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SUMMARY OF PROGRESS IN QUANTIFYING THE POTENTIAL CONTRIBUTION OF AMAZONIAN DEFORESTATION TO THE GLOBAL CARBON PROBLEM

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SUMMARY

Conversion of Brazil's Legal Amazon (5×10^6 km^2) to cattle pasture would make a significant contribution to the global carbon problem over the few decades that the forest could be expected to remain in existence. The present paper updates my previous calculation of the magnitude of this contribution (best current estimate: 49.7 G tons long-term release), and reviews controversies surrounding the biomass of Amazonian forests and the importance of various possible carbon sinks within the region.

RESUMO DO PROGRESSO OBTIDO NA QUANTIFICAÇÃO DO POTENCIAL DE CONTRIBUIÇÃO DO DESMATAMENTO DA AMAZÔNIA PARA O PROBLEMA DO CARBONO GLOBAL.

RESUMO

A conversão da Amazônia Brasileira Legal (5×10^6 km^2) em pastagens representaria uma contribuição significante ao problema global do carbono, dentro das próximas décadas em que se espera que a floresta continue existindo. Este trabalho atualiza cálculos anteriores sobre a grandeza dessa contribuição (melhor estimativa corrente: 49.7 G ton. de liberação a longo prazo), e faz uma revisão das controvérsias acerca da biomassa das florestas Amazônicas e a importância de possíveis reservas de carbono dentro da região.

Introduction

Brazil's Amazon region is being converted to cattle pasture at a rapid rate (FEARNSIDE, 1983). Calculations of what environmental impacts would ensue from a hypothetical complete conversion are necessary to provide decision-makers with the information they need to judge whether taking action to contain deforestation would be worth the substantial financial and political costs of achieving that goal. The present paper updates and amplifies my discussion of "Brazil's Amazon Forest and the Global Carbon Problem" that appeared recently in Interciencia (FEARNSIDE, 1985).

The Interciencia paper reviewed the academic controversies surrounding the potential role of deforestation as a source of atmospheric CO_2 and the interpretation of these releases in terms of climatic change. A calculation was made of the biomass and carbon stock of the natural vegetation and surface soil in Brazil's 5×10^6 km^2 Legal Amazon. The calculation for vegetation is summarized here in Tables I and II. Sources of the information used can be found in FEARNSIDE (1985)[1].

TABLE I - Biomass of vegetation types in the Brazilian Legal Amazon (m tons ha^{-1} dry weight)

Vegetation Type	Live Above Ground	Below Ground	Litter and Dead Above ground	Total
Upland Dense Forest	251.7	86.3	23.5	361.5
Scrub Forest (Cerrado)	37.8	25.2	7.7	70.7
Montane Forest	198.0	64.8	3.15	265.95
Other Upland Forest Types	277.5	70.3	22.2	370.0
Humid Savanna (upland + flooded)	71.5	31.9	6.7	110.1
Flooded Forests (Várzea + Igapõ)	158.1	54.2	3.34	215.64
Mangroves	162.5	150.0	102.1	454.6

Improving the Dense Forest Biomass Estimate

Since the bulk of the Amazon region's biomass and carbon stock is in the dense forest vegetation type, improving the reliability of the estimate for this type will have the greatest impact on the final results. Since forest biomass varies greatly in different parts of the region, in addition to high variability over distances of a few

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meters, reliance on the few available direct estimates from destructive techniques carries the risk of error from inadequate sampling. There is an inevitable tradeoff between using a small number of high-quality measurements and the representativeness gained from a wider base of less reliable ones. In this case, incorporation of indirect approximations of biomass derived from forestry inventories is probably justified.

TABLE II - Carbon stocks in "natural" vegetation in the Brazilian Legal Amazon.

Vegetation Type	Area (Km^2)	Live above Ground	Below ground	Litter and dead above ground
Upland Dense Forest	3,063,000	34.69	11.90	3.239
Scrub Forest (Cerrado)	1,290,520	2.20	1.46	0.450
Montane Forest	26,000	0.23	0.08	0.004
Other Upland Forest Types	259,000	3.23	0.82	0.260
Humid Savanna. (upland + flooded)	165,000	0.53	0.24	0.050
Flooded Forests (Vārzea + Igapō)	70,000	0.50	0.17	0.011
Mangroves	1,000	0,01	0,01	0,005
T O T A L S	4,874,520	41.39	14.68	4.02

TOTAL CARBON 60.09 G tons

As mentioned in my previous paper, BROWN and LUGO (1984) used timber volume estimates from existing forestry inventories done by the Food and Agriculture Organization of the United Nations (F.A.O.) to arrive at a biomass value of only, 155.1 m tons ha^{-1} for "tropical American closed undisturbed productive broadleaf forests". Anyone who has actually weighed biomass directly in the Brazilian Amazon has arrived at values more than double this figure (Table III). Timber volume inventories are subject to error because they measure only large trees -- above a minimum of 25 cm diameter at breast height (DBH) in the data base used by BROWN and LUGO (1984: Figure 1 caption). BROWN and LUGO used a factor of 1.6 to correct the biomass of boles $\geq$ 10 cm DBH to total biomass and a factor of 1.2 to convert "merchantable volume" for trees > 25 cm DBH to an estimated value for bole biomass for trees $\geq$ 10 cm DBH. The understory was ignored, but this would affect the estimates by less than 2% (BROWN and LUGO, 1984: 1291). While both correction factors appear reasonable, the result for "tropical American closed undisturbed broadleaf forests" is so much lower than values from direct measurements that closer scrutiny is necessary before accepting it as applying to the Brazilian Amazon.

A rough calculation can be made of biomass in the Brazilian Amazon employing the methods and most of the data base used by BROWN and LUGO. The four volumes of data published by F.A.O. that BROWN and LUGO used in the Brazilian portion of their study are available at Manaus (HEINSDIJK, 1957, 1958 a, b, c). One volume used by BROWN and LUGO that was not published by F.A.O. is not available at Manaus (JAPIASSU and GŌES FILHO, 1974), and one volume not used by BROWN and LUGO is available (GLERUM, 1960). The results for the 16 localities surveyed in the volumes available at Manaus are presented in Table IV. The mean estimate for total biomass is 226.1 m tons ha^{-1}. Using this as the biomass value for upland dense forest in my calculation for the Brazilian Legal Amazon, the total carbon store is 41.42 G tons -- a reduction of 31.1% from the value given in my paper.

TABLE III - Biomass estimates in upland dense forest in Brazilian Amazonia$^{(a)}$

Above Ground	Total	Location	Reference
247.84	(355.9)$^{(b)}$	Tucuruī	Cardenas et al., 1982
255.60	(367.1)$^{(b)}$	Manaus	Klinge and Rodrigues, 1974$^{(c)}$
353.4	507.5	Manaus	Klinge et al., 1975
	354	Jari	Jordan and Russell, 1983$^{(d)}$
	155.1	"Tropical American undisturbed productive broadleafed forests"	Brown and Lugo, 1984

(a) Metric tons ha^{-1} dry weight.

(b) Estimated using ratio of above ground to total biomass measured by Klinge et al. (1975).

(c) An extension of the direct measurement (Klinge et al., 1975) to 5 nondestructive quadrat and transect forest surveys in the Manaus area (see Fearnside, 1985: Table I, note d). Klinge (personal communication, 1985) now believes that the higher value based solely on direct measurement is the more trustworthy of the two. I have used the lower value therefore biased the outcome toward lesser impact of deforestation.

(d) "Wood" biomass only.

TABLE IV - Biomass from forest volume surveys in Brazilian Amazonia

Locality	Volume[(a)] (m^3 ha^{-1})	Biomass[(b)] (m tons ha^{-1})	Reference[(c)]
Santarém (Slope or "Flanco" forest)	135	160.7	Vol. 1, p. 113
Santarém (plateau or "planalto" forest)	223	265.5	Vol. 1, p. 113
Amapá	162	192.8	Vol. 1, p. 113
West of Portel	314	373.8	Vol. 1, p. 113
Caxuana	271	322.6	Vol. 2, p. 35
Portel	228	271.4	Vol. 2, p. 35
Cametá Oeste	192	228.6	Vol. 2, p. 35
Rio Aripiuns	146	173.8	Vol. 3, p. 13
Maués	169	201.2	Vol. 3, p. 82
Canumã (Canhuma)	164	195.2	Vol. 3, p. 82
South of Belém	210	250.0	Vol. 4, p. 35
Acará	217	258.3	Vol. 4, p. 35
Rio Capim	194	230.9	Vol. 4, p. 35
Piriá	161	191.7	Vol. 5, p. 01
Gurupi	131	155.9	Vol. 5, p. 01
Maracassumé	122	145.2	Vol. 5, p. 01
$\bar{X}$ =	189.9	226.1	
SD =	52.6	62.6	
n =	16	16	

(a) Volume over bark for free boles (stump to first main branch or to 7 cm diameter) of all living trees ≥ 25 cm DBH, as reported in F.A.O. surveys.

(b) Biomass calculated from volume using 0.62 average wood density, 1.2 to correct for trees between 10 and 25 cm DBH, and 1.6 to convert bole biomass to total biomass for trees ≤ 10 cm DBH (see text).

(c) Vol. 1 = Heinsdijk, 1957; Vol. 2 = Heinsdijk, 1958c; Vol. 3 = Heinsdijk, 1958a; Vol. 4 = Heinsdijk, 1958b; Vol. 5 = Glerum, 1960.

In converting volumes to biomass values, BROWN and LUGO applied a more sophisticated procedure than that used in deriving Table IV. They selected a subsample of surveyed hectares within which they computed the mass of individual trees by classing them into species groups and applying a mean wood density for each group. PIRES (1978: 613), a botanist who was resident in Belém during the period when the F.A.O. surveys were carried out, has strongly criticized the survey for the methods used in tree identification, which he states can produce error rates as high as 90%. Therefore the more refined density computations used by BROWN and LUGO (1984) may well not have produced a result any more accurate than that derived in Table V by applying BROWN and LUGO's (1984: 1291) 0.62 mean wood density value for Tropical America directly to the volume figures appearing in the F.A.O. reports, and may well be less reliable for having used only a subsample rather than the full F.A.O. data set.

BROWN and LUGO's (1984) value of 155.1 m tons ha^{-1} is lower than the volume-derived estimates for all but one of the 16 localities in Brazilian Amazonia presented in Table IV, making it highly unlikely that a value this low applies to the Brazilian Amazon. BROWN and LUGO used areas of forest types derived from maps of meteorological data, which is an improvement over the simple mean of sampled localities given in Table IV. It is difficult to imagine, however, that correction of forest type areas would result in a difference of this magnitude. The inclusion of areas outside of the Brazilian Amazon in BROWN and LUGO's estimate is a more likely explanation. In any case, even if their Tropical America value were used in place of my 361.5 m tons ha^{-1} for upland dense forests, the carbon release from the Legal Amazon would be 31.64 G tons (a 47.3% reduction). As pointed out in my Interciencia paper, "climatically significant amounts of carbon would be released by clearing the region's forests, even if the much lower timber-volume-based value were to prove correct" (p. 182).

Where, then, do we stand with respect to a best estimate for dense forest biomass in the Brazilian Amazon? Despite the approximations involved in using volume data from forestry surveys of large trees, the use of these data sets to estimate biomass is a promising approach. Since the localities of the estimates in Tables III and IV do not overlap, probably the best available estimate at present would be a mean for the 19 localities from combining the two tables (using KLINGE et al. 1975 for the Manaus value in Table III; see Table III, note c). The resulting mean for dense forest biomass is 254.5 m tons ha^{-1}.

The lower dense forest biomass would bring the total carbon load for the Brazilian Amazon to 145.34 G tons (using 0.45 for carbon content)-- a 24.5% reduction from the estimate given in my earlier paper. Using BROWN and LUGO's (1982, 1984) value of 0.50 for carbon content, the carbon total for the Brazilian Amazon would be 50.38 G tons, or 16.2% lower than the estimate in the Interciencia paper.

Future improvements on the above estimate for dense forest biomass are likely to result from the analysis (now in progress) of volume and destructive sampling data from the same location. Data of this type have been collected in an area near Manaus under study by the National Institute for Research in the Amazon (INPA) and World Wildlife Fund-Us (WWF-US). Preliminary analysis of the destructive sampling portion of the study at Fazenda Porto Alegre and Fazenda Dimona confirms the high biomass estimates of other studies in the Manaus area. The biomass data, combined with JUDY RANKIN's survey of over 30,000 trees $\geq$ 10 cm DBH (all with botanical collections), should provide the key to improved interpretation of forestry surveys throughout the Amazon.

Deep Soil Layers

The Interciencia article estimate was conservative in ignoring release of soil carbon from below 20 cm depth (FEARNSIDE, 1985: 182). BROWN and LUGO (1982: 183) estimated carbon stocks to 100 cm based on 20 cm depth samples using the relationship that the top 20 cm contain 45% of the soil carbon in a 100 cm profile. Preliminary results from the soil survey in the INPA/WWF-US Biological Dynamics of Forest Fragments (formely "Minimum Critical Size of Ecosystems") Project reserves near Manaus indicate a similar value of 42% (N = 3

TABLE V - Carbon release of Brazilian Legal Amazon where converted to pasture (G tons C)

and	Fearnside (1985)	With pasture biomass revised	With dense forest and pasture biomass revised	Current best estimate: revised biomasses Carbon contents(a)
BIOMASS				
Forest(b)	60.09	60.09	45.34	50.38
Pasture	0.21	2.34	2.34	2.60
Release	59.88	57.75	43.00	47.78
SOIL				
Forest(b) (0.91% C)	5.10	5.10	5.10	5.10
Pasture (0.56% C)	3.14	3.14	3.14	3.14
Release	1.96	1.96	1.96	1.96
TOTAL RELEASE	61.84	59.71	44.96	49.74

(a) Value for carbon content for vegetation 0.50 rather than 0.45 (see text).

(b) Here "forest" refers to all natural vegetation types (see Table I).

profiles). Applying this to the surface soil values used in the *Interciencia* article would add another 2.76 tons to the soil carbon release, bringing the total to 64.54 G tons -- a 4.4% increase (see Table V).

Improved Estimate of Pasture Biomass

The value for pasture biomass from HECHT's (1982) work at Paragominas, Pará (used in the *Interciencia* paper) can now be replaced with a value from my work at Ouro Preto do Oeste, Rondônia. I consider the value from Rondônia to be more reliable because it includes monitoring of dry weight biomass over a full annual cycle at two sites. The revised calculation of carbon release is given in Table V. Average pasture biomass is significantly higher (10.67 m tons dry weight ha^{-1} as opposed to 0.95 m tons ha^{-1}), but the total carbon release declines by only 3.4% to 59.71 G tons.

Non-Natural Vegetation

The biomass and carbon stock estimates in the *Interciencia* paper (and in Tables III and IV) are for natural vegetation. Since a part of the region has already been converted to other vegetation forms, including secondary forest, carbon releases would be slightly lower for conversion to cattle pasture starting from present land uses. Reliable values for the area of secondary forest are difficult to obtain since only the youngest stands can be detected on LANDSAT satellite imagery (FEARNSIDE, 1982).

LANLY (1982) has published a world-wide compilation for F.A.O. of official statistics on forest areas. I do not know the basis of the official communications used as the information base for LANLY's (1982) report. His tabulations for "Tropical America" (lumped for 23 countries) present areas for primary and secondary forests in "closed" and "open" formations (LANLY, 1982: 50). The areas of secondary forest reported correspond to 13.3% for closed forests and 22.1% for open forests; these values are higher than I would expect for the Brazilian Amazon. This may be due, in part, to the Brazilian Amazon being less densely occupied than the tropical forests in most of the other countries. Even if one accepts the percentages of secondary forest areas reported by LANLY for Tropical America as applying to Brazilian Amazonia, the effect on my estimate of carbon stocks is not great. Considering the *cerrado* as open and the remaining types as closed (with the exception of humid savanna, which is not forest), the total carbon stock would be lowered to 53.7 G tons (a decrease of 10.6%) if the average secondary forest is assumed to have 25% of the biomass of primary forest. Unfortunately, no data are available on the age or biomass distribution of secondary forests.

Carbon Content of Vegetation

I used a low value for the carbon content of forest biomass (0.45) in the *Interciencia* paper, a value used in a number of existing estimates (ATJAY et al. 1979: 141; GOLLEY, 1975 cited by HAMPICKE, 1979: 219; WOODWELL *et al*. 1978). ATJAY *et al*. (1979: 141) chose the traditional 0.45 value only "for reasons of comparison" with previous studies. Using data from ATJAY *et al's* review (1979: 142) of measurements of carbon content of plant parts, BROWN and LUGO (1982: 174) calculated an average value of 0.51 for forest carbon content. Adopting the 0.50 value used in BROWN and LUGO's (1982, 1984) calculations is probably justified since the ATJAY *et al*. data are more compelling than mere tradition. Using 0.50 as the value for carbon content increases the resulting carbon stocks by 11.1% (Table V).

Sinks for Carbon Within the Region

Charcoal

Formation of charcoal during forest burning prevents some of the carbon in the forest biomass from entering the atmosphere (See FEARNSIDE, 1985: 181). A conservative value was chosen for the carbonization factor. As mentioned in my earlier paper (p. 180), the 11.9% weighted carbonization factor derived from GOUDRIAAN and KETNER (1984) used in the calculations was suspected to be high. Our measurements at INPA in a burn near Manaus have since confirmed this, yielding a value about one-third of the one used. Although variability among farms is high (FEARNSIDE, nd, 1986), impact of deforestation would probably be somewhat greater than that shown by the calculations on page 180 in my earlier paper.

Some carbon would accumulate in soils under pastures on a time scale of centuries through the deposition of inert charcoal from repeated burning of the pasture or of secondary forests between intermittent use of the land as pasture. On the time scale of a few decades for which impacts are considered here, however, the amount of carbon deposited as charcoal would be minimal in comparison with the massive releases from removal of the forest.

Regeneration of Secondary Forests

One sink that could absorb a small part of the carbon released is growth of secondary forests (FEARNSIDE, 1985: 180-181). While no survey exists of the ages or biomasses of secondary forests at the time of cutting following abandonment of pasture, the cases I have observed near Altamira, Pará have been much lower than 50% of original biomass -- the figure used in my *Interciencia* paper as an illustration of how even a recovery to this level would still result in climatically significant carbon releases.

LUGO and BROWN have argued that regeneration of secondary forests could largely negate the effects of deforestation (BROWN, 1980; BROWN and LUGO, 1982; LUGO and BROWN, 1981, 1982). As explained in my *Interciencia* article (p. 181 and note 4), the recovery rates for secondary forest in shifting cultivation (used in LUGO and BROWN's arguments) are much more rapid than the recovery rates in degraded pastures. Since it is pasture that replaces the bulk of the forest now being cleared in the Brazilian Amazon (FEARNSIDE, 1983), these arguments are misleading.

Ballpark estimates of the impact of secondary forest or abandoned pasture replacing the original forest, as compared to a baseline scenario of complete replacement by grazed cattle pasture, are illustrated in Table VI. Even a hypothetical complete replacement of the cattle pasture with secondary forest of an assumed average biomass of 50 m tons ha^{-1} results in a change in carbon release of less than 15%.

Carbon Dioxide "Fertilization"

A third factor that some have claimed could absorb carbon is the vegetations's response to higher levels of atmospheric CO_2. CO_2 "fertilization" would supposedly permit both enhanced growth of existing forests and the spread of forests into presently nonforested areas (e.g. IDSO, 1984). Reasons to doubt that higher CO_2 levels would result in net increases in carbon uptake include the fact that forest growth is not limited by low CO_2 but rather by such factors as nutrients, water and sunlight, and that climate changes from deforestation (whether from CO_2 or other causes) would reduce tree growth (lower precipitation) and accelerate decomposition (higher temperature) (GOUDRIAAN and ATJAY, 1979; LISS and CRANE, 1983: 33).

Soil Erosion

A fourth sink is the erosion of some of the carbon in the soil and litter. Deposition of eroded material in marine sediments would prevent part of the carbon from reaching the atmosphere. RICHEY et al. (1980: 1350) have studied organic carbon transport and oxidation in the Amazon River, and conclude that it discharges about 0.05 G tons year^{-1} into the ocean (0.1 G tons total of transported + oxidized carbon, with 50% of the total being oxidized in the river). The study indicates that about 60% is contributed by tributaries below Iquitos, Peru -- implying that the contribution from the Brazilian Amazon is about 0.03 G tons year^{-1}. Of the river's carbon from soil erosion, most comes from the Andes rather than the Brazilian Amazon. Most of the carbon reaching the ocean is in dissolved rather than particulate form. For example, in the measurement at the lowest sampling station for which complete data are available (high water measurement at Tapajõs, 768 km above the Amazon's mouth), only 18% of the carbon was particulate. It should be noted that this is based on surface samples, and inclusion of the deeper layers and bedload would raise the percentage of solid material (NB: RICHEY et al. adjusted the values for annual transport given earlier to approximate the total load). Much of the dissolved carbon would not be deposited in ocean sediments, and would therefore remain exposed to oxidation. The current annual contribution to ocean sinks from erosion in the Brazilian Amazon is an as yet unquantified fraction of the approximately 0.03 G ton total transported out of the region. In any case, these present day values are small relative to potential releases from forest clearing. However, erosion could increase greatly with large scale deforestation. Substantial erosion rates have been measured under annual crops (FEARNSIDE, 1980), and recent measurements (in preparation) indicate lower but still significant erosion rates under cattle pasture. In the near future we hope to have better information on

TABLE VI - Carbon release under different scenarios for land use replacing forest in the Legal Amazon

Scenario	Biomass (m tons ha^{-1})	Carbon store[(a)] (G tons)	Carbon release (G tons)	Percent difference from baseline
Baseline				
All grazed pasture	10.67	2.34	59.71	0
Abandoned pasture	27[(b)]	5.9	56.14	6.0
Second growth	50	10.9	51.12	14.4
Original forests	variable (dense forest = 361.5)[(c)]	60.09	0	100

(a) Assumes carbon contents of 0.45 (as in Fearnside, 1985).

(b) Approximate total biomass based on a measurement at Altamira of aboveground biomass in a pasture that had been abandoned for 2 years.

the potential magnitude of erosion as a carbon sink (as well as its impact on agricultural sustainability).

Conclusion

The present paper continues the effort initiated earlier to interpret in terms relevant to policy the mass of highly diverse and scattered information on the potential role of Amazonian deforestation in CO_2-induced climate change. The conclusions of the earlier review are robust after incorporating additional information in the calculations. A best present estimate for the longterm release of converting the Legal Amazon to cattle pasture is 49.7 G tons C (19.6% lower than my previous estimate). Even should conversion to cattle pasture take place at a rate considerably slower than that implied by recent trends, the release of CO_2 would be likely to exceed 20% of the current annual release from fossil fuel for the decades that forest continues to exist. The impact of CO_2 released from conversion to pasture adds to the list of environmental and human costs of deforestation, and indicates the wisdom of implementing policy measures to control the process[2].

Note

[1] I welcome this opportunity to correct an inconsistency between the table and the text of the Interciencia paper with regard to aboveground and total biomass. The second of the two references to "above ground" biomass on page 180, and the tree references on page 184 are incorrect, and should be changed to read "total" biomass. The table is correct, as are the calculations with the exception of the following modification (which increases rather than decreases the amount of carbon ultimately released). On page 180 the fraction converted to charcoal was incorrectly applied to the total biomass (60.09 G tons), rather than to the smaller above ground value (45.41 G tons). The amount of carbon stored as charcoal was thereby exaggerated, and the long term impact of deforestation on carbon release to the atmosphere understated by 3.2%. The two references to 54.69 G tons on page 180 should be changed to 56.44 G tons.

[2] Data on forest biomass and burning at Manaus were collected under a grant from World Wildlife Fund-US; MICHAEL KELLER, FERNANDO MOREIRA FERNANDES, and NEWTON LEAL FILHO executed the biomass harvesting. Data on pasture and second growth biomass were collected under a grant from the Science and Technology Component of Projeto POLONOROESTE; GABRIEL DE LIMA FERREIRA, ROBERTO APARECIDO CUSTODIO, FERNANDO MOREIRA FERNANDES and RONALDO GOMES CHAVES participated in the fieldwork. Drying facilities were provided by the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) at Altamira and by INPA's Centro de Pesquisa de Produtos Florestais (CPPF) at Manaus.

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