Special Section

A Contemporary Assessment of Change in Humid Tropical Forests

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Abstract: *In recent decades the rate and geographic extent of land-use and land-cover change has increased throughout the world's humid tropical forests. The pan-tropical geography of forest change is a challenge to assess, and improved estimates of the human footprint in the tropics are critical to understanding potential changes in biodiversity. We combined recently published and new satellite observations, along with images from Google Earth and a literature review, to estimate the contemporary global extent of deforestation, selective logging, and secondary regrowth in humid tropical forests. Roughly 1.4% of the biome was deforested between 2000 and 2005. As of 2005, about half of the humid tropical forest biome contained 50% or less tree cover. Although not directly comparable to deforestation, geographic estimates of selective logging indicate that at least 20% of the humid tropical forest biome was undergoing some level of timber harvesting between 2000 and 2005. Forest recovery estimates are even less certain, but a compilation of available reports suggests that at least 1.2% of the humid tropical forest biome was in some stage of long-term secondary regrowth in 2000. Nearly 70% of the regrowth reports indicate forest regeneration in hilly, upland, and mountainous environments considered marginal for large-scale agriculture and ranching. Our estimates of the human footprint are conservative because they do not resolve very small-scale deforestation, low-intensity logging, and unreported secondary regrowth, nor do they incorporate other impacts on tropical forest ecosystems, such as fire and hunting. Our results highlight the enormous geographic extent of forest change throughout the humid tropics and the considerable limitations of the science and technology available for such a synthesis.*

Keywords: deforestation, forest degradation, forest disturbance, forest regrowth, secondary forest, selective logging, timber harvesting

Una Evaluación Contemporánea del Cambio en Bosques Tropicales Húmedos

Resumen: *En décadas recientes, la tasa y extensión geográfica del uso de suelo y el cambio de cobertura de suelo han incrementado en los bosques tropicales húmedos del mundo. La evaluación de la geografía pantropical del cambio forestal es un reto, y mejores estimaciones de la huella humana en los trópicos son críticas para entender los cambios potenciales en la biodiversidad. Combinamos observaciones de satélite recientemente publicadas y nuevas, además de imágenes de Google Earth y una revisión de literatura, para estimar la extensión global contemporánea de la deforestación, la tala selectiva y el crecimiento secundario en bosques tropicales húmedos. A grosso modo, 1.4% del bioma fue deforestado entre 2000 y 2005. En 2005, casi la mitad del bioma de bosque tropical húmedo contenía 50% o menos de cobertura arbórea. Aunque no directamente comparable con la deforestación, las estimaciones geográficas de la tala selectiva indican que por lo menos 20% del bioma bosque tropical húmedo tenían algún nivel de explotación de madera entre 2000 y 2005. Las estimaciones de recuperación de bosques son aun más inciertas, pero una compilación de reportes disponibles sugiere que por lo menos 1.2% del bioma bosque tropical húmedo estaba en alguna etapa*

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de recuperación en 2000. Casi 70% de los reportes de recuperación indican que regeneración de bosques en ambientes montañosos considerados marginales para la agricultura y ganadería a gran escala. Nuestras estimaciones de la huella humana son conservadoras porque no detectan la deforestación a escala muy pequeña, la tala de baja intensidad ni el crecimiento secundario no reportado, tampoco incorporan otros impactos sobre los ecosistemas forestales tropicales, como el fuego y la cacería. Nuestros resultados resaltan la enorme extensión geográfica del cambio forestal en el trópico húmedo y las considerables limitaciones de la ciencia y tecnología disponibles para tal síntesis.

Palabras Clave: bosque secundario, deforestación, degradación del bosque, explotación de madera, recuperación del bosque, tala selectiva

Introduction

Humid tropical forests cover about 19.6 million km^2 of the Earth's surface, and harbor the richest biological diversity in the terrestrial world (Pimm & Sugden 1994). People have been active in tropical regions for thousands of years, but never has the impact of human enterprise in tropical forests been as profound as it is today. Humans occupy, clear, log, hunt, burn, abandon, and otherwise alter enormous tracks of forest each year. The rapid pace of change in tropical forests contributes to other global-change processes, such as increasing atmospheric carbon dioxide levels, climate change, and biological invasions (Vitousek et al. 1997).

A global tour in Google Earth (http://earth.google.com) readily shows that most tropical forests are within human reach today, yet the details of where and why the forest is changing remain difficult to appreciate at the scale of the entire humid tropical forest biome. Despite widespread concern in the international conservation science and policy development communities about tropical deforestation, continental and global perspectives on problems of tropical deforestation and degradation remain unclear. We drew on a mix of new techniques, recent data, and existing research reports to summarize the extent and intensity of human activities in tropical forests.

Beginning with the early Food and Agricultural Organization (FAO; http://www.fao.org) reports of the 1970s, forest cover and resource use have been estimated at the country level to provide a general census of human activities in tropical regions. In the late 1980s, satellite technology became more widely available, with resulting continental-scale deforestation maps providing an improved understanding of direct human effects on the humid tropical forest biome (Skole & Tucker 1993). Only in this century have the large-scale deforestation patterns become more routinely mapped (Achard et al. 2002; DeFries et al. 2002; Lepers et al. 2005; Achard et al. 2007), uncovering rates of forest loss that rival other forms of global change today.

Whereas deforestation mapping and monitoring are becoming commonplace, most efforts have not resolved the geographic extent or intensity of the forest disturbance associated with selective logging. Logging is important because it has the potential to support human livelihoods while avoiding the wholesale clearing of forests. Although timber production rates have been estimated from sawmill, sales, and export statistics (Nepstad et al. 1999; FAO 2007), these estimates cannot directly quantify the area of logged forest. The first large-scale, high-resolution satellite mapping of selective logging was published just a few years ago for the Brazilian Amazon (Asner et al. 2005). The results showed that selective logging can extend over as much forested territory as does deforestation each year. Other work suggests that logging and logging concessions are now widespread throughout Africa (Laporte et al. 2007), parts of Oceania (Shearman et al. 2008), and other Amazonian countries (Oliveira et al. 2007). A global tropical geography of selective logging operations, however, has not been developed.

Regeneration of previously cleared lands is another human-mediated process that remains poorly mapped at the global scale. From a biodiversity standpoint, the value of secondary forest is low in the initial few years following land abandonment, but increases following decades or more of recovery. Regrowth is difficult to monitor with traditional satellite observations because these observations cannot easily resolve different types of vegetation at a scale finer than "green" and "other" (Lucas et al. 2000). As a result it is often unknown whether a newly observed patch of regrowing forest is simply the result of a fallow period between clearing and reclearing events or if it is part of a socioeconomically driven trend resulting in forests that are "committed" to recovery (Rudel et al. 2009 [this issue]). It has also been difficult to determine the extent to which regrowth is natural regeneration or tree plantation. Today there is little information on the global extent of long-term regrowth in tropical forests.

The combination of deforestation, selective logging, and forest regrowth largely defines the geographic footprint of human activities in the humid tropical forest biome, yet no spatial compilations have provided a global perspective on these changes. Using satellite observations and a literature review, we present a global-scale compilation and analysis of these three major land-use change processes. Our goal is to help frame the biodiversity and extinction crisis in a spatially explicit context and to do so with respect to current drivers of forest change (Rudel et al. 2009). Given the central importance of these forest changes for the extinction crisis, it is clear that an improved global understanding of these changes is needed to assess vulnerability and potential hotspots of diversity loss, persistence, and recovery.

Mapping the Human Footprint in Tropical Forests

We compiled data from a wide range of sources to estimate the geographic extent of deforestation, selective logging, and forest regrowth in humid tropical forests of the world. Acknowledging the limited availability of spatial data, some of which provide estimates of gross rates of change, whereas others provide net rates of change over longer time periods, we limited our interpretation and analysis to general areas of human activity without attempting to define each and every forest parcel affected by people. We refer to this approach as the human tropical forest footprint, which is roughly analogous to the work of Sanderson et al. (2002), but here we focus on the major processes defining human activity in humid tropical forests.

The overall biome extent is defined at http://globalmonitoring.sdstate.edu/, which is based on the humid tropical forest portion of the map produced by Myers et al. (2000). Forests were mapped by compiling the 500-m resolution vegetation continuous field (VCF) tree canopy data (VCF Collection 4, Version 3) into the following categories: 0–50% and 50–100% forest cover as of 2005. We also calculated gross deforestation between 2000 and 2005 from the data provided by Hansen et al. (2008), which is calibrated to higher resolution data.

In contrast to deforestation, selective logging is much more challenging to map, and developing a global view requires a novel combination of data sources and methods of estimation (Supporting Information). For Brazil and Peru, we used detailed logging maps from Asner et al. (2005, 2006) and Oliveira et al. (2007). For Africa and Borneo, we compiled maps of timber concession areas and direct observations of logging roads provided by Laporte et al. (2007) and G.P.A. (unpublished data). We estimated logged areas in Papua New Guinea from maps provided by Shearman et al. (2008). An additional globally distributed set of logging polygons were generated by combining wood production statistics from the FAO (2007) with direct observations of logging infrastructure including roads, log-staging areas (called log decks), and skid trails with imagery from Quickbird, GeoEye-1, and SPOT-4 satellite provided by Google Earth. These polygons were estimated only in countries for which the FAO reported substantial logging activities ($\geq$10 million m^3/year) and where the satellite patterns of logging were most evident and similar to the logging patterns found in the studies of Asner et al. (2005, 2006), Oliveira et al. (2007), Laporte et al. (2007), and Shearman et al. (2008). Given the uncertainties involved in using logging typologies from one region to another, we limited our interpretation of these polygons to broad, regional-scale estimates of where logging operations have likely occurred in recent years. Using these methods, we surely missed tracts of low-intensity logging due to poor ground-based reporting or detection (Supporting Information). Our goal, however, was to generate a global view of humid tropical forests likely to be most heavily affected by logging activities today.

Tropical forest regrowth remains virtually unmapped at the global or even continental scale; however, a number of local and regional studies have produced area estimates of regrowing vegetation following land abandonment. We carried out a literature review to estimate the location and geographic area of tropical forests that have undergone regrowth. In most cases, we were able to select studies that reported net regrowth lasting a period of about 10 years or more. This allowed us to focus on areas committed to secondary regrowth, thus avoiding the common scenario of short-term regrowth associated with clearing and fallow cycles. We used ISI Web of Science and Google Scholar to conduct our literature search. Our keywords included *regrowth*, *recovery*, *forest transition*, *secondary forest*, *tropical*, and the names of countries falling within the tropical biomes of the world. In addition, we used the comprehensive synthesis provided by Rudel (2005), which includes regrowth studies through 2002. To ensure data were of high quality, we only incorporated studies that used at least two dates of satellite imagery (22 studies) and one extensive ground-based survey. For each study identified, we noted the location, geographic area of estimated regrowth, time scale of analysis, and the terrain (e.g., flat, hilly, and mountainous). The resulting data compilation was projected in a geographic information system (GIS) and scaled to three categories of forest regeneration area: $<$1,000 km^2, 1,000–10,000 km^2, and $>$10,000 km^2.

The Human Footprint in Tropical Forests

Areas of humid tropical forest have undergone gross deforestation from 2000 to 2005 (Fig. 1). Overall, the extent of the human footprint on humid tropical forests of the world is enormous—only a few regions, such as those in the northwestern Brazilian Amazon basin and the eastern Congo basin, remain relatively intact on contemporary time scales. In Southeast Asia and Oceania, most forests are currently under human contact via

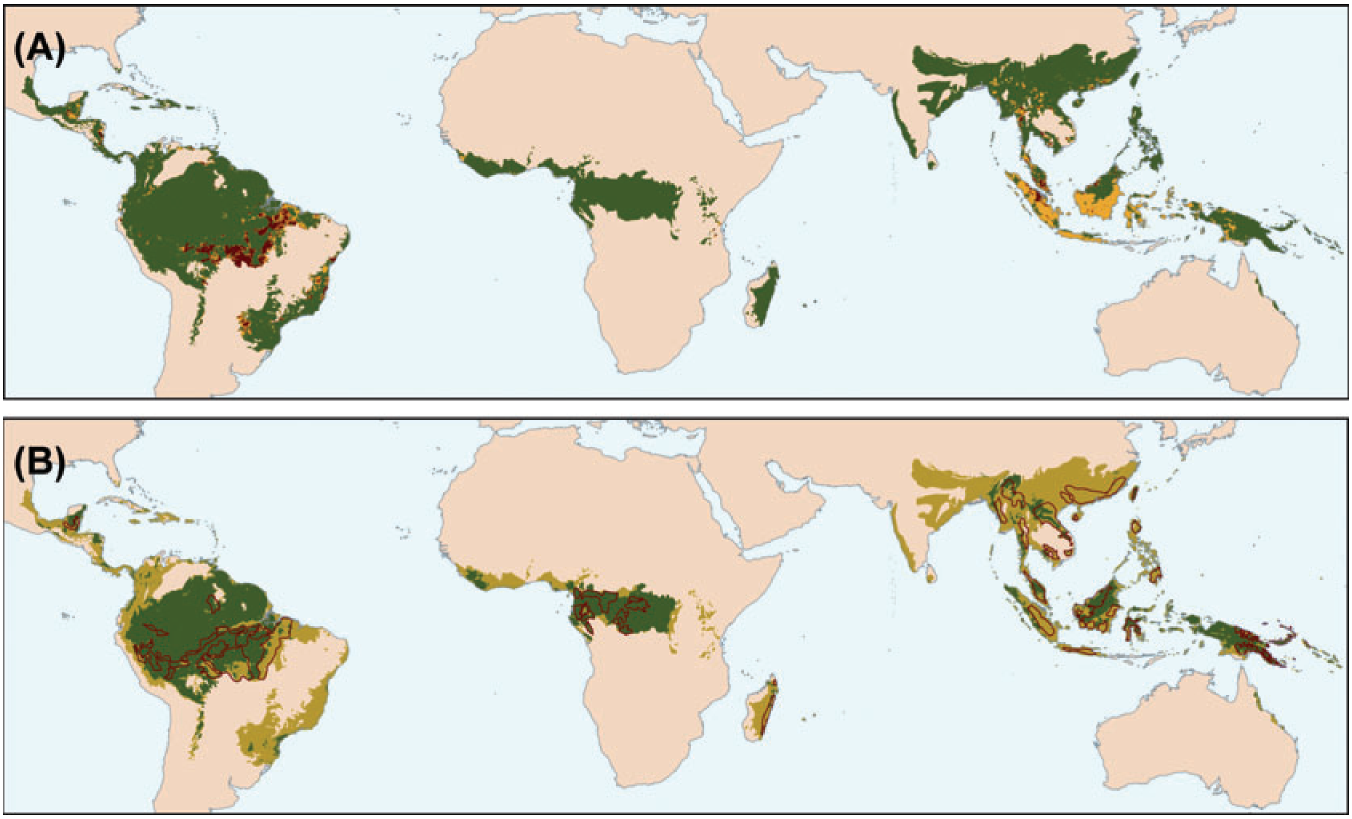

Figure 1. (a) Humid tropical deforestation from 2000 to 2005 (derived from Hansen et al. [2008]; dark green, <1% forest cover change; yellow, 1–5% change; orange, 6–10% change; red, >10% change. (b) Humid tropical forest cover as of 2005 (derived from Hansen et al. [2008]; dark green >50% tree cover; light green, <50% tree cover). Regions of major active logging operations are shown in red.

deforestation or selective logging. From 2000 to 2005, gross deforestation was 0.5%, 1.3%, 1.4%, and 1.8% in Africa, Asia-Oceania, Central America, and South America, respectively (Table 1). This sums to a loss of about 274,615 km^2, or 1.4%, of global humid tropical forests in just 5 years. Results of other studies (e.g., Achard et al. 2002), indicate higher percent changes when clearing rates are calculated against remaining forest area within the biome.

As of 2005 about half of all 500-m grid cells in the humid tropical forest biome maintained 50% or less tree cover (Fig. 1b, Table 1). In Asia/Oceania and Central America, over two-thirds of the forest has <50% tree cover at the resolution of the grid cell used by Hansen et al. (2008). In contrast, in South America, mainly the Amazon basin, more than half the humid tropical forest has more than 50% tree cover. These results show that very high-forest cover conditions are not evenly distributed across geographic regions. Nevertheless, we caution that natural forests with <100% tree cover are widespread as well, especially in Southeast Asia, and thus cannot be delineated from forests that have undergone clearing.

Logging activities strike deep into forest interiors, sometimes far from deforestation fronts (Fig. 1b). This is most evident in both Latin America and Africa, where timber-harvesting operations appear to be regionally widespread on each continent. Our definition of logging areas includes forests directly harvested, forests containing logging roads, forest canopy damage commensurate with logging operations, and logging concessions, areas immediately destined for harvest (Supporting Information). Combining these areas, a global pattern emerges that shows selective logging has become even more extensive than deforestation in many humid tropical forest regions.

Globally, about 20.3%, or more than 3.9 million km^2, of humid tropical forests have recently been allocated to selective timber harvests (Table 1), a value that is in rough agreement with the tropical timber production estimate of 3.5 million km^2 (ITTO 2005; Putz et al. 2008). Our geographically based estimate is not exactly comparable to production-based estimates because we resolved an enormous amount of illegal logging in Brazil (Asner et al. 2006), leading to higher logging estimates. In contrast, we purposely excluded the many lower intensity operations not meeting our 10 million m^3/year cut-off for inclusion in the Google Earth analysis (Supporting Information). Countries such as Ecuador, Colombia, and Venezuela fell

Table 1. Approximate geographic extent of contemporary forest cover, deforestation, and selective logging by region in the humid tropical forest biome.[a]

Region	*Total biome extent (km^2)*	*Area with 0–50% forest cover, 2005 (km^2)[b]*	*Area with 50–100% forest cover, 2005[b] ((km^2)*	*Forest area cleared 2000–2005[c] (km^2)*	*Selective logging[d] (2000s) (km^2)*
Africa	2,918,511	1,085,941 (37.2%)	1,832,569 (62.8%)	14,972 (0.5%)	561,153 (19.2%)
Asia/Oceania	7,191,529	5,234,293 (72.8%)	1,957,236 (27.2%)	93,955 (1.3%)	1,777,963 (27.2%)
Central America/ Caribbean	685,840	501,415 (73.1%)	184,425 (26.9%)	9687 (1.4%)	36,097 (5.3%)
South America	8,826,966	3,194,632 (36.2%)	5,632,334 (63.8%)	156,001 (1.8%)	1,603,166 (18.2%)
Total	19,622,846	10,016,282 (51.0%)	9,606,564 (49.0%)	274,615 (1.4%)	3,978,379 (20.3%)

[a] *Percentage of regional biome extent is in parentheses, except in the column totals (last row), where percent refers to the global biome extent. Differences in the composition, spatial extent, temporal scale, and quality of the available data make it difficult to quantitatively compare rates of deforestation and selective logging. They are listed here to provide a general global perspective on the magnitude of reported or detected contemporary changes among these land-use processes.*
[b] *Forest cover in 2005 calculated as 2000 forest cover minus losses from 2000 to 2005 with data from Hansen et al. (2008). Percent forest cover is based on percent within each 500-m grid cell, followed by conversion to vector format for global calculations.*
[c] *Calculated from Hansen et al. (2008).*
[d] *Logging does not represent actual harvested trees, but rather regional forest areas in which timber operations occur.*

just short of this production threshold (FAO 2007). Additionally, the FAO (2007) estimates that “secondary regrowth,” (defined by them as a combination of forest previously cleared for agriculture and ranching, forests having undergone human-mediated fires, and selectively logged forests) covers about 4.5 million km^2. Because our maps and the production-based estimates suggest 3.5–3.9 million km^2 of logging, it appears that selectively logged forests dominate the FAO’s secondary-forest category.

Our maps do not directly express a wide range of other human activities in the forest. Hunting, either for subsistence or bushmeat markets, is pervasive in tropical forests (Fa et al. 2002). It is well documented that hunting pressure rides the wave of deforestation and selective logging activities because hunters gain easier and more rapid access to forest interiors via new roads and logging trails (reviewed by Peres et al. 2006). Another unaccounted impact of human activity in our maps is fire, which increases in frequency on deforested lands and can increase in forests following selective logging (Nepstad et al. 1998, 1999).

Our compilation of regional forest-recovery studies suggested that at least 1.2% of the world’s humid tropical forests, or more than 235,000 km^2, was undergoing at least decadal-long secondary regrowth at the turn of the century (Table 2). This estimate is highly conservative because it is based only on published studies demonstrating reliable measures of forest-cover change and therefore does not include regrowth that predated these studies. Our estimate also focuses only on secondary forests committed to long-term (approximately 10 or more years) regrowth following clearing. We identified and reviewed many other studies that were subsequently not included in our compilation because those studies did not provide repeatable methods that used at least two dates of satellite image-based analysis or extensive field surveys. As a result we found no studies reporting committed secondary-forest regrowth in the Congo Basin (Table 2), although it is likely that small-scale regrowth is ubiquitous throughout this region. Despite these limitations, these published studies provide a useful geographic index of important regrowth areas, and this index points to the long-occupied regions of Asia and Central America as zones of secondary regrowth. Additionally, there are hotspots of secondary regrowth in areas formerly considered to be forest frontiers, such as along the main stem of the Amazon River and across the southern edge of the Brazilian Amazon basin (Fig. 2). With the exception of Africa, the areas that were deforested between 2000 and 2005 were roughly equivalent to the areas of regrowth accumulated over more than twice that period of time (Tables 1 & 2).

Our literature review also shows that secondary-forest regrowth has occurred predominantly in areas of varying topography (Table 2). About 70% of the studies we documented indicate regrowing forests on “hilly,” “mountain,” or “upland” terrain. The literature suggests that human occupation of complex terrain environments decreases when small-scale farming becomes less attractive than the larger scale agroindustrial efforts requiring large areas of relatively flat terrain (Aide & Grau 2004; Rudel et al. 2009).

Despite the limited nature of reporting of secondary regrowth worldwide, our estimates of regrowth are potentially higher than those from global satellite studies. From the satellite-based estimates of Achard et al.

Table 2. Locations and areas of forest regrowth that mainly occurred during the 1990s.[a]

Country	Ecosystem	Area (km^2)	Topography	Time scale	Reference
South America					
Argentina	tropical moist	50	hilly	1949–2006	Grau et al. 2008
Bolivia	humid montane, lowland	1460	mountains	1990–2000	Forrest et al. 2008
Brazil	tropical moist	3991	hilly	1970–1996	Baptista & Rudel 2006[b]
Brazil	tropical moist	157,973	lowlands	1991–1994	Lucas et al. 2000
Peru	tropical moist	242	no info.	1986–1997	Alvarez & Naughton-Treves 2003
	total	163,716 (1.8%)			
Central America/Caribbean					
Costa Rica	tropical dry and moist	2000	hilly	1960–2000	Arroyo-Mora et al. 2005
Dominican Republic	tropical moist	2550	mountains	1984–2002	Grau et al. 2007
El Salvador	tropical dry, moist, wet	4,800	mountains	1990–2000	Hecht & Saatchi 2007
Honduras	tropical mesic	101	mountains	1987–1996	Southworth & Tucker 2001
Mexico	tropical montane	800	mountains	1972–1980	Collier et al. 1994
Mexico	tropical moist	131	no info.	1979–2000	Dupuy et al. 2007
Mexico	tropical moist	424	no info.	1987–1997	Turner et al. 2001
Puerto Rico	tropical dry, moist, wet	1032	mountains	1991–2000	Pares-Ramos et al. 2008
Panama	tropical dry, moist, wet	5077	hilly	1992–2000	Wright & Samaniego 2008
	total	16,915 (2.4%)			
Asia/Oceania					
China	subtropical moist	6	uplands	1990s	Ediger & Huafang 2006
Laos	subtropical	10,203	uplands	1990s	Thongmanlvong & Fujita 2006
Nepal	tropical moist	11	uplands	1980s–1990s	Schreier et al. 1994
Nepal	tropical moist	38	uplands	1980s	Gautam et al. 2002
Nepal	tropical moist	4	uplands	1980s–1990s	Awasthi et al. 2002
Philippines	tropical moist	7100	uplands	1988–2002	Chokkalingam et al. 2006
Thailand	tropical moist	100	lowlands	1990s	Muttitanon & Tripathi 2005
Vietnam	tropical moist	37,116	uplands	1990s–2003	Meyroidt & Lambin 2007
	total	54,578 (0.8%)			
Africa					
Madagascar	tropical moist	0.4	hilly	1980s–1990s	Kull 1998
	total	0.4 (approx. 0%)			
biome total		235,209 (1.2%)			

[a] *In most cases, we focused on studies indicating long-term, "committed" regrowth. Values in parentheses are percentages of the humid tropical forest biome in each region (Table 1) and for the entire biome (bottom row).*
[b] *This is the only study to use purely ground-based survey techniques. All other studies used at least two dates of high-resolution satellite imagery.*

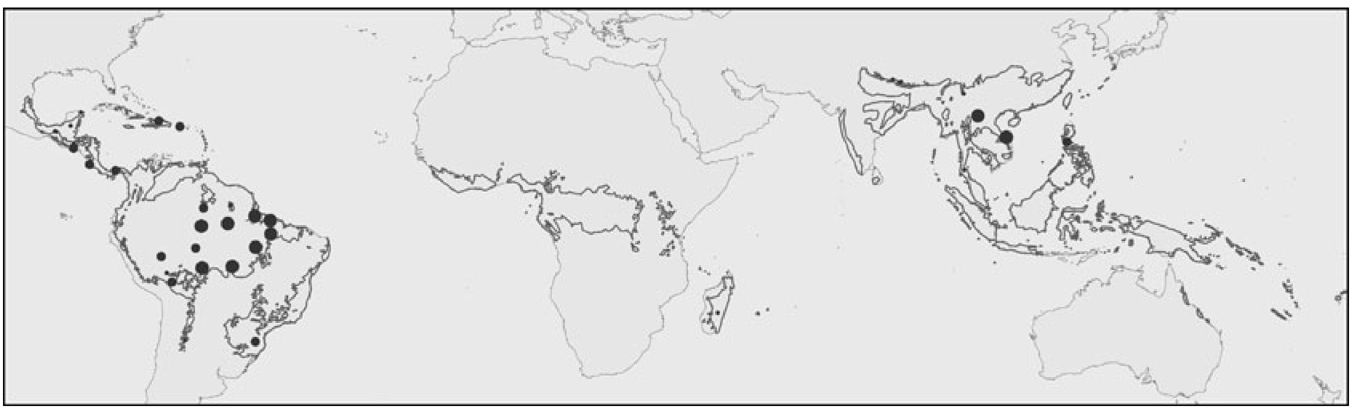

Figure 2. Global distribution of reported secondary-forest regrowth (dots), within the humid tropical forest biome (lines). Small, medium, and large dots indicate studies representing regrowth of < 1,000 km^2, 1,000–10,000 km^2, and >10,000 km^2 respectively. Regrowth studies are listed in Table 2.

(2002), we calculated decadal (1990–2000) gross increases in secondary-forest cover of 0.4%, 0.7%, and 1.9% for Latin America, Africa, and Southeast Asia, respectively. This integrates to a contemporary global increment of secondary-forest growth of 0.8% per decade, which is 50% lower than our estimate from the regional, high-resolution satellite literature (Table 2). Again, all these estimates are not exactly comparable because they involve gross annual (Achard et al. 2002) and decadal net (Table 2) rates of secondary-forest regrowth. Nevertheless, the low gross rates of regrowth presented by Achard et al. (2002) likely resulted because they weighted their high-resolution satellite sampling to areas undergoing rapid deforestation (determined with their global imagery). With this approach, portions of the tropical forest biome experiencing fairly extensive regrowth may be underrepresented if the focus is on deforestation fronts. These uncertainties, along with the fact that the FAO (2007) does not delineate secondary forest derived from clearcuts from selectively logged forest, has sparked enormous confusion in the literature and in the media. Our effort here thus highlights the critical importance of focusing more research on secondary-forest mapping and monitoring using a clear set of standards and caveats.

More broadly, we wish to reemphasize the rough nature of our deforestation, logging, and regrowth estimates presented here. The deforestation estimates are, by far, the most robust, yet global sensors often miss details of forest losses occurring in small patches (<25 ha; Defries et al. 2002), which are common in some regions. These cover estimates also do not delineate between primary, secondary, or other forest types, only percent forest cover, a limitation of current satellite technology. The footprint of logging operations is even more challenging because one can only estimate general areas showing patterns of forest thinning that are typologically consistent with the regional high-resolution maps produced from the Amazon, Congo, and Papua New Guinea. Finally, the forest regrowth estimates are the most difficult to develop because they represent only what has been reported in the literature. Our synthesis therefore conveys both the enormous geographic extent of forest change throughout the world and the considerable limitations of the science and technology available for such a synthesis.

Human Footprints in the Brazilian Amazon

The global perspective described above cannot resolve many of the key regional-scale patterns defining the human footprint in tropical forests, such as the detailed relationship between logging and clearcutting. To more closely consider these issues, we compiled very high-resolution data on deforestation and selective logging throughout a 2.5 million km^2 region of the Brazilian Amazon (Fig. 3). This region has undergone major forest changes over the past 10 years and has some of the fastest reported rates of change in the world (Achard et al. 2002). We combined 30-m resolution maps of deforestation from the Brazilian Institute for Space Science (INPE 2007) with sub-30-m resolution maps of selective logging from Asner et al. (2005). The resulting map covers the states of Acre, Mato Grosso, Pará, and Rondonia, which collectively account for about 95% of the deforestation and logging in the Brazilian Amazon (INPE 2007). Finally, we included a GIS coverage of indigenous and natural protected areas.

Our compilation highlights the spatially extensive processes of both deforestation and selective logging (Fig. 3). The map also emphasizes the geographic importance of logging, which from 1999 to 2002 added an average of 90% more area subjected to human disturbance than when accounting only for deforestation. Logging often occupies a different portion of the landscape than clearcutting for agriculture and ranching, yet Asner et al. (2006) showed that logged forest has a 400% higher probability of deforestation than unlogged forest.

The combined impacts of deforestation and logging on forest fragmentation have recently been quantified over this four-state region of the Brazilian Amazon (Broadbent et al. 2008). Annually between 1999 and 2002, deforestation and selective logging caused increases in forest edges of 0.8% and 3.1%, respectively. Based on the published average distance to which forest edges affect ecological processes (100 m), Broadbent et al. (2008) estimated that deforestation resulted in an additional approximately 3000 km^2 of "edge-affected" forest over the study period, whereas selective logging generated nearly 20,000 km^2 of edge-affected forest, often deep into intact forest areas. Although forest edges are vastly different along logging roads and other logging features, compared with forest clearcuts, the high-impact logging practices of the recent past in Brazil have nonetheless been a major force driving forest fragmentation and fire (Nepstad et al. 1999).

One more important observation is that, for the most part, protected areas spatially correlate with low rates of clearcutting and logging of humid tropical forests (Fig. 3). Despite controversy in evaluating the efficacy of protected areas for conservation (Ferraro & Pattanayak 2006), the southern Brazilian Amazon is a region of rapid agroindustrialization, and protected areas here have undergone far lower deforestation and logging than surrounding forests. This region can no longer be considered frontier, so it is at this late stage of rural and agricultural development that the protective effects of reserves become more obvious. Indigenous and nature reserves serve as safe havens for tropical biodiversity (Nepstad et al. 2006).

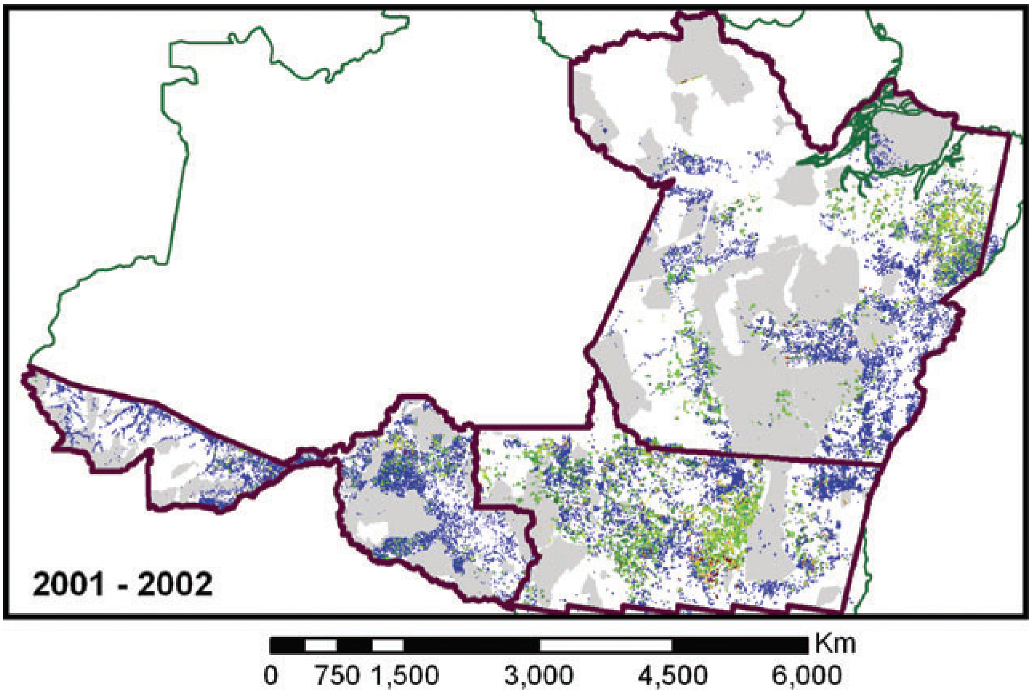

Figure 3. The geographic extent of selective logging (green, yellow or red based on logging intensity; Asner et al. [2006]) and deforestation (blue; INPE [2007]) from 2001-2002 in four states of the Brazilian Amazon. Grey indicates natural protected areas and indigenous reserves; White indicates areas either without clearing/logging or entire states not included in the compilation.

Implications for Biodiversity

When one pieces together estimates of the pan-tropical deforestation, selective logging, and regrowth, what does one learn about the world's humid tropical forests? Our analysis of the global human tropical footprint indicates sweeping regional-scale changes in forest cover and structure that most certainly affects the biodiversity of tropical forests. In the face of deforestation and forest use, the tropical biodiversity safety net provided by intact forests has frayed, with vast regions of forest under conversion, resource extraction, and disturbance. Increasingly the tropical biome has become a world of forest fragments whose size and separation determine the efficacy of safe harbors and refugia for millions of species. Secondary-forest regrowth is an important component of the safety net (Chazdon et al. 2009 [this issue]), yet the efficacy of secondary forests as buffers against tropical extinctions rests on the presumption that humans will allow these forests to recover over the long term. Trends in the biofuels and agricultural sectors drive continued forest losses at the expense of both primary and secondary-forest cover, but the potential for forest regeneration and protection is also growing with the continued push for carbon-crediting mechanisms to reward for reduced deforestation and forest degradation (REDD; Gibbs et al. 2007). The balance between such political and economic forces will determine the strength of the biodiversity safety net for the global tropical forest biome.

What can researchers do? Several research directions seem evident. The ability to map and understand the dynamics of regrowth on a global scale in these landscapes remains extremely limited, and this has kindled and continues to kindle debate and confusion as to the extent and ecological significance of secondary forests. Rapid progress is needed to improve understanding of the extent and severity of disturbances introduced by selective logging and fire. We did not address the issue of dry tropical forest changes because the data are even more scarce compared with the information we compiled on humid forests (but see Miles et al. 2006). Much more effort is needed to quantify dry forest losses and recovery around the world. More broadly, developing technologies and procedures that enable monitoring of forest disturbance and regrowth for tropical biodiversity conservation is a key challenge for land-change science in the coming years.

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Supporting Information

Estimating the extent of selective logging operations in humid tropical forests is available as part of the on-line article (Appendix S1). The author is responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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