# Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s

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**Carbon fluxes from tropical deforestation and regrowth are highly uncertain components of the contemporary carbon budget, due in part to the lack of spatially explicit and consistent information on changes in forest area. We estimate fluxes for the 1980s and 1990s using subpixel estimates of percent tree cover derived from coarse (National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer) satellite data in combination with a terrestrial carbon model. The satellite-derived estimates of change in forest area are lower than national reports and remote-sensing surveys from the United Nations Food and Agriculture Organization Forest Resource Assessment (FRA) in all tropical regions, especially for the 1980s. However, our results indicate that the net rate of tropical forest clearing increased ≈10% from the 1980s to 1990s, most notably in southeast Asia, in contrast to an 11% reduction reported by the FRA. We estimate net mean annual carbon fluxes from tropical deforestation and regrowth to average 0.6 (0.3–0.8) and 0.9 (0.5–1.4) petagrams (Pg)·yr$^{-1}$ for the 1980s and 1990s, respectively. Compared with previous estimates of 1.9 (0.6–2.5) Pg·yr$^{-1}$ based on FRA national statistics of changes in forest area, this alternative estimate suggests less "missing" carbon from the global carbon budget but increasing emissions from tropical land-use change.**

The increase of carbon dioxide in the atmosphere relative to emissions from fossil-fuel burning and land-use change indicates that terrestrial and marine environments are absorbing approximately one-half to three-quarters of the emitted carbon dioxide. Several lines of evidence indicate uptake of carbon dioxide in the terrestrial extratropical Northern Hemisphere including land-inventory data, atmospheric $CO_2$ and $O_2$ data, isotopic analyses, and ecosystem models (1–5). Regrowth on abandoned agricultural land, fire prevention, longer growing seasons, and fertilization by increased concentrations of carbon dioxide and nitrogen have been proposed as possible mechanisms responsible for the Northern Hemisphere uptake (6–8).

Future atmospheric carbon-dioxide concentrations and consequent climate change depend to a large extent on the future course of the terrestrial uptake (9). If the underlying mechanisms are no longer able to sequester carbon at some point in the future, as for example would be the case once regrowing forests mature, a larger proportion of emitted carbon dioxide would remain in the atmosphere, and carbon-dioxide concentrations would increase at a greater rate for the same level of emissions.

Atmospheric inversion studies, which calculate net sources and sinks of carbon dioxide from the spatial distribution of atmospheric concentrations, indicate a net land sink of 0.6–2.3 petagrams (Pg)·yr$^{-1}$ in the extra tropics (6). In the tropics, inverse models are poorly constrained but indicate that the region, overall, is neutral or a small source of carbon to the atmosphere (10). Although inversion studies locate and quantify the net terrestrial sources or sinks, the attribution to mechanisms and their possible future trajectories depend on quantifying the gross sources and sinks. For a net sink, the mechanisms responsible for uptake of carbon dioxide must be powerful enough to offset the sources from fossil fuel and deforestation. The carbon dioxide emitted from fossil-fuel combustion is well quantified (11), but the emission from tropical land-use change is highly uncertain. Without more precise estimates of this source term, deciphering possible mechanisms sequestering the missing carbon remains problematic.

The flux of carbon to the atmosphere from tropical land-use change is one of the largest uncertainties in the contemporary carbon budget (6, 12) because of the difficulties in quantifying deforestation and regrowth rates, initial biomass, and fate of carbon in areas where vegetation has been cleared. Estimates of carbon fluxes from tropical deforestation as reported by the Intergovernmental Panel on Climate Change (IPCC; ref. 12) from refs. 5 and 13 range from 0.6 to 2.5 Pg·yr$^{-1}$ for the 1980s, based primarily on calculations using cropland statistics from the United Nations Food and Agriculture Organization (FAO) and deforestation rates from the FAO Forest Resource Assessment (FRA).

The FRA information is obtained through national reporting supplemented by limited satellite analysis in the assessment for the 1990s (14–16). Participation of individual countries through national reporting is a strength from some perspectives, but it generates problems from varying definitions of forest cover among countries and time intervals (17). These problems are particularly acute in developing countries, where most tropical deforestation occurs.

Comparisons of national statistics from the FRA with other country-level analyses suggest that the FRA overestimated changes in forest cover in some African countries (18), Bolivia (19), and other developing countries (20, 21). For the 1990–2000 interval, the FRA also conducted a remote-sensing survey, analyzing 10% of all tropical land area (15, 21). Forest area and deforestation rates from the FRA remote-sensing survey are generally lower than the FRA (15, 22) country reports for the 1990–2000 interval for Latin America and tropical Asia, although the differences are not statistically significant. For tropical Africa, the difference is very large (3 million ha/yr), suggesting exaggerated deforestation rates in the country data (15). For the 1980–1990 interval, on which the IPCC estimates of carbon fluxes from tropical deforestation are based, the country reports are the sole source of information for the FRA analysis.

Satellite data offer the possibility of spatially and temporally consistent estimates of forest cover to complement national reports. Data acquired by the Landsat platform, with a pixel

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Abbreviations: Pg, petagram(s); FAO, United Nations Food and Agriculture Organization; FRA, Forest Resource Assessment; IPCC, Intergovernmental Panel on Climate Change; AVHRR, National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer; PTC, percent tree cover; PTCA, PTC-corrected area.

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resolution of $\approx$30 m for the thematic mapper sensor and 60 m for the multispectral scanner sensor before the early 1980s, have provided estimates of deforestation rates for individual regions such as the Amazon basin (23). However, because of cloud coverage and limited acquisitions over the past several decades, it has not been possible to obtain comprehensive coverage for the entire tropics. Global data from the early 1980s to present acquired by the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR) provide daily coverage but at a coarse spatial resolution of 8 km (24). AVHRR data at the sensor resolution of $\approx$1 km are not available for the full time series with adequate spatial coverage. In this study we estimate changes in forest area by using an approach to estimate subpixel changes in tree cover within the coarse spatial resolution of the AVHRR data. This analysis thus provides a spatially explicit alternative to the FAO's nationally reported changes in forest area and an alternative estimate for carbon fluxes over the past two decades.

## Methods and Results

The approach to estimate carbon fluxes from tropical land-use change relies on multiple sources of remote-sensing data in conjunction with a terrestrial carbon model. We estimate subpixel percent tree cover (PTC) based on the method of DeFries *et al.* (25–27) and Hansen *et al.* (28, 29) for each year in the AVHRR 1982–2000 time series. Changes in PTC are converted to forest-area changes (PTC-corrected area, PTCA) by using high-resolution Landsat data. Finally, the "bookkeeping" terrestrial carbon model (30–32), applied spatially to each grid cell, estimates carbon fluxes (PTC carbon) from deforestation and regrowth over the past two decades. The bookkeeping model tracks the amount of carbon released to the atmosphere from clearing and decay of plant material, plus the amount of carbon accumulated as vegetation grows back.

**PTC Estimates.** Based on the Pathfinder AVHRR Land data set (24, 33), we estimate PTC within each pixel (27, 29) for each year in the 1982–2000 record. The method uses regression tree analysis to estimate subpixel PTC individually for each year in the time series. Inputs to the regression tree are multitemporal metrics derived from monthly values of the five AVHRR spectral bands ranging from visible to thermal wavelengths (0.58–12.5 $\mu$m) and the normalized difference vegetation index (NDVI) calculated from the red and near-infrared bands. Monthly composites are generated from the date with maximum NDVI to reduce cloud contamination. Metrics characterize the vegetation's spectral reflectance and phenology and include annual mean, maximum, minimum, and amplitude for each of the five AVHRR bands. We grow the regression tree using a global network of training sites derived from over 200 Landsat scenes and aggregated to the 8-km resolution of the AVHRR data (27, 29). For each year in the AVHRR time series, we grow and apply a regression tree using the same training data (61,222 8-km pixels).

Because the algorithm is applied independently to each year based on training data derived from over 200 Landsat scenes, the estimate is relatively insensitive to sensor degradation and other calibration problems in the AVHRR record (34). However, misregistration between years and spurious data in any single year generates noise that complicates the interpretation of year-to-year differences in PTC. To minimize the noise, we derived estimates of PTC for three 5-yr intervals (1982–87, 1988–92, and 1992–99) by using the median value for the interval to represent PTC for the time interval. The standard error (standard deviation of residuals) for the three 5-yr intervals as compared with the training data is 11.03%.

We label a grid cell as "change" if the difference in PTC between time periods exceeds a threshold value. The threshold value, $\approx$14%, corresponds to 2 standard deviations from the mean difference in PTC between time periods for the training-site locations. The training sites were selected in locations with no change based on expert knowledge of the locations. It is possible, of course, that a small percentage of the training sites have experienced change. Differences in PTC for training pixels are assumed to represent noise if they are less than the 2 standard-deviation threshold. Because the changes in PTC are converted to changes in forest area (PTCA) and carbon (PTC carbon) by using corrections based on comparison with high-resolution data (see below), the estimates of deforestation rates do not depend on the precise selection of the threshold value.

Changes in PTC between intervals indicate extensive forest loss in the well known arc of deforestation in the Amazon basin and in southeast Asia (Fig. 1). Both decreases and increases in tree cover were observed in Africa in a patchy distribution (data not shown).

**Comparison with Forest Cover Change from High-Resolution Satellite Data.** The subpixel estimates of PTC derived from the AVHRR time series provide an index of forest change but not an absolute level. Specifically, the coarse resolution cannot detect small patches, and the procedure for eliminating false change due to noise in the data eliminates true change as well. To convert the changes in PTC to changes in forest area (PTCA), we use a correction factor based on Landsat analyses as relevant as possible to each region. Large-scale, wall-to-wall Landsat analyses, however, are available for only a few locations (Table 1), most notably the Amazon basin. The FRA remote-sensing survey provides a further check, but its 10% coverage limits its potential for calibration and validation.

To convert changes in PTC to changes in PTCA, we use a

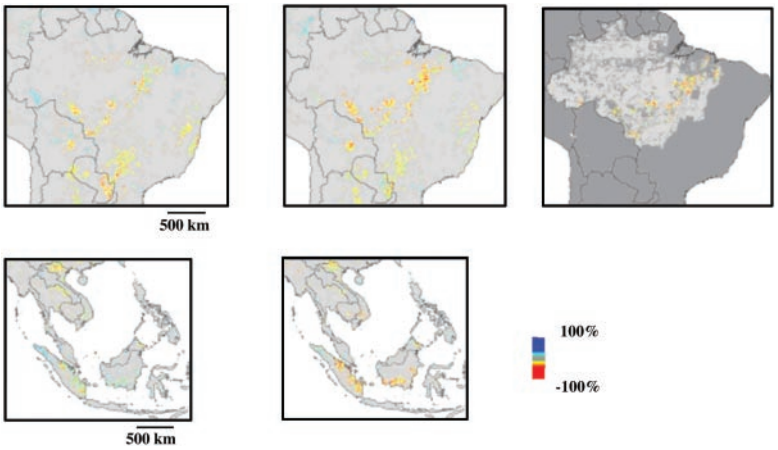

**Fig. 1.** Difference in PTC for a portion of Latin America for the 1980s (difference in median PTC of 1982–88 and 1988–92, *Upper Left*) and 1990s (difference in median PTC of 1988–92 and 1992–99, *Upper Center*) and a portion of tropical Asia for the 1980s (*Lower Left*) and 1990s (*Lower Right*). The difference in percent forest cover for 1986–92 was derived from Landsat analyses, aggregated to 8-km grid cell size, for the Brazilian Amazon based on data from the Tropical Rainforest Information Center (*Upper Right*). Dark gray in *Upper Right* indicates locations of missing data (within Amazon basin) or locations where analysis was not carried out (outside Amazon basin). Negative values (red) indicate a decline in tree cover, and positive values (blue) indicate an increase.

**Table 1. Deforestation rates estimated from high-resolution satellite imagery for comparison with estimates of changes in PTC**

| Region | Location | Source | Time period | Mean annual deforestation rate (1,000 ha·yr$^{-1}$) | Correction factor converting PTC to PTCA |
|---|---|---|---|---|---|
| Latin America | Brazil (partial coverage) | Tropical Rainforest Information Center* | mid-1980s–mid-1990s | 620 | 1.82 |
|  | 9 states in Brazilian Amazon[†] | Brazilian Space Agency (INPE) from Houghton *et al.* (32) | 1978–1998 | 1,754 | 2.56 |
| Tropical Asia | Bolivia | Steininger *et al.* (19) | 1984–1994 | 153 | 1.47 |
|  | 4 Indonesian islands[‡] | Global Forest Watch (36) | 1985–1997 | 1,479 | 3.57 |
| Africa | Democratic Republic of Congo (partial coverage) | Landsat Pathfinder for Humid Tropics[§] | mid-1980s–mid-1990s | 41 | 3.70 |

The state- and country-level analyses are used in this study to adjust the PTC estimates.

*See www.bsrsi.msu.edu/trfic.

[†] Instituto Nacional de Pesquisas Espacias (INPE) provides estimates of deforestation rates for the states of Acre, Amapa, Amazonas, Maranhao, Mato Grosso, Para, Rondonia, Roraima, and Tocantins. The value given here is the total for these states.

[‡] Analysis includes Sumatra, Kalimantan, Sulawesi, and Irian Jaya.

[§] See http://glcf.umiacs.umd.edu.

two-step correction. First, changes in PTC are expressed as crude areas, simply the product of the difference in PTC and the pixel area. These crude areas then are adjusted by a correction factor based on forest-change analysis from the most relevant Landsat-based study or studies. The conversion from PTC to PTCA varies according to the spatial patterns of deforestation (35). For example, in Bolivia, with large contiguous patches cleared for mechanized agriculture, the correction factor for converting subpixel PTC to PTCA is ≈1.5 (Table 1). In Africa, where clearing typically occurs in a more patchy distribution for small-scale agriculture, the only available correction factor is much larger: 3.7 (Table 1).

In the absence of wall-to-wall Landsat analysis with which to develop correction factors for each country, we consider a range for each continent. For Latin America, with relatively extensive Landsat-based analyses, the central estimate is the mean of the three sources listed in Table 1, with the low and high estimates from Bolivia and Instituto Nacional de Pesquisas Espacias (INPE), respectively. For southeast Asia, where Landsat-based analyses are much more limited, we use a central estimate that is the mean for all Latin American and Asian data (Table 1). The low estimate is the sum for the four Indonesian islands, and the high estimate is from Sumatra, where the most extensive deforestation has occurred. For Africa, Landsat-based analyses cover only a small fraction of the forest area. In the absence of better constraints, our central estimate is the mean based on all Landsat-based studies in Table 1. The high end of the range is estimated by comparison with the sparse Landsat analyses carried out over the Democratic Republic of Congo (http://glcf.umiacs.umd.edu), and the low end of the range is based on the correction factor for Bolivia. The FAO FRA remote-sensing survey, a 10% sample taken over each region, was not used to adjust the change in PTC estimates. Rather, it is used to assess the results of estimated deforestation and regrowth rates derived by correcting the PTC estimates with the other higher resolution analyses.

For the 1990s, the net change in forest area derived from AVHRR-based analysis corrected with high-resolution analyses (PCTA) is modestly lower than the FRA remote-sensing survey for tropical Latin America (24.3%) and tropical Asia (12.7%) (Table 2). For tropical Africa, however, the estimates are more than 80% lower. Some of this difference may be due to the limited availability of Landsat-based studies for developing appropriate correction factors, especially for sites where change occurs in very small patches across the landscape. The estimates for the 1990s from PTCA are also substantially lower than the FRA country reports for the 1990s for tropical Latin America (27.8%) and tropical Asia (16.3%), and they are dramatically lower for tropical Africa (93%). For the 1990s, total tropical net change in forest area from the central estimate of the PTCA analysis is $5.563 \times 10^6$ ha·yr$^{-1}$, 35.3% less than the $8.600 \times 10^6$ ha·yr$^{-1}$ from the FRA remote-sensing survey, and 53.6% less than the $12.000 \times 10^6$ ha·yr$^{-1}$ from the FRA country data.

For the 1980s, FRA remote-sensing data are not available. For this period, the PTCA is dramatically lower than the FRA country data: by 50.1% for Latin America, 51.1% for tropical Asia, and 92% for Africa. The PTCA total of $5.040 \times 10^6$ ha·yr$^{-1}$ is 62.6% less than the FRA total of $13.463 \times 10^6$ ha·yr$^{-1}$.

Because the PTCA analysis applies the same methodology over the length of the AVHRR record, it provides an alternative to the FRA data for assessing trends in deforestation and regrowth rates from the 1980s to 1990s. The PTCA and FRA country data indicate contrasting trends. PTCA indicates a 10.3% increase in the rate of net forest loss (accelerating forest loss) from the 1980s to the 1990s, whereas the FRA country data indicate a 10.9% decrease in the rate (decelerating loss).

**Carbon Fluxes from Tropical Deforestation and Regrowth.** The PTCA approach provides a means to estimate carbon fluxes in the 1980s and 1990s independent of the FRA country statistics. We calculate the carbon fluxes from deforestation and regrowth using a bookkeeping model (13, 31, 32) applied to each 8-km grid cell. The bookkeeping model accounts for forest clearing and regrowth by tracking (*i*) the immediate release of carbon to the atmosphere from plant material burned at the time of clearing, (*ii*) slower release of carbon from decay of slash, (*iii*) accumulation of carbon during regrowth, and (*iv*) changes in soil carbon. The fluxes are calculated on the basis of areas of clearing and regrowth, initial biomass values specified in the model, decay rates of dead plant material, and carbon uptake rates by regrowing vegetation. The rates of clearing and regrowth were based on the estimates of changes in subpixel tree cover.

Initial biomass values were set by using the values of Houghton and Hackler (30), with the forest type from a 1-km global land-cover classification (37) aggregated to 8 km according to the dominant vegetation type. For undisturbed forest, initial biomass values specified in the model were reduced linearly in proportion to the PTC in the grid cell. To test the sensitivity to assumptions about initial biomass, we ran the model with the initial biomass ±25%. Error bars represent the extreme values using the range of correction factors and the sensitivities to initial biomass assumptions. The high extreme values represent the largest correction factor applied to the high biomass assumption and the low extreme values represent the lowest correction factor applied to the low biomass assumption.

**Table 2. Changes in forest area (1,000 ha·yr$^{-1}$) from PTCA estimates, FRA/FAO remote-sensing survey, and FRA country data for the 1980s and 1990s in tropical Latin America, Asia, and Africa**

| | PTCA estimates | | FRA remote-sensing survey estimates | | FRA country data |
|---|---|---|---|---|---|
| | Mean area of decreased PTCA* | Mean area of PTCA loss minus mean area of PTCA gain* | Annual deforestation† | Annual net forest area change† | Annual net forest area change‡ |
| Tropical Latin America | | | | | |
| 1980s | 4,426 (2,916–5,085) | 3,566 (1,929–4,518) | NA | NA | 7,143 |
| 1990s | 3,982 (2,624–4,574) | 3,179 (1,698–4,043) | 4,400 | 4,200 | 4,400 |
| Percent difference§ | | −10.9% | | NA | −38.4% |
| Tropical Asia | | | | | |
| 1980s | 2,158 (1,491–2,929) | 1,195 (184–2,263) | NA | NA | 2,442 |
| 1990s | 2,742 (1,895–3,721) | 2,008 (820–3,174) | 2,500 | 2,300 | 2,400 |
| Percent difference§ | | +68.1% | | NA | −1.7% |
| Tropical Africa | | | | | |
| 1980s | 1,508 (1,054–1,508) | 279 (0–649)¶ | NA | NA | 3,878 |
| 1990s | 1,325 (926–1,325) | 376 (0–662)¶ | 2,300 | 2,100 | 5,200 |
| Percent difference§ | | +34.7% | | NA | +35.7% |
| Pantropics | | | | | |
| Percent difference§ | | +10.3% | | NA | −10.9% |

Countries included in each region are those included in pantropical remote-sensing survey of the FAO/FRA shown in figure 46-2 of ref. 15. NA, not available.

*1980s values are represented by mean value for 1984–1990 and 1990s values by 1990–1997. Areas are corrected with high-resolution analyses. Error ranges are based on the range of estimates using the correction factors between the AVHRR PTC and Landsat analyses as described in the text and Fig. 2 legend.

†From tables 1–4 in ref. 15. The FAO provides only values for the 1990s.

‡For 1990s, from tables 1–5 in ref. 15. FAO provides only net changes in forest area. For 1980s, from ref. 14, summed for countries included in remote-sensing survey for comparability with the 1990s values. The value for 1980s is the difference between mean annual change in natural forest area and plantation area.

§Percent difference between the 1980s and 1990s was calculated by subtracting the 1980s net area with change in forest cover from the 1990s net area normalized to the 1980s net area. Negative values indicate a decline in annual forest change from the 1980s to the 1990s, and positive values indicate an increase.

¶Estimates for areas with increase in PTC in Africa are highly uncertain because of less reliable mapping of PTC in savanna systems relative to forest.

The total carbon-flux estimate includes, in addition to the fluxes from our estimated changes in PTC, fluxes from land-use change that are not likely observable by even high-resolution satellite data. Nepstad *et al.* (38) estimate that carbon fluxes from "cryptic" logging activities not detectable with Landsat data account for 4–7% of carbon fluxes from deforestation in Amazonia. Houghton (39) estimates that these cryptic fluxes from logging and shifting cultivation total 0.041 Pg·yr$^{-1}$ for the 1990s (mostly occurring in Asia). Although the total fluxes from these processes remain uncertain, we add 7% to our estimates to crudely account for these sources.

To test whether the implementation of our bookkeeping model provides carbon-flux estimates in line with other published estimates, we first consider the best studied tropical country, Brazil. We estimate the net mean annual carbon flux for Brazil to be 0.15 (0.085–0.29) Pg·yr$^{-1}$ in the 1980s and 0.28 (0.17–0.49) Pg·yr$^{-1}$ in the 1990s. Most of the carbon flux is attributable to burning and decay of vegetation and slash, with only a small uptake from regrowth, which is in agreement with Houghton *et al.* (32). These estimates from PTC carbon analysis are generally within the range of previous estimates: 0.18 Pg·yr$^{-1}$ (32) mean net flux for 1989–99 and 0.26 Pg·yr$^{-1}$ (40), in the Brazilian Amazon only, and 0.174–0.336 Pg·yr$^{-1}$ for the entire land area of Brazil (13, 41, 42).

We apply the model to estimate carbon fluxes from deforestation and regrowth throughout the tropics. Initial biomass values and decay and uptake rates are identical to other estimates using the same model (13, 39) such that differences in carbon fluxes are attributable to our alternate estimates of areas undergoing deforestation and regrowth. We estimate that net carbon fluxes from tropical deforestation and regrowth in the 1980s and 1990s are 0.6 (0.3–0.8) and 0.9 (0.5–1.4) Pg·yr$^{-1}$, respectively (Fig. 2 and Table 3). The largest flux occurs in Latin America, although emissions increased most rapidly between the 1980s and 1990s in tropical Asia. Relative to the 1980s, PTCA estimates for the 1990s indicate lower rates of forest loss in Latin America and Africa and higher rates in Asia. However, the carbon-flux estimates suggest increasing emissions to the atmosphere in all continents. The increased fluxes can be attributed to (*i*) increased clearing in higher biomass forests in the 1990s relative to the 1980s (Fig. 1) and (*ii*) decreased areas reforested in the 1990s relative to the 1980s (Tables 2 and 3). These factors illustrate the importance of spatial information about the location of clearing and regrowth, not available with national level statistics, to reduce uncertainties about carbon fluxes from land-use change.

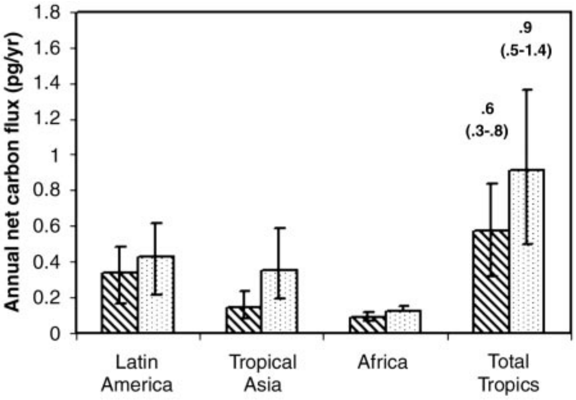

**Fig. 2.** Net carbon-flux estimates for tropical land-use change for the 1980s (diagonal stripes) and 1990s (dotted pattern). Error bars are derived from sensitivity to initial biomass values at ±25% of the value given in the bookkeeping model and the ranges derived from the correction factors between PTC estimates and high-resolution analyses. In addition to carbon fluxes from forest clearing and regrowth, the carbon-flux estimate includes an additional 7% to incorporate fluxes from logging and other processes not detectable with high-resolution analyses. To compare with previously published carbon-flux estimates, these estimates include countries listed in table 3 of ref. 30 for the regions of South and Central America, tropical Africa, and south and southeast Asia.

**Table 3. Estimated carbon fluxes (Pg·yr$^{-1}$) in tropical Latin America, Asia, and Africa**

| | Mean annual carbon loss from deforestation | Mean annual carbon gain from regrowth | Net annual carbon flux | Carbon gain/ carbon loss |
|---|---|---|---|---|
| Tropical Latin America | | | | |
| 1980s* | 0.37 (0.19–0.53) | 0.03 (0.02–0.05) | 0.34 (0.17–0.48) | 0.09 |
| 1990s* | 0.46 (0.23–0.66) | 0.03 (0.01–0.04) | 0.43 (0.21–0.62) | 0.06 |
| Tropical Asia | | | | |
| 1980s | 0.18 (0.10–0.29) | 0.03 (0.02–0.05) | 0.15 (0.08–0.24) | 0.17 |
| 1990s | 0.37 (0.20–0.61) | 0.01 (0.007–0.02) | 0.35 (0.19–0.59) | 0.04 |
| Tropical Africa | | | | |
| 1980s | 0.10 (0.08–0.14) | 0.02 (0.01–0.02) | 0.09 (0.07–0.12)† | 0.20 |
| 1990s | 0.14 (0.10–0.18) | 0.01 (0.01–0.02) | 0.12 (0.08–0.14)† | 0.07 |
| Pantropics | | | | |
| 1980s | 0.65 (0.37–0.96) | 0.08 (0.05–0.12) | 0.57 (0.32–0.84) | 0.12 |
| 1990s | 0.97 (0.51–1.55) | 0.05 (0.03–0.08) | 0.91 (0.50–1.36) | 0.05 |

Estimates include countries listed in table 3 of ref. 31 for the regions of South and Central America, tropical Africa, and south and southeast Asia to compare with IPCC estimates. Estimates include an additional 7% to account for cryptic change not observed with high-resolution satellite data.

*1980s values are represented by mean value for 1984–1990 and 1990s values by 1990–1997.

†Estimates for tropical Africa are uncertain because of the lack of data to derive PCTA from PCT estimates. If FRA 1990 remote-sensing survey results are applied to correct the fluxes rather than other Landsat analyses as described in the test, estimates are 0.14 (0.11–0.24) and 0.19 (0.14–0.24) Pg·yr$^{-1}$, respectively.

## Discussion and Conclusions

PTC estimates derived from the spatially comprehensive 18-yr (1982–2000) AVHRR record, corrected with forest-cover change estimates from higher resolution satellite data in available locations, provide alternative estimates of deforestation rates and resulting carbon fluxes independent of national-level statistics. For the decade of the 1990s, our satellite-derived estimates of net change in forest area (PTCA) are modestly lower than the FAO FRA national statistics and the FRA remote-sensing survey for Latin America (by 28 and 24%, respectively) and tropical Asia (by 16 and 13%, respectively). For the decade of the 1980s, however, when FRA remote-sensing survey results are not available, the PCTA estimates are dramatically lower than the national statistics report: by 50% for Latin America and 51% for tropical Asia. In tropical Africa, where data quality is questionable and satellite estimates are constrained by the patchy nature of forest clearing, estimates vary widely for both the 1980s and 1990s.

The result is consistent with other studies suggesting that the national statistics may be overestimating changes in forest cover in the few countries for which data are available. Overestimated deforestation rates in the 1980s mask increased deforestation rates from the 1980s to the 1990s. The FRA statistics indicate an ≈11% decrease in the annual rate of change in forest area between the two decades for the tropical countries considered in this analysis, whereas the satellite-derived PCTAs suggest an ≈10% overall increase (Table 2). In Latin America, the two estimates both indicate declines in deforestation rates, but the FRA indicates a larger decline (38%) than the PTCA estimates (11%). The large increase in tropical Asia (68% from PTCA in contrast to 2% decline from the FRA reports) occurs mostly in Indonesia due at least partially to the drought-related fires of 1997–98 (43) and reduced areas of regrowth relative to the 1980s.

The estimate of carbon fluxes from tropical land-use change is on the low end of the range reported in the IPCC, indicating that the missing carbon sink may be smaller than estimated previously. Although our results indicate that tropical forest clearing and carbon emissions accelerated from the 1980s to 1990s, the magnitude of the flux is lower than previous estimates based on changes in forest-area rates reported by the FRA. Of the three continental regions, we regard our carbon-flux estimates for tropical Africa to be the most uncertain because of difficulties in detecting patchy clearings and sparse data sources. It is unlikely, however, that this uncertainty accounts for the overall difference between our pantropics and the IPCC estimates.

The bookkeeping model to estimate carbon fluxes from changes in forest cover assumes an initial biomass for aboveground vegetation and soils and a known fate for carbon that is burned, deposited as slash, or stored in products. Although satellite data can improve the estimates of areas undergoing clearing and regrowth, the lack of spatially explicit information on the other factors contributes to the large uncertainties in carbon fluxes from tropical land-use change. Linkage of process studies with carbon models in a spatially explicit framework is needed to reduce these uncertainties.

In summary, this study suggests:

1. Overall, the rates of tropical forest clearing have increased by ≈10% from the 1980s to 1990s in contrast to FRA statistics that report declining rates. The increase is largely in southeast Asia, with only slight decreases in clearing rates in Latin America and Africa.
2. Carbon fluxes from tropical deforestation and regrowth have large uncertainties but are likely to be near the low end in the range of previous estimates based on FRA national statistics. The alternative estimate resulting from this analysis indicates annual fluxes of ≈0.6 and 0.9 Pg·yr$^{-1}$ for the 1980s and 1990s, respectively, meaning that the missing terrestrial carbon is less than half of the current IPCC estimate.
3. Satellite data provide temporally and spatially consistent estimates of changes in forest cover. Spatially explicit information on locations of clearing and regrowth, as opposed to nationally aggregated statistics, are essential to quantify carbon fluxes over nonhomogeneous landscapes. As time series of higher resolution data with frequent coverage become available for the entire tropics, estimates of forest clearing will become more accurate. Estimates of carbon fluxes from land-use change will likely become more certain, although key uncertainties remain on the spatial distribution of biomass and the fate of carbon after clearing.

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