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Quantifying changes in the rates of forest clearing in Indonesia from 1990 to 2005 using remotely sensed data sets

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Abstract

Timely and accurate data on forest change within Indonesia is required to provide government, private and civil society interests with the information needed to improve forest management. The forest clearing rate in Indonesia is among the highest reported by the United Nations Food and Agriculture Organization (FAO), behind only Brazil in terms of forest area lost. While the rate of forest loss reported by FAO was constant from 1990 through 2005 (1.87 Mha yr⁻¹), the political, economic, social and environmental drivers of forest clearing changed at the close of the last century. We employed a consistent methodology and data source to quantify forest clearing from 1990 to 2000 and from 2000 to 2005. Results show a dramatic reduction in clearing from a 1990s average of 1.78 Mha yr⁻¹ to an average of 0.71 Mha yr⁻¹ from 2000 to 2005. However, annual forest cover loss indicator maps reveal a near-monotonic increase in clearing from a low in 2000 to a high in 2005. Results illustrate a dramatic downturn in forest clearing at the turn of the century followed by a steady resurgence thereafter to levels estimated to exceed 1 Mha yr⁻¹ by 2005. The lowlands of Sumatra and Kalimantan were the site of more than 70% of total forest clearing within Indonesia for both epochs; over 40% of the lowland forests of these island groups were cleared from 1990 to 2005. The method employed enables the derivation of internally consistent, national-scale changes in the rates of forest clearing, results that can inform carbon accounting programs such as the Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) initiative.

Keywords: deforestation, Indonesia, remote sensing, change detection

1. Introduction

While the forests of Indonesia are a source of economic development, the deleterious effects of poorly regulated clearing are well documented, and include the ecological collapse of the forest ecosystem and attendant disruption of rural livelihoods (Curran *et al* 2004). There are many drivers of Indonesian forest clearing, including economic, political,

social and environmental factors. As these drivers strengthen and weaken, so do the temporal rate and spatial extent of forest cover clearing. For Indonesia, there are no consistent, reliable estimates quantifying the spatio-temporal variation of forest clearing. Divergent views on deforestation rates have been the result, hampering effective forest management and governance.

The forest clearing rate in Indonesia during the 1990s was among the highest reported by FAO (2001). Indonesia

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ranked second, behind only Brazil in terms of forest cover lost. According to Hansen and DeFries (2004), Southeast Asia as a whole, and Indonesia in particular, were a primary reason for increasing rates of global forest loss when comparing the 1990s to the 1980s. For Southeast Asia, the 1990s featured significant economic growth that led to increased exploitation of forest resources. A principal deforestation dynamic in Indonesia during this period was the expansion of oil palm estates, which grew in area from 100 000 hectares in the late 1960s to 2.5 million hectares by 1997 (Casson 2000, FWI/GFW 2002). Another change dynamic was fire. The El Niño Southern Oscillation (ENSO) event of 1997–1998 led to a prolonged drought and widespread human-induced forest fires (Stibig and Malingreau 2003), resulting in the loss of an estimated 4.8 million hectares of forest according to the United Nations Center for Human Settlements (UNCHS 2000) and as high as 9.7 million hectares according to the Asian Development Bank (ADB) and Indonesian National Development Planning Agency (INDPA) (1999). Much of this fire was thought to be related to oil palm interests profiting from anomalous climatic conditions to clear forests via fire. The convergence of political, economic and environmental factors largely favoring clearing led to anomalously high rates of forest loss during the late 1990s.

However, many of the drivers of forest clearing changed at the turn of the last century, including economic, political, social and environmental factors. The economic crisis of the late 1990s deleteriously affected Indonesia by devaluing the currency, creating credit-access problems, and reducing oil palm prices (Casson 2000). The long-tenured Suharto government was replaced by a new national government that, in turn, instituted many policy reforms. Many of the new policies affected the oil palm sector, including more stringent permitting rules and new export tax regulations, slowing its continued expansion. Combined with the poor economic conditions, this led to a reduction in palm estate expansion. For example, it is estimated that the 1999 planted palm estate acreage was 1/3 that of 1997 (Casson 2000). Environmental factors include the vast cleared areas from the ENSO fires lying idle, ready for exploitation by agro-industrial interests. Such an excess of cleared land limited additional clearing in the short term. Forest fires of the scale that occurred in 1997 and 1998 were not repeated during the 2000–2005 epoch, and a decline in timber supplies from production forests (Sunderlin 2002) reflected the increasingly limited availability of intact lowland forests.

Given the new political, economic, social and environmental dynamics of the current decade, what can be expected vis-à-vis forest clearing rates? For the current decade (2000–2005), the FAO Forest Resource Assessment 2005 (FAO 2006) reports the same rate of clearing as that of the 1990s, 1.87 million hectares per year. However, a pan-humid tropical forest clearing survey for 2000–2005 estimated a dramatically different deforestation rate for Indonesia, 0.70 million hectares per year (Hansen *et al* 2008c). This study aims to resolve this discrepancy via the use of remotely sensed data to quantify change over both epochs. The results are the first repeated application of the approach of Hansen *et al* (2008c) with the

aim of quantifying *changes* in the rates of Indonesian forest clearing.

Monitoring of forest cover clearing requires robust methods applied repeatedly using data inputs that are internally consistent, both in space and time. The objective of this study is to apply the same methodology for quantifying forest clearing for the 1990–2000 decadal and 2000–2005 half-decadal epochs to discern if rates of clearing remain unchanged. The analysis employs remotely sensed data sets to quantify forest area cleared. While the use of satellite-based observations of the earth surface for monitoring tropical deforestation is well established (Skole and Tucker 1993, INPE 2002, Achard *et al* 2002), consistent and timely monitoring of areas with frequent cloud cover such as Indonesia has not been implemented.

Forest cover loss was quantified for both epochs from satellite imagery. We employed a targeted sampling approach that used national-scale decadal AVHRR (Advanced Very High Resolution Radiometer) (1990–2000) and annual MODIS (Moderate Resolution Imaging Spectroradiometer) (2000–2005) forest cover loss indicator maps to stratify Indonesia into low, medium and high change categories (Hansen *et al* 2008c, Stehman 2005). Samples for the two epochs were selected independently and Landsat image pairs analyzed to estimate the area of forest cleared. The use of Landsat to estimate area cleared for both epochs assures a consistent result across epochs. The MODIS and AVHRR data were also incorporated in the analysis via a regression estimator. An additional analysis employed the annual MODIS forest cover loss indicator data to proportionally allocate change within the 2000–2005 epoch. For Indonesia and other countries experiencing agro-industrial scale clearing, MODIS allows for the comparison of interannual trends in clearing (Hansen *et al* 2008b).

A final analysis consisted of disaggregating the national-based samples to estimate forest clearing for sub-regions within Indonesia. The targeted sample approach enabled by the coarse resolution change indicator maps intensifies the sampling effort within sub-regions experiencing the most change. These sub-regions may be evaluated separately. For example, the pan-humid tropical sample of Hansen *et al* (2008c) had a sufficient sample size to calculate a separate national-scale estimate for Brazil, revealing that nearly one-half of all humid tropical forest clearing from 2000 to 2005 occurred in Brazil. Given that clearing in Indonesia has been concentrated within the lowlands of Sumatra and Kalimantan, estimates were derived for three important sub-regions: (1) the combined island groups of Sumatra and Kalimantan, (2) Indonesian lowlands, and (3) lowlands within Sumatra and Kalimantan. An advantage of the targeted sampling approach is that it yields a larger sample size in regions of high forest clearing thus enhancing the ability to disaggregate the national-scale estimate to provide a more meaningful and quantitative narrative of forest clearing within the overall study area.

1.1. Satellite monitoring of forest clearing

Documenting tropical forest area and forest change at national scales is a challenge. Remotely sensed data offer a suitable

information source for synoptic forest assessments. Data from earth observation satellites allow for repeated views of the land surface over time. However, implementing operational monitoring of tropical deforestation is challenging. High spatial resolution sensors that capture enough spatial detail to yield reliable change area estimates, such as Landsat, do not have repeat temporal coverage that is sufficient to overcome cloud contamination for many regions. High spatial resolution satellites also have a narrow swath and revisit intervals typically greater than 1–2 weeks. Given this stricture, timely imaging of the humid tropics is problematic due to the persistence of cloud cover in many areas (Asner 2001, Ju and Roy 2008).

Compared to other humid tropical regions, estimating Indonesian forest cover change using passive optical remotely sensed data sets is more challenging. For example, large areas of the Brazilian humid tropical forest have an annual cloud-free window in August that enables the acquisition of usable high spatial resolution imagery on an annual basis and the derivation of annual deforestation maps (INPE 2002). This is particularly true for the core areas of deforestation, including the regional change hot spot of Mato Grosso state. The latitude of Mato Grosso's forests ranges from 9° to 14° south. Indonesian humid tropical forests, on the other hand, range from 6° north to 8° south. In Indonesia, there is no reliable annual seasonality that enables the acquisition of cloud-free imagery. Indonesian forests are found exclusively in the aseasonal humid tropical zone where cloud cover is persistent. This is also true for those parts of the Amazon closer to the equator as well, but to date, these areas have not been the hot spot of change in Brazil. While Indonesia does have regions that experience similar-scale agro-industrial forest clearing as occurs in Brazil, data limitations related to atmospheric contamination have stymied efforts to accurately quantify these changes at the national scale. As a result, there is a less clear understanding of forest cover change in Indonesia. The Congo Basin is similar to Indonesia in this regard, but even more challenging due to the relative fine spatial scale of the prevailing change dynamics found there (Hansen *et al* 2008a).

Persistent cloud cover means that improved methods for automatically processing images are required to perform exhaustive mapping, as the more persistent are the clouds, the more images you need to process to acquire good land observations. This is not a problem for most of Brazil's change areas, but it is the situation in Indonesia. Exhaustive mapping of Indonesia forest cover and change using passive optical data will entail mass-processing of data to filter atmospherically contaminated pixels and to identify and characterize good land observations. Such a procedure has been implemented in the Congo Basin (Hansen *et al* 2008a), but not yet for Indonesia. To date, Indonesian epochal studies of forest cover and change have been generated using photo-interpretation methods to identify forest cover classes and change over multi-year intervals.

An option to high spatial resolution exhaustive mapping is to use moderate or coarse spatial resolution images from polar orbiting satellites that have a larger observational swath. Since the main limitation of tropical forest monitoring is successful

imaging of the land surface, such sensors offer an improved capability. Moderate and coarse spatial resolution sensors such as MODIS and AVHRR image Indonesia every 1 to 2 days, providing the best possibility for cloud-free observations. MODIS and AVHRR data may be used to provide maps where forest clearing is indicated. However, these moderate and coarse spatial resolution data are not adequate to directly estimate change area because most change occurs at sub-pixel scales for these sensors.

By integrating the complementary characteristics of moderate/coarse (MODIS/AVHRR) and high (Landsat) spatial resolution data sources, timely national-scale updates of forest cover change are achievable using a targeted sampling strategy. This sampling approach uses nationwide 5 year aggregate MODIS change indicator maps and decadal AVHRR change indicator maps to stratify Indonesia into low, medium and high change categories. Landsat image pairs are then sampled within these strata, and the Landsat imagery analyzed for estimating area of forest cleared. Targeted sampling of Landsat-scale data offers a key advantage over past approaches by overcoming the need for Landsat-scale wall-to-wall mapping to quantify rates. Missing data due to scan line gaps or cloud cover within Landsat sample blocks do not deleteriously affect the results, if the presence or absence of the missing data is not correlated with change. Hansen *et al* (2008c) showed that missing data did not materially affect their 2000–2005 pan-humid tropical forest cover loss estimation with this approach.

The objective of this research is to compare rates of forest clearing in Indonesia for two epochs, 1990–2000 and 2000–2005. The forest clearing rates are estimated via a sampling approach, with change interpreted from high resolution Landsat imagery, and using moderate or coarse resolution imagery to improve the precision of the sample-based estimates. The methodology and most of the data used to estimate the forest clearing rate for 2000–2005 are reported in Hansen *et al* (2008c). Countrywide results for 2000–2005 reported in this article differ slightly from Hansen *et al* (2008c) because the latter results included only that part of Indonesia within the humid tropical forest biome. The new results of the estimated forest clearing for 1990–2000 can be compared to the 2000–2005 estimate to address the critical question of whether the *rate* of forest clearing has changed over time. The results reported in this article also extend beyond Hansen *et al* (2008c) to include sub-national estimates of forest clearing.

2. Materials and methods

The sampling unit for the study was a square block 18.5 km × 18.5 km. Indonesia was partitioned into 5604 such blocks, and a stratified random sampling design implemented, with the blocks assigned to strata based on the anticipated amount of forest clearing in the block. Although the same partition of blocks was used for both epochs, the samples for the two epochs were selected independently. Further, the stratification was based on different derivations of anticipated forest change. That is, the forest change indicator maps that formed the basis of the stratification were derived from MODIS data for

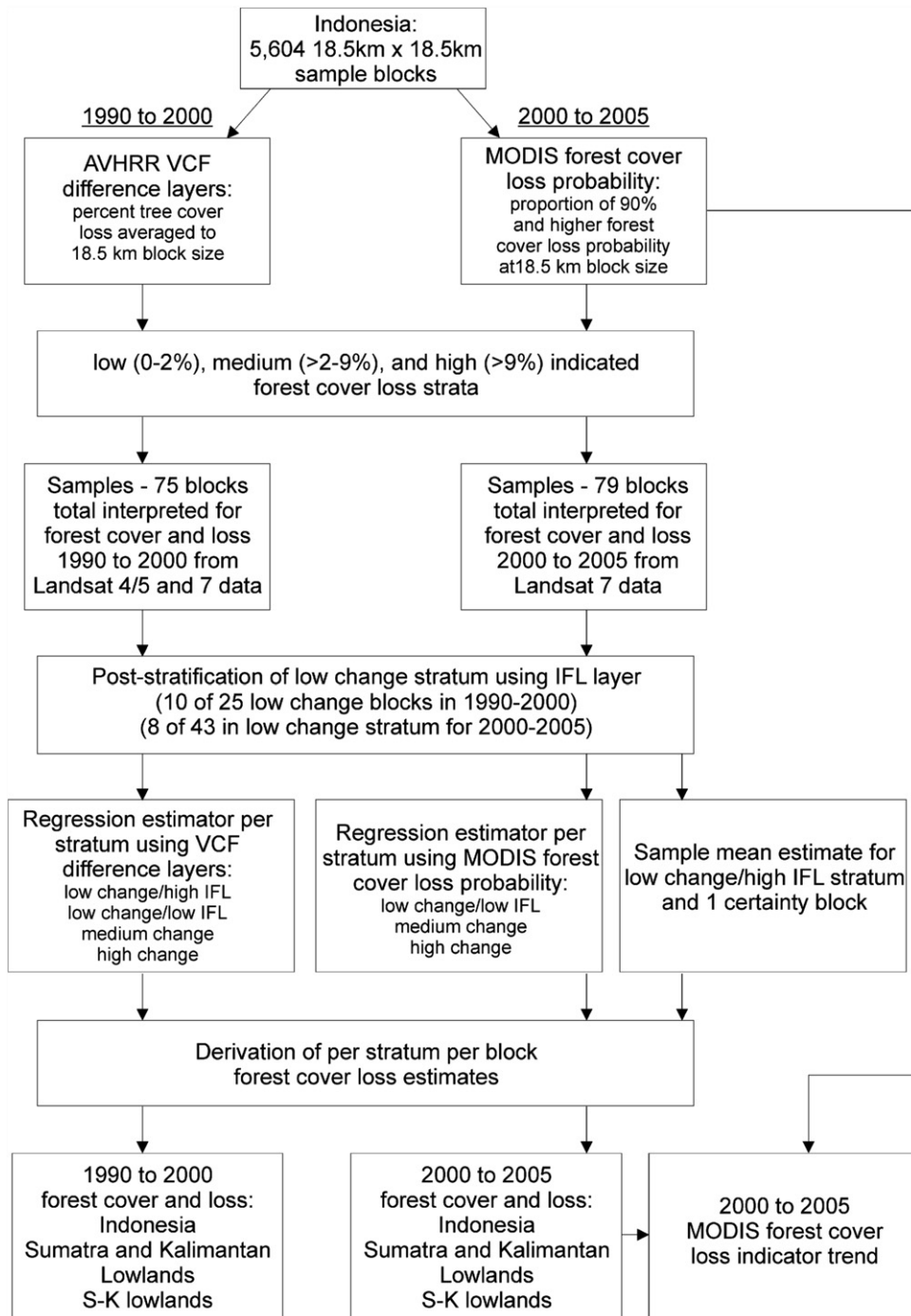


Figure 1. Schematic of methods used in this study.

the 2000–2005 epoch and from AVHRR data for the 1990–2000 epoch (MODIS data not being available for this epoch). Figure 1 is a schematic of the methods employed. An example of the MODIS forest change indicator layer from 2000 to 2005 is shown in figure 2 with the sampling frame overlain.

2.1. Data inputs

To initiate the sampling protocol, change indicator products were derived from existing products for the nominal 1990–2000 and 2000–2005 time periods. The 1990–2000 AVHRR change indicator maps were created using 8 km vegetation

continuous field (VCF) of tree cover data from 1988 through 1999 (Hansen and DeFries 2004). Annual forest cover was derived using input data from the 8 km Pathfinder data set (Agbu and James 1994), including monthly composites based on maximum NDVI (normalized vegetation difference index) (Holben 1986). The five bands include red (580–680 nm) and near-infrared (725–1000 nm) reflectance as well as three thermal bands (3550–3930, 10 300–11 300, 11 500–12 500 nm) of brightness temperature. Using a regression tree algorithm, per cent tree cover training data derived from Landsat imagery were related to the AVHRR inputs to produce annual per

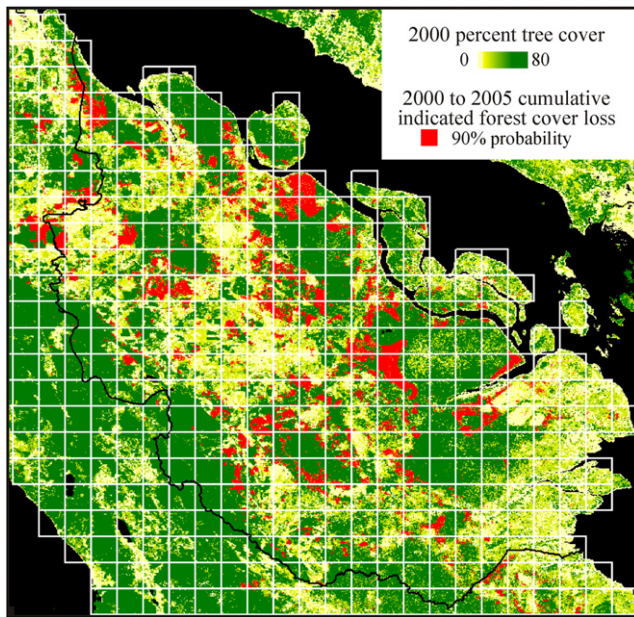


Figure 2. Full-resolution subset of MODIS indicated change for Riau Province (western boundary shown in black). Any pixel that had 90% probability or higher of indicated change from 00–01, 01–02, 02–03, 03–04, 04–05, 00–04 to 00–05 intervals is flagged. Stratification employed the per cent of these indicated 500 m change pixels per 18.5 km sample block (white frame).

cent tree cover estimates. Employing an image differencing approach, VCF tree cover change was estimated for the 1990s (Hansen and DeFries 2004). This 1990s epochal change indicator layer was averaged to provide a per cent tree cover loss estimate for each 18.5 km × 18.5 km block of Indonesia and to stratify Indonesia into high, medium and low change strata.

MODIS change indicator maps from 2000 to 2005 for the dominant global forested biomes are being made as part of a NASA-funded survey of global tree cover change. To achieve this, supervised mapping methods using a decision tree algorithm have been applied to MODIS data to produce change indicator maps. The results for the humid tropical forest biome have been subset in this national-scale study of Indonesia. To create the humid tropical forest change indicator maps, examples of forest clearing throughout the humid tropics were interpreted from high spatial resolution browse imagery and used to label MODIS-scale change and no change training sites. A supervised classification tree bagging procedure (Breiman *et al* 1984, Breiman 1996) was then employed with annual MODIS metrics as the independent variables to predict MODIS per pixel annual and 4 and 5 year change probability maps. MODIS thirty-two day composites were used as inputs and included data from the MODIS land bands (blue (459–479 nm), green (545–565 nm), red (620–670 nm), near-infrared (841–876 nm), and mid-infrared (1230–1250, 1628–1652, 2105–2155 nm)) (Vermote *et al* 2002), as well as data from the MODIS land surface temperature product (Wan *et al* 2002). The classification tree bagging algorithm related expert interpreted forest cover loss and no loss categories to the MODIS inputs. A 90% threshold was

applied to the annual and 4 and 5 year forest cover loss maps to produce per 500 m pixel forest change/no change maps (figure 2). These data were aggregated in the same way as the AVHRR change indicator maps to produce a per cent cover loss value for each block of Indonesia.

Whereas the MODIS and AVHRR forest change data are used for stratification, the estimates of forest clearing are based on area change analyses of Landsat data from 1990 to 2000 and 2000 to 2005. The images for the 1990 and 2000 epochs were obtained from the GeoCover Landsat Orthorectified dataset (<http://glovis.usgs.gov/>). For the 2005 epoch, Scan Line Corrector-Off (SLC-Off) images were used. The five TM and ETM+ reflective bands were employed in the analysis, for ETM+: green (525–605 nm), red (630–690 nm), near-infrared (775–900 nm), and mid-infrared (1550–1750, 2090–2350 nm), along with calculated NDVI. Band 1 (blue, 450–515 nm) was not used because of frequent atmospheric haze contamination. To facilitate interpretation of the Landsat block data, a relative radiometric normalization using a dark object subtraction (DOS) technique was performed on each image. Forest areas with tree canopy density >40% according to the MODIS 2000 VCF per cent tree cover map (Hansen *et al* 2003) were labeled as the dark target (Chavez 1996) and a bias adjustment applied to all bands. Automatic data gap detection and manual cloud masking were performed on both images and combined to produce a no data mask for each Landsat 1990–00 and 2000–05 image pair.

2.2. Stratification

The strata defined for the 2000–2005 epoch based on the MODIS change indicator maps were 0–2%, >2–9%, and >9% change accounting for 95.4%, 3.4%, and 1.2% of the Indonesian land surface, respectively, and a single block with the highest MODIS change was selected with certainty and represented stratum 4 (Hansen *et al* 2008c). The sample size for this epoch was 79 blocks, with the allocation to the first three strata being 43, 17, and 18. For the 1990–2000 interval, the same strata boundaries were employed, but the change was based on the AVHRR change indicator maps. Strata 1, 2 and 3 for 1990–2000 accounted for 50.0%, 35.6% and 14.4% of the Indonesian land surface, respectively. The total sample size for this epoch was 75, with equal allocation of 25 sample blocks to each of the three strata.

At the estimation stage, post-stratification was implemented within stratum 1, the low change stratum, for both epochs. This feature of the analysis was used to compensate for the difficulty possessed by both MODIS and AVHRR to capture small parcels of forest clearing. By incorporating additional information, post-stratification is designed to partition all blocks in the low change stratum into two post-strata, one consisting of blocks representing near zero change, and one consisting of blocks having a small area of forest clearing. The post-strata are not constructed from the Landsat sample data, but instead are derived from ancillary data available for all of Indonesia. These data were obtained from the Intact Forest Landscapes (IFL) project (Potapov *et al* 2008) and the MODIS 2000 VCF per cent tree cover map (Hansen *et al*

2003). For the 2000–2005 analysis, blocks that had greater than 25% IFL or less than 20% VCF tree cover, and a 90% MODIS threshold change value of 0% were placed in post-stratum 1A (blocks expected to show virtually no change), and the remaining blocks were placed in post-stratum 1B. For the 1990–2000 analysis, the same definitions were applied with the MODIS threshold change value of 0% replaced by the AVHRR change value of 0%.

Sample blocks were processed in a randomly ordered sequence. A sample was excluded if the Landsat data exhibited seasonal offsets or if less than 25% of the block had usable 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.

2.3. Sample block analysis

Each Landsat sample block was classified using a supervised classification tree bagging procedure (Breiman *et al* 1984, Breiman 1996) to yield 2000 forest cover and 1990–2000 or 2000–2005 forest clearing areas. Each block was examined in detail by one or more interpreters and the procedure iterated if necessary, including manual editing where required, to achieve accurate per block depictions of forest cover and forest clearing. Forest was defined as greater than 25% canopy cover and change was measured without regard to forest land use. All tree cover assemblages that met the 25% threshold, including intact forests, plantations, and forest regrowth, were defined as forests. Missing data per sample block consisted of hand interpreted cloud and shadow cover and data gaps from the Landsat 7 scan line corrector-off (SLC-off) malfunction. To produce the forest cover reference estimate, the MODIS 2000 VCF per cent tree cover map was regressed against the forest masks derived for the 2000 Landsat block samples and extrapolated for all blocks within Indonesia (Hansen *et al* 2008c).

2.4. Regression estimation

For each stratum, a separate regression estimator (Särndal *et al* 1992) was employed in the analysis to estimate Landsat-derived forest area loss. The regression estimator is a common strategy used in survey sampling to improve precision of the estimate of a mean or total. A simple linear regression model was applied per stratum using MODIS or AVHRR data as the explanatory variable. Because post-stratum 1A of the 2000–2005 epoch had very little area of forest clearing, the sample mean Landsat-derived clearing was used instead of a regression estimator. The models selected were the best or nearly best fitting models evaluated for a suite of auxiliary variables that included MODIS and AVHRR-derived forest loss based on different thresholds of forest cover extent and change variables. For 2000–2005 MODIS indicated change layers thresholded at 75 and 90% and aggregated to the block scale were used as ancillary variables. In addition to the 8 km AVHRR change layer, the ancillary variables used for the 1990–2000 estimates were derived from other VCF difference images, including 1992 and 1995 1 km AVHRR layers (Hansen *et al* 2002) and the 2000 MODIS VCF of tree cover. Each model was applied

per stratum and the strata estimates were then aggregated to derive national-scale forest clearing estimates.

2.5. Sub-national estimates

Adequate sample sizes existed to provide an estimate of forest clearing in each epoch for three sub-regions: Sumatra and Kalimantan, Indonesian lowlands, and lowlands within Sumatra and Kalimantan. For this study, lowlands were defined as sample blocks with average elevations of ≤ 300 m and average slopes of $\leq 1\%$. Regression estimators were not used for the sub-region analyses because the sample sizes were deemed too small to ensure that the regression estimator would not be biased. The sub-region estimates were constructed so that the change rates for sub-regions partitioning Indonesia would sum to the national-scale estimate. Forest clearing was estimated for the combined lowlands and uplands of Sumatra and Kalimantan, and for the combined lowlands and uplands of the remaining Indonesian island groups of Java, Nusa Tenggara, Sulawesi, Maluku, and Papua.

2.6. Within-epoch trend analysis

While the Landsat sample-based area estimate represents the total change over the period, the MODIS-only change maps can reveal within-epoch trends. MODIS change indicator maps were derived for both annual and multi-year intervals. The annual products enable the assessment of the relative abundance of MODIS pixels flagged from 2000 through 2005. The current analysis employed 500 m MODIS Collection 4 data. MODIS forest cover loss indicator maps were thresholded at the 90% probability per pixel per year to analyze annual trends (Hansen *et al* 2008c). Hansen *et al* (2008b) have used MODIS change indicator maps to estimate area cleared for Brazil. However, such an analysis requires extensive fine spatial resolution data for calibrating the MODIS signal as are available with the PRODES data set derived by the Brazilian Space Agency. Such data are not available for Indonesia. Here, the relative presence of change as detected by MODIS on an annual basis is used to discern within-epoch (2000–2005) trends.

A similar analysis was not possible with the 1988–1999 AVHRR annual tree cover maps. Hansen and DeFries (2004) found the AVHRR annual 8 km tree cover maps to be inconsistent at interannual timescales due to geolocational error (Agbu and James 1994), systematic shifts in the data (Young and Anyamba 1999), and deleterious effects of NDVI compositing with AVHRR inputs (Justice *et al* 1989, Moody and Strahler 1994).

3. Results

Seventy-five and seventy-nine sample blocks were analyzed, respectively, for the 1990–2000 and 2000–2005 epochs. Figure 3 displays the locations of the sample blocks and associated strata. Note the concentration of high indicated change samples in lowland Sumatra and Kalimantan. Figure 4 is a graphic representation of the national-scale result and tables 1 and 2 summarize all sample-based change estimates.

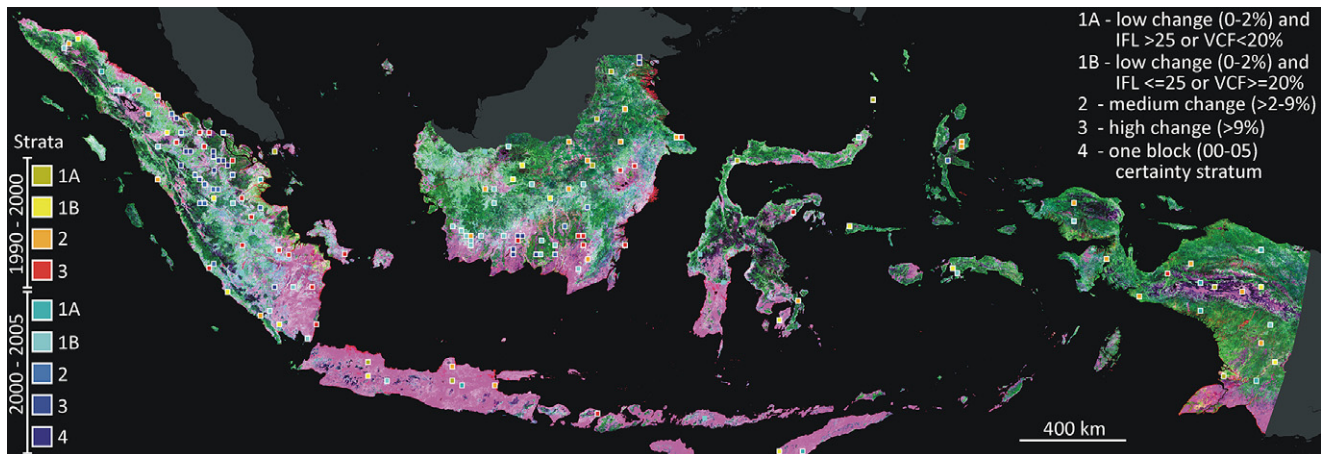


Figure 3. Sample blocks and associated strata for the 1990–2000 and 2000–2005 epochs. Each sample block is 18.5 km × 18.5 km and shown to scale. Sample blocks may be viewed at <http://globalmonitoring.sdstate.edu/projects/gfm/indonesia> for 1990–2000 and at <http://globalmonitoring.sdstate.edu/projects/gfm/humidtropics/list.html> for 2000–2005. Strata are defined by indicated forest cover loss from AVHRR data from 1990 to 2000 and MODIS data from 2000 to 2005. The background image in this figure is of MODIS time-integrated metrics for band 1 red, band 2 near-infrared and band 7 mid-infrared reflectances in r-g-b color.

Table 1. Summary of forest cover loss estimates for 1990–2000 and 2000–2005 for (a) all of Indonesia, (b) Sumatra and Kalimantan, (c) Indonesian lowlands, and Sumatra and Kalimantan lowlands, for both epochs.

	Sample size	Per cent of land area cleared	Std. error	Average annual forest area cleared (Mha)	95% confidence interval for average annual forest area cleared (Mha)
(a) Indonesia					
1990–2000	75	9.25	0.97	1.78	1.40–2.16
2000–2005	79	1.84	0.22	0.71	0.54–0.88
(b) Sumatra and Kalimantan					
1990–2000	48	12.93	1.81	1.32	0.95–1.69
2000–2005	64	2.95	0.41	0.60	0.43–0.77
(c) Lowlands					
1990–2000	39	16.93	2.91	1.46	0.97–1.95
2000–2005	48	3.22	0.36	0.55	0.43–0.67
(d) Sumatra and Kalimantan lowlands					
1990–2000	31	22.45	3.86	1.27	0.83–1.71
2000–2005	43	4.47	0.41	0.51	0.41–0.60

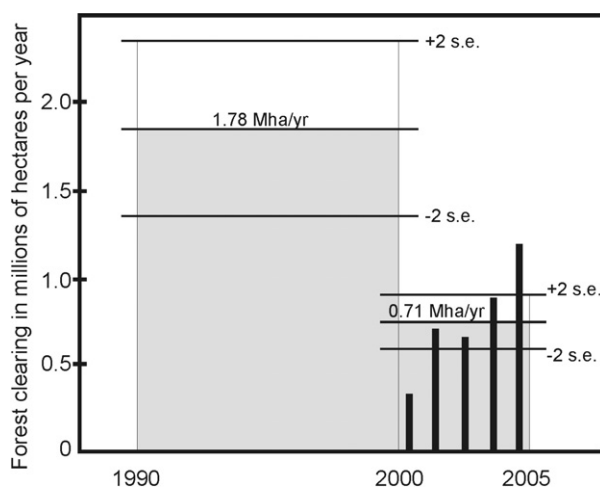


Figure 4. Estimated forest area cleared for Indonesia, 1990–2000 and 2000–2005. For 2000–2005, estimated annual change is allocated using the MODIS annual forest cover loss indicator maps (black bars).

Results indicate a dramatic decrease in forest clearing within Indonesia when comparing the 1990s to the first half of the current decade. Overall national-scale forest cover loss decreases from 1.78 Mha yr⁻¹ from 1990 to 2000 to 0.71 Mha yr⁻¹ from 2000 to 2005. The change rate of 1.78 Mha yr⁻¹ is close to the value reported by FAO of 1.87 Mha yr⁻¹ for 1990 to 2000. The 2000–2005 rate is more than 1 Mha yr⁻¹ less than the 1990s and the 2000–2005 value reported by FAO (1.87 Mha yr⁻¹).

Figure 5 spatially depicts the predictions of the regression estimation models (table 2) applied to the 5604 Indonesian sample blocks. The stratum-specific regression models for the 1990–2000 epoch captured from 40 to 64% of the variation in Landsat change per stratum (coefficient of determination, R²), meaning that the change is not precisely mapped when applied spatially. While the relative distribution is accurate (i.e. the highest change areas are found in Sumatra and Kalimantan), the absolute location-specific change is not necessarily captured in this spatial depiction. This leads to a greater spread of the change across the archipelago than

Table 2. National-scale stratum-specific results and estimated regression models for 1990–2000 and 2000–2005 forest cover loss.

1990–2000					
Strata	Number of blocks	Number of samples	Estimated per cent of all land area cleared (%)	SE (%)	Estimated area cleared (Mha)
1A	1207	10	2.64	0.65	1.09
1B	1595	15	7.73	2.57	4.23
2	1995	25	7.93	1.47	5.43
3	807	25	25.36	2.30	7.03
Total	5604	75	9.247	0.97	17.79

Stratum-specific regressions (Landsat change is expressed as per cent of block area):
 1A: Landsat change = $0.5399 + 0.3087A1$ ($R^2 = 50.6\%$),
 1B: Landsat change = $5.057 + 0.8673A2$ ($R^2 = 48.0\%$),
 2: Landsat change = $2.08 + 0.618A2 + 0.289A1$ ($R^2 = 40.5\%$),
 3: Landsat change = $6.69 + 0.6805A3 + 0.4704A2$ ($R^2 = 63.8\%$),
 where,
 A1 = 1992 1 km AVHRR tree cover – 2000 500 m MODIS tree cover
 A2 = 1990 8 km AVHRR tree cover – 2000 500 m MODIS tree cover
 A3 = 1990 8 km AVHRR tree cover – 1997 8 km AVHRR

2000–2005					
Strata	Number of blocks	Number of samples	Estimated per cent of all land area cleared (%)	SE (%)	Estimated area cleared (Mha)
1A	1748	8	0.50	0.42	0.30
1B	3590	35	1.62	0.19	2.00
2	196	17	9.82	1.03	0.66
3	69	18	23.39	1.79	0.55
4	1	1	72.30	—	0.02
Total	5604	79	1.840	0.22	3.53

Stratum-specific regressions (Landsat change is expressed as per cent of block area):
 1A: Landsat sample mean = 0.50
 1B: Landsat change = $1.202 + 0.7544B1$ ($R^2 = 19.9\%$),
 2: Landsat change = $1.687 + 0.9280B1$ ($R^2 = 71.5\%$),
 3: Landsat change = $4.532 + 0.7402B1$ ($R^2 = 65.0\%$),
 4: Landsat single block = 72.3,
 where,
 B1 = MODIS 2000–2005 forest cover loss probability thresholded at 75%.
 For stratum 1A, no regression estimation was applied, as this post-stratum had very little change.

in reality. The 2000–2005 epoch image better delineates the relative distribution of high change, due to the robustness of the MODIS signal as compared to AVHRR. Although the regression estimation adjustment of the MODIS or AVHRR per block change enables a coarse approximation of the spatial depiction of change, these products should not be considered a replacement for higher spatial resolution maps.

While the sample-based area estimates yield average change per epoch, the MODIS-only annual data reveal a within-epoch increase in clearing from 2000 to 2005. Figure 4 shows annual 500 m pixels flagged as indicating forest cover loss scaled to the overall sample-based epochal change estimate. The trend is nearly monotonic in increasing area of forest clearing for the current decade, possibly related to the recovering Indonesian economy and increasing commodity prices, including oil palm. One-third of MODIS change pixels occurred in 2005, representing a rate of 1.17 Mha yr^{-1} compared to the 5 year average of 0.71 Mha yr^{-1} . Figure 4 illustrates a dramatic, if temporary, reduction in forest clearing at the turn of the century.

The national estimates of forest clearing (table 1) were disaggregated to produce clearing rates for the lowlands and uplands of Sumatra and Kalimantan and of Java, Nusa Tenggara, Sulawesi, Maluku and Papua island groups. Figure 6 and table 3 summarize these results. Since 1990, over 40% of the lowland forests of Sumatra and Kalimantan have been cleared. The annual rate during the 1990s for this area was nearly 3.5% per year and slowed to 1.4% from 2000 to 2005. Lowland forests elsewhere in Indonesia have also been exploited, with a 13% reduction from 1990 to 2000. Most of these forests may be found in Papua, the last remaining expanse of lowland forest, though their extent is small compared to the historic range of Sumatra and Kalimantan lowland forests.

4. Discussion

4.1. Dynamics of forest clearing in Indonesia

It is clear that a dramatic reduction in forest clearing followed the high rates of change experienced in the 1990s (figure 4). The mean annual forest cover loss for the 1990s was more

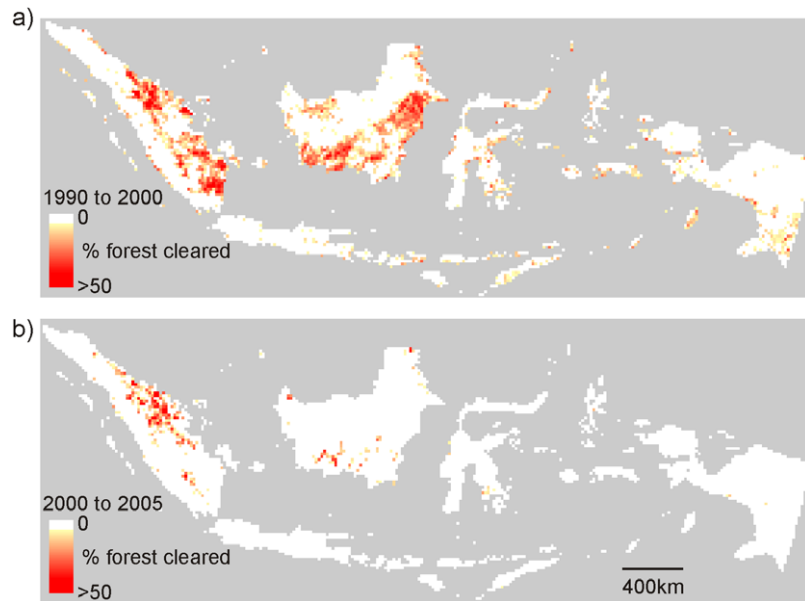


Figure 5. Predicted forest clearing (per 18.5 km block) for (a) 1900–2000, based on the stratum-specific regressions modeling Landsat-derived change as a function of AVHRR change and for (b) 2000–2005, based on the stratum-specific regressions modeling Landsat-derived change as a function of MODIS change.

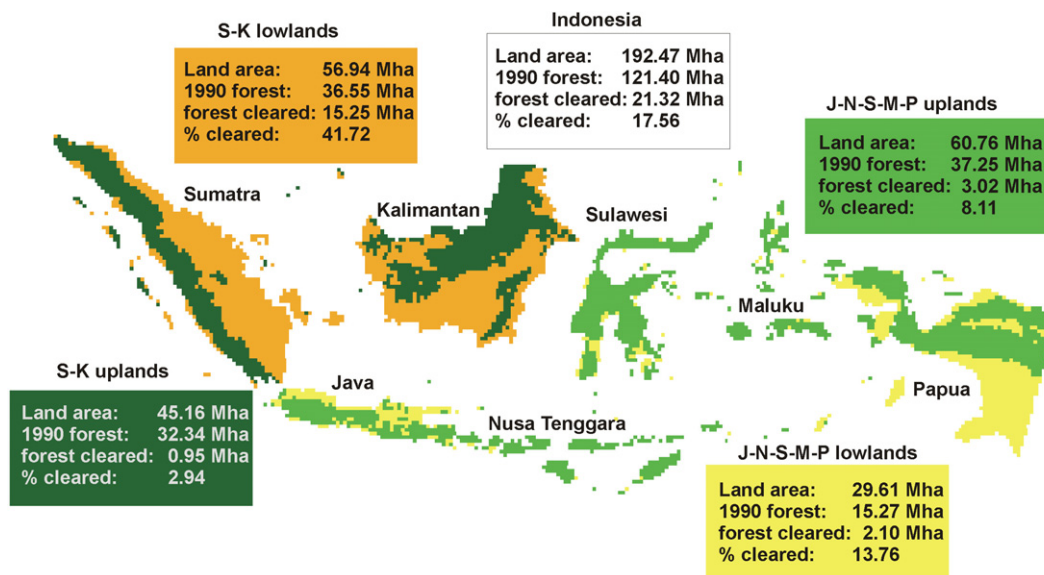


Figure 6. Estimates of national and sub-national forest cover extent and loss. S-K stands for the combined Sumatra and Kalimantan island groups. J-N-S-M-P stands for the combined Java, Nusa Tenggara, Sulawesi, Maluku and Papua island groups.

than twice that of the 5 year period from 2000 to 2005. While the major factors governing forest change favored increased clearing during this period, nearly all were reversed at or near the end of the decade and led to a dramatic decline in clearing rates. However, this does not appear to be a long-lived reversal. The MODIS interannual results illustrate a steady increase of clearing during the 2000s, indicating recent clearing rates estimated to be over 1 Mha yr⁻¹. Many of the factors that dampened clearing at the turn of the century changed, including post-crisis economic recovery and associated high oil palm commodity prices.

For the 1990–2000 epoch, we do not have an annual change indicator product with which to more fully describe the

interannual cover loss dynamic. It is clear that the fire event of 1997–98 inflates the overall mean annual forest loss during this decade. Estimates on how much forest was burned during this event differ. Subtracting the estimate from the (UNCHS 2000) report of 4.8 Mha burned in 1997–98 from our decadal estimates would result in a residual mean forest cover loss of 1.3 Mha yr⁻¹ over the decade, or 83% higher than the 2000–2005 mean value of 0.71 Mha yr⁻¹. Subtracting the estimate of the ADB/INDPA (1999) report of 9.7 Mha results in a residual mean forest cover loss of 0.81 Mha yr⁻¹, still 14% higher than the 2000–2005 mean value. If the ADB/INDPA number is accurate, the fires of 1997–98 account for over half of all change from 1990 to 2000, equal to four years of clearing in

Table 3. Estimated forest cover and forest cover cleared in millions of hectares for both 1990–2000 and 2000–2005 epochs. S-K stands for combined Sumatra and Kalimantan island groups. *Other* includes the combined Java, Nusa Tenggara, Sulawesi, Maluku and Papua island groups. Estimated sample-based rates of clearing from table 1 are shown in italics. See figure 5 for map depiction of sub-regions.

	Land area in Mha	1990 forest cover in Mha	1990–2000 annual rate cleared in Mha yr ⁻¹	1990–2000 annual % forest cleared	2000–2005 annual rate cleared in Mha yr ⁻¹	2000–2005 annual % forest cleared	Total forest cleared 1990–2005 in Mha	1990–2005 total % forest cleared	2005 forest cover in Mha
Indonesia	192.47	121.40	<i>1.78</i>	1.47	<i>0.71</i>	0.58	21.32	17.56	100.08
S-K	102.11	68.89	<i>1.32</i>	1.92	<i>0.60</i>	0.87	16.20	23.51	52.69
Non-S-K	90.36	52.51	0.46	0.87	0.11	0.20	5.12	9.75	47.39
Lowlands	86.55	51.82	<i>1.46</i>	2.82	<i>0.55</i>	1.06	17.35	33.48	34.47
Uplands	105.92	69.59	0.32	0.46	0.16	0.22	3.97	5.71	65.62
S-K-lowlands	56.94	36.55	<i>1.27</i>	3.47	<i>0.51</i>	1.40	15.25	41.72	21.30
S-K-uplands	45.16	32.34	0.05	0.15	0.09	0.28	0.95	2.94	31.39
Other lowlands	29.61	15.27	0.19	1.24	0.04	0.26	2.10	13.76	13.17
Other uplands	60.76	37.25	0.27	0.72	0.07	0.18	3.02	8.11	34.23

the Legal Amazon (INPE 2002). Even if such a large figure is discounted from the decadal mean, the 1990–2000 mean rate is still higher than that of 2000–2005. However, given that the fires were human-induced and that the lands cleared were often used for agro-industrial purposes, these areas should not be viewed in isolation from the overall change dynamic within and after the fire episode.

For both epochs, the lowlands of Sumatra and Kalimantan accounted for over 70% of total forest clearing (table 3). Clearing and fires in the lowlands of these island groups led to an annual forest cover loss of almost 3.5% for the 1990s (table 3). Figures 2, 3 and 5 highlight Riau Province in central Sumatra to be a predominant locus of forest clearing from 2000 to 2005, contributing to a lowland forest clearing rate of 1.4% per year for Sumatra and Kalimantan. A dramatic displacement of forest clearing to island groups other than Sumatra and Kalimantan has not yet occurred. The only sub-region to experience an increase in the annual rate of clearing from the 1990s to the 2000s was the Sumatra and Kalimantan uplands, possibly in response to a reduced lowland forest resource base. The overall study period documents the intensive effort to clear lowland forests that were largely intact for centuries prior to this period. The 41.3% areal reduction of lowland forest extent in 15 years for Sumatra and Kalimantan indicates an unsustainable rate of deforestation (table 3 and figure 6). This rapid decline constitutes a fundamental limitation that will constrain the maintenance of past levels of clearing.

4.2. Sampling to estimate forest clearing

Considerable debate on the appropriate use of Landsat data for regional monitoring has concerned the alternative uses of exhaustive mapping versus sampling-based approaches (Tucker and Townshend 2000, Czaplowski 2003, Stehman 2005). 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 regional scales. However, a targeted sampling approach that successfully identifies the sub-regions containing most of the change can overcome this

limitation. The ability of either the MODIS or AVHRR to efficiently stratify the region does not bias results, as a sufficient number of samples were taken per stratum to provide reliable mean estimates. However, a successful stratification and regression estimation procedure can significantly reduce uncertainties (i.e. the standard errors of the estimates). The benefit of stratification is manifested in lower standard errors and narrower confidence intervals. Confidence intervals for the national-scale forest clearing estimates are highlighted in table 1 and graphically illustrated in figure 4.

MODIS proved to be a better information source than AVHRR in the stratification and regression estimation procedure, as evidenced by the reduced standard error for the 2000–2005 epoch. The effectiveness of the MODIS change-based stratification 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. For the MODIS analysis, this ratio was 2.04, indicating a considerable advantage of stratification for Indonesia. Stratification based on the AVHRR-derived change was less successful as the ratio of the standard error expected from simple random sampling to the standard error obtained from the stratified design was only 1.10. Re-expressing this result in another way, a simple random sample of 91 blocks would have been required to achieve the same standard error obtained by a sample of 75 blocks for the stratified design based on AVHRR-derived change for 1990–2000. A simple random sample of 328 blocks would have been needed to match the standard error achieved by the sample of 79 blocks in the MODIS-based stratified design.

The problem encountered in previous studies of imprecise estimates of forest clearing attributable to the rarity of such clearing was largely overcome. The MODIS and AVHRR data permitted the assigning of each block to a change stratum, whereas past deforestation studies defined strata by delineating broad regions of suspected change (Achard *et al* 2002) rather than using objectively-derived, block-specific information. Targeted sampling of Landsat-scale data offers key advantages over past approaches. First, it overcomes the need for Landsat-scale wall-to-wall mapping to quantify rates; for Indonesia, the reality is that annual wall-to-wall mapping at high spatial

resolutions is impossible given the high frequency of cloud cover. Second, the method can be applied operationally due to its relative simplicity. The method requires an automated change indicator product, interpretation of a limited number of Landsat samples, and appropriate application of statistical principals.

5. Conclusion

This study has demonstrated an approach for synoptic monitoring of forest clearing within Indonesia. The use of a consistent methodology and data source creates the ability to compare forest clearing rates of different epochs. The results revealed an inter-epochal reduction in forest clearing, in contrast to previous results (FAO 2006) suggesting a common rate of clearing for the two epochs. Forest clearing is related to a host of drivers, including political, economic, social and environmental factors (Lambin and Geist 2006). In Indonesia, the conditions of many of these drivers changed within the period of analysis, as did the estimated forest clearing rates. Results quantify a dramatic drop in clearing within Indonesia at the turn of the last century. However, a resurgence of forest clearing since 2000 indicates this decrease to have been temporary and possibly related to the political and economic upheavals of the turn of the century.

The results for Indonesia and other such studies (Hansen *et al* 2008c, Potapov *et al* 2008) can inform a host of other research objectives, including improved econometric, climate, biodiversity conservation, hydrological, and carbon modeling efforts. For example, the method operationally targets areas of intensive change, ensuring that displacement, or leakage, of clearing activities can be quantified. When combined with carbon stock information, results from this method may enable carbon accounting efforts such as those mandated by the UNFCCC's REDD program (UNFCCC 2005).

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