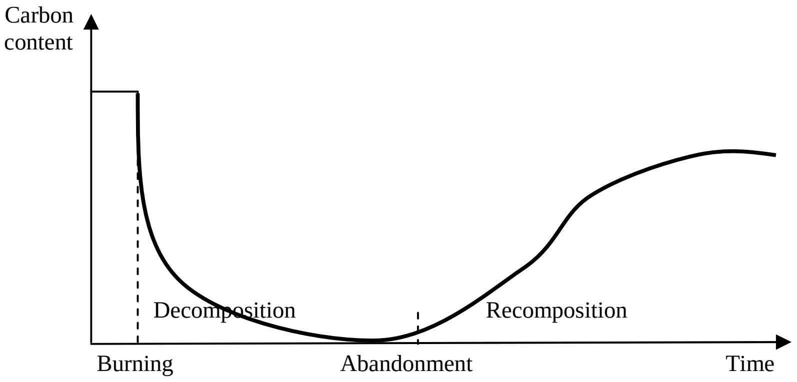
where $cav_{v,i}$ is aboveground carbon content in the original vegetation of type *v, i* periods after burning, $cav_{v,0}$ is aboveground carbon content in original vegetation type *y* before burning, r_v is the rate of carbon decomposition after burning un vegetation type *y,* and *i* is time elapsed since forest burning.

For belowground carbon we do not observe any immediate decline during forest burning, so the decay function for belowground carbon in natural vegetation becomes:

$$cbv_{v,i} \quad = \quad cbv_{v,0}\;.\,e^{-r_v^{\cdot i}}$$

where $cbv_{v,i}$ is belowground carbon content in the original vegetation of type *v, i* periods after burning,

Figure 1: Carbon contents during a slash-and-burn cycle



Reis (1996) uses the same decay rates for above and belowground carbon in which case the total carbon content in original vegetation becomes:

$$cv_{v,i} \quad = \quad cav_{v,i} + cbv_{v,i} \quad = \quad (0.7\,.\,cav_{v,0} + cbv_{v,0})\,.\,e^{-r_v^{\cdot i}} \qquad (1)$$

Houghton *et al* (1991) estimate rates of carbon decomposition of 0.5 for closed forests and 0.3 for savannas. Following Reis (1996) we assume a rate of 0.4 for other vegetation types. These rates imply that 94% of aboveground carbon in dense forests is released within 5 years, with the corresponding numbers for savanna and other vegetation types being 84%

and 91%, respectively. Within 15 years more than 99% of aboveground carbon will be emitted for all vegetation types.

In the third phase there will be a recomposition of biomass and carbon stock as secondary species invade the abandoned land. Recomposition will be relatively rapid in the beginning due to the fast growth of pioneer species (Uhl *et al* 1988, Uhl 1987, Houghton *et al* 1983) but will then slow down and converge to a new climax. Odum (1988) suggest the following specification for the recomposition of biomass and carbon content in abandoned areas:

$$cf_{v,i} \quad = \quad \frac{cm_v}{1+e^{(a_v\,-\,s_v\,.\,i)}}\,, \qquad (2)$$

where $cf_{v,i}$ is carbon content (both above- and belowground) in fallow land of age i on vegetation type v, cm_v is the climax carbon content of vegetation type v, and a_v, and s_v are parameters to be estimated.

To estimate the parameters a_v, and s_v , we make the following assumptions: i) The carbon content at the time of abandonment is equal to that of agropastoral land use, i.e. $cf_{v,0}$ = 5.9 tC/ha for ah vegetation types. ji) Fallow lands take 50 years to reach 99% of their climax carbon content.

The climax carbon contents of different vegetation types are given in Table 1. When combined with the assumptions above they yield the following values for a_v, and s_v:

Table 2: Decay parameters

Vegetation type	$a_{v,}$	s_v
Dense forest	3.0589	0.1530
Seasonal forest	2.5518	0.1429
Savanna	2.7425	0.1468
Ecological transition	3.3194	0.1583
Wetlands	2.7758	0.1474
Campinarana	2.0701	0.1333

2.3 Carbon Stocks

The carbon stock in a given municipality at time t is the sum of the carbon stock in original vegetation, CV_t, the carbon stock in crops, CK_t and the carbon stock in fallow lands, CF_t:

$$C_t \quad = \quad CV_t + CK_t + CF_t$$

The carbon stock in original vegetation consists of two parts. First, the carbon stock in undisturbed areas, and second the decaying carbon stock in deforested areas:

$$CV_t \quad = \quad \sum cv_{v,0}\,.\,(A_{v,0} - D_{v,t}) + \sum_v \; \sum_i cv_{v,i}\,.\,A^c_{v,i,t}\,,$$

where $A_{v,0}$ is area of vegetation type y at time 0, $D_{v,t}$ is deforested area on vegetation type v at time t, $A^c_{v,i,t}$ is crop area of age i on vegetation type v at time t, and $CV_{v,i,}$ the decreasing carbon contents of deforested natural vegetation given by Equation 1.

The carbon content in crops is assumed to be identical for ah crops (including planted pasture), so the carbon stock in crops becomes:

$$CK_t \quad = \quad ck \quad . \quad \sum_v \sum_i A^c_{c,i,t} \ ,$$

where *ck* is the carbon content of ah types and ages of crops.

The carbon stock in fallow areas is the sum of the carbon stock in fallow on different vegetation types and of different ages:

$$CF_t \quad = \quad \sum_v \sum_i cf_{v,i} \quad . \quad F_{v,i,t} \ ,$$

where $F_{v,i,t}$ is fallow land of age *i* at time t on vegetation type *v,* and $cf_{v,i}$ is the increasing carbon content of fallow areas given by Equation 2.

The sum of crop areas and fallow areas add up to total deforested area. Thus:

$$\sum_v D_{v,t} \quad = \quad \sum_v \sum_i A^c_{v,i,t} + \sum_v \sum_i F_{v,i,t} \ ,$$

2.4 The Age Structure of Fallow Lands

Information about the age structure of fallow lands is not available in the Amazon data set (see section 3 below), but it can be estimated, if we are willing to make some assumptions. We need assumptions both about the initial age structure of fallow lands and about the dynamic process that guides the aging and use of fallow lands.

To estimate the initial age structure, we make the assumption that the average age of fallow area in period 0 in municipality *j,* I_{oj}, is determined by the share of fallow in total agropastoral areas, D_{0j}, in such a way that a higher share of fallow implies a higher average age of fallow:

$$I_{oj} \quad = \quad K \quad . \quad \frac{F_{oj}}{D_{oj}} \ ,$$

where *K* is a parameter determined by the condition that the average age of fallow over all municipalities should equal the assumed average for Legal Amazonia, l_{0A}:

$$I_{0A} \quad = \quad \sum_j I_{0j} \quad . \quad \frac{F_{0j}}{F_{0A}} \ ,$$

and F_{0A} is total fallow area in Legal Amazonia at time 0, i.e. $F_{0A} = \sum_j F_{0j}$ F_{0A} .

The dynamic changes in the age structure is believed to be well characterized by the following two assumptions. First, when fallow areas are expanding, the increase must be fallow of age 1, while the rest of the fallow area just gets one period older. The extent of fallow of age *i* at time *t,* in a given municipality, is thus determined by:

$$\left.\begin{array}{llll} F_{t,i} & = \Delta F_t & for\ i & = \ 1 \\ F_{t,i} & = F_{t-1,i-1} & for\ i & \rangle \ 1 \end{array}\right\} \ when\ \Delta F_t \ \geq \ 0$$

Second, when fallow areas are contracting, it is because the oldest fallow is being converted to crop land again. This assumption can be following equations:

$$\left.\begin{array}{lll} F_{t,i} = F_{t-1,i-1} & for\ i \rangle 1 & if \sum_{j=2}^{i} F_{t-1,j-1} \leq \ F_t \\ F_{t,i} = F_t - \sum_{j=2}^{i*} F_{t-1,j-1} & for\ i = 1 & \end{array}\right\} \ when\ \Delta F_t \ < \ 0$$

where *i** is the maximum age of follow that is not converted to crop land (as determined by the condition in the first equation).

3. The Data

The data for this project comes from a big data base compiled and maintained at the Institute for Applied Economic Research in Rio de Janeiro, Brazil. It covers all the municipalities in Legal Amazonia, spans the period 1970-1985, and measures hundreds of variables that might be relevant for modeling deforestation and economic development in the region. For this paper, we will use only a small subset of all the variables available. These are the variables specifically describing land use and vegetation cover.

The data on original vegetation cover is provided by IBGE, who operate with 6 main categories: I) dense forest, ii) seasonal forest, iii) savanna, iv) ecological transition, v) wetlands, and vi) Campinarana. The are big regional variations in the density of the natural vegetation cover.

The agricultural censuses conducted every five years by IBGE provide the data about changes in land use. Private land used for annual crops, planted forest, planted pasture, and fallow land is considered cleared areas, while all public land plus private land kept as natural forest and natural pasture is considered virgin areas.

3.1 Summary of the Age Structure of Deforested Areas

3.1.1 The age structure of fallow lands

1970 is the initial years of our analysis and the remaining observations come at five year intervals. We assume that the average age of fallow lands in 1970 was 3.5 years and that all fallow land was 10 years old.[3] Using that assumption and the equations of section 2.4, we get an age structure as described in Tables 3 and 4.

Table 3: Estimated age structure of fallow areas in Legal Amazonia

Age group (years)	Area (million hectares)			
	1970	1975	1980	1985
0 - 5	9.2	2.4	5.0	7.4
5 - 10	3.8	7.1	1.7	4.6
10 - 15	0	1.0	5.9	1.5
15 - 20	0	0	0.5	5.4
20 - 25	0	0	0	0.4
Total	13.0	10.4	13.1	19.4

Table 4: Summary statistics for the average age of fallow areas across municipalities.

	1970	1975	1980	1985
Mean	3.5	6.6	8.6	9.6
Std. dey.	0.8	1.7	3.2	4.0
Minimum	2.5	2.5	2.5	2.7
Maximum	5.0	9.8	14.0	18.8
Num. obs.	316	315	316	316

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[3] Reis (1996) chose an initial average age 2.5 in 1975, but noted that this seemed to be too low. It also seemed to be too low for 1970, so we chose 3.5 instead. The carbon emissions results are not sensitive to changes in this parameter.

3.1.2 The age structure of crop Lands

The productivity of annual crops on tropical forest soils is very high the first couple of years while there is an abundance of nutrients from the ashes and while the land is relatively pest free after burning. Thereafter productivity drops sharply, and a long fallow period is needed before the process can be repeated. The alternative is to plant perennial crops and supply the necessary fertilizers and pesticides.

We assume that areas with annual crops and planted pasture have been cleared for 2.5 years, on average. Areas with perennial crops and planted forest is assumed to have been cleared for 7.5 years, on average.

4. Deforestation, Carbon Emissions and Economic Growth 1970—1985

4.1 Deforestation

Table 5 shows that deforestation has been very unevenly distributed across Legal Amazonia. The largest state, with the most dense forest, had lost less than 1 percent of its natural vegetation by 1985 while the more accessible states in the eastern and southern part of Legal Amazonia had lost between 15 and 30%. This pattern also shows in Table 6 which gives the percentage of each vegetation type cleared by 1985. More than 20% of ah savanna has been converted for agropastoral purposes and much of the remaining savanna is used as natural pastures. Less than 6% of the dense forest had been cleared by 1985.

Table 5: Accumulated deforestation in Legal Amazonia by 1985

State	State area (million ha)	Share deforested %
Acre	15.3	3.7
Amapá	14.3	2.5
Amazonas	157.8	0.9
Goiás	29.2	27.1
Maranhao	28.4	30.0
Mato Grosso	90.7	15.5
Pará	125.3	7.8
Rondônia	23.9	7.3
Roraima	22.5	1.6
Total	507.4	8.8

Source: **The DESMAT data set. Variables: GEAREA, PASPLA85, FLOPLA85, LATEM85, LAPER85, FAL85.**

Table 6: Accumulated deforestation in Legal Amazonia by 1985

Natural vegetation	Area (million ha)	Share deforested %
Dense forest	317.0	5.6
Seasonal forest	30.7	13.4
Savanna	78.3	20.4
Ecological transition	36.9	13.5
Wetlands	13.1	12.8
Campinarana	31.4	0.4
Total	507.4	8.8

Source: The **DESMAT** data set. Variables: **PASPLA85, FLOPLA85, LATEM85, LAPER85, FAL85, FODAR, FESAR, SAVAR, TECAR, FOPAR, CAMAR.**

It is important to take into account the uneven distribution of clearing when calculating carbon emissions. In this paper, we assume that clearing is randomly distributed across vegetation types *within each municipality,* but because of the large variations in vegetation types and clearing rates across municipalities, we get non-randomly distributed clearing across vegetation types in the whole region (see Table 6).

4.2 Carbon emissions

According to our carbon emissions model, the total carbon stock in Legal Amazonia declined from 74.7 billion tons in 1970 to 72.1 billion tons in 1985 implying average annual emissions of 168 million tC. This is a net effect arising from carbon release from the destroyed original vegetation (198 rnillion tC/year) and carbon sequestration in secondary vegetation (-30 million tC/year). Globally, annual carbon emissions amount to approximately 7.0 billion tC implying a contribution from Amazon deforestation of about 2.4%. The largest emissions carne from the southern and eastern states of Pará, Mato Grosso, Maranhão, and Goiás. See Table 7. The table also shows that the latter three states had the lowest emissions per hectare of cleared vegetation. This is due to the generally thinner natural vegetation in these states.

Table 7: Carbon emissions in ~gal Amazonia 1970—1985

State	Accumulated carbon emissions 1970-1985 (million tC)	Carbon emissions per hectare cleared 1970-1985 (tC/ha)
Acre	54.5	135.5
Amapá	31.1	119.0
Amazonas	67.1	128.4
Goiás	335.5	76.0
Maranhão	388.8	112.2
Mato Grosso	689.8	68.5
Pará	776.4	130.0
Rondónia	150.2	119.0
Roraima	22.8	101.0
Total	2,516.0	94.6

Source: The **DESMAT** data set. Variables: **PASPLAyy, FLOPLAyy, LATEMyy, LAPERyy, FALyy, FODAR, FESAR, SAVAR, TECAR, FOPAR, CAMAR** + assumptions in text

4.3 Economic growth

Total agricultural output in Legal Amazonia increased from US$ 654 million in 1970 to 2,274 million in 1985 (measured in fixed 1985-US$). Urban GDP grew even faster from US$ 1,522 million in 1970 to 11,206 million. This implies an impressive average annual GDP growth rate of 12.9%. Table 9 shows the cumulated GDP over the 1970-1985 period for the fine states in Legal Amazonia and compares it with the carbon emitted.

On average, the states obtained an accumulated GDP of $44. 1 per ton of carbon they omitted. There are big variations, however. The densely forested and largely inaccessible state of Amazonas obtained a much better trade-off between economic output and carbon emissions than the more accessible and less densely forested south-eastern states like Goiás and Mato Grosso. There are several explanations for these large differences. Goiás and Mato Grosso attracted a lot of cattle ranchers who mainly speculated in rising land prices and tax evasion while the cattle raising activity itself gave very low, if not negative, yields. The activities in Amazonas, on the other hand, were much more diversified including extractivism (mainly rubber and Brazil nuts) and a big industry related to the Manaus Free Zone.

Table 8: Carbon emissions in Legal Amazonia 1970—1985

State	Accumulated carbon *emissions* 1970-1985 (million tC)	Carbon emissions per hectare cleared 1970-1985 (tC/ha)
Dense forest	1,446.1	133.6
Seasonal forest	185.7	71.8
Savanna	499.5	52.5
Ecological transition	354.0	113.9
Wetlands	27.6	56.5
Campinarana	3.2	41.7
Total	2,516.0	94.6

Source: The **DESMAT** data set. Variab1es: **PASPLAyy, FLOPLAyy, LATEMyy, LAPERyy, FALyy, FODAR, FESAR, SAVAR, TEOAR, FOPAR, CAMAR** ± **assumptions** in text.

5. Discussion

5.1. Comparisons with other carbon emission studies

Fearnside (1992b) conducted an intensive study of carbon dynamics in the Brazilian Amazon. Rather than using a bookkeeping model, as is done in this paper, he uses a committed carbon approach, thus attributing ah carbon that would ultimately be released to the year where deforestation takes place. He concludes that clearing of 1.38 million hectares per year of primary forest was responsible for the release of approximately 270 million tC/year in the period 1989-1990. This corresponds to 196 tC/ha, which is considerably higher than our average estimate for the 1970-1985 period (94.6 tC/ha).

Table 9: Accumulated GDP in Legal Amazonia 1970—1985

State	Accumulated GDP 1970-1985 (billion fixed 1985-US$)	Average GDP per ton carbon emitted 1970-1985 ($/tC)
Acre	2.8	50.9
Amapá	2.1	67.1
Amazonas	25.5	379.4
Goiás	4.5	13.3
Maranhao	18.9	48.5
Mato Grosso	13.9	20.1
Pará	35.8	46.1
Rondónia	6.6	44.3
Roraima	1.1	47.5
Total	111.0	44.1

Source: The DESMAT data set. Variables: PASPLAyy, FLOPLAyy, LATEMyy, LAPERyy, FALyy, FODAR, FESAR, SAVAR, TECAR, FOPAR, CAMAR, PIBAGyy, PIBURByy ± assumptions in text.

Schroeder & Winjum (1994b) gives a much lower estimate of net carbon emissions from land use changes in all of Brazil. Using a bookkeeping model with gradual decomposition of carbon in cleared areas and gradual recomposition in secondary forest, they get net carbon emissions for Brazil in the range of -44 to +10 million tC/year for 1990. The large discrepancy between Fearnside (1992b) and Schroeder & Winjum (1994b) is mainly attributed to the massive carbon recomposition in secondary forests in the latter study (+245 million tC/year).

5.2 Uncertainties

5.2.1 Biomass content

Biomass contents of Amazonian forest patches vary greatly due to differences in soil characteristics, rainfall regimes, altitude, and previous natural and antropogenic disturbances. In addition, there is a large statistical variation when sampling forest patches, because biomass content is very sensitive to the presence of large trees.

There has been a vigorous debate on the forest biomass in the Brazilian Amazon (Brown Lugo 1984, 1990, 1992; Fearnside 1985, 1986, 1987, 1992; Lugo & and Brown 1986; Brown et *al* 1989). Brown *et al* (1995) notes that the estimates during the last decade differ by more than a factor of two. They provide a new study for biomass content in Rondônia and gives an estimate of the uncertainty associated with the biomass estimate. Through Monte Carlo Simulation they find that measurement errors are approximately +20% around the mean (for a 95% confidence interval).

If we use carbon contents that are 20% lower than our mean values we get a lower estimate of annual carbon release of 128 million tC per year or 72.2 tC per hectare cleared. Similarly, we get a high estimate of 207 million tC per year or 117 tC per hectare cleared. See Table 10.

Table 10: Biomass sensitivity analysis

	Low biomass content	Central biomass content	High biomass content
Average annual emissions (million tC)	128	168	207
Average emissions per hectare cleared (tC/ha)	72.2	94.6	117.0
Average **GDP** per tC emitted (1985-US$)/tC)	57.8	44.1	35.7

5.2.2 Steady state assumption

The calculations done in this paper assumes that undisturbed primary forest, which still account for the major part of the Brazilian Amazon, is in a steady state equilibrium with no net carbon gain or loss. Lugo & Brown (1992) questions this assumption of a steady state equilibrium, arguing that the rate of biomass accumulation of tropical forests is changing over time as a result of natural climatic changes, catastrophes, and past human disturbances. They cite plot level field data from Venezuela and Puerto Rico that show mature forests accumulating carbon at rates of 1 - 2 tC/ha/year (Schroeder & Winjum 1994b).

A possible explanation for the increase in steady state carbon levels is CO_2 fertilization. Studies of agricultural and wild plant species have shown typically 20-40% higher photosynthesis and growth under doubled CO_2 conditions (Rochefort & Bazzaz 1992; Körner & Arnone 1992; Idso & Kimball 1993). This effect suggests faster forest regrowth and can also help explaining a possible increase in steady state carbon stocks. Schimel (1995) notes, however, that long term, ecosystem responses may be substantially smaller than plant-level responses measured in laboratories.

Because of the huge area of primary forest in the Amazon, even the slightest change in biomass per hectare would result in significant effects on total carbon storage. If the approximately 350 million hectares of primary dense forest in the Brazilian Amazon, for example, increased its biomass with just 0.5% per year, then about 300 million tC would be sequestered every year. This number is larger than our estimate of annual carbon emitted from deforested areas. That makes it difficult to say anything certain about the net emissions from the whole of Legal Amazonia. Our analysis only applies to the net contributions from disturbed areas.

6. Conclusions

The calculations in this paper indicate that average annual carbon emissions from deforestation in the Brazilian Amazon falls in the range 128 - 207 million tC/year during the rapid development period 1970 - 1985. This corresponds to 1.8 - 3.0% of global carbon emissions from fossil fuel combustion and deforestation. The estimated range is within the range provided by other studies, but falls in the low end. This is due to two factors. First, we take into account the uneven spatial distribution of deforestation: Lower clearing costs causes deforestation to take place in the most accessible and least dense forests as long as these are available. Second, we take into account the considerable secondary regrowth and carbon sequestration that takes place when cleared land is abandoned.

During the same period, the Amazonian economy grew rapidly resulting in average annual GDP growth rates of 12.9%. This is impressive by any measure, and several studies show that settlers in the Amazon did well, especially when you take into account their generally poor background (Mattos, Uhl & Goncalves 1992; Ozorio de Almeida 1992; FAO/UNDP/MARA 1992; Jones *et al* 1992; Schneider 1992). On average during the period, there was generated $44 of GDP per ton carbon emitted. There were big variations in the benefit, however. In the state of Amazonas the benefit was as high as $379/tC. For comparison, the CO_2 tax implemented in Denmark in 1992 require households to pay $16 per ton carbon emitted and VAT-registered firms to pay half the tax (Svendsen 1996 quoted in Young 1997). It is therefore not at ah clear that stopping deforestation is the cheapest (and most just) way to curb carbon emissions. Especially not when we take into account that it will also require substantial direct costs to protect the Amazon against slash-and-burn deforestation.

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