AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL062777

**Key Points:**
- Sixty-two percent increase in net deforestation in the tropics from the 1990s to the 2000s
- Our result contradicts a 25% reduction reported by FAO
- The 7.2% decrease in net deforestation from the early 2000s to the late 2000s

**Supporting Information:**
- Figures S1 and S2 and Tables S1 and S2

**Correspondence to:**
D.-H. Kim,
rsgis@umd.edu

**Citation:**
Kim, D.-H., J. O. Sexton, and J. R. Townshend (2015), Accelerated deforestation in the humid tropics from the 1990s to the 2000s, *Geophys. Res. Lett.*, *42*, 3495–3501, doi:10.1002/2014GL062777.

Received 8 DEC 2014
Accepted 9 FEB 2015
Accepted article online 11 FEB 2015
Published online 7 MAY 2015



# Accelerated deforestation in the humid tropics from the 1990s to the 2000s

**Do-Hyung Kim[1], Joseph O. Sexton[1], and John R. Townshend[1]**

[1]Global Land Cover Facility, Department of Geographical Sciences, University of Maryland, College Park, Maryland, USA

**Abstract** Using a consistent, 20 year series of high- (30 m) resolution, satellite-based maps of forest cover, we estimate forest area and its changes from 1990 to 2010 in 34 tropical countries that account for the majority of the global area of humid tropical forests. Our estimates indicate a 62% acceleration in net deforestation in the humid tropics from the 1990s to the 2000s, contradicting a 25% reduction reported by the United Nations Food and Agriculture Organization Forest Resource Assessment. Net loss of forest cover peaked from 2000 to 2005. Gross gains accelerated slowly and uniformly between 1990–2000, 2000–2005, and 2005–2010. However, the gains were overwhelmed by gross losses, which peaked from 2000 to 2005 and decelerated afterward. The acceleration of humid tropical deforestation we report contradicts the assertion that losses decelerated from the 1990s to the 2000s.

## 1. Introduction

Tropical deforestation was among the largest anthropogenic sources of greenhouse gas emissions in the 1990s [*Gibbs et al.*, 2007]. Based on statistics from the United Nations Food and Agriculture Organization (FAO) Forest Resource Assessment (FRA) [*Food and Agriculture Organization* (*FAO*), 2010], the Intergovernmental Panel on Climate Change reported a 1.84 Gt $CO_2$ $yr^{-1}$ global decline in $CO_2$ emissions from land use change from the 1990s to the 2000s, attributed largely to a decreasing rate of deforestation [*Stocker et al.*, 2013].

However, estimates of forest area changes across the tropics prior to 2000 remain uncertain. The FRA has been criticized for inconsistencies in the definition of forest among countries and over time, as well as its dependence on national self-reporting [*Matthews*, 2001; *Defries et al.*, 2002; *Grainger*, 2008]. Previous studies have shown that the FRA overestimated changes in forest area [*Houghton*, 1999; *Steininger et al.*, 2001; *Achard et al.*, 2002; *Defries et al.*, 2002] in the 1980s and the 1990s. In the tropics especially, the FRA reported a declining rate of deforestation from the 1980s to the 1990s, while studies based on satellite data observed opposite trends [*Defries et al.*, 2002].

Recent progress in data availability and processing power have enabled national and global forest cover change assessments based on long-term archives of satellite imagery [*Townshend et al.*, 2012; *Hansen et al.*, 2013; *Sexton et al.*, 2013; *Kim et al.*, 2014]. Importantly, these satellite assessments are now possible at subhectare resolution, the scale at which most anthropogenic changes occur [*Townshend and Justice*, 1988]. Landsat data offer a spatial resolution suitable to map such changes (e.g., shifting cultivation in the rainforest) with instantaneous field of view of 30 m and effective resolution element smaller than 75 m, the minimum area for which spectral properties of the center can be assigned with at least 95% confidence [*Townshend*, 1981; *Wilson*, 1988].

In this study, we summarize a series of forest change data sets based on satellite observations in circa 1990, 2000, and 2005 "epochs" [*Sexton et al.*, 2013; *Kim et al.*, 2014] to estimate changes in tropical forest area at high (30 m) spatial resolution in 34 tropical countries from 1990 to 2005. Using a consistent definition of forest throughout, the data enable a spatiotemporally comprehensive alternative to the FAO reports and other sample-based satellite analyses [e.g., *FAO*, *Joint Research Centre* (*JRC*), 2012; *Achard et al.*, 2014]. We extend the series forward as well, from 2005 to 2010, to estimate changes in tropical forest area in the latter part of that decade and to complete the first fine-scale satellite-based estimates of change in humid tropical deforestation spanning the turn of the millennium. Several local and regional studies have been made of changing rates of deforestation between the 1990s and 2000s, but this is the first pan-tropical analysis.

**Table 1.** Definitions of Forest Used by Various Sources

| | FAO FRA [2010] | *Hansen et al.* [2013] | FRA RSS, TREES | This study |
|---|---|---|---|---|
| Basis | Land use, land cover | Land cover | Land cover | Land cover |
| Tree cover threshold | 10% | 25% | 30% | 30% |

## 2. Methods

### 2.1. Study Area

The study area comprises 34 countries spanning the humid tropics, each of which is covered at least 50% by forest biomes [*Olson et al.*, 2001]. These countries' forests comprise over 80% of forest area in the tropics [*Hansen et al.*, 2013] and dominate the forest area of the humid tropics.

### 2.2. Definitions

Consistent with the United Nations Framework Convention on Climate Change [*UNFCCC*, 2002], United Nations Food and Agriculture Organization [*UNFAO*, 2002], and the International Geosphere-Biosphere Programme (IGBP) [*Belward*, 1996], we defined forest *cover* (as opposed to forest *use* [*Belward*, 1996; *Hansen et al.*, 2010]) as parcels >1 ha in area and comprising pixels with >30% tree cover. Our definition corresponds with the definitions of IGBP classes for forest (>60% tree cover) and woody savannas (>30% tree cover) combined. Table 1 shows the differences in forest definition for each set of estimates compared in this study. It is notable that among the sources, only the FAO definition relies on dominant land use [*Stibig et al.*, 2014].

### 2.3. Data and Analysis

Five thousand four hundred forty four Landsat scenes were collected from the 1990, 2000, 2005, and 2010 epochs of the Global Land Survey (GLS) collection of Landsat images. The GLS is intended to provide full, multitemporal coverage of Earth's terrestrial surface in service of land cover mapping and change detection [*Gutman et al.*, 2008]. The original GLS data were augmented with additional images to improve radiometric calibration, reduce cloud cover, and maximize spectral discrimination of forests [*Kim et al.*, 2011]. Each image of this augmented GLS data set was atmospherically corrected to estimate surface reflectance using the LEDAPS (Landsat Ecosystem Disturbance Adaptive Processing System) [*Masek et al.*, 2006]. Forest cover in the 2000 and 2005 epochs was estimated by translation of percent-tree cover to categorical forest cover and change [*Sexton et al.*, 2013, 2015], using probability thresholds of 0.5 to detect forest loss and 0.7 to detect forest gain to account for their different detectabilities. Stable pixels identified in the 2000 and 2005 epochs were then used to extend the classification and change estimate of forest cover to the 1990 and 2010 epochs [*Kim et al.*, 2014]. Each GLS epoch spans a range of years focused on the nominal year [*Gutman et al.*, 2008], so the forest/nonforest layer in each year was accompanied by the year of image acquisition to estimate changes over time as rates. Forest cover data in 1990, 2000, and 2005 epochs are publicly available from the Global Land Cover Facility (www.landcover.org).

Forest cover change statistics—including gross forest (cover) loss, gross forest gain, and net change—were generated for the periods between the four epochs. These estimates were adjusted to account for missing data due to clouds and their shadows. The forest cover change statistics in each period were adjusted using error matrices from a global accuracy assessment [*Kim et al.*, 2014] to minimize incompatibility due to the different biases in forest cover change statistics for each period. Forest cover change statistics from 2000 to 2010 were estimated by averaging the estimates for 2000–2005 and 2005–2010 periods.

## 3. Results and Discussion

Satellite analysis revealed forest cover totals of $1340 \times 10^6$ ha in 1990, $1300 \times 10^6$ ha in 2000, and $1240 \times 10^6$ ha in 2010 across the 34 countries. These estimates are broken down by continent and by country in Table 2. During the 1990–2000 period, the annual net change across all the countries was $-4 \times 10^6$ ha yr$^{-1}$, the gross rate of loss was $4.9 \times 10^6$ ha yr$^{-1}$, and the gross rate of gain was $0.9 \times 10^6$ ha yr$^{-1}$. During the 2000–2010 period, the rate of loss was $7.8 \times 10^6$ ha yr$^{-1}$, and the rate of gain was $1.3 \times 10^6$ ha yr$^{-1}$, resulting in a $-6.5 \times 10^6$ ha yr$^{-1}$ net rate of change. Our estimates indicate a dramatic 62% ($2.5 \times 10^6$ ha yr$^{-1}$) acceleration of net forest loss from the 1990s to

**Table 2.** Landsat-Based Estimates of Forest Area ($10^6$ha) in 1990, 2000, and 2010 by Continent and Country

| | 1990 | 2000 | 2010 | | 1990 | 2000 | 2010 |
|---|---|---|---|---|---|---|---|
| Belize | 1.93 | 1.85 | 1.79 | Gabon | 23.38 | 22.92 | 22.99 |
| Bolivia | 57.95 | 56.05 | 53.06 | Liberia | 7.46 | 7.27 | 7.23 |
| Brazil | 431.47 | 412.12 | 386.4 | Madagascar | 8.93 | 8.55 | 7.58 |
| Colombia | 74.75 | 73.45 | 69.82 | Sierra Leone | 3.79 | 3.7 | 3.53 |
| Costa Rica | 3.99 | 3.9 | 3.69 | Tropical Africa | 243.58 | 241.06 | 235.12 |
| Ecuador | 15.22 | 14.95 | 14.63 | Bangladesh | 2.03 | 1.99 | 1.88 |
| Guatemala | 7.53 | 7.14 | 6.65 | Brunei Darussalam | 0.52 | 0.52 | 0.51 |
| Guyana | 18.39 | 18.23 | 18.16 | Cambodia | 7.81 | 7.5 | 6.32 |
| Honduras | 7.44 | 7.19 | 6.73 | Indonesia | 154.82 | 148.29 | 139.87 |
| Nicaragua | 6.27 | 5.98 | 4.91 | Laos | 19.22 | 18.79 | 18.14 |
| Panama | 4.6 | 4.44 | 4.01 | Malaysia | 30.12 | 28.81 | 27.18 |
| Peru | 74.31 | 73.79 | 73.04 | Myanmar | 40.12 | 39.29 | 37.5 |
| Suriname | 14.01 | 13.95 | 13.88 | Papua New Guinea | 41.81 | 41.21 | 40.54 |
| Venezuela | 51.22 | 50.33 | 47.07 | Philippines | 16.86 | 16.11 | 14.46 |
| Tropical Latin America | 769.08 | 743.37 | 703.84 | Sri Lanka | 2.91 | 2.8 | 2.45 |
| Cameroon | 20.32 | 20.21 | 19.88 | Thailand | 17.81 | 17.16 | 15.46 |
| Congo | 23.88 | 23.66 | 23.43 | Vietnam | 16.39 | 15.79 | 14.07 |
| Democratic Republic Congo | 153.23 | 152.2 | 147.93 | Tropical Asia | 350.43 | 338.24 | 318.37 |
| Equatorial Guinea | 2.59 | 2.56 | 2.54 | Pan-Tropics | 1363.08 | 1322.68 | 1257.33 |

the 2000s. This acceleration is corroborated by estimates adjusted for classification errors (supporting information). Forest area change rates by continent and country in each period area shown in Table 3.

Among the continents, Tropical Latin America showed the largest acceleration of annual net forest area loss from the 1990s to the 2000s. The trend was dominated by Brazil, where net forest area loss accelerated by 33%. Tropical Asia showed the second largest acceleration of net loss from the 1990s to the 2000s (Table 3), with similar trends across the individual countries of Indonesia, Malaysia, Cambodia, Thailand, and the Philippines. Tropical Africa showed the least amount of annual net forest area loss, whereas it showed the largest increasing rate. The steady increase of net forest loss in this area is mainly dominated by Democratic Republic of Congo and Madagascar.

Figure 1 depicts the acceleration or deceleration of annual net forest area change from the 1990s to the 2000s as a percentage of each country's land area. Overall, this shows an acceleration of forest loss from the 1990s to the 2000s, which was due to the imbalance of strong acceleration in forest loss and small acceleration in forest gains (Table 4).

Separate estimates of forest cover change statistics for 2000–2005 and 2005–2010 reveal a small deceleration of 7.5% ($0.9 \times 10^6$ ha yr$^{-1}$) in net forest loss in the later periods, due to the imbalance between small deceleration in forest loss and accelerated forest gain. The deceleration of net forest loss between 2000–2005 and 2005–2010 was mainly driven by Brazil and Tropical Asian countries (Table 4).

These national and continental trends confirm other satellite-based studies. *Ernst et al*. [2013] showed a 100% acceleration of net forest loss in the Democratic Republic Congo and an 89% acceleration in the Congo Basin from the 1990s to the 2000s, driven by increased population density, small-scale agriculture, fuel-wood collection, and forest accessibility. *Eva et al*. [2012] corroborated the trends we observed in Tropical Latin America and Brazil, showing 25% and 23% acceleration of net forest loss between the 1990s to the 2000s, changes which *Defries et al*. [2013] attributed to forest clearing for cattle pasture and soybean cultivation. *Stibig et al*. [2014] showed a 124% acceleration in forest loss in continental Southeast Asia in the 1990–2000 period. Rapid growth of agribusinesses (cattle ranching, soybean farming, and plantation agriculture) after decline of smallholder farmer-driven deforestation has been identified as a major driver of acceleration of net deforestation in this area [*Rudel et al*., 2009]. Our post-2000, national estimates of forest change were significantly correlated with those of *Hansen et al*. [2013] ($r^2 > 0.95$), who also found an overall acceleration of tropical forest loss after 2000, with an exception of Brazil. The Brazilian exception was explained by enforcement of policy, interventions in soy and beef supply chains, and expansion of protected areas [*Nepstad et al*., 2014]. Accelerated annual loss in Tropical Africa and Asia we observed was also identified by *Hansen et al*. [2013]. Our estimates complement sample-based estimates for the 1990s

**Table 3.** Changes in Forest Area (1000 ha $yr^{-1}$) From Landsat-Based Estimates Versus FRA Reports [*FAO*, 2010] for 1990–2000 and 2000–2010 in Tropical Latin America, Asia, and Africa[a]

| | This Study | | FRA [UNFAO, 2010] | |
|---|---|---|---|---|
| | 1990–2000 | 2000–2010 | 1990–2000 | 2000–2010 |
| Belize | −8 | −7 | −10 | −10 |
| Bolivia | −191 | −298.5 | −270 | −289.5 |
| Brazil | −1936 | −2571 | −2890 | −2642 |
| Colombia | −130 | −363 | −101 | −101 |
| Costa Rica | −9 | −21 | −19 | 23 |
| Ecuador | −27 | −33 | −198 | −198 |
| Guatemala | −39 | −49 | −54 | −55 |
| Guyana | −16 | −6.5 | 0 | 0 |
| Honduras | −25 | −46.5 | −174 | −120 |
| Nicaragua | −29 | −107.5 | −70 | −70 |
| Panama | −15 | −43.5 | −42 | −12 |
| Peru | −52 | −75 | −94 | −122 |
| Suriname | −5 | −7.5 | 0 | −2 |
| Venezuela | −89 | −326.5 | −288 | −288 |
| Tropical Latin America | −2570 | −3954 | −4210 | −3887 |
| Cameroon | −11 | −33.5 | −220 | −220 |
| Congo | −22 | −22.5 | −17 | −14.5 |
| Democratic Republic Congo | −104 | −426.5 | −311 | −311 |
| Equatorial Guinea | −3 | −2 | −12 | −12 |
| Gabon | −46 | 7 | 0 | 0 |
| Liberia | −19 | −3.5 | −30 | −30 |
| Madagascar | −38 | −97 | −57 | −57 |
| Sierra Leone | −9 | −16.5 | −20 | −20 |
| Tropical Africa | −251 | −594 | −667 | −664.5 |
| Bangladesh | −4 | −11 | −3 | −3 |
| Brunei Darussalam | 0 | −1 | −2 | −2 |
| Cambodia | −31 | −117 | −140 | −145 |
| Indonesia | −653 | −842 | −1914 | −497.5 |
| Laos | −43 | −65 | −78 | −78 |
| Malaysia | −130 | −163.5 | −79 | −113.5 |
| Myanmar | −83 | −179.5 | −435 | −309.5 |
| Papua New Guinea | −60 | −66.5 | −139 | −140.5 |
| Philippines | −75 | −165.5 | 55 | 55 |
| Sri Lanka | −12 | −34.5 | −27 | −22.5 |
| Thailand | −66 | −170 | −55 | −3 |
| Vietnam | −60 | −172 | 236 | 207 |
| Tropical Asia | −1218 | −1988 | −2581 | −1052.5 |
| Pan-Tropics | −4040 | −6535 | −7458 | −5604 |

[a]Negative sign indicates a net loss.

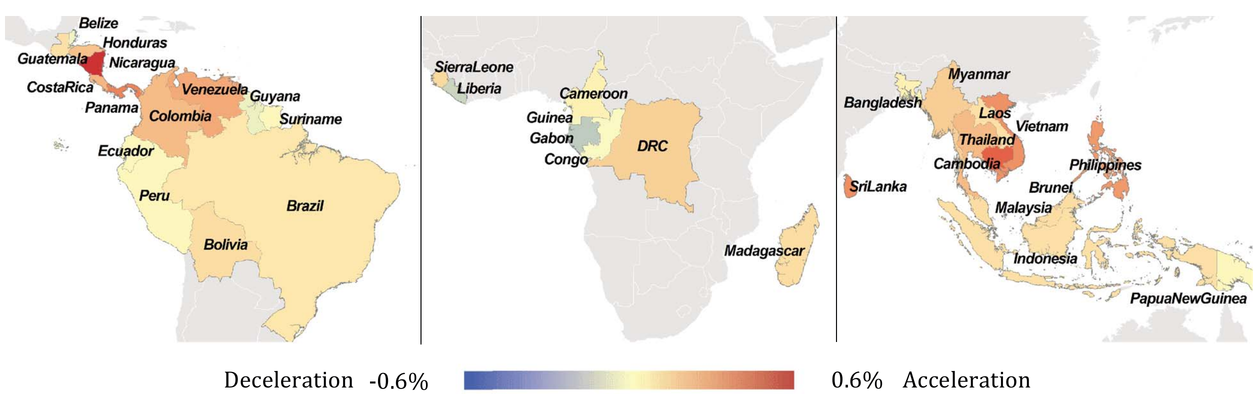


**Figure 1.** Acceleration and deceleration of net forest loss for the humid tropics between 1990–2000 and 2000–2010 periods. The values represent the difference in annual net forest area loss between the periods as a percent of land area.

**Table 4.** Forest Loss and Gain (1000 ha yr$^{-1}$) by Countries for 1990–2000, 2000–2005, and 2005–2010

| Country | 1990–2000 Loss | 1990–2000 Gain | 2000–2005 Loss | 2000–2005 Gain | 2005–2010 Loss | 2005–2010 Gain |
|---|---|---|---|---|---|---|
| Bangladesh | 6.80 | 2.58 | 8.20 | 2.07 | 22.16 | 6.01 |
| Belize | 7.94 | 0.37 | 9.24 | 2.52 | 9.11 | 2.34 |
| Bolivia | 214.86 | 23.99 | 304.27 | 45.43 | 380.60 | 42.24 |
| Brazil | 2191.39 | 255.59 | 3001.27 | 281.01 | 2787.45 | 365.45 |
| Brunei Darussalam | 1.04 | 1.05 | 1.29 | 0.19 | 0.99 | 0.40 |
| Cambodia | 38.33 | 7.32 | 141.71 | 10.33 | 107.17 | 4.34 |
| Cameroon | 20.66 | 9.80 | 37.91 | 4.09 | 48.02 | 15.42 |
| Colombia | 170.41 | 40.88 | 324.68 | 44.08 | 498.87 | 54.00 |
| Congo | 26.10 | 3.71 | 41.34 | 20.41 | 39.88 | 16.09 |
| Costa Rica | 10.81 | 1.39 | 24.81 | 3.10 | 26.19 | 6.41 |
| Democratic Republic Congo | 227.97 | 124.40 | 388.50 | 47.21 | 600.46 | 88.35 |
| Ecuador | 31.24 | 4.53 | 70.58 | 18.84 | 55.06 | 41.45 |
| Equatorial Guinea | 3.10 | 0.45 | 2.29 | 2.30 | 5.37 | 1.11 |
| Gabon | 49.53 | 3.39 | 39.88 | 29.73 | 13.07 | 36.86 |
| Guatemala | 43.68 | 4.89 | 47.54 | 2.20 | 59.10 | 6.48 |
| Guyana | 18.23 | 2.04 | 18.16 | 10.52 | 14.03 | 9.23 |
| Honduras | 26.95 | 1.65 | 41.96 | 3.41 | 61.19 | 7.14 |
| Indonesia | 789.11 | 135.99 | 1384.35 | 190.19 | 808.61 | 319.47 |
| Laos | 61.24 | 18.06 | 88.92 | 18.80 | 95.09 | 34.97 |
| Liberia | 19.13 | 0.17 | 3.35 | 0.62 | 4.64 | 0.43 |
| Madagascar | 54.48 | 16.72 | 88.60 | 19.83 | 141.28 | 16.77 |
| Malaysia | 174.84 | 44.35 | 304.51 | 36.02 | 144.40 | 85.40 |
| Myanmar | 127.61 | 44.19 | 213.81 | 48.08 | 254.41 | 61.24 |
| Nicaragua | 31.04 | 1.68 | 102.80 | 19.30 | 142.84 | 12.30 |
| Panama | 16.83 | 1.61 | 46.49 | 4.13 | 54.66 | 9.39 |
| Papua New Guinea | 64.98 | 4.73 | 149.89 | 31.39 | 64.96 | 49.89 |
| Peru | 67.08 | 15.44 | 133.18 | 23.82 | 84.69 | 43.99 |
| Philippines | 87.57 | 12.59 | 224.85 | 16.26 | 169.48 | 47.44 |
| Sierra Leone | 9.55 | 0.83 | 10.17 | 0.59 | 25.44 | 2.07 |
| Sri Lanka | 13.97 | 2.31 | 30.73 | 2.15 | 49.72 | 9.60 |
| Suriname | 6.41 | 1.21 | 16.11 | 2.90 | 8.53 | 6.73 |
| Thailand | 90.78 | 25.26 | 244.44 | 19.08 | 151.81 | 37.17 |
| Venezuela | 109.59 | 20.79 | 288.52 | 43.94 | 461.29 | 53.38 |
| Vietnam | 113.03 | 52.67 | 183.37 | 34.76 | 234.62 | 39.29 |
| Total | 4926.27 | 886.62 | 8017.75 | 1039.31 | 7625.20 | 1532.85 |

[e.g., *Ernst et al.*, 2013; *Eva et al.*, 2012; *Stibig et al.*, 2014; *Achard et al.*, 2014] and the estimates limited to the post-2000 period [e.g., *Hansen et al.*, 2013].

Table 5 shows the difference between satellite-based estimates of forest change in each time period from studies at tropical biome level. Estimates of forest change differ among satellite-based studies. The major sources of difference include differences in the definition of forest, resolution of input data, classification accuracy, and sensitivity of algorithms to detect change. Sample-based estimates vary widely, especially in estimating differences in rates of change over time. Due to similarities in spatial and temporal scales, *Hansen et al*. [2013] provide the only estimates directly comparable to ours. Our estimates for the 34 countries show strong correlation to those of *Hansen et al.* [2013], but ours are consistently higher (Table S2 in the supporting information) due in large part to different sensitivities to forest gain.

Large differences are evident between the FRA 2010 report and our estimates of forest area and change. Our long-term results contradict the *FAO* [2010] report of a 25% reduction in the rate of forest loss. Also contrary to our results, 16 out of 34 countries in the FRA main report were estimated to have a constant net rate of forest change through the 1990–2000 and 2000–2010 periods [*FAO*, 2010]. The discrepancies are likely due to differences in survey methods and definition of forest. The FRA 2010 reports forest area defined by "forest use," and it compiles country-level estimates from national reports, which have been criticized for inaccuracy and inconsistency [*Mayaux et al*., 1998; *Defries et al*., 2002; *Hansen et al*., 2008; *Grainger*, 2008; *Hansen et al*., 2013; *Achard et al*., 2014]. The difference is likely partly due to changes in the area of commodity forest plantations, which are included in most current satellite estimates as forest cover[26] but

**Table 5.** Recent Satellite-Based Estimates of Biome-Level Forest Change (1000 ha $yr^{-1}$) in the 1990s and 2000s

| | Area | 1990s | 2000s | ΔRate | Method | Data |
|---|---|---|---|---|---|---|
| *FAO, JRC* [2012] | Tropics | −5648 | −9111 | 61.3% | Sampling | Landsat |
| *FAO, JRC* [2014] | Tropics | −6000 | −7000 | 16.7% | Sampling | Landsat |
| *Achard et al.* [2002] | Humid tropics | −5800 | - | | Sampling | Advanced very high resolution radiometer (AVHRR) |
| *Achard et al.* [2014] | Tropics | −6050 | −5930 | −2% | Sampling | Landsat |
| | Humid tropics | −3960 | −3170 | −20% | Sampling | Landsat |
| *Defries et al.* [2002] | Tropics | −5563 | - | - | Wall-to-wall | AVHRR |
| *Hansen et al.* [2008, 2010] | Humid tropics | - | −5400 (gross loss) | - | Sampling | Landsat |
| *Hansen et al.* [2013] | Tropics | - | −7100 | - | Wall-to-wall | Landsat |
| | Humid tropics (34 countries) | - | −5500 | | Wall-to-wall | Landsat |
| This study | Humid tropics (34 countries) | −4040 | −6535 | 61.8% | Wall-to-wall | Landsat |

are variably reported as "forest" in the FRA report [*FAO*, 2010]. Errors from backward and forward projection based on previous FRA reports may also contribute to overestimated net forest loss for the 1990s, thus resulted in muting the effect of acceleration of forest loss during the 2000s [*Grainger*, 2008]. The difference might arise partly from a statistical bias from the satellite data gaps from clouds, especially for countries such as Indonesia (gap~30%). This may be resolved as other satellite images become available.

These findings highlight the importance of a consistent definition and method to track forest area changes. Our findings provide a consistent, spatially explicit basis for the inference of the drivers of forest cover change in various geographical and socioeconomical contexts, especially where the relationship between long-term trends in forest cover change and its drivers are hindered by inaccurate estimates of forest cover change resulting from semantic and methodological inconsistencies.

## 4. Conclusions

We applied a series of forest cover maps based on satellite imagery and a consistent, biophysical definition of forest cover to estimate the area and change of humid tropical forests in 34 countries from 1990 to 2010. Our results indicate a 62% acceleration of net forest loss over the humid tropics, from $4.04 \times 10^6$ ha $yr^{-1}$ during the 1990s to $6.54 \times 10^6$ ha $yr^{-1}$ in the 2000s—mainly driven by strong acceleration in gross forest loss in Tropical Latin America. Second, we identified a 7.2% deceleration in net forest loss, from $6.98 \times 10^6$ ha $yr^{-1}$ in the early 2000s to $6.09 \times 10^6$ ha $yr^{-1}$ in the late 2000s, due to accelerated forest gains in Tropical Asia and decelerated forest losses in Brazil. Although slower than on other continents, gross forest cover changes in Tropical Africa, dominated by changes in the Democratic Republic of Congo and Madagascar, resulted in net losses that accelerated steadily from 1990 to 2010. Our estimates reveal an acceleration of net deforestation from the 1990s to the 2000s across the humid tropics. Gross and net forest cover losses rose from the 1990s to a peak in the early 2000s and then decelerated slightly from 2005 to 2010. This acceleration contradicts commonly accepted assertions of deceleration [e.g., *Anon*, 2014].

**Acknowledgments**
This work was performed under the Global Forest Cover Change Project (www.forestcover.org), a partnership between the University of Maryland Global Land Cover Facility (GLCF) (www.landcover.org) and NASA Goddard Space Flight Center. Funding support for this study was provided by the following NASA programs: Making Earth System Data Records for Use in Research Environments (NNH06ZDA001N-MEASURES); Land Cover and Land Use Change (NNH07ZDA001N-LCLUC); and Earth System Science Research Using Data and Products from Terra, Aqua, and Acrimsat Satellites (NNH06ZDA001N-EOS). The GLS data sets were prepared by Rachel Headley (USGS). Global forest change data are freely available via the GLCF. The authors provide thanks to Matthew Hansen and his group for creating and providing their Landsat-based forest cover change data. We thank Maureen Kelly for her help in preparing the manuscript, and we thank Anupam Anand and Chengquan Huang for their help in accuracy assessments. D.H.K. and J.O.S. developed the image analysis. D.H.K. and J.R.T. conceived and designed the research. D.H.K. performed the research and led the writing of the manuscript. All authors participated in writing the manuscript.

The Editor thanks an anonymous reviewer for assisting in the evaluation of this paper.

## References

Achard, F., H. D. Eva, H.-J. Stibig, P. Mayaux, J. Gallego, T. Richards, and J.-P. Malingreau (2002), Determination of deforestation rates of the world's humid tropical forests, *Science*, *297*(5583), 999–1002.

Achard, F., et al. (2014), Determination of tropical deforestation rates and related carbon losses from 1990 to 2010, *Global Change Biol.*, *20*(8), 2540–2554.

Anon (2014), International: A clearing in the trees, The Economist 23 Aug 2014. Printed edition.

Belward, A. S. (1996), The IGBP-DIS Global 1 km Land Cover Data Set "DISCover": Proposal and Implementation Plans, Report of the Land Recover Working Group of IGBP-DIS. IGBP-DIS.

DeFries, R. S., R. A. Houghton, M. C. Hansen, C. B. Field, D. Skole, and J. Townshend (2002), Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s, *Proc. Natl. Acad. Sci. U.S.A.*, *99*(22), 14,256–14,261.

DeFries, R. S., M. Herold, L. Verchot, M. N. Macedo, and Y. Shimabukuro (2013), Export-oriented deforestation in Mato Grosso: Harbinger or exception for other tropical forests?, *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, *368*(1619), 20120173.

Ernst, C., P. Mayaux, A. Verhegghen, C. Bodart, M. Christophe, and P. Defourny (2013), National forest cover change in Congo Basin: Deforestation, reforestation, degradation and regeneration for the years 1990, 2000 and 2005, *Global Change Biol.*, *19*(4), 1173–1187.

Eva, H. D., et al. (2012), Forest cover changes in Tropical South and Central America from 1990 to 2005 and related carbon emissions and removals, *Remote Sens.*, *4*(5), 1369–1391.

Food and Agriculture Organization (FAO) (2010), Global Forest Resources Assessment 2010 Main Report, Rome, Italy.

FAO, JRC (2012), Global forest land-use change 1990–2005 FAO Forestry Paper, 169.

Gibbs, H. K., S. Brown, J. O. Niles, and J. A. Foley (2007), Monitoring and estimating tropical forest carbon stocks: Making REDD a reality, *Environ. Res. Lett.*, *2*(4, 45023).

Grainger, A. (2008), Difficulties in tracking the long-term global trend in tropical forest area, *Proc. Natl. Acad. Sci. U.S.A.*, *105*(2), 818–823.

Gutman, G., R. Byrnes, I. Masek, S. Covington, C. Justice, S. Franks, and R. Headley (2008), Towards monitoring changes at a Globa the Global Land S, *Photogramm. Eng. Remote Sens.*, *74*(1), 6–10.

Hansen, M. C., et al. (2008), Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data, *Proc. Natl. Acad. Sci. U.S.A.*, *105*(27), 9439–9444.

Hansen, M. C., S. V. Stehman, and P. V. Potapov (2010), Quantification of global gross forest cover loss, *Proc. Natl. Acad. Sci. U.S.A.*, *107*(19), 8650–8655, doi:10.1073/pnas.0912668107.

Hansen, M. C., et al. (2013), High-resolution global maps of 21st-century forest cover change, *Science*, *342*(6160), 850–853.

Houghton, R. A. (1999), The annual net flux of carbon to the atmosphere from changes in land use 1850–1990, *Tellus B*, *51*(2), 298–313.

Kim, D. H., R. Narashiman, J. O. Sexton, C. Huang, and J. R. Townshend (2011), Methodology to select phenologically suitable Landsat scenes for forest change detection, in *Geoscience and Remote Sensing Symposium (IGARSS)*, 2011 IEEE International, pp. 2613–2616, IEEE, Vancouver, Canada.

Kim, D. H., et al. (2014), Global, Landsat-based forest-cover change from 1990 to 2000, *Remote Sens. Environ.*, *155*, 178–193.

Masek, J. G., et al. (2006), A Landsat surface reflectance dataset for North America, 1990–2000, *Geosci. Remote Sens. Lett. IEEE*, *3*(1), 68–72.

Matthews, E. (2001), Understanding the FRA 2000, *Oceania*, *88*(201,992), 129.

Mayaux, P., F. Achard, and J.-P. Malingreau (1998), Global tropical forest area measurements derived from coarse resolution satellite imagery: A comparison with other approaches, *Environ. Conserv.*, *25*(01), 37–52.

Nepstad, D., et al. (2014), Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains, *Science*, *344*(6188), 1118–1123.

Olson, D. M., et al. (2001), Terrestrial Ecoregions of the World: A New Map of Life on Earth, A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity, *BioScience*, *51*(11), 933–938.

Rudel, T. K., R. Defries, G. P. Asner, and W. F. Laurance (2009), Changing drivers of deforestation and new opportunities for conservation, *Conserv. Biol.*, *23*(6), 1396–1405.

Sexton, J. O., et al. (2013), Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error, *Int. J. Digital Earth*, *6*(5), 427–448.

Sexton, J. O., et al. (2015), A model for the propagation of uncertainty from continuous estimates of tree cover to categorical forest cover and change, *Remote Sens. Environ.*, *156*, 418–425.

Steininger, M. K., C. J. Tucker, J. R. G. Townshend, T. J. Killeen, A. Desch, V. Bell, and P. Ersts (2001), Tropical deforestation in the Bolivian Amazon, *Environ. Conserv.*, *28*(2), 127–134.

Stibig, H. J., F. Achard, S. Carboni, R. Raši, and J. Miettinen (2014), Change in tropical forest cover of Southeast Asia from 1990 to 2010, *Biogeosciences*, *11*(2), 247–258.

Stocker, T. F., et al. (2013), IPCC, 2013: Climate change 2013: The physical science basis, Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.

Townshend, J. R. (1981), The spatial resolving power of Earth resources satellites, *Prog. Phys. Geogr.*, *5*(1), 32–55.

Townshend, J. R., and C. O. Justice (1988), Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations, *Int. J. Remote Sens.*, *9*(2), 187–236, doi:10.1080/01431168808954847.

Townshend, J. R., et al. (2012), Global characterization and monitoring of forest cover using Landsat data: Opportunities and challenges, *Int. J. Digital Earth*, *5*(5), 373–397.

UNFAO (2002), United National Food and Agriculture Organization, Expert meeting on harmonizing forest-related definitions for use by various stakeholders, Rome, Italy.

UNFCCC (2002), Report of the Conference of the Parties on its Seventh Session, held at Marrakesh from 29 October to 10 November 2001 [The Marrakesh Accords & the Marrakesh Declaration], Addendum Part two: Action taken by the Conference of Parties. Marrakesh, Morocco.

Wilson, A. K. (1988), The effective resolution element of Landsat Thematic Mapper, *Int. J. Remote Sens.*, *9*(8), 1303–1314, doi:10.1080/01431168808954938.