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Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s

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[1] Recent figures on net forest cover change rates of the world's tropical forest cover are used for the calculation of carbon fluxes in the global budget. By applying our deforestation findings in the humid tropics, complemented by published deforestation figures in the dry tropics, to refereed data on biomass, we produced new estimates of net carbon emissions. These estimates are supported by recent, independent estimations of net carbon emissions globally, over the Brazilian Amazon, and by observations of atmospheric CO_2 emissions over Southeast Asia. Our best estimate for global net emissions from land-use change in the tropics is at 1.1 ± 0.3 Gt C yr^{-1}. This estimate includes emissions from conversion of forests (representing 71% of budget) and loss of soil carbon after deforestation (20%), emissions from forest degradation (4.4%), emissions from the 1997–1998 Indonesian exceptional fires (8.3%), and sinks from regrowths (−3.3%). *INDEX TERMS:* 4806 Oceanography: Biological and Chemical: Carbon cycling; 1694 Global Change: Instruments and techniques; 1640 Global Change: Remote sensing; 1610 Global Change: Atmosphere (0315, 0325); *KEYWORDS:* carbon fluxes, land cover change, tropical deforestation

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1. Introduction

[2] In the debate related to global carbon budget, there remain large uncertainties associated with estimating the CO_2 release due to land-use change (mainly referring to tropical deforestation) [*Prentice et al.*, 2001]. These scientific uncertainties can be grouped into three main categories: (1) the true level of tropical deforestation and degradation, (2) the amount of biomass and of soil carbon for different forest types, and (3) the spatial distribution of these forest types. Our knowledge concerning the rates of change of the tropical forests remains surprisingly limited. The uncertainty of these rates has implications on the estimation of global carbon emissions due to land-use change. The IPCC has pointed out that "the uncertainty ranges – in average annual budget of CO_2 perturbations for 1980 to 1998 – result partly from our limited ability to determine accurately the changes in the carbon balance resulting from human-induced emissions" [*Bolin and Sukamar*, 2000]. Global carbon emissions from land-use change are estimated to fall within the range of +0.5 to +3.0 GtC yr^{-1} for the 1990s [*Houghton*, 2003a]. The errors are estimated to be approximately ±50% for tropical regions based on the experience of *Houghton* [2003b].

[3] Our work's contribution to quantifying the global carbon budget issue is related to the true level of deforestation in the humid tropics, and not to the amount of forest biomass. Indeed, we apply the findings of our survey on tropical deforestation in the 1990s [*Achard et al.*, 2002] to existing published and refereed data on biomass and methods, for the calculation of net carbon emissions. In our previous study, we found that deforestation in the humid tropics was lower than expected. To make an estimation of net carbon flux from deforestation and re-growth for the whole tropical belt, we used a rough figure for forest cover change in the dry tropics.

[4] In this current work, we improve this carbon flux estimate by refining the methodology, by using the most reliable published data for forest cover change in dry forests, and by refining the biomass data that we previously used for the tropical forests. Our main concern is to avoid underestimation of carbon emissions because our previous work led to a much lower figure than generally accepted until now.

2. Materials and Methods

2.1. Data on Deforestation Rates in the Humid Tropics

[5] The evergreen and seasonal forests of the tropical humid bioclimatic zone covered by our remote sensing work (the "TREES Project") correspond closely to those forests defined by the Food and Agricultural Organization (FAO) as "Closed Broadleaved Forest" [*FAO*, 1993]. We did not document the woodlands and forests of the dry tropics except for continental Southeast Asia where seasonal forests are intermixed with humid forests. The forest cover figures reported by our remote sensing study refer to (1) the humid tropical forest biome of Latin America excluding both Mexico and the Atlantic forests of Brazil, (2) the

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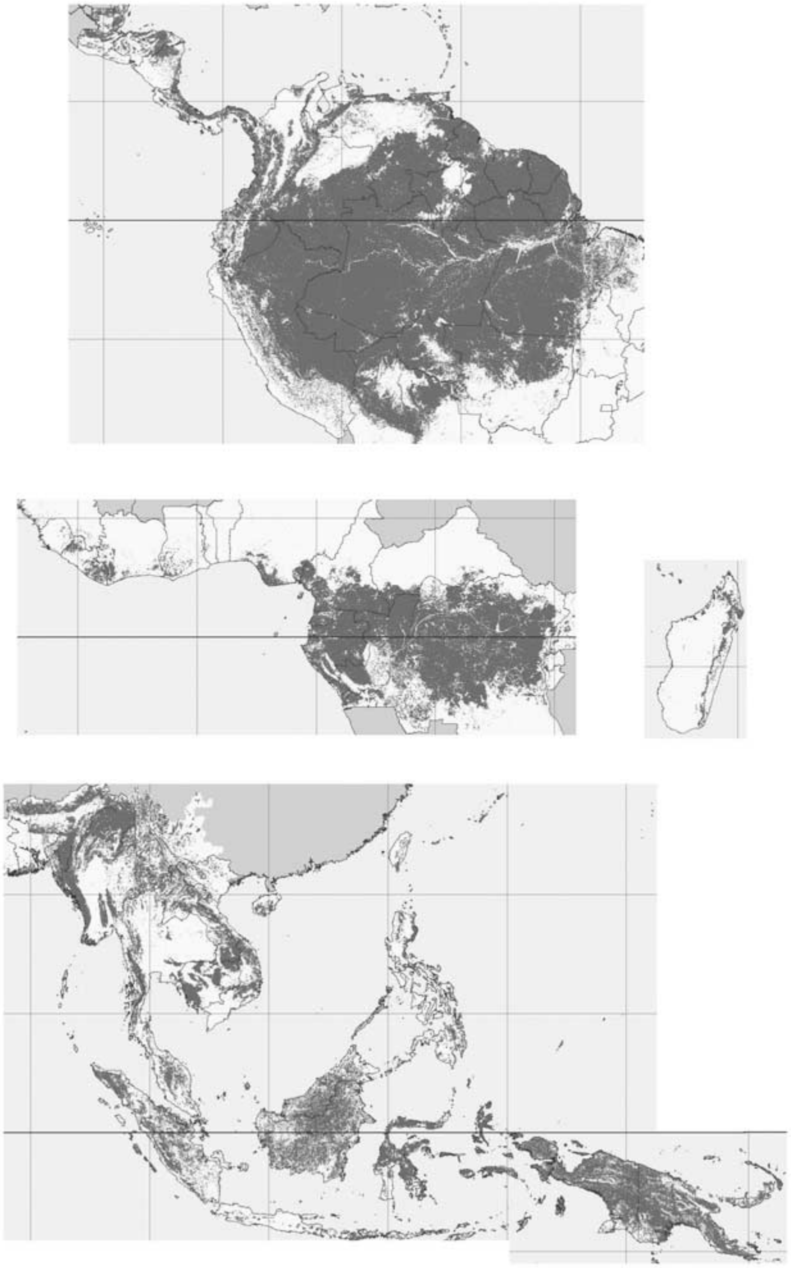

Figure 1. Humid tropical forest biome of the TREES domain with the exception of the Western Ghats forests of India (forests are represented in green). See color version of this figure at back of this issue.

humid tropical forest biome of Africa (Guineo-Congolian zone and Madagascar), and (3) the humid tropical forest biome of Southeast Asia and India, including the dry biome of continental Southeast Asia (Figure 1). This whole area is referred as the TREES domain later in the text.

[6] For the TREES domain, we have defined deforestation as the conversion from forests (closed, open, or fragmented forests, plantations, and forest regrowths) to non-forest lands (mosaics, natural non-forest such as shrubs or savannas, agriculture, and non-vegetated). Reforestation (or re-growth) is the conversion of non-forest lands to forests, and degradation is defined as the process within the forests whereby there is a significant reduction in either tree density or in the proportion of forest cover (from closed forests to open or fragmented forests). The TREES estimates were produced for four regions: (1) Pan Amazon and Central America, (2) Brazilian Amazonia and Guyanas, (3) Africa, and (4) Southeast Asia. The resulting estimates of global humid tropical forest area change for the period 1990–1997 showed a marked reduction of natural forests: The annual deforested area for the humid tropics is estimated at 5.8 ± 1.4 million hectares with a further 2.3 ± 0.7 million hectares of forest where degradation can be visually inferred from satellite imagery (Table 1). Large

Table 1. Humid Tropical Forest Cover Estimates for the years 1990 and 1997 and Mean Annual Change Estimates During the 1990 to 1997 Period[a]

	Pan-Amazon (10^6 ha)	Amazonia (10^6 ha)	Africa (10^6 ha)	Southeast Asia (10^6 ha)	Global (10^6 ha)
Total study area	578	577	337	446	1937
Forest cover in 1990	249 ± 20	420 ± 37	198 ± 13	283 ± 31	1150 ± 54
Forest cover in 1997	243 ± 20	411 ± 36	193 ± 13	270 ± 30	1116 ± 53
Annual deforested area	1.1 ± 0.6	1.4 ± 0.9	0.85 ± 0.30	2.5 ± 0.8	5.8 ± 1.4
Annual regrowth area	0.20 ± 0.11	0.08 ± 0.11	0.14 ± 0.11	0.53 ± 0.25	1.0 ± 0.32
Annual degraded area	0.61 ± 0.46	0.22 ± 0.21	0.39 ± 0.19	1.1 ± 0.44	2.3 ± 0.71

[a] Sample figures were extrapolated linearly to the dates 1 June 1990 and 1 June 1997. Average observation dates are February 1991 and May 1997 for Latin America; February 1989 and March 1996 for Africa and May 1990 and June 1997 for Southeast Asia. Estimation intervals are at 95% confidence level (determined through a re-sampling bootstrap approach).

non-forest areas were also re-occupied by forests, mostly by young re-growth on abandoned land along with some forest plantations. The three continents revealed considerable differences in percentage change rates.

[7] The TREES deforestation rate estimates are valid for the period 1990–1997. We extrapolate linearly these estimates to the 1997–2000 period, with the exception of two key regions, the Brazilian Amazon and Indonesia, for which we include recently published data.

[8] We use the estimates of the Brazilian National Space Agency over Brazilian Amazonia over the period 1997–2000 [*Instituto Nacional De Pesquisas Espacias* (*INPE*), 2002] for our Brazilian Amazonia and Guyanas region, and we added the estimate of damaged lowland forests (excluding the peat swamp forests which are accounted for in section 2.4) in Indonesia during the 1997–1998 exceptional fire events [*Asian Development Bank* (*ADB*), 1999] to our estimate for the Southeast Asia region. These data are the most reliable data for these key regions.

2.2. Data of Deforestation Rates in the Non-Trees Domain

[9] To provide an estimate of global net emissions from land-use change for all tropics, we need to account also for the forest cover changes in the "non-TREES domain," which includes mainly the woodlands and forests of the dry tropics. We have to rely on published estimates of forest cover change outside our study domain, although we produced recent maps of the whole tropical domain for the year 2000 [*Eva et al.*, 2004; *Mayaux et al.*, 2004; *Stibig et al.*, 2003].

[10] Whereas previously [*Achard et al.*, 2002] we made a rough hypothesis by considering forest cover changes in the non-TREES domain to be at the same level as in the TREES domain, here we rely on the FAO estimates [*FAO*, 2001a, 2001b], which are generally considered as reference figures for forest cover assessment in the tropics. The FAO provides in principle two estimates for the full tropics separately through two methodological approaches: (1) country survey (CS), which is based on the compilation and standardization of national data, and (2) remote sensing survey (RSS), which provides statistical estimates at continental level derived from forest cover change maps (interpretation of 30-m resolution satellite imagery). In this study we make use of the FAO RSS estimates for the non-TREES domain for the following reasons: First, internal inconsistencies have been highlighted for the FAO CS estimates [*FAO*, 2001b, chap. 46], which might be due to the difficulties to standardize country level data obtained from official intergovernmental processes [*Matthews*, 2001]; second, it is well accepted that a sample can provide reliable estimates of deforestation if the sample size is sufficiently large [*Czaplewski*, 2003]. TREES and FAO RSS estimates can be considered as complementary as they are both based on a statistical sampling strategy using satellite imagery and have been designed to give continental estimates [*Achard et al.*, 2002; *FAO*, 2001a]. Both methods provide measurement of tropical forest cover change in a uniform, independent, and repeatable manner, and moreover are consistent with each other. The FAO RSS uses a random sample covering 10% of the whole tropical belt, designed for forest cover estimation, whereas our method used a stratified systematic sample covering 6.5% of the humid tropical domain, designed for forest cover change estimation. Indeed, even with a 30% smaller total survey area and a lower sampling rate, the TREES approach provided a slightly better accuracy for the measurement of tropical forest cover change: The standard errors of pan-tropical change estimates range ∼15% for FAO RSS and ∼13% for our approach. Last, the FAO RSS survey can not be used directly (i.e., without our estimates) because biome (humid versus dry) estimates are not provided at continental level. The FAO RSS estimates cannot be directly compared to our estimates over the TREES domain as they refer to the whole continents, but they can be used to estimate forest area change for the tropical zones not covered by our study by subtracting our TREES estimates from the FAO RSS estimates for the three continents (South America, Africa, and Southeast Asia).

[11] We use the FAO RSS definition of forest "f2" which comprises the closed and open forest classes, and a fraction of the fragmented forest class [*FAO*, 2001b, p. 308], as this definition is the closest to ours. Deforestation is there defined as the sum of all area transition from forest to non-forest classes.

2.3. Data on Forest Biomass, and Soil Carbon and Biomass Losses Due to Deforestation and Degradation

[12] To use our deforestation results for global carbon emissions estimates, we rely on the latest published information on forest biomass. We consider existing national figures of total carbon vegetation biomass derived from the actual biomass density without roots [*Brown*, 1997] as a

Table 2. Regional Carbon Biomass Parameters and Change Rate Figures Used as Input Data in the Carbon Model and Regional Net Carbon Flux Estimates for 1 Year of Deforestation, Degradation, and Regrowth During the 1990s Over a 10-Year Committed Period[a]

	Pan-Amazon TREES Domain	Amazonia TREES Domain	Africa TREES Domain	Asia TREES Domain	Latin America Non-TREES Domain	Africa Non-TREES Domain
			Carbon Model Parameters			
Maximum C biomass, tC ha^{-1}	155	223	171	181	56	43
Mean C biomass, tC ha^{-1}	129	186	143	151	47	36
Minimum C biomass, tC ha^{-1}	103	149	115	121	38	29
Soil Carbon loss, tC ha^{-1}	24	24	20	30	17	10
Maximum degradation C loss, tC ha^{-1}	39	56	43	45	14	11
Mean degradation C loss, tC ha^{-1}	26	37	29	30	9	7
Minimum degradation C loss, tC ha^{-1}	13	19	14	15	5	4
C regrowth rate, tC ha^{-1} yr^{-1}	2.8	5.5	3.4	3.8	0.5	0.5
Nb of years for full regrowth	46	35	42	40	94	72
			Change Rates			
Deforestation rate, 10^6 ha yr^{-1}	1.08 ± 0.55	1.43 ± 0.88	0.85 ± 0.30	2.84 ± 0.90	1.9 ± 1.1	1.5 ± 0.6
Degradation rate, 10^6 ha yr^{-1}	0.61 ± 0.46	0.22 ± 0.21	0.39 ± 0.19	1.07 ± 0.44	n.s.	n.s.
Regrowth rate, 10^6 ha yr^{-1}	0.20 ± 0.11	0.08 ± 0.11	0.14 ± 0.11	0.53 ± 0.25	n.s.	0.07 ± 0.05
			Net C Fluxes Over 10 Years			
Maximum net emissions, 10^6 tC	153 ± 88	260 ± 171	125 ± 52	456 ± 167	106 ± 51	60 ± 23
Mean net emissions, 10^6 tC	128 ± 74	220 ± 146	104 ± 44	385 ± 143	93 ± 45	53 ± 20
Minimum net emissions, 10^6 tC	103 ± 60	180 ± 121	83 ± 36	315 ± 119	81 ± 40	45 ± 17

[a]Here n.s. stands for not significant. The non-TREES domain of Southeast Asia (dry domain of India) is not considered as the forest area change estimates for this area are not significant.

starting point. Brown's study presents methods that are available for estimating biomass density along with biomass density estimates for many tropical countries. To obtain regional estimates, we weight these country biomass figures by the FAO 1990 forest area country figures [*FAO*, 2001b] complemented by our forest area estimate for Brazilian Amazonia and Guyanas region. As Brown's estimates do not include dead material, we add 20% for below-ground vegetation (root) biomass. This percentage is derived from a regression between above-ground biomass and root biomass for over 150 sites in the world [*Cairns et al.*, 1997]. Further, biomass is assumed to be 50% carbon [*Brown and Lugo*, 1982], this factor being used by the Intergovernmental Panel on Climate Change [*IPCC*, 1997]. The resulting regional estimates are provided in Table 2 under the name "Mean C biomass."

[13] The error range of such forest biomass data is suggested to be high. Indeed, a recent comparison of seven surveys of biomass in Amazonian forests showed little agreement in either total biomass for the region or in its distribution [*Houghton et al.*, 2001] with average estimates of the seven surveys being 100, 156, 178, 183, 192, 196, and 232 t C ha^{-1}. For testing the sensitivity of our method to the biomass parameter, we add or subtract 20% to or from our Brown-derived forest carbon biomass figures to obtain regional estimates of "Minimum C biomass" or "Maximum C biomass" (Table 2). For example, the Brown-derived forest carbon biomass figure for the Brazilian Amazonia and Guyanas region is 186 t C ha^{-1} and the resulting regional range (from 149 t C ha^{-1} to 223 t C ha^{-1}) covers all previous referred estimates except the lowest and the highest.

[14] In this study we further consider soil carbon losses when converting forests into cultivated lands. For such, we use existing figures of carbon in soil for undisturbed forests and cultivated lands [*Houghton*, 1999]. Resulting regional soil carbon loss figures are provided in Table 2.

[15] For carbon losses due to forest degradation, we considered that a fraction of 0.2 of the original carbon in forest biomass is lost during the degradation process. This fraction is derived as the average of the 10–30% range of lower carbon biomass content of degraded forests in Tropical Asia [*Houghton*, 1999]. We tested the sensitivity to this parameter by using fractions of 0.1 and 0.3 for minimum and maximum estimates (Table 2).

2.4. Estimation of Carbon Fluxes

[16] Carbon fluxes can be computed using fractions of biomass assumed to be converted to CO_2 resulting from deforestation, degradation and regrowth processes. In order to be comparable with the latest estimate of terrestrial net source of carbon for the 1990s by *Houghton* [2003b] and to avoid missing processes [*House et al.*, 2003], we use Houghton's "bookkeeping" model [*Houghton*, 1999; *Houghton et al.*, 2000]. This bookkeeping model accounts for forest clearing and regrowth by tracking (1) the immediate release of carbon to the atmosphere from plant material burned at the time of clearing, (2) slower release of carbon from decay of slash, (3) accumulation of carbon during regrowth, and (4) changes in soil carbon. The fractions of initial forest biomass burned, left as slash, removed from products, and converted to element carbon through burning are taken at 0.2, 0.7, 0.08, and 0.02. The annual rates of decay are assumed to be (1) 0.1 yr^{-1} for wood removed from site and (2) 0.001 yr^{-1} for elemental carbon. For biomass left as slash, we used two values of initial rate with an exponential decrease in time: 0.1 yr^{-1} for a "best estimate" and 0.4 yr^{-1} to test the sensitivity to this parameter [*Houghton et al.*, 2000]. It has to be noticed that decay constants of 0.3, 0.4, and 0.5 yr^{-1} were used for

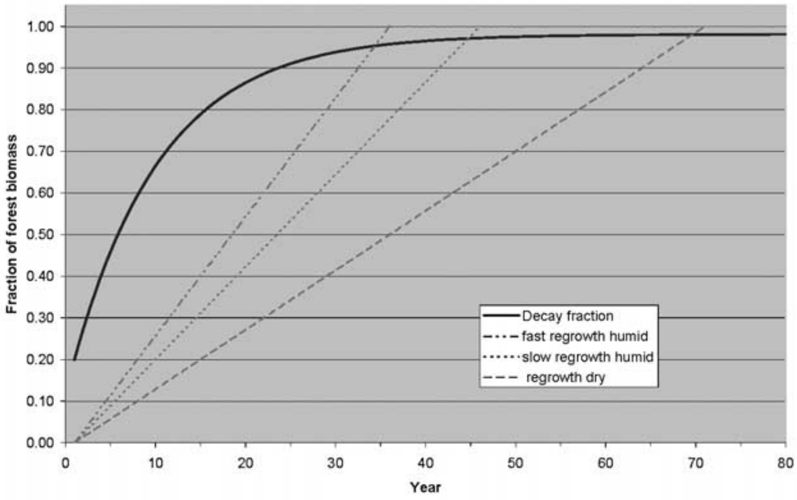

Figure 2. Fractions of biomass assumed to be converted to CO_2 or to be regrown resulting from deforestation and regrowth processes.

woodland, tropical seasonal forest, and tropical moist forest, respectively, in an earlier publication by *Houghton* [1999]. With the slash decay constant at 0.1 yr^{-1}, the initial (first year) total fraction of converted biomass is 0.28 and increases to 0.69 over a 10-year period when including future sources embodied in first-year decay pools, then to 0.92 over a 25-year period (Figure 2). When using 0.4 yr^{-1} as slash decay constant, the total fraction of converted biomass becomes 0.44 for first year, 0.94 over a 10-year period, and 0.97 over a 25-year period. We use the same conversion fractions for the biomass loss due to degradation (Table 3). For the soil carbon, we assume the annual decay rate to be 0.2 yr^{-1} of the total soil carbon loss corresponding to a new soil steady state after 5 years [*Houghton*, 1999].

[17] The accumulation of carbon on abandoned lands reverted to forests is taken as a linear function derived from Houghton's model [*Houghton et al.*, 2000] with a maximum accumulation after full regrowth within 35 to 46 years for the humid domain (Figure 2 and Table 2). These high carbon accumulation rates are probably valid, as our study is only concerned with human-induced changes over a short period (the last decade).

[18] To compute the actual carbon flux for the 1990s, we must make assumptions of what has happened in previous years, using simulations of "committed" flux over future years as a proxy estimate for emissions caused by deforestation in the past. From our annual deforestation, degradation, and regrowth estimates, we can compute three estimates of carbon fluxes: the initial flux of first year, the "committed" flux for the next 10 years (including future sources and sinks), and the "committed" flux for the next 25 years. This is a sort of moving average window which can be looked either as forward-looking or as backward-looking. The first-year flux will obviously underestimate the impact of the land-cover change, while the 25-year committed flux implies that the deforestation, degradation, and regrowth rates have been constant for the past 25 years. The 10-year committed flux has been assumed to be more representative. We do not assume that regenerating forests will remain undisturbed over the next 10 years, but only that regrowth, degradation, and deforestation rates remained at the same level for the previous decade, i.e., over a period of 10 years.

[19] To the 10-year sum of these annual carbon flux estimates we add the estimate of carbon emissions caused by the exceptional fires in Indonesia in 1997–1998, as this was a unique but major event during the late 1990s and was not considered in our TREES estimates. These fires damaged 2.4 million ha of peatland, resulting in 0.88 ± 0.07 Gt C (intermediate estimate) emissions of carbon in the atmosphere [*Page et al.*, 2002]. This intermediate estimate is confirmed by the emission estimate at around 1 Gt C

Table 3. Parameters of The Carbon Release Model

	Fraction of Initial Biomass	Annual Decay Rate, yr^{-1}	Total Fraction of Converted Biomass		
			First Year	10 Years	25 Years
Forest C loss from clearing					
Burned when cleared	0.2	–	0.2	0.2	0.2
Left as slash	0.7	0.1–0.4	0.07–0.23	0.44–0.69	0.64–0.74
Removed from products	0.08	0.1	0.01	0.05	0.07
Converted to element carbon	0.02	0.001	0.000	0.002	0.005
Total C loss from clearing	1		0.28–0.44	0.69–0.94	0.92–0.97
Soil C loss from clearing	1	0.2	0.2	1	1
Loss from degradation	1		0.28–0.44	0.69–0.94	0.92–0.97

Table 4. Estimation of Annual Net Forest Area Change Rates in the Non-TREES Domain for the 1990s[a]

	TREES Domain		All Tropics		Difference (All Tropics - TREES Domain)	
Continent	TREES (10^{6}ha yr^{-1})	FAO CS (10^{6}ha yr^{-1})	FAO RSS f2 (10^{6}ha yr^{-1})	FAO CS (10^{6}ha yr^{-1})	FAO RSS f2 (10^{6}ha yr^{-1})	FAO CS (10^{6}ha yr^{-1})
Southeast Asia	−2.0 ± 0.8	−2.5	−2.0 ± 1.2	−2.4	−0.0	−0.0
Africa	−0.7 ± 0.3	−1.2	−2.2 ± 0.8	−5.2	−1.5	−4.0
Latin America	−2.2 ± 1.2	−2.7	−4.1 ± 2.2	−4.4	−1.9	−1.7
Global	−4.9 ± 1.3	−6.4	−8.3 ± 2.6	−12.0	−3.4	−5.7

[a] The "non-TREES domain" is defined as all dry tropics with the exception of the deciduous forests in Southeast Asia (but with the dry forests of India), and includes all Mexico forests and the Atlantic forests of Brazil. FAO RSS (Remote Sensing Survey) f2 definition of forest "comprises the closed and open forest classes, and a fraction (two ninths) of the fragmented forest class"; it was constructed to match the forest definition used in the country reporting [*FAO*, 2001a, p. 308]. These figures are available only at continental level including all types of tropical forests. Average observation dates are June 1990 and March 1997 for the TREES study. The average reference years for latest area data used by FAO CS are 1991 for Africa and South America and 1995 for Asia and Central America. The average observation dates of the FAO RSS exercise are December 1988 and July 1997. FAO CS estimate for Southeast Asia at -2.4×10^6 ha yr^{-1} (all tropics), includes 0.04×10^6 ha yr^{-1} net reforestation in India the leading to a higher rounded estimate for the TREES domain at -2.5×10^6 ha yr^{-1}. Estimation intervals are at 95% confidence level.

obtained through an inverse modeling approach applied on observed atmospheric CO_2 measurements [*Schimel and Baker*, 2002] and by a more recent estimate of fire emissions anomaly due to the El Niño event at 1.34 ± 0.67 Gt C which includes all types of fires (land clearing, pasture maintenance, agricultural waste burning, forest and savanna fires) [*van der Werf et al.*, 2004].

3. Results

3.1. Estimates of Deforestation Rates

[20] The resulting regional estimates of forest cover change can be found in Table 2. For the TREES Brazilian Amazon and Guyanas region, using the estimate of gross deforestation in the humid domain of Brazilian Amazon for the period 1997–2000 at -1.48×10^6 ha yr^{-1} [*INPE*, 2002], this leads to an average estimate of gross deforestation in this region during the 1990s at -1.43×10^6 ha yr^{-1}.

[21] For the TREES Southeast Asia region, adding the estimate of burned lowland forest areas (with varying degrees of damage) during the exceptional fire events in Indonesia in 1997–1998 at 3.28×10^6 ha [*ADB*, 1999], it leads to a regional estimate of gross deforestation during the 1990s at -2.84×10^6 ha yr^{-1}.

[22] For the non-TREES domain our FAO-derived forest area change estimates are only significant for Latin America (the forests of Mexico, the Atlantic forests of Brazil, and the whole dry domain) and Africa (the whole dry domain) (Table 4). For Southeast Asia our study covers the same zone as the FAO surveys with the only exception of the dry domain of India. We also computed the difference between the change matrices from the FAO RSS and our own study [*Achard et al.*, 2002, Supplementary Online Information], to obtain the deforestation, degradation and regrowth rates by continents (Table 5). The regrowth and degradation rates for the non-TREES domains of all three continents are found to be insignificant or meaningless from this approach.

3.2. Estimates of Global Net Emissions From Land-Use Change in the Tropics

[23] Table 6 provides the detailed carbon flux estimates for the two domains (TREES and non-TREES). Our estimate of the 10-year committed flux using the mean value for carbon biomass is 0.98 ± 0.30 Gt C yr^{-1} for the 1990s. When using the min-max intervals for forest biomass and degradation carbon loss, the 10-year committed flux estimate ranges from 0.81 ± 0.25 Gt C yr^{-1} to 1.16 ± 0.35 Gt C yr^{-1}. Using a slash constant decay at 0.4 yr^{-1} (instead of 0.1 yr^{-1}) the 10-year committed flux would become 1.27 ± 0.38 Gt C yr^{-1} with mean parameters and would range between 1.03 ± 0.31 Gt C yr^{-1} and 1.50 ± 0.46 Gt C yr^{-1} with min-max intervals.

Table 5. Estimates of Tropical Forest Cover for the Year 1990 and Mean Annual Change Estimates During the 1990 to 1997 Period for the Non-TREES Domain[a]

	Latin America (10^6 ha)	Africa (10^6 ha)	Southeast Asia (10^6 ha)	Global (10^6 ha)
Forest cover in 1990	140 ± 12	307 ± 22	negative	408 ± 19
Annual deforested area	1.9 ± 1.1	1.5 ± 0.6	negative	3.1 ± 1.0
Annual regrowth area	n.s.	n.s.	negative	negative
Annual net forest area change	−1.9 ± 1.1	− 1.5 ± 0.6	n.s.	− 3.4 ± 1.1
Annual degraded area	negative	negative	negative	negative

[a] The estimates are obtained by the formula (FAO Remote Sensing Survey estimate minus TREES estimate). We used the FAO Remote Sensing Survey (RSS) f2 definition of forest which "comprises the closed and open forest classes and a fraction (two ninths) of the fragmented forest class". Here n.s. stands for not significant; negative means that the difference does not make sense, for example, the FAO RSS f2 estimate of degradation for all tropics (0.48 10^{6}ha yr^{-1}) is lower than the TREES estimate of degradation for the humid tropics (2.29 10^{6}ha yr^{-1}). For the whole non-TREES domain the estimate of annual net forest area change (3.4 10^{6}ha yr^{-1}) is higher than the estimate of annual deforested area (3.1 10^{6}ha yr^{-1}) because for Southeast Asia the FAO RSS f2 estimate of deforestation (2.2 10^{6}ha yr^{-1}) is lower than the TREES estimate (2.5 10^{6}ha yr^{-1}). Estimation intervals are taken as the maximum relative estimation intervals at 95% confidence level of the two estimates (FAO RSS and TREES).

Table 6. Annual Carbon Flux Estimates (10^6 tC) for 1 Year of Deforestation, Degradation, and Regrowth During the 1990s Over Three Committed Periods[a]

Flux Estimates	TREES Domain	Non-TREES Domain	Global
	Fluxes Over 1 Year		
Deforestation emissions			
With mean C biomass	262 ± 76	39 ± 10	301 ± 85
Soil carbon emissions	32 ± 7	9 ± 3	42 ± 10
Emissions from degradation	19 ± 7	-	19 ± 7
Sinks from forest regrowth	4 ± 2	-	4 ± 2
Net emissions mean estimate	309 ± 92	49 ± 13	358 ± 105
	Fluxes Over 10 Years		
Gross emissions from deforestation			
With maximum C biomass	794 ± 229	119 ± 29	914 ± 258
With mean C biomass	663 ± 191	99 ± 24	762 ± 216
With minimum C biomass	531 ± 153	80 ± 19	610 ± 173
Soil carbon emissions	160 ± 35	47 ± 16	209 ± 52
Emissions from degradation			
With maximum fraction	70 ± 27	-	70 ± 27
With mean fraction	47 ± 18	-	47 ± 18
With minimum fraction	23 ± 9	-	23 ± 9
Sinks from forest regrowth	35 ± 17	-	35 ± 17
Net emissions			
Maximum estimate	992 ± 309	166 ± 46	1,158 ± 355
Mean estimate	837 ± 262	146 ± 41	983 ± 303
Minimum estimate	682 ± 215	126 ± 36	808 ± 251
	Fluxes Over 25 Years		
Deforestation emissions			
With mean C biomass	875 ± 253	131 ± 32	1,006 ± 285
Soil carbon emissions	162 ± 36	47 ± 16	209 ± 52
Emissions from degradation (mean fraction)	62 ± 24	-	62 ± 24
Sinks from forest regrowth	87 ± 43	-	88 ± 43
Net emissions mean estimate	1,012 ± 355	177 ± 49	1,189 ± 404

[a] Maximum, mean and minimum estimates of net emissions are corresponding to maximum, mean, and minimum input data of forest carbon biomass and degradation carbon loss used for calculating gross emissions from deforestation and degradation.

[24] Summing up our 10-year committed global net flux estimate over 10 years and adding the contribution of the Indonesian forest fires, the global carbon emission estimate for the 10-year period June 1990 to June 2000 would amount to 10.7 ± 3.1 Gt C. Considering our 10-year committed flux with maximum input parameters (constant decay at 0.4, maximum carbon biomass and degradation fraction at 0.3), a maximum net emissions estimate would then be 15.9 ± 4.6 Gt C for the same period, in which the Indonesian fires contribute for 5.5%. We consider 1.07 ± 0.31 Gt C yr^{-1} as our "best" estimate for global annual net emissions due to forest cover change in the tropics during the 1990s and 1.59 ± 0.46 Gt C yr^{-1} as a maximum estimate. Our best estimate includes emissions from conversion of forests using a mean value for carbon biomass (representing 71% of budget) and loss of soil carbon (20%) due to deforestation, emissions from forest degradation (4.4%), emissions from the 1997–1998 Indonesian fires (8.2%), and sinks from regrowths (−3.3%).

4. Discussion

4.1. Comparison With Other Estimates of Deforestation and Regrowth Rates

[25] We previously compared our estimates of deforestation rates in the humid tropics with the FAO Country Survey (CS) estimates which are widely used and provided an explanation of the 23% difference found [*Achard et al.*, 2002]. To complement this earlier comparison, we compare here our Brazilian Amazon and Guyanas regional estimate to independent estimates of (1) Brazilian Amazon and (2) the Guyanas. For the first sub-region, we used the Brazilian average estimate of net change [*INPE and IBAMA*, 1997; *INPE*, 2000] adjusted to humid forests. This latter estimate is produced from the comprehensive annual national monitoring program conducted by INPE (The Brazilian National Space Agency). To correct the INPE data for deciduous forests contribution, we excluded dry forests, cerradao, and caatingas. From the overall estimate of gross deforestation in Legal Amazonia from INPE for the period 1990–1997 (-1.64×10^6 ha yr^{-1}), there is a proportion of the dry forest types. Breaking down the deforestation estimates of INPE by forest physiognomy, around 16% of the annual deforestation in Legal Amazonia occurs in these dry forests cerradao and non-forest areas. It is probable that a small proportion of the "contact zone" forest is also dry forest. For the comparison, we therefore subtract 16% from INPE's figure (-1.64×10^6 ha yr^{-1}) to obtain a lower value (-1.38×10^6 ha yr^{-1}). For the second sub-region, the Guyanas, the sum of FAO net change national estimates (-0.05×10^6 ha yr^{-1}) was used as an estimate of gross deforestation. The resulting estimate of gross deforestation for humid forests in the Brazilian Amazon and Guyanas region from these combined sources is -1.43×10^6 ha yr^{-1}. Our own regional estimate ($-1.40 \pm 0.74 \times 10^6$ ha yr^{-1}) is remarkably close to this estimate, with a 2% relative difference. As the INPE Legal

Table 7. Comparison of TREES Humid Tropical Forest Area Estimates With FAO Estimates[a]

	Forest Area 1990			Annual Forest Area Change 1990–1997 (2000)		
Continent	TREES, 10^6 ha	FAO CS, 10^6 ha	FAO RSS f2, 10^6 ha	TREES, 10^6ha yr^{-1}	FAO CS, 10^6ha yr^{-1}	FAO RSS f2, 10^6ha yr^{-1}
Southeast Asia	283 ± 31	302	244 ± 41	−2.0 ± 0.8	−2.5	−2.0 ± 1.2
Africa	198 ± 13	218	506 ± 72	−0.7 ± 0.3	−1.2	−2.2 ± 0.8
Latin America	669 ± 57	652	808 ± 102	−2.2 ± 1.2	−2.7	−4.1 ± 2.2
Global	1,150 ± 54	1,172	1,558 ± 131	−4.9 ± 1.3	−6.4	−8.3 ± 2.6

[a] FAO Country Survey (FAO CS) estimates are restricted to the humid domain from the country tables [*FAO*, 2001a]. India is included with Southeast Asia but excluding 41 10^6 ha of dry forest for India. For Africa and Latin America we corrected the country estimates to the humid domain by multiplying the forest area by the proportion of rain and mountain forests, excluding the moist and dry forests [*FAO*, 2001b, Appendix 3]. Mexico is excluded from Latin America. FAO RSS (Remote Sensing Survey) f2 definition of forest "comprises the closed and open forest classes, and a fraction (two–ninths) of the fragmented forest class"; it was constructed to match the forest definition used in the country reporting [*FAO*, 2001a, p. 308]. These figures are available only at continental level including all types of tropical forests (humid and dry domains). TREES forest cover net change estimates are interpolated to the June 1990 to June 1997 period. Average observation dates are June 1990 and March 1997 for the TREES study. FAO CS forest cover net change estimates are reported for the 1990–2000 period. The average reference years for latest area data used by FAO CS are 1991 for Africa and South America and 1995 for Asia and Central America. The average observation dates of the FAO RSS exercise are December 1988 and July 1997. Estimation intervals are at 95% confidence level.

Amazonia sub-regional estimates are derived from wall-to-wall assessments using high-resolution satellite images and as they are representing 96% of the forest area change in the region, this provides an independent confirmation that our method allows for a determination of continental humid tropical forest cover change in a more reliable way than previously available.

[26] The FAO RSS estimates cannot be directly compared to our estimates for Latin America and Africa as they are meaningful only at the continental level including the whole non-TREES domain. But a comparison can be made for Southeast Asia, as the domains covered by the FAO RSS study and the TREES study are the same with the exception of the dry domain of India. In India, net forest cover change estimate is relatively low with a rate of 38,000 ha yr^{-1} [*FAO*, 2001a]. Table 7 shows that the two estimates of annual net forest area change (TREES and FAO RSS) for Southeast Asia are very close: 2.0 ± 0.8 × 10^6 ha yr^{-1} and 2.0 ± 1.2 × 10^6 ha yr^{-1}, respectively. This confirms our hypothesis that the FAO RSS estimates are consistent with ours and indeed are the most appropriate to use for the non-TREES domain. The estimates of annual deforestation in the non-TREES domain for the period 1990–1997 lead to two large figures (Table 5) or Latin America and Africa. The first estimate (1.9 ± 1.1 × 10^6 ha yr^{-1}) includes Mexico and the dry part of Brazilian Legal Amazonia, which together should explain around half of this figure when considering independent estimates: 0.63 × 10^6 ha yr^{-1} of annual change in Mexico [*FAO*, 2001b], and 0.26 × 10^6 ha yr^{-1} of deforestation in the dry part of Legal Amazonia [*INPE and IBAMA*, 1997]. A much higher independent estimate of deforestation for Mexico was published recently: 1.13 × 10^6 ha yr^{-1} for the period 1993–2000 [*Secretaría de Medio Ambiente y Recursos Naturales*, 2001] which, even if not yet validated, would still be consistent with our regional figure.

[27] Our estimates of area regrowth rates may be biased because our sampling strategy was specifically developed for estimating deforestation but not forest regrowth. Indeed, for the Brazilian Amazon and Guyanas region and for Africa, our estimates of regrowth rates over a 10-year period would lead to regrowth areas of 0.8 × 10^6ha and 1.4 × 10^6ha, respectively. These figures can be compared to independent estimates of tropical forest regeneration areas in the Brazilian Legal Amazon [*Lucas et al.*, 2000a] and in the Southern Cameroon [*Lucas et al.*, 2000b] for the early 1990s: 7.6 × 10^6ha and 8.2 × 10^6ha for early (<5 years) and late (>5 years) colonization phases in Legal Amazon; 0.4 × 10^6ha and 2.2 × 10^6ha for early and late colonization phases in Southern Cameroon. This comparison leads us to think that forest regrowths may be underestimated, probably as a result of our conservative definition of forest regrowth (only when trees height >5 m), related to the difficulty to identify reliably areas of younger regrowth.

4.2. Comparison With Other Forest Biomass Data

[28] In our study we rely on the latest published information on forest biomass. The error range of such biomass estimates is suggested to be as high as ±20% to ±60% [*Brown et al.*, 1995; *Watson et al.*, 2000]. This is partially caused by the considerable variation of the root biomass in tropical forests, but also by the extrapolation from point surveys to regional estimates. However, a number of other recent surveys of forest biomass lead either to similar carbon biomass estimates as compared to our mean estimate, or to estimates within our minimum-maximum interval. The carbon biomass estimates derived from these independent surveys are: 169 ± 12 t C ha^{-1} in a 50-ha forest plot in Panama [*Chave et al.*, 2003], 47 t C ha^{-1} for the semi-deciduous forests of Venezuela [*Fearnside*, 1997], 32 t C ha^{-1} and 35 t C ha^{-1} for Mexico and Paraguay [*FAO*, 2003], 85 t C ha^{-1} and 179 t C ha^{-1} for seasonal and moist lowland forests of Africa [*Brown*, 1997], a forest area weighted estimate at 126 t C ha^{-1} for the African TREES domain [*FAO*, 2003], 37 t C ha^{-1} for African open forests [*Zhang and Justice*, 2001], 46, 112 and 135 t C ha^{-1} for dry, seasonal, and moist lowland forests of continental tropical Asia, 104 and 164 t C ha^{-1} for seasonal and moist lowland forests of insular tropical Asia [*Brown*, 1997], a forest area weighted estimate at 60 t C ha^{-1} for Southeast Asia except India [*FAO*, 2003] (this latest low estimate is due to a figure of 82 t C ha^{-1} for Indonesia). These independent surveys

Table 8. Comparison Between Different Annual Carbon Flux Estimates (Net Emissions in Gt C yr^{-1}, i.e., 10^9 tC yr^{-1}) During the 1990s[a]

Flux Estimates	TREES Domain	Non-TREES Domain	Global
Our previous estimate [*Achard et al.*, 2002]	0.64 ± 0.21	0.32	0.96
This study's minimum estimate (using decay constant at 0.1, minimum forest biomass and degradation losses without soil carbon nor Indonesian fire emissions)	0.51 ± 0.18	0.08 ± 0.02	0.59 ± 0.20
This study's best estimate (using decay constant at 0.1, mean forest biomass including soil carbon and degradation losses plus Indonesian fire emissions)	0.92 ± 0.27	0.15 ± 0.04	1.07 ± 0.31
This study's maximum estimate (using decay constant at 0.4, maximum forest biomass, including soil carbon and degradation losses plus Indonesian fire emissions)	1.38 ± 0.41	0.21 ± 0.06	1.59 ± 0.46
Houghton's [2003b] estimate			2.2 ± 0.8

[a]Net emissions in Gt C yr^{-1}, i.e., 10^9 tC yr^{-1}.

lead to higher figures than our mean values for only one specific sub-biome, the moist lowland forests, which covers a limited part of the whole humid domain.

[29] Moreover, *Houghton et al.* [2001] mention that deforestation is not spatially distributed in a homogeneous fashion across Amazonia. More than half of the clearing of the 1990s has taken place in forests of lower biomass in the Mato Grosso and Rondônia states. The seven surveys of biomass in Amazonian forests reported by *Houghton et al.* [2001] lead to a mean biomass at 152 ± 7 t C ha^{-1} when calculated over areas of actual deforestation, this estimate being close to our regional minimum carbon figure (149 t C ha^{-1}). As our mean carbon biomass input values are in the range of or lower than recently published surveys, our resulting carbon flux estimates should not be underestimated from the use of these data.

4.3. Comparison With Other Estimates of Carbon Flux

[30] For the Brazilian Amazon and Guyanas region, comparison with other studies support the assumption that the 10-year committed flux figure does not underestimate the actual annual net flux. Indeed our 10-year committed flux estimate for this region comes to 0.22 ± 0.14 Gt C yr^{-1} (Table 2) including 0.03 Gt C of soil carbon emissions, and corresponds well with the *Houghton et al.* [2000] estimate of annual net flux over the period 1989 to 1998 without accounting for soil carbon at 0.18 Gt C yr^{-1}. For the same region, an estimate of annual "100-year committed" flux at 0.26 Gt C yr^{-1} [*Fearnside*, 1997] compares well with the 75-year committed flux estimate which can be derived from our method at 0.29 ± 0.21 Gt C yr^{-1}. The close rapport between our committed flux estimates and these two independent estimates highlights the consistency of our carbon emission estimate.

[31] Furthermore, net emissions of CO_2 in Southeast Asia during the 1990s have been estimated from observed atmospheric CO_2, using the inverse modeling approach [*Schimel and Baker*, 2002]. This latter analysis reveals that net emissions for Southeast Asia without the South China Sea region were in the range 0.3 to 0.5 Gt C yr^{-1} during the 1990s with the exception of years 1995 (at around 0.7 Gt C yr^{-1}), 1997–1998 (between 1 and 1.5 Gt C yr^{-1}) and 1999–2000 (close to 0 Gt C yr^{-1}). Thus our mean figure for this other major region (0.38 Gt C yr^{-1}) is supported by this independent approach.

[32] Surface-atmosphere CO_2 fluxes have been estimated from an intercomparison of atmospheric CO_2 inversion models at global level [*Gurney et al.*, 2002]. The "mean posterior flux" estimate over tropical land (tropical America, northern Africa, tropical Asia) is 1.14 ± 1.2 GtCyr^{-1}. There is again a close rapport between our global best net flux estimate (1.07 ± 0.31 GtCyr^{-1}) and this independent estimate even if this latter includes both sources due to tropical land-use change and sinks due to enhanced growth.

[33] A complementary approach to our study [*DeFries et al.*, 2002] examines the full spatial extent of the tropics at a coarse resolution of 8 km and provides estimates of sub-pixel percent tree cover from the early 1980s to the late 1990s. By calibrating the changes in percent tree cover with available analyses from high resolution satellite data, the study provides an estimate of changes in tropical forest area for the past 2 decades. Like our study, the analysis indicates lower rates of net forest change than the FAO country estimates at 5.56×10^6 ha yr^{-1} for the 1990s. The study also applied the percent tree cover estimates in a similar bookkeeping carbon model approach. The results from this study converge on similar conclusions to ours with a net carbon flux estimate from clearing and regrowth in tropical forests at 0.9 ± 0.5 Gt C yr^{-1} for the 1990s.

[34] Our best estimate of the actual global annual net flux from land use change in the tropics for the period June 1990 to June 2000, amounting at 1.1 ± 0.3 Gt C yr^{-1} is far lower than the estimate of the total annual net emission from land-use change ("primarily in the tropics") for the period 1989 to 1998 reported by IPCC [*Watson et al.*, 2000] at 1.6 ± 0.8 Gt C yr^{-1}, and than the estimate of terrestrial net source of carbon for the 1990s by *Houghton* [2003b] at 2.2 ± 0.8 Gt C yr^{-1} (Table 8).

4.4. Contributions of Forest Regrowths, Soil Carbon, and Forest Degradation

[35] Regeneration of forests on abandoned land (forest regrowths) represents a minor contribution to our estimates of net carbon flux budget (−3.3%), but if, as mentioned above, we have underestimated forest regrowth area rates, and hence the associated sink, then our net carbon emission estimates would be overestimated.

[36] We had pointed out [*Eva et al.*, 2003] that our previous carbon budget estimate for the humid tropics (Table 8) may be overestimated, contrary to what has been concluded by other authors [*Fearnside and Laurance*, 2003]. This earlier estimate did not account for loss of soil carbon from deforestation and loss of carbon from forest degradation which were mentioned as sources of uncertainties as much more difficult to quantify. We account here for soil carbon loss, which contribution represents 20% of the net estimate. Other studies do not consider such losses as they are small relative to the change in biomass and are inconsistent in direction [*Houghton et al.*, 2000]. We account also for forest degradation although selective logging and small-scale forest fragmentation processes are not included because these processes are below the minimum mapping unit of our study [*Sgrenzaroli et al.*, 2002]. However, three considerations have to be made: (1) The impact of selective logging on carbon emissions may not be very significant because there is no burning, the damage to soils can be expected to be smaller than in the case of forest conversion and there regrowth occupies quickly the openings; (2) in most of the tropics, selective logging is an initial phase in the deforestation process through post-logging colonization or increase of the fire susceptibility [*Cochrane*, 2003]. When such logged forests have been later transformed to non-forest, we counted 100% of the forest area as deforested with 100% biomass content. A certain percentage of biomass lost through selective logging and non-visible degradation may be therefore compensated in our deforestation estimates. (3) Also in the case that a forest regrowth is re-cleared during the 1990s, it is reflected in our deforestation rate; that is, we will account for much higher carbon emissions than will happen in reality. Thus our new estimate for the humid tropics (0.92 ± 0.27 Gt C yr^{-1}) including all these contributions should be quite exhaustive and more realistic than the previous.

5. Conclusions

[37] This study uses an existing approach for quantifying net carbon emissions from land use change in the tropics using the most recent published rates of forest cover change. The resulting new estimates have implications for the global carbon cycle. The increase of carbon dioxide in the atmosphere relative to estimated emissions from fossil fuel burning and land use change on one hand and uptake by oceans on the other leaves a substantial amount of carbon "missing" from the budget. The most recent Intergovernmental Panel on Climate Change (IPCC) report infers the land-atmosphere flux, the residual between atmospheric sources (fossil fuel emissions) and sinks (ocean uptake and observed atmospheric increase), at -1.4 ± 0.7 Gt C yr^{-1} for the 1990s [*Prentice et al.*, 2001], leading to a "missing residual sink" from -2 to -4 Gt C yr^{-1} if the carbon source from tropical land use change is assumed to be the same as estimated from the 1980s. The land-atmosphere flux represents the difference between the carbon source from land use change and the missing residual sink. The greater the flux from land use change, the greater the amount of "missing" carbon. More recently, *Houghton* [2003b] considered a 2.9 ± 1.1 Gt C yr^{-1} estimate for the residual terrestrial carbon sink as robust, but pointed out that the responsible mechanisms are uncertain. Spatially explicit information on tropical land use change has been one of the major obstacles to improved understanding of the land-atmosphere flux, and emissions from tropical land use change is one of the most uncertain in the global carbon budget. Our study applies the bookkeeping carbon model to our estimates of deforestation rates to provide an alternative estimate for this term in the carbon budget.

[38] A main conclusion of our study is that the source of atmospheric carbon from tropical deforestation could be substantially smaller than the 1.6 ± 0.8 Gt C yr^{-1} previously reported by the IPCC [*Watson et al.*, 2000] or the 2.2 ± 0.8 Gt C yr^{-1} more recently estimates by *Houghton* [2003a, 2003b]. Considering our best estimate of global net emissions from land-use change in the tropics, about 1.1 ± 0.3 Gt C yr^{-1}, it leads us to believe that the residual terrestrial uptake for the 1990s must be -2.5 ± 1.1 Gt C yr^{-1} using the current IPCC land atmosphere flux estimate [*Prentice et al.*, 2001] or -1.8 ± 1.2 Gt C yr^{-1} using the latest net terrestrial flux published estimate [*Plattner et al.*, 2002].

[39] These new data will help reduce uncertainties in the global carbon budget. The lower deforestation rate found by us, evidently, has a major impact, reducing significantly the estimated carbon emission. The purpose of our paper is to demonstrate this impact. We demonstrate also the impacts on global emissions of other sources of uncertainties, in particular the estimation of forest carbon biomass and forest degradation.

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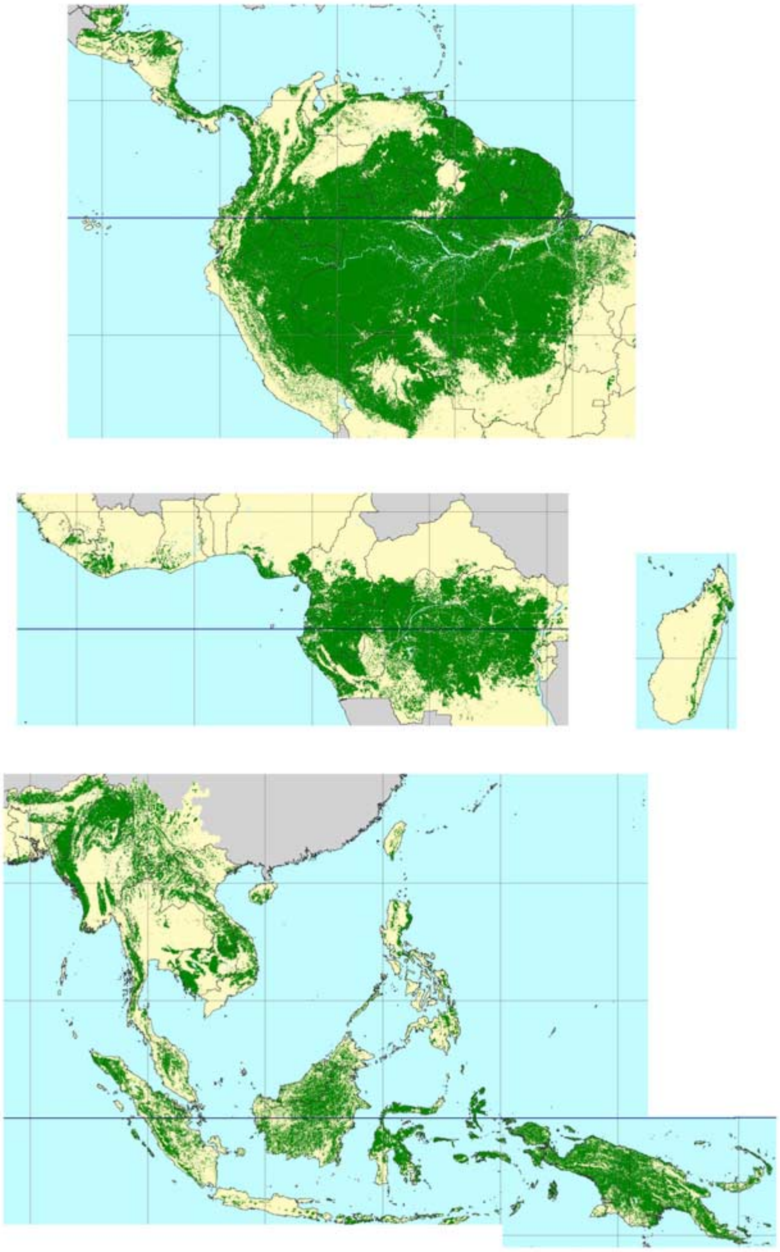

Figure 1. Humid tropical forest biome of the TREES domain with the exception of the Western Ghats forests of India (forests are represented in green).