Forest Clearing in the Pantropics: December 2005–August 2011

David Wheeler, Robin Kraft, and Dan Hammer

Abstract

This report summarizes recent trends in large-scale tropical forest clearing identified by FORMA (Forest Monitoring for Action). Our analysis includes 27 countries that accounted for 94 percent of clearing during the period 2000–2005. We highlight countries with relatively large changes since 2005, both declines and increases. FORMA produces indicators that track monthly changes in the number of 1-sq.-km. tropical forest parcels that have experienced clearing with high probability. This report and the accompanying spreadsheet databases provide monthly estimates for 27 countries, 280 primary administrative units, and 2,907 secondary administrative units. Countries' divergent experiences since 2005 have significantly altered their shares of global clearing in some cases. Brazil's global share fell by 11.2 percentage points from December 2005 to August 2011, while the combined share of Malaysia, Indonesia, and Myanmar increased by 10.8. The diverse patterns revealed by FORMA's first global survey caution against facile generalizations about forest clearing in the pantropics. During the past five years, the relative scale and pace of clearing have changed across regions, within regions, and within countries. Although the overall trend seems hopeful, it remains to be seen whether the decline in forest clearing will persist as the global economy recovers.

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Preface

This paper marks the first publication of global data from FORMA (Forest Monitoring for Action). FORMA parses freely available satellite imagery to identify monthly clearing activity in humid tropical forests. At the time of this writing, FORMA provides five years of monthly data on large-scale clearing from December 2005 through August 2011, at 1 km spatial resolution. Specifically, FORMA estimates the probability that each 1 km^2 parcel of previously-forested land has been cleared since January 2000. We provide a more detailed explanation of the methodology in Appendix 2.

Designed to analyze data from NASA's MODIS sensor, FORMA has three distinctive roles: (1) Identification and mapping of new "hotspots" where clearing probabilities have exceeded a significance threshold of 50%; (2) Consistent identification of large-scale clearing at local, regional, national and international levels; (3) A steadily-growing record of large-scale forest clearing that is updated each month.

The choice to use free MODIS data reflects our primary objectives: pantropical coverage, rapid updates and low cost. The FORMA algorithms will be applied to imagery at higher spatial (500 m^2) and temporal (16-day) resolution as the algorithms are evaluated and refined in the coming months. Other forest monitoring systems and methodologies offer data at significantly higher spatial resolution, but at the cost of less frequent updates and more expensive processing. FORMA provides users with a new set of capabilities that are complementary to those offered by other systems.

The spatial resolution of the MODIS data limits FORMA's ability to identify small-scale or scattered clearing activities. But recent research indicates that large-scale clearing and contiguous micro-clearing associated with logging or conversion to plantations, pastureland and new settlements account for the majority of current tropical deforestation (Chomitz, et al., 2007; Rudel, 2005). As we show in this paper and its predecessor (Hammer, Kraft and Wheeler, 2008), FORMA's accuracy and update frequency make it an effective early warning system for such forest-clearing activity.

More effective monitoring, policy analysis and conservation management will be needed as REDD+ and other programs begin spending billions of dollars to reduce tropical forest clearing. We hope that FORMA will make a useful contribution to this effort.

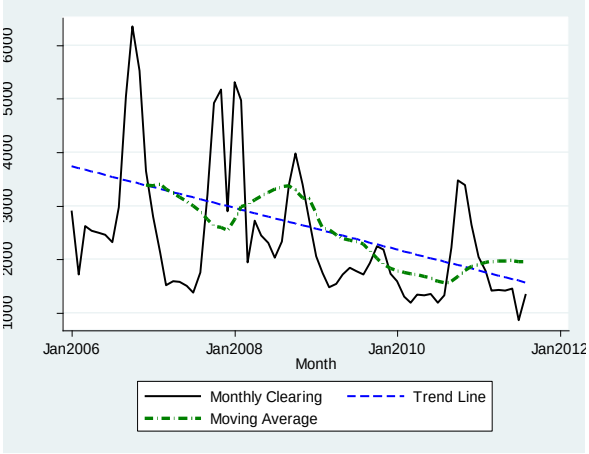
Summary of Findings

This report summarizes recent trends in large-scale tropical forest clearing identified by FORMA (Forest Monitoring for Action). Our analysis includes 27 countries that accounted for 94% of clearing during the period 2000-2005 (Hansen et al., 2008 – see Table 1). We highlight countries with relatively large changes since 2005, both declines (Brazil, Indonesia, Paraguay, Bolivia) and increases (Myanmar, Peru, Malaysia, Venezuela). FORMA will soon cover 25 additional countries that include other significant actors in recent clearing (e.g., Colombia, Guatemala, Nicaragua, Argentina, Ecuador) and important tropical forest sites (e.g. the Democratic Republic of the Congo, Cameroon, Gabon).

FORMA produces indicators that track monthly changes in the number of 1 sq. km. tropical forest parcels that have experienced clearing with high probability. This report and the accompanying spreadsheet databases provide monthly estimates for 27 countries, 280 primary administrative units (e.g., provinces) and 2,907 secondary administrative units (e.g., subprovinces).

Figure 1 displays monthly changes in tropical forest parcels cleared with high probability from December 2005 to August 2011, along with a 12-month moving average and regression trend line. The moving average is clearly dominated by a drop from September 2008 to September 2010, which coincides with the onset of the global economic crisis. Overall, the results in Figure 1 and Table 1 suggest that tropical forest clearing has dropped by about 42% since 2005.

Figure 1: Tropical Forest Clearing, 2005–2011



While the total has dropped significantly during the global recession, widely-divergent country patterns highlight the continued importance of local and regional factors in forest clearing. Among the 27 countries in our assessment, clearing has declined in 12, increased in 14, and remained roughly constant in 1. Overall clearing has been mostly driven by large

declines in Brazil and Indonesia. Across regions, clearing in FORMA countries has declined by 50% in Latin America, 16.5% in Asia and 12.7% in Africa.

Countries' divergent experiences since 2005 have significantly altered their shares of global clearing in some cases. Brazil's global share fell by 11.2 percentage points from December 2005 to August 2011, while the combined share of Malaysia, Indonesia, and Myanmar increased by 10.8.

Within countries, new patterns have emerged as well. Our paper illustrates FORMA's potential for sub-national analyses with two exercises. The first is a global "hotspots" analysis that identifies the top 25 provinces for forest clearing in July/August, 2011. It suggests a striking Asian role in recent changes, with most of the hotspots in Indonesia, Malaysia, Myanmar and Lao PDR. The relatively few Latin American hotspots are located at the southwestern and northeastern periphery of Amazonia, and western peripheral areas of the Atlantic Forest in Brazil and Paraguay.

The second exercise maps changes since 2005 in secondary administrative units in Indonesia and Brazil. The maps show that, despite sharp national declines in both countries, their regions display great diversity in forest clearing. In Indonesia, the overall decline has been largely driven by decreased clearing in the southern and central areas of Sumatra and Kalimantan. But these have been partially offset by increases in the western and northern areas of both islands. Brazil also exhibits a striking pattern of regional divergence: The national decrease in forest clearing largely reflects declines across a broad swath of southern Amazonia, but these have been partially offset by increases in a roughly-parallel swath of northern Amazonia

To summarize, the diverse patterns revealed by FORMA's first global survey caution against facile generalizations about forest clearing in the pantropics. During the past five years, the relative scale and pace of clearing have changed across regions, within regions and within countries. Although the overall trend seems hopeful, it remains to be seen whether the decline in forest clearing will persist as the global economy recovers. The FORMA database will be updated regularly, and we hope that it will support a significant expansion of research, policy analysis and conservation monitoring at the global, regional, national and sub-national levels.

1. Introduction

Leading climate scientists estimate that annual greenhouse gas (GHG) emissions will have to decline by over 90% by 2050 to avert severe climate change. About 15% of GHG emissions are generated by deforestation, mostly in tropical countries. It follows that any viable effort to mitigate climate change will have to address forest clearing and its economic drivers. Fortunately, international efforts to curb clearing through conservation payments are gaining traction, as indicated by $3.5 billion pledged for projects within the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) framework. The payment stream for REDD+ projects is potentially massive; early estimates suggest that total funding will amount to $25-$30 billion annually. However, despite this surge in financial support, there is still no timely and globally-consistent method for monitoring tropical forest clearing. Forest Monitoring for Action (FORMA) has been designed to help fill this information gap.

FORMA uses free, constantly-updated satellite data to identify large-scale tropical forest clearing. It builds on work by Hansen et al. (2008, 2010), Souza (2006, 2009), Hammer, et al. (2009), Townshend, et al. (2008), Asner (2009), Jarvis (2009) and Hoekman, et al. (2009). This work is creating new, high-resolution forest information systems based on NASA's MODIS (Moderate Resolution Imaging Spectrometer) and Landsat programs, as well as airborne light detection and ranging (LiDAR). Drawing on advances for the MODIS system, we initially published a FORMA database for forest clearing in Indonesia at 1 km resolution by month, from 2006 to November 2009 (Hammer et al., 2009). Our Indonesia implementation followed the development and testing of a FORMA prototype for Brazil, where we could test FORMA's accuracy using publicly-available data from Brazil's PRODES and DETER forest-monitoring programs. Publication of this paper marks the expansion of FORMA to coverage of clearing in the humid tropical forests of Asia, Africa and Latin America.

In developing FORMA, we have focused on building an automated and operationally useful system with monthly update capability. We recognize that ex-post evaluations of conservation projects will use higher-resolution imagery (≤ 30 m). Indeed, innovative high-resolution work of this kind is being done by research teams around the world. But cloud cover and large data volumes make comprehensive, consistent, high-resolution monitoring of large areas difficult at sub-annual frequency. FORMA avoids this pitfall because MODIS data are updated every 1-2 days and combined into 8-, 16- and 32-day composite datasets. We currently use 32-day composites, but are moving FORMA to MODIS data at higher spatial resolution and temporal frequency. Our methodology is consistent across space and time, and does not depend heavily on any single, potentially cloudy image. Our work on FORMA has been inspired by the pioneering development of near-real-time monitoring capacity for Brazil by its national space agency (INPE), and Carlos Souza and his colleagues at IMAZON. In effect, FORMA extends this approach to all humid tropical forests.

We have designed FORMA to provide immediately-usable information for policymakers, researchers, conservation project staff, protected-area managers, research teams that study

deforestation, and other professionals who require rapidly-updated information on forest clearing. FORMA's outputs can also be aggregated to produce monthly reports on forest clearing for local areas, sub-national political units, countries, and entire regions. Rapidly-updated information from FORMA will promote more timely and comprehensive evaluations of forest conservation programs, as well as enabling research on deforestation to focus on the most recent trends.

In this paper and the accompanying databases, we combine FORMA's estimates for 1 km^2 parcels into comparable indices of large-scale forest clearing for countries, primary administrative units (e.g. states, provinces) and secondary administrative units (e.g., subprovinces). Our methodology can also be applied to tertiary administrative units, protected areas, commercial development zones, and other areas of interest. This paper is accompanied by a spatially-formatted database of estimated forest-clearing status for each 1 km^2 parcel in the humid tropical forest region covered by FORMA.

Our methodology combines parcel-level probabilities into area indices of large-scale forest clearing in four steps: (1) Select 1 km^2 parcels whose estimated probability of clearing since 2000 exceeds a significance threshold of 50%[1]; (2) Assign values of 1 to these parcels, and 0 to the others; (3) Sum the values within a given polygon (e.g. administrative unit, protected area, etc.); (4) Calculate monthly changes in this summed total. These changes are FORMA's monthly indices of new clearing activity. They can be generated from December 2005 to provide a running index of total large-scale forest clearing.

In this paper, we analyze monthly FORMA estimates from December 2005 to August 2011 for tropical forest areas in 27 countries: 12 in Asia (Bangladesh, Cambodia, China, India, Indonesia, Lao PDR, Malaysia, Myanmar, Nepal, Papua New Guinea, Thailand and Vietnam), 9 in Latin America (Bolivia, Brazil, French Guiana, Guyana, Mexico, Paraguay, Peru, Suriname and Venezuela), and 6 in Sub-Saharan Africa (Burundi, Central African Republic, Guinea, Kenya, Republic of Congo and Tanzania).

In the accompanying spreadsheet databases, we include forest clearing indices for the 27 countries, their 280 primary administrative units (henceforth primary units) and 2,907 secondary administrative units (henceforth secondary units). We hope that the database will support new empirical studies of tropical forest clearing. In this paper, we limit ourselves to reporting broad trends that are readily observable in the data. In a recently-published econometric paper (Wheeler et al., 2011), we analyze the determinants of these trends in Indonesia.

The remainder of the paper is organized as follows. Section 2 provides an overview of trends at the global, regional and national levels. In Section 3, we use a "hotspots" methodology

[1] A higher threshold will reduce the rate of false-positive identifications of cleared parcels, but increase the rate of false negatives. We believe that the forthcoming re-specification of FORMA to 500 m resolution will significantly reduce false-negative identifications.

and detailed mapping exercises to investigate sub-national patterns of change. We summarize and conclude the paper in Section 4.

2. Global, Regional and National Forest Clearing, 2006–2011

2.1. Global Clearing

Figure 1 (page iii) displays monthly changes in tropical forest parcels cleared with high probability from December 2005 to August 2011, along with a 12-month moving average and a regression trend line.[2] The series tracks total clearing for all 27 countries covered by this paper. The 12-month moving average is dominated by a sharp drop from September 2008 to September 2010, which coincides with the onset of the global economic crisis. For the entire period, the FORMA data suggest that tropical forest clearing has dropped by 42.3%. We are not convinced that this drop is primarily attributable to a fall in global demand for forest products since, as we show below, increases and decreases in forest-clearing are about evenly represented across FORMA countries. In any case, our global result is certainly good news for carbon emissions reduction and biodiversity conservation.

2.2. Regional and National Clearing

While total clearing has dropped sharply since 2005, widely-divergent patterns at the regional and country levels highlight the importance of local factors. Table 1 and Figure 2 display results for the 27 countries and 3 regions in our assessment. Declines have occurred in 12 countries, led by Brazil, Indonesia, Paraguay, Bolivia and China. But forest clearing has increased in 14 countries, led by Myanmar, Peru, Malaysia, and Venezuela.

Table 1 presents country information drawn from 12-month moving averages; the final 7 rows present summaries for country groups and regions. Several striking patterns are evident in the table:

- The skewed distribution of forest clearing across the 27 countries, which accounted for 94% of pantropical clearing during 2000-2005 (Hansen, et al., 2008). In December 2006 and August 2011, the shares of 27-country clearing accounted for by the top 5 countries (summary row (3)) were 94.6% and 93.7%, respectively.[3]

[2] The moving average is the mean of the current month and the previous 11 months. The regression trend line is fitted to the moving average series.

[3] In descending order, the top 5 countries in each period were: December, 2006 [Brazil (72.3%), Indonesia (13.2%), Malaysia (6.4%), Paraguay (2.4%), Bolivia (1.3%)]; August, 2011 [Brazil (61.0%), Indonesia (16.5%, Malaysia (12.2%), Myanmar (2.1%), Paraguay (1.9%)].

- A shift in regional shares (summary rows (5)-(7)), with Latin America's declining from 76.9% to 66.5% and Asia's increasing from 22.5% to 32.5%.

- The dominant roles of Brazil and Indonesia in the overall decline in forest clearing since 2005. Summary row (1) shows that with these two countries included in the global total, the forest clearing indicator fell from 3,380.4 in December 2006 to 1,951.7 in August 2008 – a 42.3% decrease. With Brazil and Indonesia excluded (summary row (2)), total clearing fell from 493.0 to 439.3, or 10.9%..

- The declining share of Brazil in overall forest clearing: from 72.3% of the global total in December 2006 to 61.0% in August 2011.

- Divergent experiences in the Amazon region, with decreases in Brazil and Bolivia but increases in Peru, Venezuela, Guyana, Suriname and French Guiana.

- The changing roles of Indonesia, Malaysia and Myanmar. Indonesia's decline in forest clearing was sharp, but still proportionately less than Brazil's. The result was an increase in Indonesia's global share from 13.2% to 16.5%. At the same time, increases in Malaysia and Myanmar (summary row (4)) elevated their combined share from 6.8% in December, 2006 to 14.3% and near-parity with Indonesia in August 2011.

Figure 1 presents plots of monthly clearing indicators, 12-month moving averages and linear regression trend lines for the countries with the most significant changes in Asia, Africa and Latin America. The five Asian countries have divergent trends and fluctuations around trend: Indonesia exhibits a sharp overall decline, but with two periods of countervailing increase; China exhibits monotone decrease at a decreasing rate, converging near zero by August, 2011. The Laotian pattern is similar, with some fluctuations. Strong overall growth with fluctuations is evident for Malaysia and Myanmar through mid-2010. Then the two countries diverge, with a large increase in Malaysia and below-trend clearing in Myanmar.

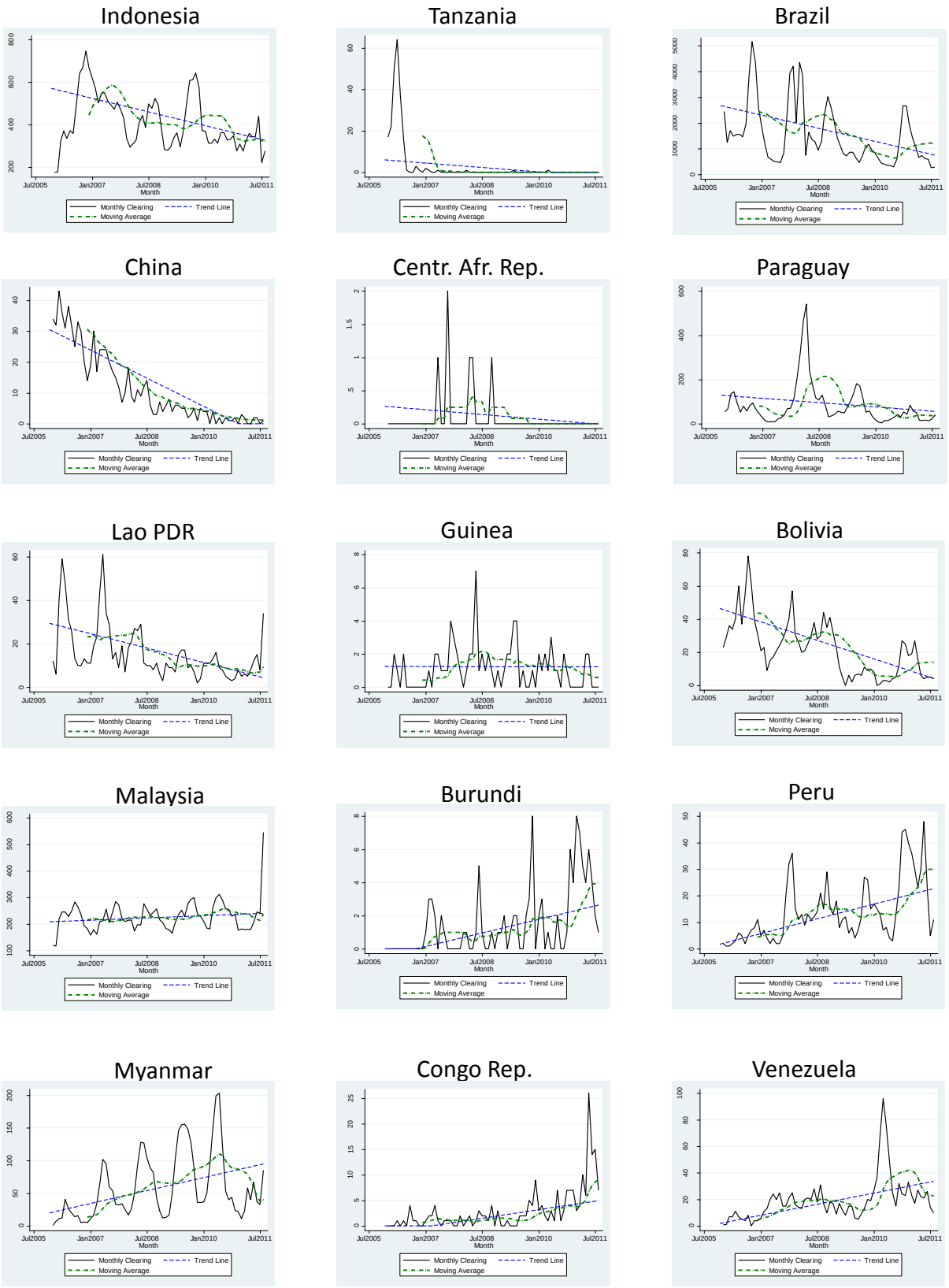
As indicated in Table 1, typical changes have been smaller for the African countries than elsewhere. And the region exhibits striking diversity in patterns: Tanzania has a sharp early decline to near-zero clearing; Central African Republic and Guinea both have surges in 2007, followed by declines through 2011. In contrast, Burundi and Congo Republic exhibit strong patterns of growth in clearing, with the suggestion of acceleration after 2008.

In Latin America, all five countries in Figure 1 exhibit two significant periods of fluctuation around trend, whether declining or increasing. The pattern of decline is strikingly similar for Brazil and Bolivia, while the sharp overall increases in Peru and Venezuela are also characterized by two apparent cycles. The Paraguayan decline also goes through two cycles, although the first is more pronounced.

Table 1: Comparative Trends in Forest Clearing, Dec. 2006 – Aug. 2011

	Monthly Clearing (12-Month Moving Average)		Change in Monthly Clearing		Share of Total Forest Clearing		
Country	Dec. 2006	Aug. 2011	Units	%	Dec. 2006	Aug. 2011	Change in Share
Brazil	2,442.25	1,191.33	-1,250.92	-51.2	72.25	61.04	-11.21
Indonesia	445.08	321.08	-124.00	-27.9	13.17	16.45	3.28
Paraguay	81.33	37.08	-44.25	-54.4	2.41	1.90	-0.51
Bolivia	43.67	14.00	-29.67	-67.9	1.29	0.72	-0.57
China	30.67	1.17	-29.50	-96.2	0.91	0.06	-0.85
Mexico	20.58	0.58	-20.00	-97.2	0.61	0.03	-0.58
Tanzania	17.67	0.00	-17.67	-100.0	0.52	0.00	-0.52
Laos	23.25	9.33	-13.92	-59.9	0.69	0.48	-0.21
India	13.25	1.17	-12.08	-91.2	0.39	0.06	-0.33
Vietnam	4.50	2.50	-2.00	-44.4	0.13	0.13	-0.01
Thailand	2.50	0.92	-1.58	-63.3	0.07	0.05	-0.03
Bangladesh	0.17	0.00	-0.17	-100.0	0.00	0.00	0.00
Central African Republic	0.00	0.00	0.00		0.00	0.00	0.00
Nepal	0.00	0.08	0.08		0.00	0.00	0.00
Guinea	0.42	0.58	0.17	40.0	0.01	0.03	0.02
French Guiana	1.00	1.25	0.25	25.0	0.03	0.06	0.03
Suriname	0.25	0.83	0.58	233.3	0.01	0.04	0.04
Guyana	0.08	0.92	0.83	1,000.0	0.00	0.05	0.04
Kenya	2.25	4.67	2.42	107.4	0.07	0.24	0.17
Cambodia	8.50	12.42	3.92	46.1	0.25	0.64	0.38
Burundi	0.00	4.00	4.00		0.00	0.20	0.20
Papua New Guinea	3.83	8.00	4.17	108.7	0.11	0.41	0.30
Republic Of Congo	0.67	9.08	8.42	1,262.5	0.02	0.47	0.45
Venezuela	4.92	22.67	17.75	361.0	0.15	1.16	1.02
Malaysia	215.42	237.92	22.50	10.4	6.37	12.19	5.82
Peru	4.42	29.83	25.42	575.5	0.13	1.53	1.40
Myanmar	13.67	40.33	26.67	195.1	0.40	2.07	1.66
(1) Overall Totals	3,380.4	1,951.7	-1,428.6	-42.3	100.0	100.0	0.0
(2) Totals w/o Brazil and Indonesia	493.0	439.3	-53.7	-10.9	14.6	22.5	8.0
(3) Total, Top 5 Countries	3,227.8	1,827.7	-1,426.3	-44.2	94.6	93.7	-1.0
(4) Malaysia and Myanmar	229.1	278.3	49.2	21.5	6.8	14.3	7.5
(5) Latin America	2,598.50	1,298.49	-1,300.01	-50.0	76.88	66.53	-10.34
(6) Asia	760.84	634.92	-125.91	-16.5	22.49	32.54	10.01
(7) Africa	21.01	18.33	-2.66	-12.7	0.62	0.94	0.32

Figure 2: Comparative Forest-Clearing Trends, 2005 – 2011



The contrasting patterns in Figure 1 strongly suggest the importance of country-specific dynamics during the past five years. The factors driving short-run changes in forest clearing remain largely unexplored, since the time series data needed for detailed econometric studies were unavailable before the advent of FORMA. In a recently-published spatial econometric paper on Indonesia (Wheeler, et al., 2011), we find significant roles for lagged changes in several short-run economic variables – forest product prices, demands, exchange rates and real interest rates – as well as fluctuations in rainfall (heavy rain impedes the burning that is an important part of large-scale forest clearing). In addition, we find important roles for topography, communications infrastructure and zoning for commercial development. It seems likely that future research on other countries will reveal similar causal dynamics. For the present, however, we are limited to speculation about the sharp cross-country differences that FORMA has revealed.

3. Sub-National Trends

As the accompanying spreadsheet databases reveal, the national trends reported above mask great diversity in local forest-clearing patterns. Many countries with overall decreases in forest clearing contain areas with increased clearing, and countervailing patterns are also common in countries with increases in total clearing. We cannot hope to explore all the important and interesting patterns revealed by FORMA's high-resolution temporal outputs, and we hope that many colleagues will join the effort. In this paper, we illustrate two potential uses of FORMA's sub-national data. At the global level, we present a "hotspots" analysis that highlights particularly significant outbreaks of local forest clearing across the pantropics. At the national level, we use detailed mapping exercises to explore recent forest clearing patterns in Indonesia and Brazil.

3.1. Global Hotspots

The hotspot concept has been used to identify areas with two salient features: an attribute that commands policy priority, and a high level of threat to that attribute. Two attributes have dominated hotspot analyses of tropical forests: local biodiversity value and sequestered carbon. Myers, et al. (2000) identify biodiversity hotspots, where "exceptional concentrations of endemic species are undergoing exceptional loss of habitat."[4] Treating biomes as undifferentiated, Hansen et al. (2008) concentrate on forest clearing and identify tropical forest hotspots as areas characterized by either large-scale forest clearing or high rates of clearing relative to forest cover in 2000.

We follow Hansen in this paper, while recognizing the importance of differences in local biodiversity value. Because we focus on short-period trends, we identify two geographic hotspot components: exceptional base levels of forest clearing, and exceptional rates of

[4] op cit, p. 853.

Table 2: FORMA Top 25 Hotspots: July/August, 2011

Region	Country	State/Province	(1) Rank[a]	(2) Clearing (July, 2011)	(3) Clearing (August, 2011)	(4) % Change (2)→(3)	(5) Geometric Mean $(2)^{0.5}(4)^{0.5}$
Latin America	Brazil	Rondonia	7	28	38	35.7	31.6
	Brazil	Minas Gerais	8	5	14	180.0	30.0
	Brazil	Bahia	19	8	11	37.5	17.3
	Brazil	Acre	19	5	8	60.0	17.3
	Brazil	Amapa	25	1	3	200.0	14.1
	Paraguay	Canindeyu	11	7	13	85.7	24.5
	Paraguay	San Pedro	19	7	10	42.9	17.3
	Paraguay	Itapua	25	3	5	66.7	14.1
Africa	Kenya	Rift Valley	4	12	32	166.7	44.7
Asia	Indonesia	Kalimantan Timur	6	11	23	109.1	34.6
	Indonesia	Sumatera Barat	8	1	10	900.0	30.0
	Indonesia	Sumatera Utara	8	33	42	27.3	30.0
	Indonesia	Kalimantan Selatan	11	3	9	200.0	24.5
	Indonesia	Sumatera Selatan	11	10	16	60.0	24.5
	Indonesia	Jambi	11	3	9	200.0	24.5
	Indonesia	Aceh	16	8	12	50.0	20.0
	Indonesia	Bengkulu	16	5	9	80.0	20.0
	Indonesia	Kalimantan Tengah	19	20	23	15.0	17.3
	Indonesia	Sulawesi Tengah	19	1	4	300.0	17.3
	Laos	Bolikhamxai	15	1	6	500.0	22.4
	Laos	Savannakhet	19	2	5	150.0	17.3
	Malaysia	Sarawak	1	114	315	176.3	141.8
	Malaysia	Sabah	2	37	160	332.4	110.9
	Malaysia	Johor	16	2	6	200.0	20.0
	Malaysia	Kedah	25	2	4	100.0	14.1
	Myanmar	Chin	3	1	26	2500.0	50.0
	Myanmar	Rakhine	5	29	48	65.5	43.6
	Myanmar	Kachin	25	1	3	200.0	14.1

[a] Tied ranks for equal values, cutoff at rank 25

change in clearing. Our hotspot score for each administrative unit is the geometric mean of the level and rate of change of forest clearing.[5] For this exercise we focus on primary administrative units (e.g. states, provinces). However, the same methodology could be applied to nations, second- or third-level administrative units, or any other bounded geographic areas.

Figure 3 displays the top 25 hotspots for July/August 2011 among the 280 primary administrative units in FORMA's 27 countries. Table 2 displays the associated states and provinces, along with hotspot ranks, components, and numerical scores. More than 25 areas are identified because some have identical scores. Four hotspot clusters are apparent in Figure 3:

- The periphery of Brazil's Amazon region (Rondonia, Acre, Amapa);
- The periphery of the Atlantic Forest region in Brazil (Bahia, Minas Gerais) and Paraguay (Canindeyu, San Pedro, Itapua);
- A northern arc in Southeast Asia through Myanmar (Chin, Rakhine, Kachin) and Lao PDR (Bolikhamxai, Savannakhet);
- A very large cluster in Southeast Asia that includes peninsular Malaysia (Johor, Kedah), Malaysian Borneo (Sarawak, Sabah) and three Indonesian islands: Kalimantan (Kalimantan Timur, Kalimantan Selatan, Kalimantan Tengah), Sumatra (Sumatera Utara, Sumatera Barat, Jambi, Sumatera Selatan, Bengkulu, Aceh,) and Sulawesi (Sulawesi Tengah).

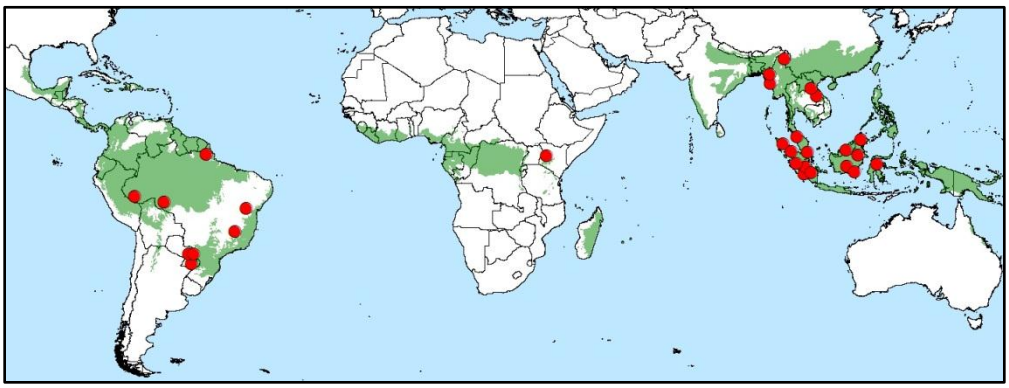
With the exception of Kenya's Rift Valley (rank #4), all of the hotspots with the highest scores are in Malaysia (Sarawak (#1), Sabah (#2)) and Myanmar (Chin (#3), Rakhine (#5)). These results highlight the recent dominance of the Southeast Asian countries in global dynamics. In Table 2, 19 of the hotspots are in Southeast Asia, 8 are in Latin America and 1 is in Africa.

3.2. Changes within Countries: Illustrations for Indonesia and Brazil

The spatial resolution of the FORMA database is 1 km^2, making it possible to assess patterns of change across highly-disaggregated geographic units. For this illustration, we disaggregate to second-level administrative units in Indonesia (kabupatens) and Brazil (municipios). The same exercise (and even more spatially-disaggregated exercises) could be performed for any

[5] The geometric mean of clearing (C) and its growth rate (G) is their exponentially-weighted product, $C^{\rho}G^{\rho}$, where ρ=0.5. We use the geometric mean because it is well-known; other values of ρ will yield nearly-identical rankings. For ρ=1 and constant total clearing, each area's score (CG) is identical to the change in its share of total clearing. We also use this approach to scoring because it generates rankings that are relatively insensitive to outlier values and independent of measurement units.

Figure 3: FORMA Top-25 Hotspots for July/August, 2011



Humid Tropical Forest, 2000 (Source: Hansen et al. [2003, 2006])

Top-25 State/Province Hotspot

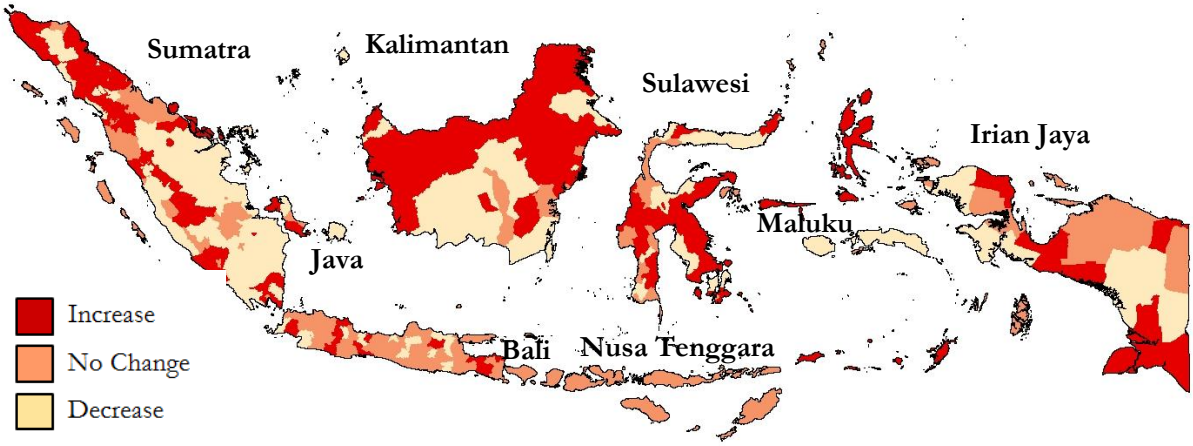
other FORMA country. As Figure 2 shows, forest clearing has declined sharply in Indonesia and Brazil since 2005. Both countries are large and diverse, however, and national declines may mask divergent patterns of regional change. To investigate these patterns, we divide FORMA's 69 monthly observations into 34- and 35-month periods: December 2005 - September 2008, and October 2008 – August 2011. Within each period, for each administrative unit, we calculate the average monthly value (m) of the FORMA forest clearing indicator. Then we calculate the ratio [$r=m_2/m_1$] and divide the units into those characterized by reduced clearing ($r < 0.9$), little or no change ($0.9 \leq r \leq 1.1$), and increased clearing ($r > 1.1$).

Figures 4 and 5 display the results, with kapupaten and municipio boundaries suppressed to provide an uninterrupted view of spatial patterns. In both countries, our color-coded maps reveal complex patterns of change that include large areas where forest clearing has declined, increased, and remained roughly constant. In Indonesia, the regional balance has clearly shifted in Sumatra and Kalimantan, the islands that have accounted for most of the country's forest clearing. Sumatra exhibits broad patterns of decline in the southern and east-central areas, while clearing has increased in the northern and western areas. In Kalimantan, there has been a clear shift away from the southern and central areas toward the west and north. Similar geographic diversity characterizes the other island regions where significant forest clearing has occurred: Sulawesi, Maluku and Irian Jaya.[6]

To summarize, Indonesia's overall decline in forest clearing since 2005 largely reflects declines in south/central Sumatra and Kalimantan, with partially-offsetting increases in the northern and western areas of the two islands. We investigate the sources of these changes in Wheeler, et al. (2011). Our econometric analysis of kabupaten-level FORMA data indicates

[6] Java and Bali are almost entirely cleared, although changes still occur in small areas, as shown in Figure 4. Nusa Tenggara has little moist tropical forest.

Figure 4: Indonesia: Regional Changes in Forest Clearing, [Dec. 2005 - Sept. 2008] vs. [Oct. 2008 – Aug. 2011]



that changes in clearing reflect a complex interplay of numerous factors that affect the economics of forest clearing for plantation agriculture. These factors include global market prices and product demands, interest and exchange rates, communications infrastructure, zoning for commercial production and physical factors (rainfall, topography).[7]

In Figure 5, Brazil exhibits similarly-striking patterns of change. In the Amazon region, declines in forest clearing have occurred across a broad territorial band that runs from Amazonas Rondonia and Mato Grosso in the south and west to Para and Maranhao in the east. At the same time, forest clearing has increased in a broad parallel band from Acre and Amazonas, through Roraima, to Amapa. Patterns of change are more complex and localized in the Atlantic Forest region, with alternating patterns of increase, stability and decrease in a coastal band extending southward from Bahia to Rio Grande do Sul.

Forest clearing in Brazil's Amazon region has been extensively analyzed in studies that have identified many determinants, including population scale and density, distance from markets, the quality of transport infrastructure, agricultural input prices, physical factors such as topography, precipitation and soil quality, and commercial zoning.[8]

The newly-available FORMA data, coupled with recent advances in spatial econometric estimation, may permit a re-assessment of such results. Employment of these new resources by Wheeler, et al. (2011) for Indonesia has yielded insignificant results for numerous factors identified as important determinants of forest clearing by previous research. Our results may or may not hold for Brazil and other countries. We hope that colleagues will use the new FORMA data for spatial econometric panel estimation in forest-clearing studies for many other countries.

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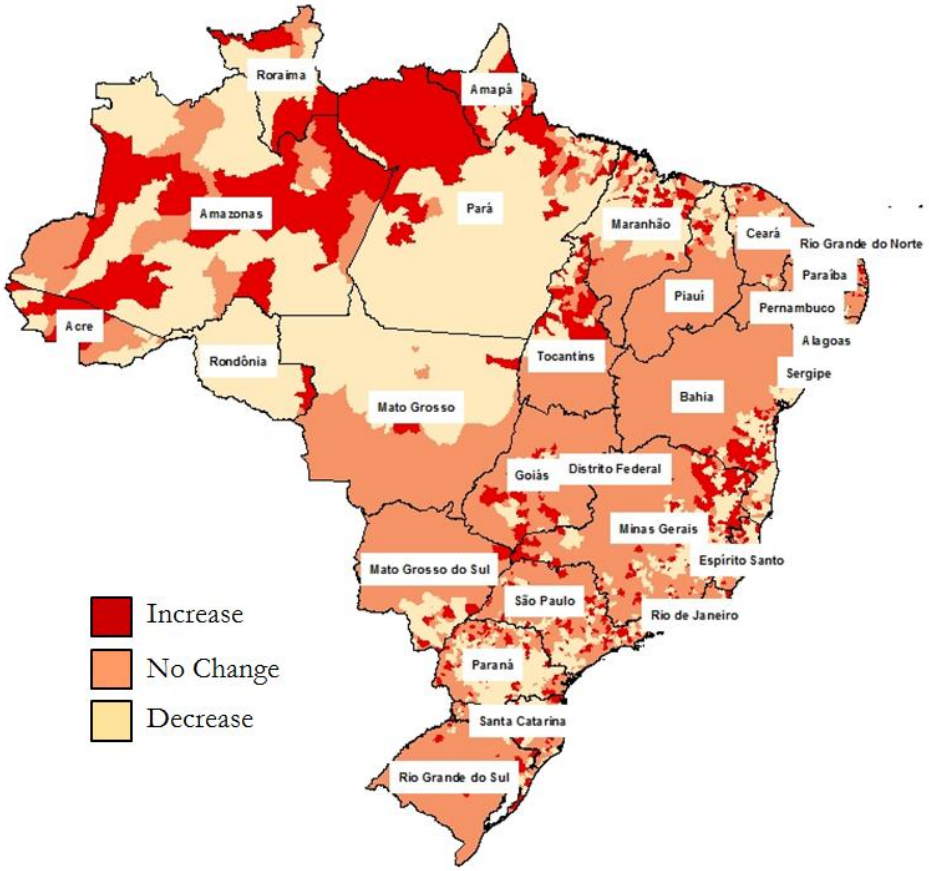
[7] For other empirical studies of Indonesian forest clearing, see San, et al. (2000) and Zikri (2009).

[8] See particularly Pfaff (1997), Cattaneo (2001), Igliori (2006) and Ewers, et al. (2008).

Figure 5: Brazil: Regional Changes in Forest Clearing, [Dec. 2005 - Sept. 2008] vs. [Oct. 2008 – Aug. 2011]



4. Summary and Conclusions

This report has summarized broad trends in recent tropical forest clearing identified by FORMA (Forest Monitoring for Action). We focus on large-scale clearing since 2005 in 27 countries that Hansen, et al. (2008) identify as accounting for 94% of clearing during 2000-2005. The current version of FORMA tracks monthly changes in the number of 1 sq. km. tropical forest parcels that have experienced clearing with high probability. [9]

For the pantropics as a whole, we find a sharp drop in forest clearing since 2005. Figure 1 shows that the drop is focused in the period from September 2008 to September 2010, which coincides with the onset of the global economic crisis. For the entire period since 2005, the indicator suggests that tropical forest clearing has dropped by 42.3%.

While total clearing has dropped during the global recession, widely-divergent patterns at the country level indicate the continued importance of local and regional factors in forest clearing dynamics. Among the 27 countries in our assessment, reductions have occurred in 12 (led by Brazil, Indonesia, Paraguay, Bolivia and China), while increases have occurred in 14 (led by Myanmar, Peru, Malaysia and Venezuela). Across regions, clearing has declined significantly in Asia, Latin America, and sub-Saharan Africa.

The individual roles of major forest-clearing countries have fluctuated markedly since 2005. At the global level, Brazil's share of global clearing fell by 11 percentage points from December 2005 to August 2011, while three Southeast Asian countries exhibited notable gains in share: Malaysia (+5.8), Indonesia (+3.3) and Myanmar (+1.7). Overall, Latin America's share of global clearing in our FORMA database fell from 76.9% to 66.5%, while Asia's share increased from 22.5% to 32.5% and Africa's share increased from 0.6% to 0.9%. We will revisit this assessment once FORMA coverage has been extended to several countries with large tracts of uncleared tropical forest. These include the Democratic Republic of the Congo (9.6% of uncleared forest in 2000), Colombia (4.8%), Cameroon (1.8%), Gabon (1.4%) and Ecuador (1.0%).[10]

We illustrate FORMA's potential to support sub-national analyses with two exercises. The first is a global "hotspots" analysis that identifies the top 25 provinces for forest clearing in July/August, 2011. The analysis reveals a striking Southeast Asian dominance, with most of the hotspots in Indonesia, Malaysia, Myanmar and Lao PDR. The relatively few Latin American hotspots are located at the southwestern and northeastern periphery of Amazonia and western peripheral areas of the Atlantic Forest in Brazil and Paraguay.

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[9] A forthcoming version will increase spatial resolution to 500 m.

[10] See Appendix 1 for information on past forest clearing and uncleared forest extent in the 27 FORMA countries and 25 additional countries.

The second illustrative exercise maps changes since 2005 in secondary administrative units in Indonesia and Brazil. The maps show that, despite sharp national declines in both countries, their regions continue to display great diversity in forest clearing. In the case of Indonesia, an overall decline, driven by decreased clearing in the southern and central areas of Sumatra and Kalimantan, has been accompanied by partially-offsetting increases in the western and northern areas of the two islands. Brazil also exhibits a striking pattern of regional change, with the national decrease in forest clearing driven by declines across a broad swath of southern Amazonia, but partially offset by increases in a roughly-parallel swath of northern Amazonia

To summarize, the diverse patterns revealed by FORMA's first global survey caution against facile generalizations about forest clearing in the pantropics. During the past five years, the relative scale and pace of clearing have changed across regions, within regions and within countries. Although the overall trend seems extremely hopeful, it remains to be seen whether the decline in forest clearing will persist as the global economy recovers. The database generated by the FORMA project will now be updated regularly, and we hope that it will support a significant expansion of research, policy analysis and conservation monitoring at the global, regional, national and sub-national levels.

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Appendix 1: FORMA's Coverage of Humid Tropical Forests

FORMA will ultimately expand to countries that include over 99% of humid tropical forests. At present, it covers 27 countries in Asia, Latin America, and Africa:

- **Asia/Pacific:** Bangladesh, Cambodia, China, India, Indonesia, Lao PDR, Malaysia, Myanmar, Nepal, Papua New Guinea, Thailand, Vietnam

- **Latin America/Caribbean:** Bolivia, Brazil, French Guiana, Guyana, Mexico, Paraguay, Peru, Suriname, Venezuela

- **Africa:** Burundi, Central African Republic, Congo Republic, Guinea, Kenya, Tanzania

Table A1 provides information for 52 countries that account for over 99% of the world's humid tropical forest, with current FORMA countries listed in the top half.[11] FORMA and non-FORMA countries are respectively ranked by their shares of humid tropical forest clearing in 2000-2005, as estimated by Hansen, et al. (2008). The table also includes countries' estimated shares of uncleared tropical forest in 2000[12], as well as cumulative shares

According to these estimates, the FORMA countries accounted for 93.8% of clearing in 2000-2005, and 76.5% of uncleared tropical forest in 2000. The distribution of clearing is highly skewed, with only 5 countries accounting for 82% of clearing (Brazil (61.9%), Indonesia (10.1%), Malaysia (5.0%), Myanmar (2.6%) and Paraguay (2.3%). The distribution of uncleared forest is also skewed, but less so, with the top 5 countries accounting for 60.4%.[13] From 2000-2005, the countries with most notable disparities between clearing activity and uncleared forest were Brazil (32.5% of uncleared forest but 61.9% of clearing), Malaysia (1.9% uncleared vs. 5.0% of clearing) and Paraguay (.25% vs. 2.3%).

As FORMA expands, priority will be given to coverage of five countries that accounted for at least 1% of uncleared tropical forest in 2000: Democratic Republic of the Congo (9.6%), Colombia (4.8%), Cameroon (1.8%), Gabon (1.4%) and Ecuador (1.0%).

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[11] Table A1 does not incorporate humid tropical forest tracts in some island states in the Caribbean, Indian and Pacific Oceans, as well as Australia, the US, and some territories administered by Australia, New Zealand, the US, Japan, the UK and France.

[12] This estimate is constructed from MODIS (Moderate Resolution Imaging Spectrometer) satellite data for 1 sq. km. parcels in the global humid tropical forest biome. We follow scientific convention by assigning uncleared status to parcels with MODIS Vegetation Continuous Field (VCF) values greater than 25. For more complete information, see Hansen, et al. (2003, 2006).

[13] Please note that countries are ranked in descending order by forest clearing, not uncleared forest.

Table A1: Tropical Forest Country Shares: Clearing, 2000-05; Extent, 2000

		Share of Humid Tropical Forest Clearing, 2000–2005	Cumulative Share	Share of Humid Tropical Forest, 2000	Cumulative Share
Countries Covered by First FORMA Report	Brazil	61.937	61.9	32.509	32.5
	Indonesia	10.122	72.1	8.334	40.8
	Malaysia	5.040	77.1	1.899	42.7
	Myanmar	2.598	79.7	3.130	45.9
	Paraguay	2.307	82.0	0.251	46.1
	China	1.771	83.8	4.432	50.6
	Venezuela	1.461	85.2	3.505	54.1
	Lao PDR	1.456	86.7	1.297	55.4
	Thailand	1.253	87.9	0.893	56.3
	Bolivia	1.142	89.1	2.739	59.0
	Peru	0.886	90.0	5.143	64.1
	Cambodia	0.863	90.8	0.235	64.4
	Papua New Guinea	0.831	91.7	2.700	67.1
	India	0.693	92.4	1.635	68.7
	Mexico	0.576	92.9	1.122	69.8
	Vietnam	0.356	93.3	0.647	70.5
	Guyana	0.194	93.5	1.441	71.9
	Tanzania	0.107	93.6	0.068	72.0
	Bangladesh	0.061	93.7	0.081	72.1
	Suriname	0.049	93.7	1.177	73.2
	Congo, Rep.	0.033	93.7	1.763	75.0
	Guinea	0.024	93.8	0.072	75.1
	French Guiana	0.019	93.8	0.688	75.8
	Kenya	0.015	93.8	0.067	75.8
	Nepal	0.009	93.8	0.119	75.9
	Burundi	0.006	93.8	0.008	76.0
	Central African Republic	0.003	93.8	0.516	76.5
Other Tropical Forest Countries	Colombia	2.224	96.0	4.826	81.3
	Guatemala	0.915	96.9	0.333	81.6
	Argentina	0.648	97.6	0.495	82.1
	Nicaragua	0.477	98.1	0.213	82.3
	Ecuador	0.397	98.5	0.965	83.3
	Congo, Dem. Rep.	0.204	98.7	9.592	92.9
	Philippines	0.154	98.8	0.529	93.4
	Cameroon	0.142	99.0	1.835	95.3
	Cote d'Ivoire	0.133	99.1	0.183	95.4
	Sierra Leone	0.120	99.2	0.179	95.6
	Honduras	0.119	99.3	0.226	95.8

		Share of Humid Tropical Forest Clearing, 2000–2005	Cumulative Share	Share of Humid Tropical Forest, 2000	Cumulative Share
Other Tropical Forest Countries (continued)	Nigeria	0.107	99.4	0.211	96.1
	Panama	0.093	99.5	0.191	96.3
	Ghana	0.080	99.6	0.130	96.4
	Madagascar	0.065	99.7	0.758	97.1
	Costa Rica	0.064	99.8	0.172	97.3
	Gabon	0.064	99.8	1.361	98.7
	Liberia	0.051	99.9	0.671	99.3
	Angola	0.029	99.9	0.018	99.4
	Sri Lanka	0.012	99.9	0.086	99.4
	Uganda	0.011	99.9	0.053	99.5
	Brunei Darussalam	0.009	99.9	0.041	99.5
	Haiti	0.005	99.9	0.012	99.6
	Martinique	0.004	99.9	0.002	99.6
	El Salvador	0.002	99.9	0.004	99.6

Appendix 2: FORMA Methodology

FORMA utilizes data recorded daily by the Moderate Resolution Imaging Spectrometer (MODIS), which operates on NASA's Terra and Aqua (EOS PM) satellite platforms. Although its signal-processing algorithms are relatively complex, FORMA is based on a common-sense observation: Tropical forest-clearing involves the burning of biomass and a pronounced temporary or long-term change in vegetation color, as the original forest is cleared and replaced by pastures, croplands or plantations. Accordingly, FORMA constructs forest-clearing indicators from MODIS-derived data on the incidence of fires and changes in vegetation color as identified by the Normalized Difference Vegetation Index (NDVI). It then calibrates to local forest-clearing by fitting a statistical model that relates the MODIS-based indicator values to the best available information on actual forest-clearing in each area. FORMA incorporates local diversity by dividing each country into WWF ecoregions and separately fitting the model to data for each ecoregion. The dependent variable for each pixel is coded 1 if it has experienced forest-clearing with high probability during the relevant time period, and 0 otherwise. The MODIS-based indicator values are the independent variables.

For all tropical countries except Brazil, the best identification of recent forest clearing has been published in the Proceedings of the National Academy of Sciences by Hansen, et al.[14]

[14] Hansen, M.C., Stehman, S.V., Potapov, P.V., Loveland, T.R., Townshend, J.R.G., DeFries, R.S., Pittman, K.W., Stolle, F., Steininger, M.K., Carroll, M., Dimiceli, C. 2008. Humid tropical forest clearing from 2000 to

(2008), who estimate the incidence of forest-clearing for 500m parcels in the humid tropics. We calibrate FORMA using the map of forest cover loss hotspots (henceforth referred to as the FCLH dataset) published by Hansen, et al. for the period 2000-2005.[15]

Using the FCLH pan-tropical dataset for 2000-2005, FORMA fits the calibration model to observations on forest-clearing for 1 km^2 cells in each country and ecoregion. As we document in Hammer, et al. (2009), the model's predicted probability distribution provides a very close match to the spatial incidence of FCLH forest-clearing. FORMA then applies the fitted model to monthly MODIS indicator data for the period after December 2005. The output for each month is a predicted forest-clearing probability for each 1 km^2 parcel outside of previously-deforested areas, as identified in the FCLH map. FORMA selects parcels whose probabilities exceed 50%.

Since FORMA identifies individual cells where forest-clearing has occurred with high probability, it is straightforward to add across cells within a geographic area to produce an index of forest-clearing activity in that area. Even small geographic areas can include thousands of 1 km cells, so error-averaging ensures robust index values.[16]

2005 quantified using multi-temporal and multi-resolution remotely sensed data. PNAS, 105(27), 9439-9444. www.pnas.org/cgi/doi/10.1073/pnas.0804042105

[15] In Brazil, higher resolution estimates are also available annually from the INPE PRODES program. We have used these estimates to test the accuracy of our FCLH-based calibration methodology. For more information on PRODES, see Projeto PRODES: Monitoramento da Floresta Amazonica Brasileira por Satelite. http://www.obt.inpe.br/prodes/

[16] For example, a square area 50 km on a side contains 2,500 1 km cells.