Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data


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Forest cover is an important input variable for assessing changes to carbon stocks, climate and hydrological systems, biodiversity richness, and other sustainability science disciplines. Despite incremental improvements in our ability to quantify rates of forest clearing, there is still no definitive understanding on global trends. Without timely and accurate forest monitoring methods, policy responses will be uninformed concerning the most basic facts of forest cover change. Results of a feasible and cost-effective monitoring strategy are presented that enable timely, precise, and internally consistent estimates of forest clearing within the humid tropics. A probability-based sampling approach that synergistically employs low and high spatial resolution satellite datasets was used to quantify humid tropical forest clearing from 2000 to 2005. Forest clearing is estimated to be 1.39% (SE 0.084%) of the total biome area. This translates to an estimated forest area cleared of 27.2 million hectares (SE 2.28 million hectares), and represents a 2.36% reduction in area of humid tropical forest. Fifty-five percent of total biome clearing occurs within only 6% of the biome area, emphasizing the presence of forest clearing “hotspots.” Forest loss in Brazil accounts for 47.8% of total biome clearing, nearly four times that of the next highest country, Indonesia, which accounts for 12.8%. Over three-fifths of clearing occurs in Latin America and over one-third in Asia. Africa contributes 5.4% to the estimated loss of humid tropical forest cover, reflecting the absence of current agro-industrial scale clearing in humid tropical Africa.

quantifying rates of humid tropical forest cover clearing is critical for many areas of earth system and sustainability science, including improved carbon accounting, biogeochemical cycle and climate change modeling, management of forestry and agricultural resources, and biodiversity monitoring. Concerning land cover dynamics, humid tropical forest clearing results in a large loss of carbon stock when compared with most other change scenarios. The humid tropical forests are also the site of considerable economic development through direct forestry exploitation and frequent subsequent planned agro-industrial activities. The result is that tropical forests and their removal feature prominently in the global carbon budget (1). In addition, the humid tropics include the most biodiverse of terrestrial ecosystems (2), and the loss of humid tropical forest cover results in a concomitant loss in biodiversity richness.

Assessing the dynamics of this biome is difficult because of its sheer size and varying level of development within and between countries. To date, there is no clear consensus on the trends in forest cover within the humid tropics. Grainger (3) illustrated this point mainly through the use of data from the Food and Agriculture Organization of the United Nations Forest Resource Assessments (4–6) and consequently emphasized the need for improved monitoring programs. A practical solution to examining trends in forest cover change at biome scales is to employ remotely sensed data. Satellite-based monitoring of forest clearing can be implemented consistently across large regions at a fraction of the cost of obtaining extensive ground inventory data. Remotely sensed data enable the synoptic quantification of forest cover and change, providing information on where and how fast forest change is taking place. Various remote-sensing-based methods have been prototyped within this biome (5, 7–11) and combined with information on carbon stocks to estimate carbon emissions (8, 12, 13). The method presented here advances the science of monitoring forest cover change by employing an internally consistent and efficient probability-based sampling approach that synergistically employs low- and high-spatial-resolution satellite datasets. The results represent a synoptic update on rates of forest clearing within the humid tropics since 2000. For this study, forest clearing equals gross forest cover loss during the study period without quantification of contemporaneous gains in forest cover due to reforestation or afforestation. The method presented could be implemented repeatedly for both forest cover loss and gain in establishing internally consistent biome-scale trends in both gross and net forest cover loss and/or gain.

Moderate spatial resolution (250 m, 500 m, and 1 km) data from the MODerate Resolution Imaging Spectroradiometer (MODIS) are imaged nearly daily at the global scale, providing the best possibility for cloud-free observations from a polar-orbiting platform. However, MODIS data alone are inadequate for accurate change area estimation because most forest clearing occurs at sub-MODIS pixel scales. High-spatial-resolution Landsat data (28.5 m), in contrast, do allow for more accurate measurement of forest area cleared. However, because of infrequent repeat coverage, frequent cloud cover, and data costs, the use of Landsat data for biome-scale mapping is often precluded. Integrating both MODIS and Landsat data synergistically enables timely biome-scale forest change estimation.

We used MODIS data to identify areas of likely forest cover loss and to stratify the humid tropics into regions of low, medium, and high probability of forest clearing. A stratified random sample of 183 18.5-km × 18.5-km blocks taken within these...
regions was interpreted for forest cover and forest clearing by using high-spatial-resolution Landsat imagery from 2000 and 2005. Typically, Landsat imagery has been used to provide regional forest area change estimates because its sufficiently high spatial resolution enables the detection of most forest clearing events (11, 14, 15). Consistent with this practice, our estimates of forest clearing are based on interpreting Landsat imagery for the 183 sample blocks selected. Our sampling strategy differs from previous efforts (5, 8) in that we took advantage of forest clearing information available from independent imagery, the MODIS change indicator maps, to define strata and to construct regression estimators of forest clearing.

Results

Our results reveal that rates of clearing in the biome remain comparable with those observed in the 1990s (5, 8, 9). Forest clearing is estimated to be 1.39% (SE 0.084%) of the total biome area. This translates to an estimated forest area cleared of 27.2 million hectares (SE 2.28 million hectares) and represents a 2.36% reduction in year-2000 forest cover. Fig. 1 depicts the spatial variation in gross forest cover loss from 2000 to 2005. The biome can be divided into three regions of forest clearing intensity. The first region consists of areas with >5% clearing per block and largely captures the current centers of agro-industrial scale clearing in South America and Insular Southeast Asia. Of the total biome area cleared, 55% occurs in this region that constitutes only 6% of the biome area, illustrating the presence of forest clearing “hotspots” (region 1 in Fig. 1). The second region of 0.7–5% clearing per block constitutes 44% of the biome area. This region consists of less spatially concentrated clearing and accounts for 40% of all clearing within the biome. The other 5% of forest clearing is found within a third region consisting of the remaining predominantly intact forest zones (35% of the biome area) and areas largely deforested before 2000 (15% of the biome area).

Our findings emphasize the predominance of Brazil in humid tropical forest clearing (Table 1). By area, Brazil accounts for 47.8% of all humid tropical forest clearing, nearly four times that of the next highest country, Indonesia, which accounts for 12.8% of the total. Over three-fifths of clearing occurs in Latin America and over one-third in Asia. Forest clearing as a percentage of year-2000 forest cover for Brazil (3.6%) and Indonesia (3.4%) exceeds the rest of Latin America (1.2%), the rest of Asia (2.7%), and Africa (0.8%). Beyond the arc of deforestation in Brazil, Latin American hotspots include northern Guatemala, eastern Bolivia, and eastern Paraguay. As a percentage of year-2000 forest cover, Paraguay features the highest areal proportion of change hotspots, indicating an advanced, nearly complete forest clearing dynamic. Indonesian island groups of Sumatra, Kalimantan, Sulawesi, and Papua feature varying degrees of forest removal, with Sumatra the site of the most intense recent large-scale clearing and Papua a measurable but low level of forest clearing. Riau province in Sumatra has the highest indicated change within Indonesia. Hot spots of clearing are present in every state of Malaysia, and clearing in Cambodia along its border with Thailand is among the highest of indicated change hot spots. Africa, although a center of widespread, low-intensity selective logging (16), contributes only 5.4% to the estimated loss of humid tropical forest cover. This result reflects the absence of current agro-industrial scale clearing in humid tropical Africa.

Our results reveal a higher degree of regional variation in forest clearing than currently portrayed by the only other source.

Fig. 1. Forest clearing and forest cover in the humid tropical forest biome, 2000–2005. Total forest clearing over the study period is estimated to be 27.2 million hectares (SE 2.28 million hectares). Regional variation in clearing intensity is shown: Region 1 covers 6% of the biome and contains 55% of clearing; region 2 covers 44% of the biome and contains 40% of forest clearing; and region 3 covers 50% of the biome and contains 5% of forest clearing. Data from this figure are available at http://globalmonitoring.sdsstate.edu/projects/gfm.
of information for the pan-tropics during the study period, the 2005 Forest Resource Assessment (FRA) report from the Food and Agriculture Organization of the United Nations (6). The FRA 2005 report highlights Africa and South America as having the highest rates of forest area loss, both in excess of 4 million hectares per year. For those African countries predominantly within the humid tropics, our humid-tropics-only estimate is less than one-third of the FRA estimate. For both this study and the FRA, Brazil and Indonesia are the countries featuring the highest forest clearing rates. However, our results differ as to the relative magnitude of change. For Brazil and Indonesia, the FRA reports annual change in forest area from 2000 to 2005 equal to 3.10 and 1.87 million ha/yr, respectively (6). Our estimates of forest clearing for Brazil and Indonesia are 2.60 and 0.70 million ha/yr, respectively. The results for Indonesia represent a dramatic decrease from 1990 to 2000 clearing rates.

Discussion

Our strategy incorporating the MODIS-derived forest clearing information in both the sampling design (stratification) and estimation (regression estimator) components of the monitoring strategy yielded the requisite precision and cost efficiency desired for an operational monitoring protocol at the pantropical scale. The standard error we obtained for the biome-wide estimated forest loss of the humid tropics was comparable with those reported by the Food and Agriculture Organization of the United Nations in 2000 (5) and Achard et al. (8), but we were able to achieve this level of precision with much smaller sample coverage. The total area of Landsat imagery sampled in our study was 0.21% of the biome, whereas previous studies (5, 8) used samples covering 10% and 6.5% of the tropical domain. Our sampling strategy thus yields precise estimates of forest clearing based on an areal sample coverage that could be sustainable from an effort and cost standpoint for future monitoring goals. Our approach is readily adaptable to other high-resolution sensors because the success of the strategy derives from advantageously incorporating the MODIS data in both the sampling design and analysis components.

Considerable debate on the appropriate use of Landsat data for regional monitoring has concerned the alternative uses of exhaustive mapping versus sampling-based approaches (17–19). Data limitations, namely cloud cover and costs of imagery, have been the principal arguments against exhaustive mapping. The challenge to a sampling approach is that change is typically rare at the scale of a biome. Consequently, a critical requirement for obtaining precise sample-based estimates is to construct strata that effectively identify areas of intensive forest clearing. The use of expert opinion to delineate broad regions of suspected change has been used to achieve this end (8). In contrast, we implemented a more spatially targeted approach to stratification, using MODIS imagery to flag areas of likely forest clearing. The MODIS imagery allowed assigning each 18.5-km × 18.5-km block in the biome individually to a stratum, thus improving on the broader regional strata used previously (8). Furthermore, MODIS imagery allows for the identification of clearing on an annual basis and therefore provides a more temporally resolved view of change than possible with Landsat data alone. An additional criticism of the sampling approach is the absence of a spatial representation of where in the biome forest clearing is occurring. We address this concern by applying the stratum-specific regression models relating Landsat-derived clearing to MODIS-derived clearing at the support of the 18.5-km × 18.5-km blocks to predict clearing for each block (Fig. 1). This spatial depiction of forest clearing takes advantage of the respective strengths of the complete coverage MODIS imagery and the high spatial resolution of the Landsat imagery. The more frequent temporal coverage of the MODIS imagery alleviates the problem of cloud cover obscuring tropical areas during the few available Landsat overpasses (20). Calibrating the MODIS-derived clearing values based on the Landsat-derived clearing observed on the sample blocks compensates for the inability of the larger MODIS pixel size (500 m) to detect smaller areas of clearing that are observable from the 28.5-m Landsat pixels. Although area estimates derived from coarser-resolution data are commonly calibrated by using a nonrandom sample of high-resolution data (21, 22), a strength of our approach is that by implementing a probability sampling design to collect the

Table 1. Regional estimates of humid tropical forest area cleared

<table>
<thead>
<tr>
<th>Region</th>
<th>Percent of biome area</th>
<th>Percent contribution of region to forest loss in the biome</th>
<th>Within-region forest loss as percent of land area (SE)</th>
<th>Within-region forest loss as percent of year 2000 forest area</th>
<th>Blocks sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>27.09</td>
<td>47.8</td>
<td>2.45 (0.14)</td>
<td>3.60%</td>
<td>53</td>
</tr>
<tr>
<td>Americas sans Brazil</td>
<td>21.27</td>
<td>12.6</td>
<td>0.82 (0.13)</td>
<td>1.23</td>
<td>10</td>
</tr>
<tr>
<td>Indonesia</td>
<td>9.16</td>
<td>12.8</td>
<td>1.95 (0.20)</td>
<td>3.36</td>
<td>77</td>
</tr>
<tr>
<td>Asia sans Indonesia</td>
<td>27.60</td>
<td>21.4</td>
<td>1.08 (0.33)</td>
<td>2.68</td>
<td>31</td>
</tr>
<tr>
<td>Africa</td>
<td>14.88</td>
<td>5.4</td>
<td>0.50 (0.13)</td>
<td>0.76</td>
<td>12</td>
</tr>
<tr>
<td>Pan-Americas</td>
<td>48.36</td>
<td>60.4</td>
<td>1.73 (0.10)</td>
<td>2.56</td>
<td>63</td>
</tr>
<tr>
<td>Pan-Asia</td>
<td>36.76</td>
<td>34.3</td>
<td>1.29 (0.25)</td>
<td>2.90</td>
<td>108</td>
</tr>
<tr>
<td>Biome total</td>
<td>100</td>
<td>100</td>
<td>1.39 (0.084)</td>
<td>2.36</td>
<td>183</td>
</tr>
</tbody>
</table>

Table 2. Stratified sampling design

<table>
<thead>
<tr>
<th>MODIS change (≥90%)</th>
<th>Humid tropics (excluding Indonesia)</th>
<th>Indonesian humid tropics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratum no.</td>
<td>No. of blocks sampled</td>
<td>Percent of stratum sampled</td>
</tr>
<tr>
<td>0–2%</td>
<td>1A</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>18</td>
</tr>
<tr>
<td>2–9%</td>
<td>2</td>
<td>23</td>
</tr>
<tr>
<td>&gt;9%</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>—</td>
<td>4 (certainty)</td>
<td>5</td>
</tr>
</tbody>
</table>
sample of high-resolution data, we retain the rigorous design-based inference framework (23) to support the statistical validity of our estimates. Furthermore, by construction, the aggregate predicted change over any defined subregion of the biome (Table 1) equals the estimated forest cover loss derived from the sample blocks, thus ensuring internal consistency between the mapped (Fig. 1) and estimated forest loss.

The results of this analysis highlight the need for internally consistent biome-scale monitoring to accurately depict relative variations in forest clearing dynamics within and between countries. Results from national-scale studies that employ varying methods, definitions, and input data may result in incompatible products that preclude regional syntheses (24). Biome-scale forest cover and change estimates derived from remotely sensed data offer a way forward for monitoring forests in support of both basic earth science research and policy formulation and implementation. For example, these results could be combined with information on carbon stocks to support carbon accounting programs such as the “Reducing Emissions for Deforestation and Degradation” (REDD) initiative (25). Such an approach could be implemented at both national and regional scales for the synoptic assessment of forest cover change and the monitoring of intra- or international displacement, or leakage, of forest cover clearing.

Although forest resources are a key component of economic development in this biome, forest governance is greatly hindered by a lack of timely information on change within the forest domain. A monitoring strategy combining data from sensors at

**Fig. 2.** Examples of Landsat sample blocks characterized to estimate forest cover and change from 2000 to 2005. Each block covers 18.532 km per side and has been reprojected into local Universal Transverse Mercator coordinates. The strata are created by using the biome-wide MODIS 2000 to 2005 forest clearing probability maps. (a) Sample block from the MODIS change strata 1 and 5. (b) Sample block from MODIS change strata 2 and 6. (c) Sample block from MODIS change strata 3 and 7. (d) Sample block from MODIS change certainty strata 4 and 8. All blocks used in this analysis can be viewed at http://globalmonitoring.sdstate.edu/projects/gfm.
multiple temporal and spatial resolutions offers a feasible and
cost-effective methodology to produce timely, precise, and
internally consistent estimates of biome-wide forest clearing for
5-year updates, and even annual updates for areas where rapid
forest clearing is taking place (i.e., South America).

Methods

The humid tropical forest biome was delineated by using the World Wildlife
Fund ecoregions map (26) as the primary reference. Biome-wide forest change
indicator maps were created by using annual MODIS imagery for 2000–2005.
We used a classification tree bagging algorithm (27) to produce per MODIS
pixel annual and 4- and 5-year change probability maps within the humid
tropics. MODIS 32-day composites were used as inputs and included data from
the MODIS bands: 319–389 nm; 443–459 nm; 545–565 nm; red, 620–679
nm; near infrared, 841–876 nm; and mid infrared, 1230–1250, 1628–1652, and
2105–2155 nm (28), as well as data from the MODIS Land Surface Tempera-
ture product (29). To produce a more generalized annual feature space that
enabled the extension of spectral signatures to regional and interannu-
alscales, the 32-day composites were transformed to multitemporal annual
metrics. Annual metrics capture the salient features of phenological variation
without reference to specific time of year and have been shown to perform as
well or better than time-sequential composites in mapping large areas (30,
31). For each annual and 4- and 5-year interval, a total of 438 image inputs
were used (146 metrics per year plus their calculated differences). The classi-
fication tree bagging algorithm related the expert-interpreted forest cover
loss and no loss categories to the MODIS inputs. We applied a threshold to the
annual and 4- and 5-year forest cover loss maps at various change probability
values to produce per-500-m pixel forest change/no change maps. For each
map, the 500-m pixel data were aggregated to produce a percent cover loss
value (threshold dependent) for each block in the biome.

Standard error calculations based on ancillary data from another tropical
deforestation study (9) led to the decision to use square sample blocks of 18.5
km per side grouped into strata (0–2%, 2–9%, and >9% forest clearing) as
defined by the MODIS change indicator map using a threshold that corre-
sponds to 90% probability (see supporting information (30 Figs. 51 and 52).
The sample was further stratified geographically as resources were available
to prototype the methodology for Indonesia before biome-wide implemen-
tation. The three MODIS-defined strata were used in both the Indonesian
tropics and in the tropics outside of Indonesia (Table 2). The sample size
allocated per stratum was initially determined by optimal allocation (32) but
was modified slightly to obtain more sample blocks in the high forest loss
strata. The six blocks with the highest MODIS-derived loss were placed in a
certainty stratum. The effectiveness of the MODIS-change-based stratifi-
cation can be quantified by estimating the ratio of the standard error of a
simple random sample to the standard error for our stratified random sample
(32). For Indonesia, this ratio was 2.04, and for the rest of the tropics, this ratio
was 1.16, indicating a considerable advantage of stratification for Indonesia,
and a modest advantage for the rest of the tropics.

Each Landsat sample block was classified by using a supervised decision tree
classifier (33) to yield 2000 forest cover and 2000–2005 forest clearing areas.
Each block was examined in detail by one or more interpreters, and the
procedure was iterated if necessary, including manual editing where required,
to achieve accurate per block detections of forest cover and forest clearing.
Forest was defined as >25% IFL or <20% VCF tree cover, and a 90% MODIS threshold change
value of 0% were placed in poststrata 1A and 5A (areas expected to show virtually
no change), and the remaining blocks were placed in poststrata 1B and 5B.

Fig. 3 illustrates the relationship between the expert-interpreted Landsat
block change and the operationally implemented MODIS block change, using
a 75% change probability threshold. For each stratum, a separate regression
estimator (32) was used in the analysis to estimate Landsat-derived forest area
loss. The simple linear regression model applied to strata 2, 3, 5B, 6, and 7 used
the MODIS 75% threshold data as the explanatory variable (y axis of Fig. 3).
A two-variable linear model was applied to stratum 1B that used both the
MODIS 75% and 90% threshold data. A regression estimator was not applied
to strata 1A and 5A because these poststrata had very little change. Therefore,
for these strata the estimates were based on the sample mean Landsat-derived
clearing. The models selected were the best or nearly best fitting models
evaluated for a suite of auxiliary variables that included MODIS-derived forest
loss based on different thresholds and forest cover variables. Each model
was applied per stratum and then aggregated to derive biome-scale forest clear-
ing estimates. Subregional estimates were calculated for the three continents
and for Brazil and Indonesia, all of which had enough samples to yield
estimates of forest clearing with reasonable standard errors. Three other
subregions (Fig. 1) were defined based on per block clearing thresholds to
highlight biome-scale variations in clearing intensity.

Sample blocks were processed in a randomly ordered sequence. A sample
was excluded if the Landsat data exhibited seasonal offsets or image misreg-
istration, or if <25% of the block had useable data (area unaffected by SLC-off
data gaps and cloud cover). In any of these cases, the next sample block in the
randomly ordered list was processed. Just over 10% of samples did not meet
the analysis criteria. The number of blocks excluded by stratum and by region
and the distribution of the percent useable data for the blocks included in the
sample are documented in Table S1. To evaluate possible biases introduced by
having to exclude cloud-covered blocks, the MODIS change probability and IFL
data were used to construct regression imputed values (23) for the excluded
blocks. The forest loss estimates were recomputed by using weighted means
derived from the observed sample values and the imputed values (for each
stratum). For the full biome, the estimated forest loss incorporating the
imputed values was 1.35%, compared with the reported estimate of 1.39%.

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Fig. S1. Maps of MODIS forest cover loss probability per study interval (a), thresholded forest cover loss at 90% probability (occurring within any of the study intervals) (b), sampling strata (0–2%, 3–9%, >9%, and certainty strata with selected samples outlined in cyan) (c), and final change area estimate based on regression estimation procedure (d). The images are centered on 55.09°W, 12.06°S in Mato Grosso state, Brazil, and is 926.6 km \( \times \) 463.3 km in size. For a and b, white is areas outside of the humid tropical forest biome, black is forest, and beige is nonforest as defined by a 25% Vegetation Continuous Field tree cover threshold.
Fig. S2. Maps of MODIS forest cover loss probability per study interval (a), thresholded forest cover loss at 90% probability (occurring within any of the study intervals) (b), sampling strata (0–2%, 3–9%, >9%, and certainty strata with selected samples outlined in cyan) (c), and final change area estimate based on regression estimation procedure (d). The images are centered on 101.69°E, 1.25°N in Riau province, Indonesia, and is 926.6 km x 463.3 km in size. For a and b, white is areas outside of the humid tropical forest biome, black is forest, and beige is nonforest as defined by a 25% Vegetation Continuous Field tree cover threshold.
Table S1. Effect of missing data due to cloud cover and SLC-off gaps on the final sample of blocks used for the Landsat-derived observation of forest cover and forest loss

<table>
<thead>
<tr>
<th>Stratum/region</th>
<th>No. of sample blocks classified</th>
<th>No. of sample blocks excluded</th>
<th>First quartile</th>
<th>Median</th>
<th>Third quartile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>87</td>
<td>17</td>
<td>55</td>
<td>73</td>
<td>84</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>3</td>
<td>56</td>
<td>73</td>
<td>86</td>
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<tr>
<td>3</td>
<td>50</td>
<td>6</td>
<td>65</td>
<td>80</td>
<td>89</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>0</td>
<td>66</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>Africa</td>
<td>12</td>
<td>0</td>
<td>56</td>
<td>67</td>
<td>81</td>
</tr>
<tr>
<td>Asia*</td>
<td>31</td>
<td>2</td>
<td>49</td>
<td>69</td>
<td>82</td>
</tr>
<tr>
<td>Indonesia</td>
<td>77</td>
<td>21</td>
<td>56</td>
<td>71</td>
<td>82</td>
</tr>
<tr>
<td>South America†</td>
<td>63</td>
<td>3</td>
<td>68</td>
<td>83</td>
<td>90</td>
</tr>
</tbody>
</table>

*Excluding Indonesia.
†Including one sample block in North America.