Determination of Deforestation Rates of the World's Humid Tropical Forests

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A recently completed research program (TREES) employing the global imaging capabilities of Earth-observing satellites provides updated information on the status of the world's humid tropical forest cover. Between 1990 and 1997, 5.8 ± 1.4 million hectares of humid tropical forest were lost each year, with a further 2.3 ± 0.7 million hectares of forest visibly degraded. These figures indicate that the global net rate of change in forest cover for the humid tropics is 23% lower than the generally accepted rate. This result affects the calculation of carbon fluxes in the global budget and means that the terrestrial sink is smaller than previously inferred.

Loss of forest cover affects climate. Global forest assessments such as those undertaken by the Food and Agriculture Organization (FAO) (*1*) are designed to measure the area of and the trends in the extent of the world's forests. The humid tropical forests deserve our special attention because demographic, economic, and social changes continue to exert considerable pressure on forest cover and conditions in this region (*2*), and our knowledge concerning their distribution and rates of change remains surprisingly limited. The Intergovernmental Panel on Climate Change (IPCC) has pointed out that "for tropical countries, deforestation estimates are very uncertain and could be in error by as much as ±50%" (*3*). The uncertainty of such estimates suggests that total global carbon emissions from land-use changes fall within the range of +0.8 to +2.4 gigatons of carbon (GtC) year^{-1} for the 1990s (*4*–*5*). Here we estimate the changes in humid tropical forest cover from satellite remote sensing imagery, with better global consistency and with greater accuracy than previously available, in order to understand their implications for the global carbon budget.

The evergreen and seasonal forests of the tropical humid bioclimatic zone covered by our work correspond closely to those forests defined by the FAO as closed broadleaved forests (*6*) and by the World Conservation Union as closed forests (*7*). We do not document the woodlands or the forests of the dry tropics, except for continental Southeast Asia, where the seasonal forests are intermixed with the humid forests (table S1). All figures reported here refer to the humid tropical forest biome of Latin America, excluding Mexico and the Atlantic forests of Brazil; the humid tropical forest biome of Africa (Guineo-Congolian zone and Madagascar); and the humid tropical forest biome of Southeast Asia and India, including the dry biome of continental Southeast Asia.

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We developed a statistical sampling strategy using satellite imagery to provide a reliable measurement of change in tropical forest cover in a uniform, independent, and repeatable manner. The method is based on (i) the establishment of subcontinental forest distribution maps for the early 1990s at 1:5,000,000 scale, derived from 1-km^2 spatial resolution satellite images; (ii) the generation of a deforestation risk map, identifying so-called "deforestation hot-spot areas" with knowledge from environmental and forest experts from each region (*8*); (iii) the definition of five strata as defined by the forest and hot-spot proportions obtained from the previous steps; (iv) the implementation of a stratified systematic sampling scheme with 100 sample sites (Fig. 1) covering 6.5% of the humid tropical domain, which was designed for change assessment by including higher sampling probabilities in deforestation hot-spot areas; (v) the change assessment for each site, based on the interpretation of fine spatial resolution (20 to 30 m) satellite imagery acquired at two dates closest to our target years, 1990 and 1997, and performed by local partners using a common approach; and (vi) the statistical estimates of forest and land cover transitions at the continental level using the data that were obtained by linearly interpolating between the two reference dates. Because we applied an unequal probability sampling scheme, a nonclassical statistical estimator (derived from the Horwitz-Thompson estimator) was used (*9*). The sampling accuracy (standard error) was estimated with a resampling (bootstrap) method.

The results of our study show that in 1990 (the Kyoto Protocol baseline year) there were about 1150 ± 54 × 10^6 hectares (ha) of humid tropical forest (Table 1). The estimated change in global humid tropical forest area for the period from 1990 to 1997 shows a marked reduction of dense and open natural forests: The annual deforested (*10*) area for the humid tropics is estimated at 5.8 ± 1.4 × 10^6 ha, plus a further 2.3 ± 0.7 × 10^6 ha of forest where degradation could be visually inferred from satellite imagery. Large nonforest areas were also reoccupied by forests, but these areas were mainly young regrowth on abandoned land, along with some forest plantations. Both are very different from natural forests in ecological, biophysical, and economic terms and therefore are not an appropriate counterbalance to the loss of mature forests.

The three continents we examined revealed considerable differences in percentage change rates (Table 1). Southeast Asia had the highest percentage deforestation rate, and Africa lost its forests at about half the rate of Southeast Asia. Latin America showed the lowest percentage rate, but at a rate of 2.5 × 10^6 ha year^{-1}, the annual loss of forest area was almost the same as the loss estimated for Southeast Asia. Forest degradation shows a similar overall pattern: most prominent in Southeast Asia, intermediate

Table 1. Humid tropical forest cover estimates for the years 1990 and 1997 and mean annual change estimates during the 1990–1997 period. All figures are × 10^6 ha. Sample figures were extrapolated linearly to the dates 1 June 1990 and 1 June 1997. Average observation dates were February 1991 and May 1997 for Latin America, February 1989 and March 1996 for Africa, and May 1990 and June 1997 for Southeast Asia. Estimated ranges are at the 95% confidence level.

	Latin America	Africa	Southeast Asia	Global
Total study area	1155	337	446	1937
Forest cover in 1990	669 ± 57	198 ± 13	283 ± 31	1150 ± 54
Forest cover in 1997	653 ± 56	193 ± 13	270 ± 30	1116 ± 53
Annual deforested area	2.5 ± 1.4	0.85 ± 0.30	2.5 ± 0.8	5.8 ± 1.4
Rate	0.38%	0.43%	0.91%	0.52%
Annual regrowth area	0.28 ± 0.22	0.14 ± 0.11	0.53 ± 0.25	1.0 ± 0.32
Rate	0.04%	0.07%	0.19%	0.08%
Annual net cover change	−2.2 ± 1.2	−0.71 ± 0.31	−2.0 ± 0.8	−4.9 ± 1.3
Rate	0.33%	0.36%	0.71%	0.43%
Annual degraded area	0.83 ± 0.67	0.39 ± 0.19	1.1 ± 0.44	2.3 ± 0.71
Rate	0.13%	0.21%	0.42%	0.20%

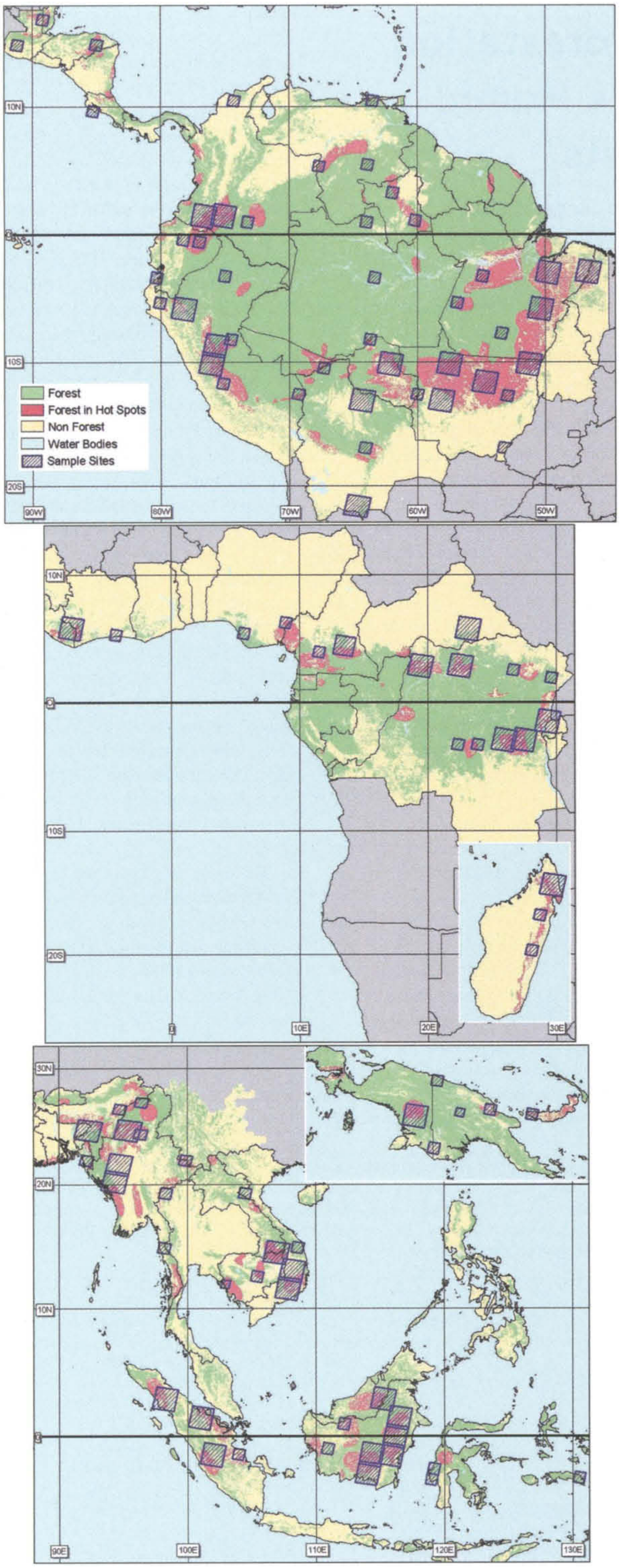

Fig. 1. Locations of the 100 observation sites around the tropics.

in Africa, and lowest in Latin America. These estimates represent only the portion of degradation identifiable using our methodology, which does not include processes such as selective logging. Reforestation was dominant in Southeast Asia, but it occurred mainly through the transition of former mosaics and woodlands to forest. Reforestation occurred less frequently in Latin America as compared with Southeast Asia and was very limited in Africa.

Globally, the main forest conversion process in the humid tropics was the transformation of closed, open, or fragmented forests to agriculture at a rate of 3.09×10^6 ha year^{-1} (Table 2). The major forest changes were largely confined to a number of hot-spot areas where change rates were alarmingly high: Annual transformation rates of more than 2.5% were measured at 16 sample sites. In Latin America, the transformation from closed, open, or fragmented forests to agriculture by clear-cutting dominated (1.72×10^6 ha year^{-1}) (table S2). This process is concentrated in hot spots (Table 3), where forests are increasingly fragmented, heavily logged, or burned. In addition, 3.61×10^6 ha year^{-1} of mosaics or savanna-woodlands were transformed into agriculture in Latin America. Surprisingly the estimated percentage rate of deforestation for Africa was higher than that for Latin America, with very high local rates in Madagascar and Côte d'Ivoire. In Africa, 310,000 ha year^{-1} of forests were transformed to agriculture, with a further 280,000 ha year^{-1} into mosaics and 200,000 ha year^{-1} into savannas or woodlands. For Southeast Asia, the change estimate indicates a high annual deforestation rate and a substantial annual rate of detectable degradation. In total, 1.06×10^6 ha year^{-1} of forests were converted into agriculture and 650,000 ha year^{-1} into mosaics. A further 550,000 ha year^{-1} of forests were degraded into savanna or woodlands. At the same time, about 650,000 ha year^{-1} of mosaics or savanna-woodlands changed to agriculture.

How do our estimates of forest area and forest area change compare to the FAO figures (*1*)? The latter are widely used in spite of the highlighted internal inconsistencies [chapter 46 in (*11*)] arising from the difficulties in standardizing national data obtained from different countries (*12*). For comparison, we adjusted the FAO figures to the humid tropical domain for the countries included in our survey (*13*). Our 1990 global forest area estimate (indicated as TREES-II in Table 4) shows only a 1.9% relative difference as compared with the FAO estimate (+3% for Latin America, –9% for Africa, and –6% for Southeast Asia). More striking, our global estimate of net forest area change during the 1990–1997 period is 23% lower than the FAO estimate.

The use of secondary information, expert opinions, and outdated country data by the FAO may explain these differences (*14*). Already, the FAO forest area estimates for the year 1990 (*1*)

Table 2. Forest cover changes in the humid tropics from June 1990 to June 1997. All area figures are $\times 10^6$ ha. The forest class definitions were made according to those applied by the FAO Forest Resource Assessment Exercise (*11*) using two parameters: tree cover (canopy density within a forest stand) and forest proportion (forest stand density within the mapping unit). An area assigned to one of the forest classes had a forest proportion of more than 40% in which the forest stands have a tree cover of more than 10%. When the forest proportion was at least 70%, the area was considered closed forest if the tree cover was more than 40% and open forest if the tree cover was between 10 and 40%. When the forest proportion was between 40 and 70%,the area was defined as fragmented forest. Plantations and forest regrowth are grouped as nonnatural forest. Referring to the nonforest classes, mosaics were defined as containing a forest proportion between 10 and 40%. Other natural vegetation such as shrub or grassland, but also agricultural land, may have still contained a forest proportion or a tree cover up to 10%. For forest cover calculations, we applied forest cover weights per class as determined by an independent postassessment of the observation site results (*8*). The total forest cover estimates in 1990 and 1997 were derived by the addition per class of the weighted forest cover areas. Bold figures indicate the total forest cover in 1990 and 1997; underlined figures indicate the unchanged area for each land cover class between the two dates.

1990		1997	Forest classes: Closed	Forest classes: Open	Forest classes: Fragmented	Forest classes: Plant/regrow	Nonforest classes: Mosaics	Nonforest classes: Natural	Nonforest classes: Agriculture	Nonforest classes: Unvegetated	Forest cover in 1990	
		Cover weight	*100*	*100*	*75*	*100*	*25*	*0*	*0*	*0*	Per class	**Total**
Forest classes	Closed	*100*	902.3	11.2	4.1	1.1	4.6	3.4	16.3	1.1	944	
	Open	*100*	1.7	120.6	2.4	0.1	1.2	1.6	2.3	0.2	130	
	Fragmented	*75*	1.8	1.0	37.8	0.1	3.0	1.0	3.1	0.2	36	
	Plant/regrow	*100*	0.0	0.1	0.0	7.2	0.1	0.3	1.2	0.1	9	
Nonforest classes	Mosaics	*25*	0.9	0.1	0.5	0.1	108.5	3.2	10.4	0.6	31	
	Natural	*0*	1.0	0.4	0.2	0.3	4.1	377.1	21.6	1.4	0	
	Agriculture	*0*	0.6	0.3	0.3	0.3	2.6	3.6	232.9	0.6	0	
	Unvegetated	*0*	0.0	0.0	0.0	0.1	0.0	0.8	0.5	33.7	0	**1150**
Forest cover in 1997		Per class	908	134	34	9	31	0	0	0		
		total								**1116**		

were found to be much higher than the previous FAO estimates for the same year (*6*), with the exception of South America (*12*). Furthermore, our TREES-II forest area estimates for 1990 are very close to our estimates from a previous TREES-I study (*15*) that used coarse-spatial-resolution maps calibrated with a sample of high-spatial-resolution maps (*16*). Our forest area change estimates are lower than the FAO estimates that were adjusted to the humid domain (*17*) by an amount of -0.5×10^6 ha year^{-1} for each continent. In Southeast Asia, the FAO estimate for Indonesia (which represents 39% of the forest area of this region) is largely based on national remote sensing–derived information for earlier years (1985 and 1997) and does not include the exceptional fire event in Indonesia in 1997–1998 (*18*, *19*) (neither does our survey). In Africa, the difference can be explained by the very low in-country forest monitoring capacities of most countries.

In Latin America, our estimates refer to two subregions: the Brazilian Amazon and Guyanas subregion and the pan-Amazon and Central America subregion. Our Brazilian Amazon and Guyanas subregion estimates (420 $\pm$ 37 $\times 10^6$ ha of forest area in 1990 and $-1.32 \pm 0.74 \times 10^6$ ha year^{-1} of forest area change) are close to estimates from other sources (401×10^6 ha and -1.43×10^6 ha year^{-1}) (*20*), with small relative differences (5 and 9%). Because the latter regional estimates were derived from wall-to-wall assessments using high-resolution satellite images, the similarity in estimates provides an independent confirmation that our method allows for a determination of global humid tropical forest cover change in a more reliable way than was previously available and highlights the importance of this new estimate of forest area change in the humid tropics.

Table 3. Annual deforestation rates, as a percentage of the 1990 forest cover, for selected areas of rapid forest cover change (hot spots) within each continent.

Hot-spot areas by continent	Annual deforestation rate of sample sites within hot-spot area (range)
Latin America	0.38%
Central America	0.8–1.5%
Brazilian Amazonian belt	
Acre	4.4%
Rondônia	3.2%
Mato Grosso	1.4–2.7%
Pará	0.9–2.4%
Colombia-Ecuador border	~1.5%
Peruvian Andes	0.5–1.0%
Africa	0.43%
Madagascar	1.4–4.7%
Côte d'Ivoire	1.1–2.9%
Southeast Asia	0.91%
Southeastern Bangladesh	2.0%
Central Myanmar	~3.0%
Central Sumatra	3.2–5.9%
Southern Vietnam	1.2–3.2%
Southeastern Kalimantan	1.0–2.7%

Our data can help reduce the amount of uncertainty in calculating net carbon flux from deforestation (*21*) and regrowth in the humid tropics. To estimate net carbon flux, we considered existing regional figures of total carbon vegetation biomass derived from the actual biomass density without roots (*22*) as a starting point. These figures are weighted by the 1990 forest area, and we added 20% for belowground vegetation (root) biomass, accepting that root biomass varies considerably in tropical forests (*22*). The error range of such biomass estimates is suggested to be as high as ± 30 to $\pm 60\%$. Carbon was assumed to be 50% of biomass (*3*). The resulting regional estimates are 129 tons of carbon (tC) ha^{-1} for the pan-Amazon and Central America region, 190 tC ha^{-1} for the Brazilian Amazon forests (*23*), 179 tC ha^{-1} for tropical moist Africa, and 151 tC ha^{-1} for Southeast Asia. Carbon fluxes can then be computed using the fractions of biomass that are assumed to be converted to CO_2 as a result of the deforestation and regrowth carbon rates, which are proportional to initial forest biomass (*24*). The fractions of biomass converted are 0.2 from initial forest biomass burned, 0.008 annual

Table 4. Comparison of TREES humid tropical forest cover estimates with FAO estimates. TREES-II, this study; TREES-I, previous study (*15*). FAO country estimates are derived from the country tables (*1*). India was included with Southeast Asia but not 41 × 10^6 ha of India's dry forest. 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 [appendix 3 in (*11*)]. Mexico was excluded from Latin America. The TREES estimates of net change in forest cover were interpolated to the June 1990–June 1997 period. Average observation dates were June 1990 and March 1997 for the TREES study. FAO forest cover net change estimates are reported for the 1990–2000 period. The average reference years for the latest area data used by the FAO are 1991 for Africa and South America and 1995 for Asia and Central America. Estimated intervals are at the 95% confidence level.

	Forest area for the year 1990 (10^6 ha)			Annual forest area change, 1990–1997 (10^6 ha $year^{-1}$)	
	TREES-II	TREES-I	FAO country	TREES-II	FAO country
Southeast Asia	283 ± 31	281	302	−2.0 ± 0.8	−2.5
Africa	198 ± 13	207	218	−0.7 ± 0.3	−1.2
Latin America	669 ± 57	671	652	−2.2 ± 1.2	−2.7
Global	1150 ± 54	1,158	1,172	−4.9 ± 1.3	−6.4

rate from decay of wood removed from the site for a 10-year period, and 0.07 initial annual rate with an exponential decrease in time from the decay of biomass left as slash. The initial (first-year) total fraction of 0.28 increases to 0.72 over a 10-year period, when including future sources embodied in first-year decay pools, and to 0.97 over a 75-year period. The accumulation of carbon on abandoned lands that reverted to forests (*24*) is taken as 2.8, 5.5, 5.0, and 3.8 tC ha^{-1} $year^{-1}$ for the pan-Amazon, Brazilian, African, and Southeast Asian regions, respectively, with a maximum accumulation of 129, 190, 179, and 151 tC ha^{-1}.

From our annual deforestation and regrowth estimates, we can compute three estimates of carbon flux: an initial flux for the first year, a "committed" flux for the next 10 years (including future sources and sinks), and a "committed" flux for the next 75 years. The first-year flux will obviously underestimate the impact of the land-cover change. The 75-year committed flux implies that the deforestation and regrowth rates that we have measured have been constant for the past 75 years. The 10-year committed flux has therefore been assumed to be more representative than the 75-year committed flux. For the Brazilian Amazon, comparison with other studies supports this assumption: Our 10-year and 75-year committed flux estimates for this region are 0.19 ± 0.12 GtC $year^{-1}$ and 0.24 ± 0.18 GtC $year^{-1}$, which correspond well with the estimates of 0.18 GtC $year^{-1}$ of annual net flux over the period from 1989 to 1998 (*24*) and 0.26 GtC $year^{-1}$ of annual 100-year committed flux (*25*).

Using our 10-year committed flux figure as a good estimate of the actual annual net flux leads to a global estimate of 0.64 ± 0.21 GtC $year^{-1}$ for the period from 1990 to 1997. This estimate is far lower than the estimate of total annual net emission from land-use changes, primarily in the tropics, for the period from 1989 to 1998 as reported by the IPCC (1.6 ± 0.8 GtC $year^{-1}$) (*3*). Considering that the net change in forest area is lower in the dry tropics than in the humid tropics (*11*) and that the biomass of dry tropical forests is less than half that of humid tropical forests (*22*, *26*), a maximum estimate of global net emissions from land-use change in the tropics would be about 0.96 GtC $year^{-1}$. Even if this figure does not include loss of carbon from forest degradation, which is much more difficult to estimate, this result leads us to believe that the residual terrestrial uptake must be smaller than previously inferred.

References and Notes

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9. Materials and methods are available as supporting material on *Science* Online.
10. Deforestation is defined as the conversion from forest (closed, open, or fragmented forests; plantations; and forest regrowths) to nonforest lands (mosaics, natural nonforest such as shrubs or savannas, agriculture, and nonvegetated). Reforestation (or regrowth) is the conversion of nonforest lands to forests. Degradation is defined as a process within forests that leads to a significant reduction in either tree density or proportion of forest cover (from closed forests to open or fragmented forests).
11. *Global Forest Resources Assessment 2000 Main Report* (FAO, Rome, 2001).
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13. The FAO estimates were extracted for the corresponding countries, restricted to the humid domain (using the FAO definitions of rain and mountain ecofloristic zones), and aggregated to the continental level.
14. As "in many countries, primary information on forest area was not available or was not reliable," FAO "had to rely on secondary information and/or expert estimates" (*11*). In particular, the average reference years for the latest area data are 1991 for Africa and South America and 1995 for Asia and Central America (*11*). Furthermore, "a high proportion of developing countries had to rely on expert opinion for the latest area estimates" (*11*). Comparisons may be less informative because of the expert extrapolations to the 1990–2000 period.
15. P. Mayaux, F. Achard, J. P. Malingreau, *Environ. Conserv.* **25**, 37 (1998).
16. In the previous method (27), the 1-km resolution baseline forest continental input maps were the same as for the present study, but the set of high-resolution imagery was different (30 sites were selected instead of 100, and at different locations). Also, the baseline maps were used in a different way in the previous study, to derive the two calibration covariables—forest area and fragmentation—for all 100-km^2 grid cells of the humid tropical zone, rather than to derive two sampling covariables, forest area and hot-spot area, for the sample frame and for the regions.
17. The FAO net change estimate for Africa before adjustment, mainly from the contributions of a few countries that include a large proportion of dry forests (Cameroon, Côte d'Ivoire, Democratic Republic of Congo, and Nigeria), is –1.9 × 10^6 ha $year^{-1}$. The Latin America FAO net change estimate before adjustment, including contributions of deciduous forests from Bolivia, Colombia, Peru, Venezuela, and Brazil, is −3.6 × 10^6 ha $year^{-1}$ (11).
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20. We used two other estimates for the Brazilian Amazon: the LANDSAT Pathfinder 1988 forest area estimate (28) normalized to 1990 (362 × 10^6 ha) and the Brazilian average estimate of net change (29) corrected for deciduous forest contributions (–1.38 × 10^6 ha $year^{-1}$). For the Guyanas region, the FAO estimates were used.
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23. The Brazilian Amazon estimate is the average of two estimates: 186 tC ha^{-1} and 195 tC ha^{-1}. The first estimate was derived from 310 tC ha^{-1} of actual biomass density without roots (22), and the second was an average of three estimates: 145, 210, and 232 tC ha^{-1} (24).
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30. Supported by the Directorate General for Environment of the European Commission. We thank the local partners from tropical countries who interpreted the imagery over the sample sites, in particular the regional coordinators: G. Leclerc, Centro Internacional de Agricultura Tropical, Colombia; A. Dorado, Ecoforca, Brazil; P. S. Roy, Indian Institute of Remote Sensing; U. R. Wasrin Syafii, Bogor University, Indonesia; M. Massart, IMAGE-Consult, Belgium; A. M. H. Faramalala, Foiben-Taosarintanin'i Madagasikara, Madagascar. The contribution of R. Drigo, Istituto Agronomico per l'Oltremare, Italy, to the consistency assessment is also acknowledged. We thank P. Janvier and A. Brink for assistance in developing the Geographic Information System (GIS) database; S. Fritz for assistance with the GIS representation of Fig. 1; and A. Belward, P. Kennedy, G. Matteucci, and the anonymous reviewers for their constructive comments on the manuscript.

Supporting Online Material

www.sciencemag.org/cgi/content/full/297/5583/999/DC1

Materials and Methods

Fig. S1

Tables S1 and S2

7 February 2002; accepted 8 July 2002