Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010

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Abstract
As reported by FAO (2005 State of the World’s Forests (Rome: UNFAO), 2010 Forest Resource Assessment (FRA) 2010/095 (Rome: UNFAO)), Indonesia experiences the second highest rate of deforestation among tropical countries. Hence, timely and accurate forest data are required to combat deforestation and forest degradation in support of climate change mitigation and biodiversity conservation policy initiatives. Within Indonesia, Sumatra Island stands out due to the intensive forest clearing that has resulted in the conversion of 70% of the island’s forested area through 2010. We present here a hybrid approach for quantifying the extent and change of primary forest in Sumatra in terms of primary intact and primary degraded classes using a per-pixel supervised classification mapping followed by a Geographic Information System (GIS)-based fragmentation analysis. Loss of Sumatra’s primary intact and primary degraded forests was estimated to provide suitable information for the objectives of the United Nations Framework on Climate Change (UNFCCC) Reducing Emission from Deforestation and Forest Degradation (REDD and REDD+) program. Results quantified 7.54 Mha of primary forest loss in Sumatra during the last two decades (1990–2010). An additional 2.31 Mha of primary forest was degraded. Of the 7.54 Mha cleared, 7.25 Mha was in a degraded state when cleared, and 0.28 Mha was in a primary state. The rate of primary forest cover change for both forest cover loss and forest degradation slowed over the study period, from 7.34 Mha from 1990 to 2000, to 2.51 Mha from 2000 to 2010. The Geoscience Laser Altimeter System (GLAS) data set was employed to evaluate results. GLAS-derived tree canopy height indicated a significant structural difference between primary intact and primary degraded forests (mean height 28 m ± 8.7 m and 19 m ± 8.2 m, respectively). The results demonstrate a method for quantifying primary forest cover stand-replacement disturbance and degradation that can be replicated across the tropics in support of REDD+ initiatives.

Keywords: deforestation, forest degradation, change detection, remote sensing, Landsat, Indonesia

1. Introduction
Deforestation and forest degradation are the second leading causes of anthropogenic greenhouse emissions following...
fossil fuel combustion, accounting for over 17% of global carbon dioxide emissions (IPCC 2007). Consequently, deforestation and forest degradation have become an important issue concerning climate change mitigation, highlighted in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report in 2007. About 75% of the emissions from tropical deforestation and forest degradation have been from developing countries containing large extents of tropical forest, including Brazil, the Democratic Republic of the Congo and Indonesia (IPCC 2007, MoF 2008a). Global initiatives such as the United Nations Framework Convention on Climate Change (UNFCCC)’s program on Reducing Emissions from Deforestation and Forest Degradation (REDD and REDD+) aim to mitigate climate change by reducing tropical forest cover loss and forest degradation.

Indonesian forests account for 2.3% of global forest cover (FAO 2010) and represent 39% of Southeast Asia forest extent (Achard et al 2002). As home to the third most extensive humid tropical rainforest, Indonesia plays a significant role in overall REDD objectives. In addition, Indonesia’s forests feature high floral and faunal biodiversity (FWI/GWF 2002, MoF 2003a), the maintenance of which would be an important co-benefit of reducing forest cover loss. Besides the high biodiversity, almost 65 million, or about 27% of the Indonesian population depends directly on these forests (FWI/GWF 2002) for their livelihoods. As a consequence of economic and population pressure, Indonesia experiences one of the world’s highest deforestation rates, second only to Brazil (FAO 2001, 2006a, Hansen et al 2008b, 2009) with an estimated annual gross emission from deforestation of 502 million t CO₂ equivalent (MoF 2008a). Indonesia is thus faced with a challenge appropriate for REDD in simultaneously sustaining key forest ecosystem services as well as the livelihoods of local populations that rely on them.

Forest ecosystems, notably primary forests of the humid tropics, shelter a major portion of terrestrial biological diversity (MacKinnon 1997) including an estimated 80% of all terrestrial species (Carnus et al 2006), and contain 70–90% of terrestrial aboveground and belowground biomass (Houghton et al 2009). These forests are often converted to monoculture forest plantations (Carnus et al 2006, Stephens and Wagner 2007) and agro-industrial estates such as oil palm (Barlow et al 2007, Koh and Wilcove 2008), greatly reducing forest biodiversity and carbon storage of forest biomass. The forests on the island of Sumatra in Indonesia are home to over 10,000 plant species, 201 mammal species, and 580 avifauna species (Whitten et al 2000, MoF 2003a). However, rapid land use conversion in support of agro-industrial development have led to the removal of natural forest cover with a corresponding loss of biodiversity and forest carbon stocks (Whitten et al 2000, Casson 2000).

The most significant REDD initiative to date in Indonesia is the $1000 000 000 program of the Norway–Indonesia partnership that has mandated a moratorium of logging within Indonesia’s primary forests (Letter of Intent (LOI 2010) of Norway and Indonesia, Presidential Instruction No. 10 2011). While there are some exceptions to the moratorium (Murdijyarso et al 2011), the principal objective is to reduce emissions by limiting the clearing of primary forests. To confirm the program’s success, timely and accurate information on primary forest extent and its change due to both deforestation and forest degradation is required. Improved national forest monitoring methods for Indonesia are currently being undertaken by the Ministry of Forestry and the Indonesia Space Agency as part of the Indonesia National Carbon Accounting System (INCAS). However, no national-scale products have been publicly released yet. Developing cost-effective operational algorithms for primary forest monitoring is important for verifying the performance of the moratorium.

Forest degradation has been emphasized within the international forestry community, including the United Nations Forum on Forest (UNFF), and the 2010 Target of the Convention on Biological Diversity (CBD) (Simula 2009). While the definition of forest varies considerably within the global forestry community (Fuller 2006), progress has been made and nominal definitions defined in support of REDD monitoring objectives. Quantifying and mapping forest degradation, on the other hand, is less mature and arriving at a common standard is a challenge (Simula 2009). The lack of a universal definition of forest degradation causes complications when REDD+ projects are implemented (Sasaki and Putz 2009). Indeed, quantifying forest degradation is more difficult compared to deforestation, as deforestation represents a stand-replacement disturbance and a permanent conversion of land use, while forest degradation does not represent a change in land use and the outcome is by definition still a forest land cover (FAO 2004, 2007). This study reports on the quantification of forest cover change in support of deforestation and forest degradation mapping. Two methods are used separately and combined to yield a spatially explicit time series of stand-replacement disturbance and forest degradation for the island of Sumatra in Indonesia. Primary forest loss is estimated using per-pixel classification methods. Subsequently, geographic information system-based methods are used to incorporate the presence of human disturbances as an indicator of forest degradation. Forest cover loss was mapped for 2000–10 time interval using per-pixel change detection approach pioneered by Broich et al (2011b).

Cloud cover is a major problem in working with optical remotely sensed data sets in humid tropical forest environments such as Indonesia and Brazil (Hoekman 1997, Asner 2001, Hansen et al 2008b, 2009). Unlike Brazil, for example, Indonesia does not have a seasonally cloud-free window, requiring more data intensive methods to overcome persistent cloud cover (Broich et al 2011b). For Brazil, the regular acquisition (Fuller 2006, INPE 2012) of annual cloud-free imagery over the ‘arc of deforestation’ facilitates the application of advanced methods in detecting selective logging in quantifying degradation. Direct per-pixel methods like those of Souza et al (2003) and Asner et al (2005) employ Landsat data to map degradation in the Amazon Basin. However, for such methods to work, images must be acquired within weeks of the logging event due to the
ephemeral nature of the signal in time series multi-spectral imagery. For regions with persistent cloud cover, such as Indonesia, timely data for mapping degradation using such direct methods are not viable.

Another difference concerns the dynamics of forest cover in Indonesia, the vast majority of which does not result, strictly speaking, in deforestation. Most forest cover loss is quickly followed by forest cover gain in the form of timber plantations and palm estates (Uryu et al. 2008, Hansen et al. 2008b). Fast growing tree species (e.g., Acacia mangium) used for industrial tree plantations (MoF 2008a) grow three to five meters annually during the first five years (Matsumura 2011, Jones 2012). The combination of rapid recovery of forest canopies and the paucity of viable cloud-free observations poses a unique monitoring challenge.

Current land cover and land use maps of Indonesia are made via photo-interpretation methods (MoF 2011). Forest is broadly classified into primary and secondary/degraded forest, identified by the appearance of human disturbance (Adeney et al. 2009, FAO 2010). The secondary/degraded forest class represents forests fragmented or affected by commercial logging, while primary forest represents undisturbed or intact forests (MoF 2003b, 2005). Boundaries between primary and secondary/degraded forests are manually delineated by multiple operators. The approach is time-consuming and the use of multiple interpreters across space and through time compromises the consistency of the output map products. Regardless, the accuracy of the forest classes is reported to be high (>90%), based on field verification and local knowledge of the operators (MoF 2011).

The objective of our research was to map the forest cover disturbance within the primary forests of Sumatra Island (Indonesia) from 1990 to 2010 using Landsat data. Primary forests were characterized into primary intact and primary degraded subclasses using a hybrid approach. Total extent of primary forest was derived from a per-pixel direct mapping approach and coupled with a fragmentation analysis using the Intact Forest Landscape (IFL) method (Potapov et al. 2008). The difference in the extent of primary forest and intact forest landscape was taken as the extent of primary degraded forest.

Forest cover changes for both forest cover loss due to stand-replacement disturbance and forest degradation from 1990 to 2010 were mapped independently and trends of change within primary intact and primary degraded forests were quantified. Our research aims to answer the following research questions: (a) what is the extent of primary intact and primary degraded forests in Sumatra; (b) what are the rates of primary forest cover loss, both stand-replacement disturbance and degradation; and (c) in what official forest land use zones have these changes occurred?

2. Materials and methods

2.1. Definitions and rationale

According to the FAO Global Forest Resource Assessment (FAO 2006a), forest is defined by the presence of trees with land covering more than 0.5 ha. The trees should be able to reach a minimum height of 5 m in situ and a canopy cover of at least 10%. For the purposes of national forest accounting and management, Indonesian forest is defined as an area with a minimum mapping unit of 0.25 ha that is covered by trees higher than 5 m with a canopy cover of more than 30% (MoF 2008a). For this study, we employed the Indonesian definition of forest with a focus on forests composed of indigenous tree species and lacking near-term evidence of stand-replacement disturbance (FAO 2005). Forest timber and pulp plantations, oil palm estates and secondary forest are excluded from the analysis. Our definition of primary forest includes intact and degraded states, or natural forests consisting of native tree species that have not been cleared and converted to other land uses.

Intact forest consists of native tree species where there are no clearly visible indications of human activities (MoF 1989) and the ecological processes are not significantly disturbed (FAO 2006b). We employed the IFL method to map the extent of primary intact forest, which is defined as an unbroken expanse of natural ecosystems within areas of current forest extent, without signs of significant human activity, and having an area of at least 500 km² (Potapov et al. 2008). Degraded primary forest is a natural forest which has been fragmented or subjected to forest utilization including wood and or non-wood forest product harvesting that alters the canopy cover, and overall forest structure (ITTO 2002). Forest management practices leading to degradation, such as selective logging, are evidenced by the presence of logging roads, logging patios, or forest canopy gaps. Primary intact forest is mature forest absent of and removed from such disturbance features. For simplicity, we define forest cover loss as an area having experienced a stand-replacement disturbance, and define forest degradation as an area having experienced a transition from primary intact forest to primary degraded forest.

2.2. Data

2.2.1. Satellite imagery. Satellite data inputs included Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 5 Thematic Mapper (TM) imagery downloaded from the US Geological Survey National Center for Earth Resources Observation and Science via the GLOVIS data portal (http://glovis.usgs.gov/). Both Landsat archive data and Global Land Survey (GLS) data were used. All images from 1985 to 2010 with cloud cover less than 50% for 37 Landsat scene footprints covering Sumatra were selected and downloaded. In total, 3129 ETM+ and 193 TM images from 1999 to 2011, and 54 archival and 37 Global Land Survey (GLS) TM images from 1985 to 1995 were used in our analysis. Images were resampled to a 60 m spatial resolution to reduce false change detection due to residual misregistration effects. To remove cloud/cloud shadow affected observations, a per-pixel quality assessment was implemented using a set of pre-defined cloud/cloud shadow detection rules. All images were normalized using MODIS atmospherically corrected reflectance data (Hansen et al 2008a, Potapov et al 2012) as a normalization target.
over pseudo-invariant land cover features. Red (630–690 nm), near-infrared (760–900) and short-wave infrared (1550–1750, 2080–2350 nm) spectral bands were used for analysis.

Source images were used to create time-sequential image composites nominally centered on 1990, 2000, 2005 and 2010. Additionally, a set of multi-temporal metrics (for 2000–5 and 2005–10 time intervals) representing surface reflectance change within the analyzed time intervals were generated, as previously described by Potapov et al. (2012). Multi-temporal metrics are derived from sets of viable land surface observations and include minimum, maximum, median and selected percentile reflectance values per band, as well as the slope of linear regression per band versus observation date. Due to incomplete cloud-free coverage for 1990, all but 7.4% of the Sumatran land area was covered by the resulting image composite. The time-sequential image composites were used for visual image interpretation, classification training and IFL mapping while multi-temporal metrics, together with digital elevation data and slope derived from Shuttle Topography Radar Mission (SRTM) (Rabus et al. 2003), were used as inputs for the supervised classification.

As part of the primary intact and degraded forest cover map assessment, we used LiDAR (light detection and ranging) data from the GLAS (Geoscience Laser Altimetry System) instrument onboard the IceSat-1 satellite. GLAS was launched in January 2003 and collects laser pulses in an ellipsoidal footprint of approximately 65 m, spaced about 172 m apart along the orbital track. We acquired the GLAS Release 28 (L1A Global Altimetry Data and the L2 Global Land Surface Altimetry Data) data set over Sumatra from the National Snow and Ice Data Center (NSIDC, http://nsidc.org/data/icesat). GLAS vertical waveforms of returned energy and associated data on elevation, signal beginning, signal end and noise were used to initially screen the data sets; additional screening was conducted to remove the effects of cloud cover and a series of other factors before the calculation of canopy height and the height of median energy (HOME), as described in Goetz et al. (2010) and Goetz and Dubayah (2011).

2.2.2. GIS data sets. Official provincial boundaries (figure 1(a)), forest land use zones, and land cover digital maps of Sumatra were obtained from the Ministry of Forestry of Indonesia (MoF 2010). According to Indonesian Forestry Law (article 6 UU-41, 1999) forest land is officially divided into three major land use zones based on purpose and function: protection forest (hutan lindung), conservation forest (hutan konservasi) and production forest (hutan produksi). Production forest is further subdivided into regular production forest (hutan produksi tetap), limited production forest (hutan produksi terbatas) and convertible production forest (hutan produksi konversi). A summary of the Indonesian forest land use zones is shown in table 1 along with a map of Sumatran forest land use zones in figure 1(b).

2.3. Mapping the extent of primary forest

Primary forest cover mapping employed Landsat composites and multi-temporal metrics as input data and was performed using a two-step supervised classification. The first step of classification included mapping areas with tree canopy cover of 30% and above for the 1990 and 2000 reference years. We used a decision tree algorithm, a hierarchical classifier that splits independent data (Landsat inputs) into more homogeneous subsets regarding class membership (Breiman et al. 1984). The training data were a binary training data set of tree cover and non-tree cover, created using photo-interpretation of the circa 1990 and 2000 image composites, respectively.

The resulting tree canopy cover class was subsequently classified into primary forest and other tree cover classes in a second procedure using a similarly created training data set representing primary forest and other tree cover classes. The
Table 1. A summary of Indonesian forest land use zones: forest classes, function, possible management practices and consequences of each class (percentage represents only Sumatra).

| Forest land use                      | Code % | Purpose/function                                                                 | Possible management practices | Consequences (under sustainable forest management) |
|--------------------------------------|--------|----------------------------------------------------------------------------------|-------------------------------|---------------------------------------------------|
| Forestland                           | 59.2   | Designed as a forestland                                                          | Forest uses                   | Dynamic forest                                     |
|                                       |        | Preserving the biodiversity of flora fauna and their ecosystem                   | Forest preservation           | Stable forests without any deforestation and forest degradation |
| Conservation forest                  | HK     | 10.6                                                                             |                               |                                                   |
| Protection forest                    | HL     | 13.0                                                                             | Forest protection             | Stable forests without any deforestation and very low intensity of forest degradation |
| Production forest                    | 35.5   | Providing the forest products mainly from timber extraction                      | Forest production             | Dynamic deforestation and forest degradation       |
| Limited production forest            | HPT    | 9.0                                                                              | Limited logging (due to topographical condition) | Forest degradation                                  |
| Regular production forest            | HP     | 15.5                                                                             | Selective logging             | Temporary deforestation                           |
|                                      |        | Forest plantations                                                               | Post-loggning silvicultural treatments |                                               |
| Convertible production forest        | HPK    | 11.1                                                                             | Clear cutting                 | Permanent and temporary deforestation             |
| Non-forestland                       | APL    | 40.8                                                                             | Other uses                    |                                                   |
|                                       |        | Outside forestland and designated for other uses                                 |                               |                                                   |
|                                       |        | (agriculture land, settlements etc)                                             |                               |                                                   |

classified areas of other tree cover and non-tree cover from the first step classification were aggregated into a non-primary forest class, which included non-treed lands as well as other non-primary forest types, such as timber plantations and oil palm estates. The same algorithm was applied and the same procedures repeated for the mosaics of year 1990 and 2000. We used reference data from GoogleEarth™ and local knowledge to create classification training data and to perform post-classification manual primary forest mask corrections for obvious commission and omission errors. The primary author was an image interpreter for the Indonesian forest resource mapping of 2003, 2005 and 2008 (MoF 2003b, 2005, 2008b). The algorithm flowchart is shown in figure 2.

2.4. Primary forest change mapping and monitoring

As seen in figure 2 primary forest cover loss from 1990 to 2000 was mapped by comparing primary forest extent of circa 1990 and 2000, each mapped independently. Change from 2000 to 2005, and from 2005 to 2010, was mapped with a decision tree model using forest cover loss and non-forest cover loss training sites manually created, as demonstrated by Broich et al (2011b), and applied to the multi-temporal metrics of the 2000–5 and 2005–10 intervals. Decision tree algorithms have been successfully used to characterize remote sensing data (Hansen et al 1996, 2003).

Two different methods were used in mapping primary forest extent and loss due to data limitations. Specifically, the lack of data for the 1990s was a limitation in applying a direct change detection mapping approach. Unlike Landsat 7 ETM+, which has a global acquisition strategy that ensures regular coverage of the global land surface, Landsat 5 TM data were not regularly acquired over Indonesia. As a result, for 1990, nearly 10% of the island was not covered by cloud-free data, and the data richness was limited precluding using multi-temporal metric approach for change detection. Thus, a simple post-classification comparison, with expert editing, was employed to map the 1990 to 2000 primary forest cover loss. In contrast, change detection mapping approach was employed to map the 2000–10 primary forest cover loss. The first complete image coverage was available for circa year 2000. From the year 2000 primary forest map, forest cover loss from the 2000–5 and 2005–10 intervals was subtracted to create the primary forest maps of 2005 and 2010. In figure 2, per-pixel mapping of primary forest extent and forest cover loss is shown in the box labeled (A).

2.5. IFL mapping and monitoring

The year 2000 IFL map used in this paper is a part of global map developed by a group of scientists and environmental NGOs and is available through a dedicated web site (www.intactforests.org). The IFL method is a fragmentation analysis
Figure 2. Scheme of methodology used to map the primary forests, including primary intact and primary degraded forests, and its change in terms of deforestation and forest degradation from 1990 to 2010; box A is the approach of per-pixel mapping of primary forest extent and forest cover loss; box B is the other approach of IFL method for mapping of primary intact forest and the loss of primary intact forest cover.

2.6. Combining primary forests and IFL

We incorporated the two different approaches to quantify primary degraded forest extent and change over time. Primary intact forest was represented by the IFL. Remaining primary forest from the per-pixel mapping method is labeled as degraded forest. Figure 3 illustrates the primary (intact and degraded) forests maps for a subset of Riau and Jambi provinces. Four sets of primary forest maps of years 1990, 2000, 2005 and 2010 were produced (figure 4). The maps of primary forest and its change from 1990 to 2010 together with the map of IFL and its change from year 1990 to 2010 allow for the derivation of change estimates over the period of study. To study forest management practices, we examined the extent of primary intact and primary degraded forests and their change between epochs as a function of province boundary and forest land use zone.

3. Results

3.1. Primary forest extent and change over time

Sumatra primary forest extent for 1990, 2000, 2005 and 2010 is shown in table 2 and figures 4–6. By definition, total primary forest and primary intact forest can only lose or maintain areal extent. Remaining total primary forest cover in 2010 was 30.4% of the total land area. Primary forest extent was nearly halved over the 20 yr study period.

As summarized in table 2, primary forest cover loss in Sumatra from 1990 to 2010 totaled 7.54 Mha. An additional 2.31 Mha of primary forest was degraded by 2010. The total primary forest area lost was 35.7% of 1990 primary forest area. An additional 11% of 1990 primary intact forest was degraded. In total, nearly half (47%) of 1990 Sumatran primary forest was either cleared or degraded during the study period. Primary forest cover loss in the 1990s was far greater...
Figure 3. Landsat TM and ETM+ image composites for circa year 1990, 2000, 2005 and 2010, with a 5–4–3 spectral band combination (left); and classification results (right). Classes: primary intact forest (dark green), primary degraded forest (light green), non-primary forest land (light yellow), and no data/clouds (light gray). The non-primary forest land class is an aggregate area of other tree cover and non-tree cover. A—Riau Province (centered at 101°37′E 0°9′S). B—Jambi province (centered at 103°59′E 1°37′S).

than in the 2000s. The 1990s total of primary forest cover loss of 5.43 Mha is more than double the 2000s total of 2.11 Mha. Of cleared primary intact forest cover, the 1990s experienced over ten times the area converted compared to the 2000s (0.26–0.02 Mha).

For the entire study period, the rate of forest loss was 0.38 Mha/yr, and the rate of forest degradation was 0.12 Mha/yr. The first decade of analysis (1990–2000) contributed 72% of forest loss and 83% of forest degradation. The rate of loss was about 0.54 Mha/yr and comparable to the estimated rate of forest cover loss for Sumatra from 1985 to 1997 of 0.56 Mha/yr (Holmes 2000a, 2000b). The second decade (2000–10) accounted for 28% of forest loss and 17% of forest degradation for the two-decade study period. The rate of forest loss was 0.21 Mha/yr, less than half of the rate of the 1990s.

3.2. Spatial and temporal primary forest cover loss per province

Each province in Sumatra has its own history of forest cover change. For example, forest fires played major role in forest clearing in South Sumatra (Tacconi 2003), while rubber plantations and ‘jungle rubber’ collection were the primary sources of forest degradation in Jambi (Tomich and Van Noorwijk 1995, Ketterings et al 1999). Additionally, in 2000 Indonesia applied a new decentralization policy (Seymour and Turner 2002) providing regional autonomy (Law No. 22/1999) and authority to provinces and districts in sharing revenue from land use fees and taxes (Law No. 25/1999). The decentralization policy provides a rationale for quantifying provincial-scale information pertinent to forest management.
The primary forest cover loss over two decades for eight provinces in Sumatra was summarized in table 3. The percent primary forest loss for the provinces of Riau and South Sumatra exceeded 50% of their 1990 primary forest extent; the province of Jambi experienced a primary forest loss in excess of 40%. For these three provinces, as in Sumatra as a whole, most forest loss was within forests already degraded by 1990. Only Riau experienced a significant forest cover loss within primary intact forests. Primary intact forest loss in Riau accounted for nearly 68% of all primary intact forest loss in Sumatra. Riau contributed 46% of total Sumatran forest degradation, followed by Nanggro Aceh Darussalam/Aceh (23%) and Jambi provinces (12%). For all provinces, there was a dramatic decline in primary intact forest loss between 1990 and 2010.
Figure 5. The expanse of primary intact forest, primary degraded forests and non-primary of Sumatra from year 1990 to 2010; about 7.4% of the data for 1990 was not available.

Figure 6. Sumatra forest cover change from year 1990 to 2010. (a) Total 1990 primary intact forest loss shown in orange and total 1990 primary degraded forest loss in red. (b) Same change dynamics on top of Landsat ETM+ circa 2010 image composite with 5–4–3 spectral band combination. (c) Change dynamics through 2010 within 1990 primary intact forests, where changes consist of forest loss (clearing) and forest degradation. (d) Change dynamics through 2010 within 1990 primary degraded forests, where change is due solely to forest cover loss (clearing). The background image of (b) illustrates the existence of both non-treed and other tree cover types, such as oil palm, within the non-primary forest class.

the 1990s and 2000s, reflecting the near exhaustion of intact lowland forests. Clearing of degraded forests also declined for all provinces, with Riau coming closest to a sustained inter-decadal rate; for Riau, primary degraded forest loss in the 2000s was 85% that of the 1990s. Remaining primary intact forest in 2010 was located largely in Aceh (40%), West
Table 3. Primary forests extent and its change in eight provinces of Sumatra for two decades from year 1990 to 2010. (Note: PD: primary degraded forest, PI: primary intact forest; For. deg.: forest degradation.)

| Province      | Primary forests (year 1990) | Forest change (1990–2000) | Primary forests (year 2000) | Forest change (2000–10) | Primary forests (year 2010) |
|---------------|-----------------------------|---------------------------|-----------------------------|------------------------|-----------------------------|
|               | Total                       | PD | PI | For. deg. | Total                       | PD | PI | For. deg. | Total                       | PD | PI | For. deg. |
| N Aceh        | 3.86                        | 1.78 | 2.08 | 0.41 | 0.02 | 0.44 | 3.43 | 1.81 | 1.62 | 0.11 | 0.003 | 0.09 | 3.32 | 1.79 | 1.53 |
| Sumut<sup>a</sup> | 2.53                        | 2.12 | 0.41 | 0.42 | 0.001 | 0.06 | 2.12 | 1.76 | 0.35 | 0.19 | 0.001 | 0.12 | 1.92 | 1.69 | 0.24 |
| Sumbar<sup>b</sup> | 2.69                        | 1.96 | 0.73 | 0.28 | 0.002 | 0.06 | 2.40 | 1.73 | 0.67 | 0.11 | 0.003 | 0.08 | 2.29 | 1.70 | 0.59 |
| Riau           | 5.67                        | 4.18 | 1.49 | 1.69 | 0.18 | 0.99 | 3.80 | 3.49 | 0.32 | 1.27 | 0.01 | 0.07 | 2.53 | 2.29 | 0.23 |
| Jambi          | 2.65                        | 1.94 | 0.71 | 0.80 | 0.04 | 0.26 | 1.82 | 1.40 | 0.41 | 0.30 | 0.001 | 0.01 | 1.51 | 1.11 | 0.40 |
| SumSel<sup>c</sup> | 2.28                        | 1.97 | 0.31 | 1.28 | 0.003 | 0.02 | 0.99 | 0.71 | 0.28 | 0.06 | 0.001 | 0.01 | 0.94 | 0.67 | 0.27 |
| Bengkulu       | 1.04                        | 0.47 | 0.57 | 0.22 | 0.02 | 0.09 | 0.81 | 0.34 | 0.46 | 0.04 | 0.001 | 0.01 | 0.77 | 0.32 | 0.45 |
| Lampung        | 0.39                        | 0.31 | 0.09 | 0.07 | 0.0002 | 0.001 | 0.32 | 0.23 | 0.09 | 0.01 | 0.001 | 0.003 | 0.31 | 0.23 | 0.08 |
| Total          | 21.11                       | 14.73 | 6.39 | 5.16 | 0.26 | 1.92 | 15.69 | 11.48 | 4.21 | 2.09 | 0.02 | 0.40 | 13.58 | 9.79 | 3.79 |

<sup>a</sup> Sumut: Sumatra Utara (North Sumatra).
<sup>b</sup> Sumbar: Sumatra Barat (West Sumatra).
<sup>c</sup> SumSel: Sumatra Selatan (South Sumatra).

Sumatra has always been a key area for oil palm production in the country (Tomich et al. 2001), with Riau as the leading province (Tambunan 2006). The very high rates of Riau primary forest loss over the study period were likely due to the intensive establishment of oil palm and forest timber and pulp plantations (Holmes 2000a, 2000b, Nawir et al. 2007, Uryu et al. 2008). By the late 1990s, most of the Riau lowland forests had been converted, leaving mainly peat swamps (Holmes 2000a) as the remaining natural intact forest cover, which in the 2000s have been the location of forest clearing and conversion. In contrast to Riau is Aceh province. In 1990, Aceh’s primary forest extent was second to Riau’s. By 2010, the primary forest of Aceh was the greatest (24% of the island total), consisting of the largest remaining primary intact forest and second largest extent of primary degraded forests. These forests, in particular primary intact forest, have been preserved by the less accessible upland landforms and their conservation and protection land use status (figure 1). Aceh also had been a place of conflict between a local separatist group and the government of Indonesia from 1976 to 2005 (Ross 2005). Political instability most likely also limited the secure access to the primary forest.

3.3. Spatial and temporal forest cover change over forest land use

The primary forest change over the two decades for each forest land use zone in Sumatra was quantified (table 4). Within the forest land uses, the highest rates of forest loss were in primary degraded forests of the regular production forest (HP), convertible production forest (HPK) and limited production forest (HPT) land uses. These land uses accounted for 32.5%, 17.1% and 15.8% of the total loss, respectively. For primary intact forest, about 50% of the loss occurred within the regular production forest land use (HP). Forest degradation rates were the highest within regular production (HP), protection forests (HL) and conservation forests (HK). It is worth noting that logging is not allowed within protection and conservation forests (HL and HK). Thus this degradation is an indication of illegal logging occurrence within the protection and conservation forests, particularly in the second decade of the study (Broich et al. 2011a).

The proportion of forest loss in the three official land uses that either prohibit (HL and HK), or severely restrict clearing (HPT), increased over the study period (from 24% to 29% of total forest loss). The forest land use with the highest proportion of 2000s forest loss to 1990s forest loss was the limited production forest (HPT); these data indicate pressure on an increasingly rare primary forest resource base. In 1990, 14% of primary forests were located in the outside forest land use (APL); 96% of these forests were degraded. By 2010, outside forest land use (APL) accounted for 8.7% of Sumatran primary forest.

Within the forest land uses, production forests as a whole (HP, HPT and HPK) accounted for 65.8% of the total forest cover loss, comparable to 5% of protection forests (HL), and 4% of conservation forests (HK). These data designate the importance of establishing forest management units over production and protected areas, as encouraged by the Government of Indonesia (Forestry Laws UU 41/1999, Government regulations PP 44/2004, PP 6/2007), as one of the REDD and REDD+ strategies in Indonesia (MoF 2008a).

3.4. Product comparison and accuracy assessment

For assessment of our results, we employed the Ministry of Forestry of Indonesia (MoF) land cover maps year 2000 (figure 7(b)) derived from photo-interpretation (MoF 2011). This is the only MoF product coincident with our epochal map products and it was previously and independently assessed by intensive field verification, yielding an accuracy of 88% for all 23 land cover classes and 98% for forest and non-forest classes (MoF 2011). We regrouped the classes of the MoF map into primary intact forest, primary degraded forest, and...
non-primary forest classes. The overall agreement of total primary forest (combined primary degraded and primary intact forest) for year 2000 was 92% (producer’s agreement 86% and user’s agreement 93%). When treating primary degraded and primary intact forest classes separately, the overall agreement was 79% (producer’s agreement 56%, user’s agreement 71% for primary intact class, and producer’s agreement 90%, user’s agreement 82% for primary degraded class).

We also employed the GLAS data set (figure 7(a)) to evaluate our map product. Canopy height was useful for assessing differences between primary intact and degraded forest classes and the HOME metric was also used given previous evidence of its relationship to forest canopy structure and aboveground biomass (Drake et al 2002a, Baccini et al 2008). GLAS data from 2006 were analyzed together with primary intact, primary degraded and non-primary forest areas in 2005, assuming that forest change between 2005 and 2006 would be small and not deleteriously affect the comparison. Results indicated a structural difference between the primary intact (mean value of tree height 28 m ± 8.7 m), primary degraded forests (19 m ± 8.2 m), and non-primary forest covered with trees/other tree cover (13 m ±5.2 m), as characterized using the combination of primary forest mapping and the IFL buffering of forest near human infrastructure (figure 8). A t-test with 95% confidence interval applied and indicated the significant difference of tree height from GLAS shots between primary intact and primary degraded; between primary degraded and non-primary classes covered with trees; and between primary intact and non-primary classes covered with trees. While per-pixel processing of the Landsat time series data cannot be used to discriminate these forest types, the addition of the IFL analysis enabled their characterization, as both GLAS metrics capture a structural difference between primary intact and primary degraded forests.

Figure 7. Data used for product evaluation: (a) GLAS L1A and L2 (year 2006) shots in black dots on top of Sumatra primary forests extent for 2005; (b) the land cover map of the Ministry of Forestry of Indonesia year 2000, presented in eight classes from an original 23 classes. For product comparison, the last six classes (except clouds) were regrouped as the non-primary forest class.

Table 4. Primary forests extent and its change in forestland use zone of Sumatra for two decades from year 1990 to 2010 (see table 1 for forest land use zones in code).

| Forestland use zone (in code) | Primary forests (year 1990) | Forest change (1990–2000) | Primary forests (year 2000) | Forest change (2000—10) | Primary forests (year 2010) |
|-----------------------------|---------------------------|--------------------------|---------------------------|--------------------------|---------------------------|
|                            | Total PD PI               | PD PI                    | Total PD PI               | PD PI                    | Total PD PI               |
| HL                          | 4.21 2.27 1.94 0.22 0.02 0.42 | 3.97 2.47 1.50 0.15 0.003 0.16 | 3.81 2.47 1.34          |
| HK                          | 4.22 1.67 2.56 0.24 0.03 0.31  | 3.95 1.73 2.22 0.04 0.01 0.16 | 3.90 1.84 2.06          |
| HP                          | 4.84 3.74 1.11 1.60 0.13 0.72 | 3.11 2.87 0.25 0.76 0.01 0.03 | 2.35 2.14 0.21          |
| HPT                         | 2.89 2.37 0.52 0.74 0.04 0.31 | 2.11 1.94 0.17 0.41 0.003 0.04 | 1.70 1.57 0.13          |
| HPK                         | 1.90 1.75 0.15 0.85 0.03 0.10 | 1.03 1.01 0.02 0.39 0.0001 0.001 | 0.63 0.61 0.02          |
| APLa                        | 3.05 2.93 0.12 1.51 0.02 0.05 | 1.52 1.47 0.05 0.33 0.001 0.01 | 1.18 1.15 0.03          |
| Total                       | 21.11 14.73 6.39 5.16 0.26 1.92 | 15.69 11.48 4.21 2.09 0.02 0.40 | 13.58 9.79 3.79         |

a APL: outside forest land use zone; HL: protection forests; HK: conservation forests; HP: regular production forests; HPT: limited production forests; HPK: convertible production forests; PD: primary degraded forest; PI: primary intact forest; For. deg.: forest degradation.
Figure 8. Mean and standard deviation values for GLAS metrics of (a) tree height and (b) HOME from 2006 GLAS L1A and L2 shots within non-primary, primary degraded and primary intact forests of Sumatra. Summary t-tests with the following degrees of freedom each yielded p-values of \( \leq 0.000 \) for the 95% confidence interval: 24,423 for non-primary/primary degraded; 16,834 for non-primary/primary intact; 9,299 for primary degraded/primary intact.

4. Discussion

4.1. Mapping and monitoring primary intact and primary degraded forests

Our study produced a new set of maps quantifying the extent of primary degraded and primary intact forests in Sumatra over a 20 yr period using a hybrid approach of per-pixel mapping and GIS-buffering of observable disturbances and human infrastructure. This hybrid approach integrated supervised classification methods with expert-based image interpretation of Landsat ‘wall-to-wall’ mapping. Comparisons with official MoF maps and forest structure metrics from GLAS data indicate a viable quantification of total primary forest extent and primary intact and degraded forest subclasses.

GLAS-derived tree height indicated significant differences of forest vertical structure. Mean values of tree height from GLAS shots for primary intact, primary degraded and non-primary forest are significantly different to each other, as we excluded the non-primary/other tree cover and no-trees areas. The height of median energy (HOME) which is calculated by finding the median of the entire LiDAR signal both from canopy and ground (Drake et al. 2002a) also shown similar indication. Majority of the HOME waveform come from the upper portion of the canopy profile (Drake et al. 2002b). Thus, forest with higher trees and large canopy like primary intact forest gives higher HOME compare to the forests with shorter trees and smaller canopy like primary degraded forests.

Landsat data capture sufficient spatial detail to derive reliable change area estimates in Indonesia (Achard et al. 2002, Curran et al. 2004, Hansen et al. 2009, Miettinen and Liew 2010). Reliable maps of forest cover disturbance can be achieved through the combined use of medium spatial resolution satellite images, such as Landsat or Satellite Pour l’Observation de la Terre (SPOT), if interpreted by experts with local knowledge (Liew et al. 1998, Tucker and Townshend 2000). The global acquisition strategy of Landsat 7 (Arvidson and Gasch 2001) facilitated mapping for the 2000–10 epoch, while a traditional post-classification approach with expert intervention was required to map the comparatively data poor 1990–2000 epoch. The ‘wall-to-wall’ mapping approach overcomes limitations of sampling methods in the estimation of forest cover loss (Tucker and Townshend 2000), and also provides a more application-ready product in assessing impacts, such as fragmentation and forest degradation (Steininger et al. 2001), on aboveground carbon stock dynamics and ecosystem services and co-benefits for forest conservation (Stickler et al. 2009).

4.2. Temporal and spatial forest cover change in Sumatra

Over the past 60 yr, Sumatra has experienced intensive industrial forestry and agricultural development that has significantly reduced the area of natural forest. In 1950, forest covered 71.2% of Sumatra (Hannibal 1950 as reported by FWI/GWF 2002), which was reduced to 49% by 1985 and to 35% by 1997 (Holmes 2000a). We estimated that remaining 1990 primary forest extent covered 47% of Sumatra, and that this was reduced to 33% by 2000 and to 30% by 2010. Slowing of primary forest cover loss is partly the result of a greatly diminished resource base, particularly of lowland primary forests. Hansen et al. (2009) highlighted a recent increase in primary forest loss in the upland forests of Sumatra and Kalimantan, possibly in response to an exhausted lowland forest resource.

Of the dominant drivers of forest cover loss, including agricultural expansion, wood extraction and infrastructure extension (Curran et al. 2004, Fuller et al. 2004, Mayaux et al. 2005), the underlying causes of forest cover loss in Sumatra are related to the expanding global markets for pulp, timber and oil palm (Holmes 2000a, 2000b, Nawir et al. 2007, Uryu et al. 2008, Hansen et al. 2008b). In addition to mechanical clearing of forests to establish agroforestry projects, other direct causes for Sumatra include fires (Holmes 2000a, 2000b, Nawir et al. 2007, Uryu et al. 2008), illegal logging (Nawir et al. 2007, Tacconi 2003, Uryu et al. 2008), transmigration programs (FWI/GWF 2002), and smallholder clearance for tree crops (Holmes 2000a, 2000b). A summary of the direct causes of primary forest cover change for the past
Table 5. A Summary for illustrating the primary forest change drivers in Sumatra over years. (Note: sources: summarized from Tomich and Van Noorwijk 1995, Ketterings et al 1999, Sunderlin et al 2000, Holmes 2000a, 2000b, FWI/GWF 2002, Tacconi 2003, Curran et al 2004, Nawir et al 2007, Tacconi 2007, Uryu et al 2008, Hansen et al 2008b and Laumonier et al 2010.)

| Periods                     | Main drivers of forest cover loss | Other drivers of forest cover loss | Main drivers of forest degradation |
|-----------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Beyond our time frame for analysis |                                    |                                   |                                    |
| 1950–70                     | • Agriculture expansion notably rice cultivation • Smallholder clearance for rubber and coffee • Shifting cultivation | • Transmigration programs for tree crops (rubber, cocoa and coffee) and labor for timber industry |                                    |
| 1970–90                     | • Large-scale commercial logging concessions • Large-scale forest plantations | • Fires 1982–3 |                                    |
| During our time frame for analysis |                                    |                                   |                                    |
| 1990–2000 (the first decade of analysis) | • Agriculture expansion mainly oil palm estate | • Fires 1997–98 | • Uncontrolled and controlled selective logging within forest logging concession • Illegal logging |
| 2000–2010 (the second decade of analysis) | • Establishment of pulp-paper and sawn-timber plantations | • Transmigration programs • Spontaneous transmigrants activities • Smallholder clearance for tree crops | • Illegal logging |
|                                | • Agriculture expansion mainly oil palm estate • Expansion of pulp-paper and sawn-timber plantations | • Transmigration programs • Spontaneous transmigrants activities • Limited fires | |
Bengkulu, North Sumatra and Lampung in order to preserve the largest remaining tracts of primary forest.

The Indonesian logging moratorium is imposed on all official forest land uses. No new concessions are to be granted under the moratorium. However, moratorium exemptions exist for forest concessions in which licenses were already established prior to the moratorium period (Presidential Instruction No. 10/2011, Murdiyarso et al 2011). Under the moratorium, no clearing or logging outside of pre-existing concessions should occur within 2011–3. However, it must be noted that of Sumatran primary forest in 2010 located within moratorium-designated lands, over half exists in already protected status HL and HK forest land uses (56.8%). Another 17.0% exists in already established concessions with exemptions for logging and forest plantations. A total of 8.7% is in other APL land uses, with licenses controlled by the National Land Authority (BPN). The remaining 17.5% is HP primary forest newly designated as off-limits to logging and clearing. It is only this portion of the official forested land that has been set aside by the moratorium. However, as shown by the rates of primary forest clearing and degradation in all forest land uses, governance is lacking in enforcing official forest land use policy. This fact brings into question the potential effectiveness of government mandated restrictions on new concessions such as the moratorium. Regardless, government efforts for establishing forest management units (FMU) within HP forest land (Forestry Laws UU 41/1999, Government regulations PP 44/2004, PP 6/2007) could provide a framework for maintaining forests set aside by the moratorium.

The method presented here could be used to verify the success of the moratorium and more generally the successful enforcement of official forest land use policies. In addition to the moratorium, the government of Indonesia monitors forest conversion processes including the maintenance of logged over forests, e.g. through enrichment planting (Adjers et al 1995). It is also charged with monitoring the utilization of forests which have been converted to plantations. Regardless, the designated forest land uses cannot effectively maintain Indonesia’s forest resources unless forest law enforcement is strictly undertaken. The dynamics captured in this study illustrate a non-sustainable trend of forest conversion and degradation in Sumatra. Improved management of existing forest land use allocations is necessary for forest conservation and climate change mitigation policy initiatives to succeed.

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