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

Belinda Arunarwati Margono[1,2]**, Svetlana Turubanova**[3]**,
Ilona Zhuravleva**[4]**, Peter Potapov**[3]**, Alexandra Tyukavina**[3]**,
Alessandro Baccini**[5]**, Scott Goetz**[5] **and Matthew C Hansen**[3]

[1] Geographic Information Science Center of Excellence (GIScCE), South Dakota State University,
Brookings, SD 57007, USA
[2] The Ministry of Forestry (MoF) of Indonesia, Jakarta 10270, Indonesia
[3] Department of Geography, University of Maryland, College Park, MD 20742, USA
[4] Greenpeace Russia, 125040 Moscow, Russia
[5] Woods Hole Research Center, Falmouth, MA 02540, USA

E-mail: Belinda.Margono@sdstate.edu and bmargono@umd.edu

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 $\pm$ 8.7 m and 19 m $\pm$ 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 CO_2 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 plants 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 $1 000 000 000 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 (Murdiyarso *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 expanse 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 cover 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 km^2 (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
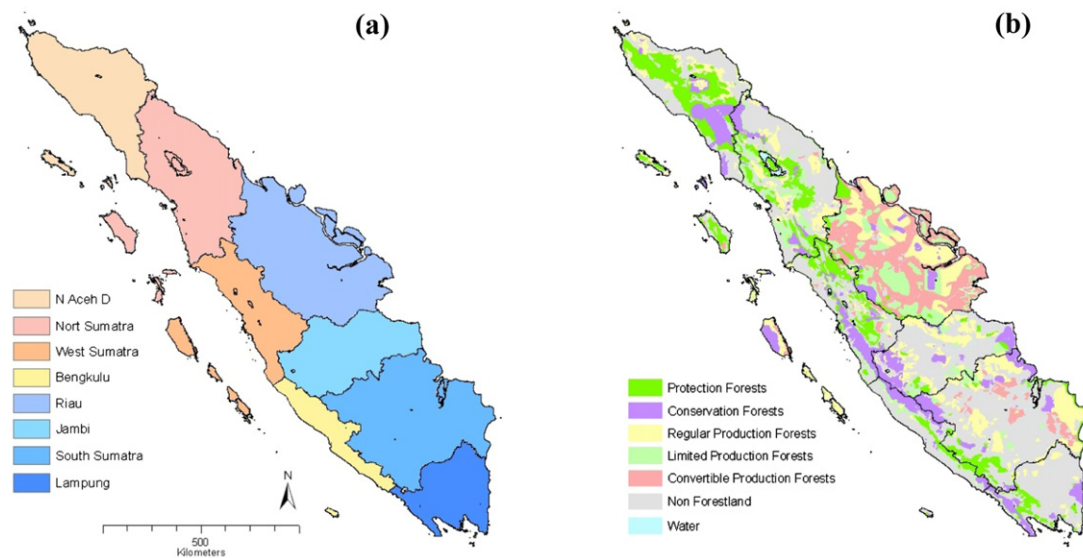
Figure 1. (a) Eight provinces of Sumatra (Nanggroe Aceh Darussalam, North Sumatra, West Sumatra, Bengkulu, Riau, Jambi, South Sumatra, and Lampung). (b) Forest land use zones for Sumatra.

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
Conservation forest	HK	10.6	Preserving the biodiversity of flora fauna and their ecosystem	Forest preservation	Stable forests without any deforestation and forest degradation
Protection forest	HL	13.0	Protecting the water system to prevent flooding, control erosion, protect sea water intrusion and maintain soil fertility	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	Low intensity logging (due to topographical condition)	Limited logging Very selective logging Very limited clear cutting Post-logging silvicultural treatments	Forest degradation
Regular production forest	HP	15.5	Logging Forest plantations	Selective logging Post-logging silvicultural treatments Clear cutting	Temporary deforestation Forest degradation
Convertible production forest	HPK	11.1	Logging	Clear cutting	Permanent and temporary deforestation
			Agriculture estate Other uses		Forest degradation
Non-forestland	APL	40.8	Outside forestland and designated for other uses (agriculture land, settlements etc)		Permanent deforestation Forest degradation Reforestation

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^TM 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
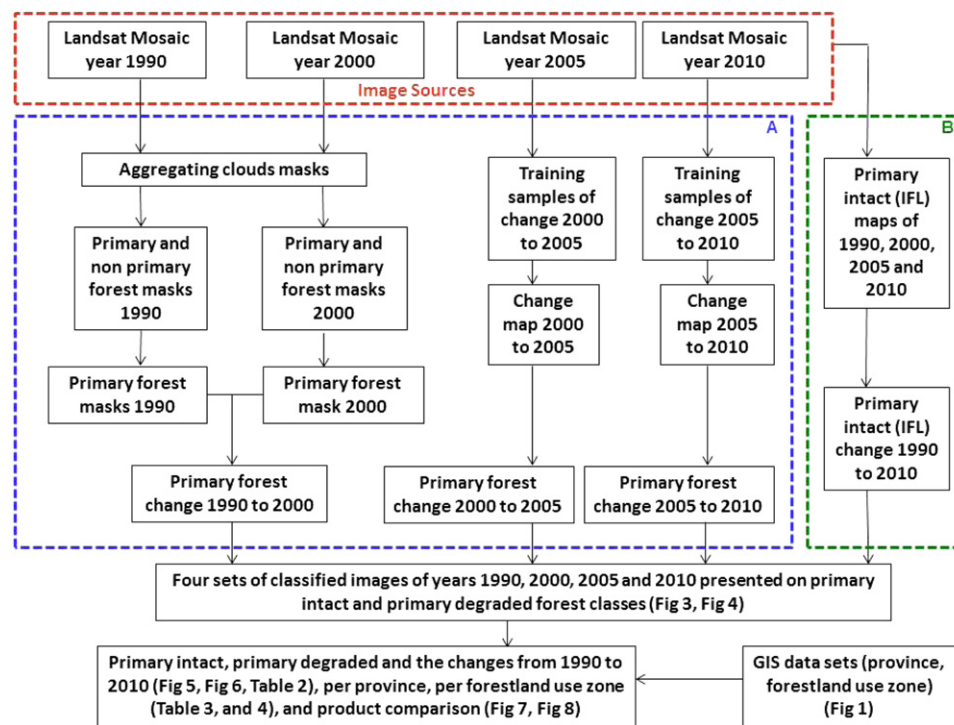
Figure 2. Scheme of methodology used to map the primary forests, including primary intact and primary degraded forests, and its change in terms of deforestation and forest degradation from 1990 to 2010; box A is the approach of per-pixel mapping of primary forest extent and forest cover loss; box B is the other approach of IFL method for mapping of primary intact forest and the loss of primary intact forest cover.

based on a GIS-buffering approach further updated through expert visual interpretation, as described in Potapov *et al* (2008). The year 2000 IFL map has been updated at the national scale for 2005 and 2010 using time-sequential image composites. We used indications of recent human activity such as clearing for agricultural expansion and forest plantation establishment, logging roads and other infrastructure developments (Fuller 2006, Adeney *et al* 2009) to map the observable disturbances in each epoch. Buffering and patch analysis were also performed to update the IFL change circa 2005 and 2010. We subtracted the changes from the 2000 IFL map to create IFL for 2005 and 2010. In addition, a retrospective analysis of IFL change was performed for Sumatra using the circa 1990 Landsat image mosaic. The IFL method, in contrast to the approaches of Asner *et al* (2005) and Souza *et al* (2003), is an indirect characterization method that relies on the mapping of human-built infrastructure and other persistent signs of human activity within and adjacent to mature forests to infer degradation. For this study, fragmentation due to disturbances and logging roads is quantified using the IFL method, illustrated in figure 2, box (B).

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
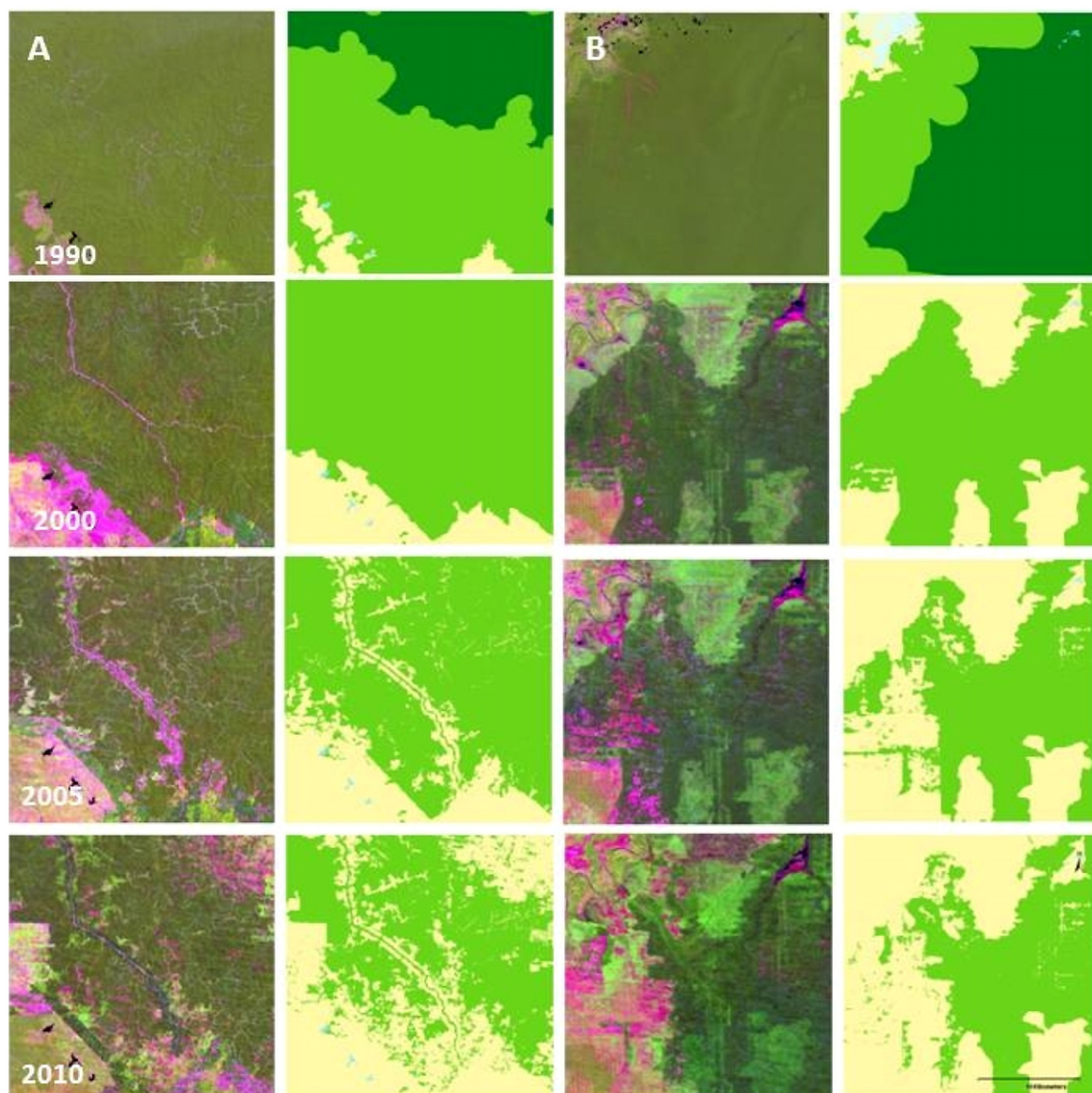
Figure 3. Landsat TM and ETM+ image composites for circa year 1990, 2000, 2005 and 2010, with a 5–4–3 spectral band combination (left); and classification results (right). Classes: primary intact forest (dark green), primary degraded forest (light green), non-primary forest land (light yellow), and no 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.
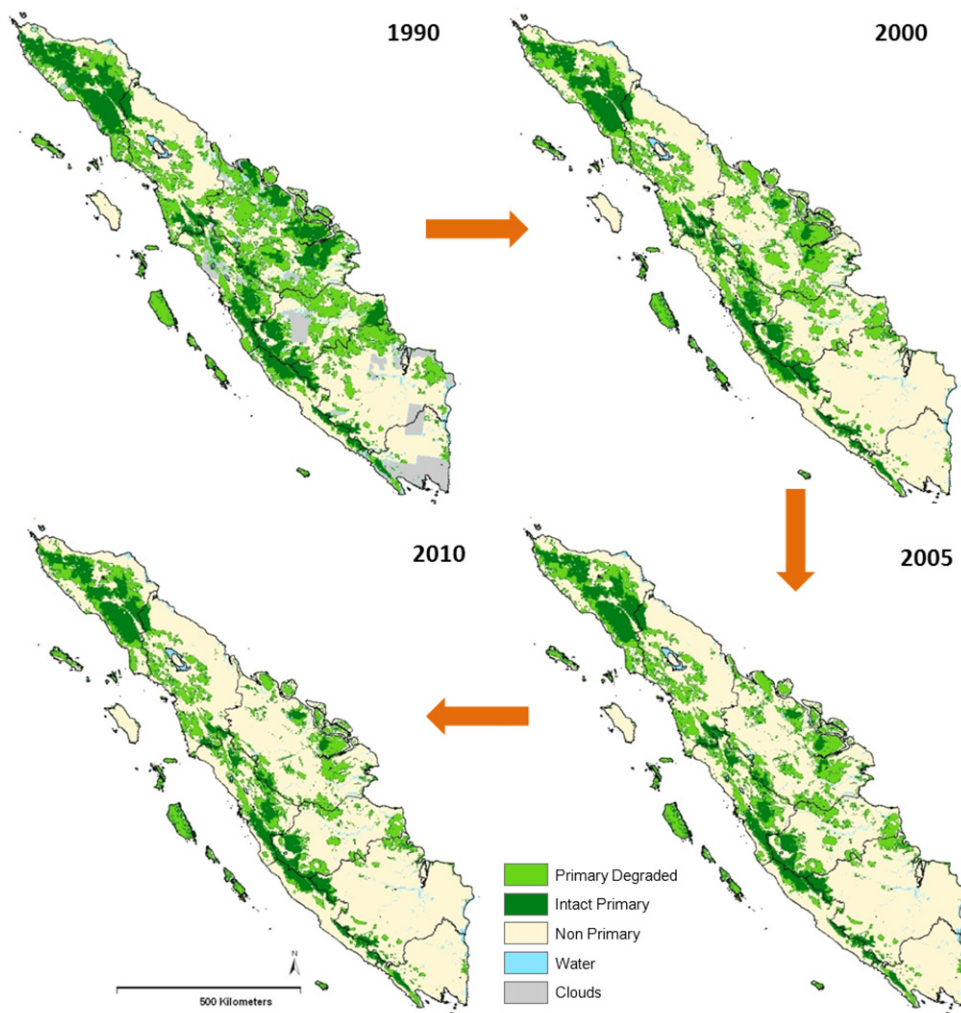
Figure 4. Four depictions of Sumatra primary forest extent and change for 1990, 2000, 2005 and 2010.

Table 2. Primary forests extent, land cover types, and the forest cover change in Sumatra for two decades from year 1990 to 2010. (Note: The areas are presented in millions of hectares and are rounded to nearest 0.01 million ha.)

Dominant forests and land cover types	Area (million hectares)								
	Year 1990	Forest change (1990–2000)		Year 2000	Forest change (2000–10)		Year 2010	Forest change (1990–2010)	
		Forest loss	Forest degradation		Forest loss	Forest degradation		Forest loss	Forest Degradation
Primary degraded forest	14.73	5.16	—	11.48	2.09	—	9.79	7.25	—
Primary intact forest	6.39	0.26	1.92	4.21	0.02	0.40	3.79	0.28	2.31
Total primary forests	21.11	5.43	1.92	15.69	2.11	0.40	13.58	7.54	2.31
Non-primary	20.27			29.01			31.12		
Clouds	3.31			0.001			0.001		
Water	20.43			20.43			20.43		
Total land area	44.69			44.69			44.69		

The primary forest cover loss over two decades for eight provinces in Sumatra was summarized in table 3. The per cent 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 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 Nanggroe Aceh Darussalam/Aceh (23%) and Jambi provinces (12%). For all provinces, there was a dramatic decline in primary intact forest loss between
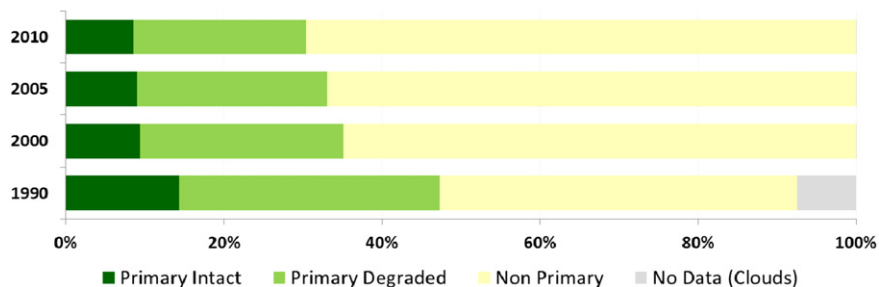
Figure 5. The expanse of primary intact forest, primary degraded forests and non-primary of Sumatra from year 1990 to 2010; about 7.4% of the data for 1990 was not available.
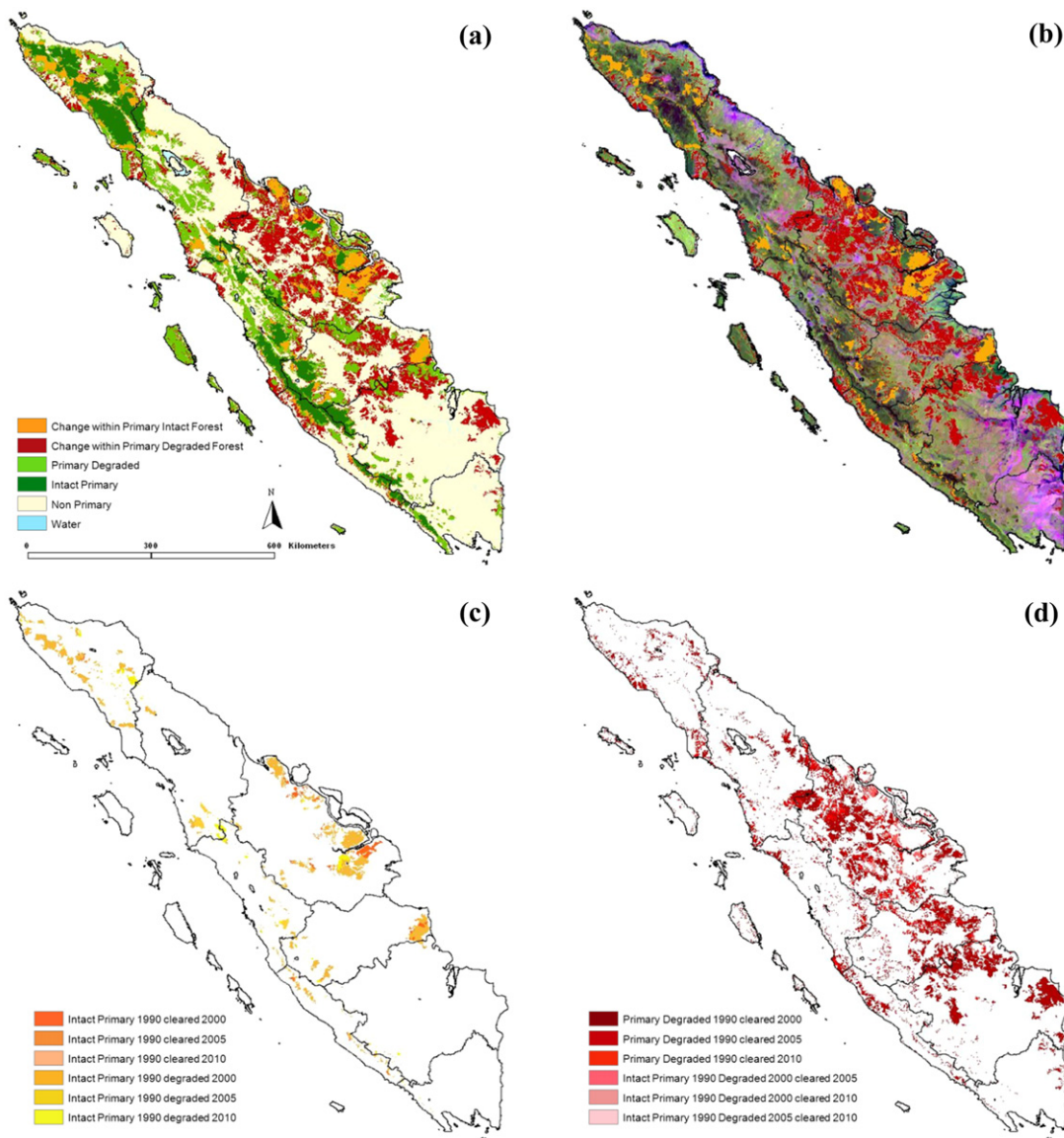

Figure 6. Sumatra forest cover change from year 1990 to 2010. (a) Total 1990 primary intact forest loss shown in orange and total 1990 primary degraded forest loss in red. (b) Same change dynamics on top of Landsat ETM+ circa 2010 image composite with 5–4–3 spectral band combination. (c) Change dynamics 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.)

	Area (million hectares)															
	Primary forests (year 1990)			Forest change (1990–2000)			Primary forests (year 2000)			Forest change (2000–10)			Primary forests (year 2010)		
				Forest loss		For. deg.				Forest loss		For. deg.			
	Total	PD	PI	PD	PI		Total	PD	PI	PD	PI		Total	PD	PI
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[a]	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[b]	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[c]	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

[a] Sumut: Sumatra Utara (North Sumatra).

[b] Sumbar: Sumatra Barat (West Sumatra).

[c] Sumsel: Sumatra Selatan (South Sumatra).

Sumatra (15%), and Bengkulu (12%) provinces, which are all located along the Sumatra uplands.

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
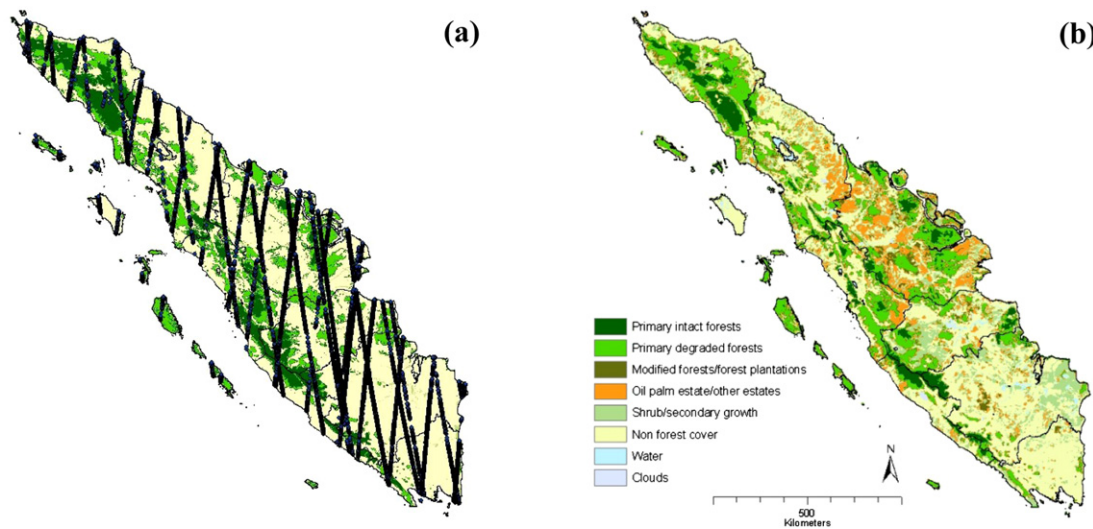
Figure 7. Data used for product evaluation: (a) GLAS L1A and L2 (year 2006) shots in black dots on top of Sumatra primary forests extent for 2005; (b) the land cover map of the Ministry of Forestry of Indonesia year 2000, presented in eight classes from an original 23 classes. For product comparison, 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)	Area (million hectares)														
	Primary forests (year 1990)			Forest change (1990–2000)			Primary forests (year 2000)			Forest change (2000—10)			Primary forests (year 2010)		
				Forest loss		For. deg.				Forest loss		For. deg.			
	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
APL[a]	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.

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 $\pm$ 8.7 m), primary degraded forests (19 m $\pm$ 8.2 m), and non-primary forest covered with trees/other tree cover (13 m $\pm$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.
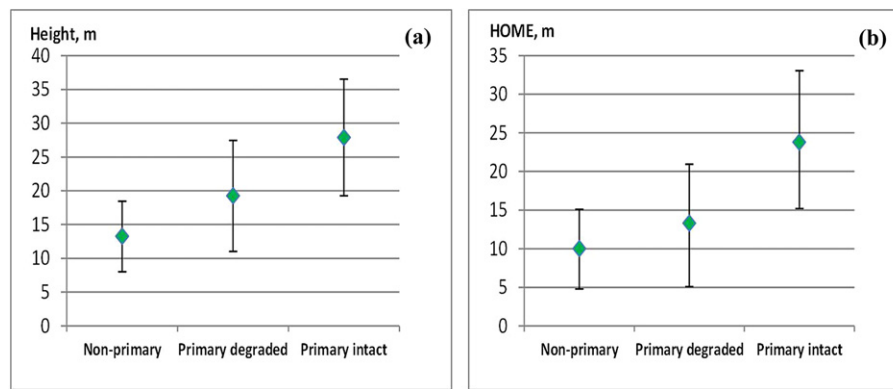
Figure 8. Mean and standard deviation values for GLAS metrics of (a) tree height and (b) HOME from 2006 GLAS L1A and L2 shots within non-primary, primary degraded and primary intact forests of Sumatra. Summary *t*-tests with the following degrees of freedom each yielded *p*-values of $\ll 0.000$ for the 95% confidence interval: 24 423 for non-primary/primary degraded; 16 834 for non-primary/primary intact; 9299 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 differ 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, FWI/GWF 2002, Tacconi 2003, Uryu *et al* 2008), illegal logging (Nawir *et al* 2007, Tacconi 2007), 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		
1970–90	• Large-scale commercial logging concessions • Large-scale forest plantations	• Transmigration programs for tree crops (rubber, cocoa and coffee) and labor for timber industry • Fires 1982–3	
During our time frame for analysis			
1990–2000 (the first decade of analysis)	• Agriculture expansion mainly oil palm estate • Establishment of pulp-paper and sawn-timber plantations	• Fires 1997–98 • Transmigration programs • Spontaneous transmigrants activities • Smallholder clearance for tree crops	• Uncontrolled and controlled selective logging within forest logging concession • Illegal logging
2000–2010 (the second decade of analysis)	• Agriculture expansion mainly oil palm estate • Expansion of pulp-paper and sawn-timber plantations	• Transmigration programs • Spontaneous transmigrants activities • Limited fires	• Illegal logging

60 yr in Sumatra is provided in table 5. Considering the scale of the observed changes over the study period, it is clear that large-scale commercial logging and agro-industrial development are the main drivers of Sumatran forest loss. Illegal logging also occurred during the study period, as illustrated by an increasing rate of forest degradation within protection and conservation forests compared to other forest land uses (table 4). We note that illegal logging, by some estimates, accounts for more than half of total domestic timber production (FWI/GWF 2002). A high rate of forest degradation within protected forests (HL) was possibly triggered by the breakdown of centralized political authority in early 2000, and the inability of provincial governments to adequately enforce forest codes (Nawir *et al* 2007, Uryu *et al* 2008).

5. Conclusion

The hybrid approach of per-pixel mapping of stand-replacement disturbance and GIS-buffering of observable disturbances and human infrastructure is viable for quantifying the extent and change over time of the primary forests of Sumatra, Indonesia. The change, as illustrated in figure 6, has been concentrated in the northeast of the island and documents an intensive conversion of lowland forest cover that is slowing due to the near exhaustion of the lowland primary forest resource base. The products derived using this approach are useful for a number of applications, including direct integration with available forest carbon stock and other ancillary data in spatially explicit emissions estimates associated with deforestation and forest degradation. Another potential use of these maps would be to target field work in developing an *in situ* carbon stock data base. By using the satellite-derived primary forest maps as a stratifier, resources for *in situ* forest inventory work may be more strategically allocated. Finally, the map itself can be used to target areas in need of improved enforcement of the official forestry code.

The primary degraded and primary intact forest loss in Sumatra from 1990 to 2010 varied between province and official forest land use. Overall primary forest loss was high, with nearly one-half of 1990 primary forests having been cleared or degraded by 2000. According to Indonesian Forestry Laws (article 18 UU 41/1999), to sustainably manage the forest a minimum 30% of total land of an island has to remain naturally forested. Therefore, implementation of the logging moratorium within Sumatra's remaining primary forests is vital, especially considering that the remaining primary forest resource is not evenly distributed. The current moratorium of logging in Sumatra could focus on the remaining lowland forests of Riau, Jambi and South Sumatra, where the primary forests are nearly exhausted. Another priority would be the uplands of Aceh, West Sumatra,

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.

Acknowledgments

References

Achard F, Eva H D, Stibig H J, Mayaux P, Gallego J, Richards T and Malingreau J P 2002 Determination of deforestation rates of the world's humid tropical forests *Science* **297** 999–1002

Adeney J M, Christensen N L Jr and Pimm S L 2009 Reserves protect against deforestation fires in the Amazon *PLoS One* **4** e5014

Adjers G, Hadengganan S, Kuusipalo K and Vesa L 1995 Enrichment planting of Dipterocarps in logged-over secondary forest: effect of width, direction and maintenance method of planting line on selected *Shorea* species *For. Ecol. Manag.* **73** 259–70

Arvidson T and Gasch J 2001 Landsat 7's long-term acquisition plan-an innovative approach to building a global imagery archive *Remote Sens. Environ.* **78** 13–26

Asner G P 2001 Cloud cover in Landsat observations of the Brazilian Amazon *Int. J. Remote Sens.* **22** 3855–62

Asner G P, Knapp D E, Broadbent E N, Oliveira P J C, Keller M and Silva J N 2005 Selective logging in the Brazilian Amazon *Science* **310** 480–2

Baccini A, Laporte N, Goetz S J, Sun M and Dong H 2008 A first map of tropical Africa's above-ground biomass derived from satellite imagery *Environ. Res. Lett.* **3** 045011

Barlow J *et al* 2007 Quantifying the biodiversity value of tropical primary, secondary, and plantation forests *Proc. Natl Acad. Sci.* **47** 18555–60

Breiman L, Friedman J H, Olshen R A and Stone C J 1984 *Classification and Regression Trees* (Monterey, CA: Wadsworth and Brooks/Cole)

Broich M, Hansen M, Stolle F, Potapov P, Arunarwati B M and Adusei B 2011a Remotely sensed forest cover loss shows high spatial temporal variation across Sumatera Kalimantan Indonesia 2000–2008 *Environ. Res. Lett.* **6** 014010

Broich M, Hansen M C, Potapov P, Adusei B, Lindquist E and Stehman S V 2011b Time-series analysis of multi-resolution optical imagery for quantifying forest cover loss in Sumatra and Kalimantan, Indonesia *Int. J. Appl. Earth Observ. Geoinf.* **13** 277–91

Carnus J M, Parrotta J, Brockerhoff E, Arbez M, Jactel H, Kremer A, Lamb D, O'Hara K and Walters B 2006 Planted forests and biodiversity *J. For.* **104** 65–77

Casson A 2000 *The Hesitant Boom: Indonesia's Oil Palm Sub-Sector in an Era of Economic Crisis and Political Change (Occasional Paper No. 29)* (Bogor: Center for International Forestry Research (CIFOR))

Curran L M, Trigg S N, McDonald A K, Astiani D, Hardiono Y M, Siregar P, Caniago I and Kasischke E 2004 Lowland forest loss in protected areas of Indonesian Borneo *Science* **303** 1000–2

Drake J B, Dubayah R O, Clark D B, Knox R G, Blair J B, Hofton M A, Chazdon R L, Wheishampel J F and Prince S D 2002a Estimation of tropical forest structural characteristics using large-footprint lidar *Remote Sens. Environ.* **79** 305–19

Drake J B, Dubayah R O, Knox R G, Clark D B and Blair J B 2002b Sensitivity of large-footprint lidar to canopy structure and biomass in a neotropical rainforest *Remote Sens. Environ.* **81** 378–92

FAO (Food and Agricultural Organization) 2001 Global Forest Resources Assessment 2000 *FAO Forestry Paper No. 140* (Rome: United Nation Food and Agricultural Organization (UNFAO))

FAO (Food and Agricultural Organization) 2004 *Global Forest Resources Assessment Update 2005 Term and Definitions (Final Version)* (Rome: UNFAO)

FAO (Food and Agricultural Organization) 2005 *State of the World's Forests* (Rome: UNFAO)

FAO (Food and Agricultural Organization) 2006a Global Forest Resources Assessment 2005 *FAO Forestry Paper No. 147* (Rome: UNFAO)

FAO (Food and Agricultural Organization) 2006b Choosing a forest definition for the clean development mechanism *Forests and Climate Change Working Paper No. 4* (Rome: UNFAO)

FAO (Food and Agricultural Organization) 2007 Definitional issues related to reducing emission from deforestation in developing countries *Forests and Climate Change Working Paper No. 5* (Rome: UNFAO)

FAO (Food and Agricultural Organization) 2010 Global Forest Resources Assessment 2010 Country Report Indonesia *Forest Resource Assessment (FRA) 2010/095* (Rome: UNFAO)

Fuller D O 2006 Tropical forest monitoring and remote sensing: a new era of transparency in forest governance? *Singap. J. Trop. Geogr.* **27** 15–29

Fuller D O, Jessup T C and Salim A 2004 Loss of forest cover in Kalimantan, Indonesia, since the 1997–1998 El Nino *Conserv. Biol.* **18** 249–54

FWI/GWF 2002 *The State of the Forest-Indonesia* (Bogor: Forest Watch Indonesia) (Washington DC: Global Forest Watch–World Resource Institute) (available at www. globalforestwatch.org/common/indonesia/sof.indonesia. english.low.pdf)

Goetz S J and Dubayah R O 2011 Advances in remote sensing technology and implications for measuring and monitoring forest carbon stocks and change *Carbon Manag.* **2** 231–44

Goetz S J, Sun M, Baccini A and Beck P S A 2010 Synergistic use of space-borne LiDAR and optical imagery for assessing forest disturbance: an Alaska case study *J. Geophys. Res. Biogeosci.* **115** G00E07

Hansen M C, DeFries R S, Townshend J R G, Carrol M, Dimicelli C and Sohlberg R A 2003 Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continuous fields algorithm *Earth Interact.* **7** 15

Hansen M C, Dubayah R O and DeFries R S 1996 Classification trees: an alternative to traditional land cover classifiers *Int. J. Remote Sens.* **17** 1075–81

Hansen M C, Roy D P, Lindquist E, Adusei B, Justice C O and Alstatt A 2008a A method for integrating MODIS and Landsat data for systematic monitoring of forest cover and change in the Congo Basin *Remote Sens. Environ.* **112** 2495–513

Hansen M C, Stehman S V, Potapov P V, Pittman K W, Margono A B and Stolle F 2009 Quantifying changes in the rates of forest clearing in Indonesia from 1990 to 2005 using remotely sensed data sets *Environ. Res. Lett.* **4** 034001

Hansen M C *et al* 2008b Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data *Proc. Natl Acad. Sci.* **105** 9439–44

Hoekman D H 1997 Radar monitoring system for sustainable forest management in Indonesia *IGARSS '97: 1997 Int. Geoscience and Remote Sensing Symposium (Singapore, 3–8 August 1997)* vol 4, pp 1731–3 (doi:10.1109/IGARSS.1997.609048)

Holmes D 2000a *Deforestation in Indonesia: A Review of the Situation in Sumatra, Kalimantan and Sulawesi* (Jakarta: The World Bank)

Holmes D 2000b *Where Have All the Forests Gone? Environment and Social Development East Asia and Pacific Region Discussion Paper* (Jakarta: The World Bank)

Houghton R A, Hall F and Goetz S J 2009 Importance of biomass in the global carbon cycle *J. Geophys. Res.* **114** G00E03

INPE (Instituco Nacional de Pesquisas Espaciais (National Institute for Space Research)) 2012 *Estimates a Reduction in Amazonia Deforestation from PRODES System* (available at www.inpe. br/ingles/news/news.php?Cod_Noticia=271)

IPCC (Intergovernmental Panel on Climate Change) 2007 *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed B Metz, O R Davidson, P R Bosch, R Dave and L A Meyer (Cambridge: Cambridge University Press) (available at www.ipcc.ch/pdf/ assessment-report/ar4/wg3/ar4-wg3-ts.pdf)

ITTO (International Tropical Timber Organization) 2002 ITTO guidelines for the restoration, management and rehabilitation of degraded and secondary tropical forests *ITTO Policy Development Series No. 13*

Jones N 2012 *Forestry Plantation Agroforestry. Net* (available at http://agroforestry.net/pubs/Jonestech4.html)

Ketterings Q M, Wibowo T T, Van Noordwijk M and Penot E 1999 Farmers' perspectives on slash-and-burn as a land clearing method for small-scale rubber producers in Sepunggur Jambi province Sumatra Indonesia *For. Ecol. Manag.* **120** 157–69

Koh L P and Wilcove D S 2008 Is oil palm agriculture really destroying tropical biodiversity? *Conserv. Lett.* **1** 60–4

Laumonier Y, Uryu Y, Stuwe M, Budiman A, Setiabudi B and Hadian O 2010 Eco-floristic sectors and deforestation threats in Sumatra: identifying new conservation area network priorities for ecosystem-based land use planning *Biodivers. Conserv.* **19** 1153–74

Liew S C, Lim O K, Kwoh L K and Lim H 1998 A study of the 1997 forest fires in South East Asia using SPOT quicklook mosaics *IGARSS '98: 1998 Int. Geoscience and Remote Sensing Symposium (Seattle, 6–10 July 1998)* vol 2, pp 879–81 (doi:10.1109/IGARSS.1998.699613)

LOI 2010 Letter of Intent between the Government of the Kingdom of Norway and the Government of the Republic of Indonesia *Cooperation on Reducing Greenhouse Gas Emission from Deforestation and Forest Degradation*

MacKinnon K 1997 The Ecological foundations of biodiversity protection *Last Stand: Protected Areas and Defense of Tropical Biodiversity* ed R Kramer, C Van Schaik and J Johnson (New York: Oxford Univeristy Press)

Matsumura N 2011 Yield prediction for *Acacia mangium* plantations in Southeast Asia *Formath* **10** 295–308

Mayaux P, Holmgren P, Achard F, Eva H, Stibig H-J and Branthomme A 2005 Tropical forest cover change in the 1990s and options for future monitoring *Phil. Trans. R. Soc.* B **360** 373–84

Miettinen J and Liew S C 2010 Degradation and development of peatlands in peninsular Malaysia and in the islands of Sumatra Borneo since 1990 *Land Degrad. Dev.* **21** 285–96

MoF (Ministry of Forestry of Indonesia) 1989 *Dictionary of Forestry Terms* (Jakarta: Departemen Kehutanan Republik Indonesia)

MoF (Ministry of Forestry of Indonesia) 2003a *Tropical Rainforest Heritage of Sumatra* (Directorate General of Forest Protection and Nature Conservation (PHKA), Ministry of Forestry, Indonesia) (available at http://whc.unesco.org/uploads/ nominations/1167.pdf)

MoF (Ministry of Forestry of Indonesia) 2003b *Rekalkulasi Sumber Daya Hutan (Forest Resource Recalculation) Indonesia Tahun 2003* (Jakarta: Badan Planology Kehutanan Departemen Kehutanan Indonesia)

MoF (Ministry of Forestry of Indonesia) 2005 *Rekalkulasi Penutupan Lahan (Land Cover Recalculation) Indonesia Tahun 2005* (Jakarta: Badan Planology Kehutanan Departemen Kehutanan Indonesia)

MoF (Ministry of Forestry of Indonesia) 2008a IFCA (Indonesian Forest Climate Alliance) 2007 *Consolidation Report: Reducing Emissions from Deforestation and Forest Degradation in Indonesia* (Jakarta: Forestry Research and Development Agency (FORDA))

MoF (Ministry of Forestry of Indonesia) 2008b *Rekalkulasi Penutupan Lahan (Land Cover Recalculation) Indonesia Tahun 2008* (Jakarta: Badan Planology Kehutanan Departemen Kehutanan Indonesia)

MoF (Ministry of Forestry of Indonesia) 2010 *Digital Forest Land Use, Land Cover and Administrative Boundary Maps* (displayed at http://webgis.dephut.go.id/ditplanjs/index.html)

MoF (Ministry of Forestry of Indonesia) 2011 *Rekalkulasi Penutupan Lahan (Land Cover Recalculation) Indonesia Tahun 2009/2010* (Jakarta: Badan Planology Kehutanan Departemen Kehutanan Indonesia)

Murdiyarso D, Dewi S, Lawrence D and Seymour F 2011 Indonesia's forest moratorium: a stepping stone to better governance? *Working Paper No. 76* (Bogor: CIFOR)

Nawir A A, Murniati and Rumboko L 2007 *Forest Rehabilitation in Indonesia: Where to After More Than Three Decades?* (Bogor: CIFOR)

Potapov P V, Turubanova S A, Hansen M C, Adusei B, Broich M, Altstatt A, Mane L and Justice C O 2012 Quantifying forest cover loss in Democratic Republic of the Congo 2000–2010 with Landsat ETM+ data *Remote Sens. Environ.* at press (doi:10.1016/j.rse.2011.08.027)

Potapov P V *et al* 2008 Mapping the world's intact forest landscapes by remote sensing *Ecol. Soc.* **13** 51 (online journal URL www.ecologyandsociety.org/vol13/iss2/art51/)

Rabus B, Eineder M, Roth A and Bamler R 2003 The Shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar ISPRS *J. Photogram. Remote Sens.* **57** 241–62

Ross M L 2005 Resource and rebellion in Aceh Indonesia *Understanding Civil War: Evidence and Analysis* ed P Collier and N Sambanis (Washington, DC: The World Bank)

Sasaki N and Putz F E 2009 Critical need for new definitions of 'forest' and 'forest degradation' in global climate change agreements *Conserv. Lett.* **2** 226–32

Seymour R and Turner S 2002 Otonomi daerah: Indonesia's decentralization experiment *N.Z. J. Asian Stud.* **4** 33–51

Simula M 2009 Towards defining forest degradation: comparative analysis of existing definitions *Forest Resources Assessment Working Paper No. 154* (Rome: UNFAO)

Steininger M K, Tucker C J, Townshend J R G, Killeen T J, Desch A, Bell V and Ersts P 2001 Tropical deforestation in the Bolivian Amazon *Environ. Conserv.* **28** 127–34

Stephens S S and Wagner M R 2007 Forest plantations and biodiversity: a fresh perspective *J. For.* **105** 307–13

Stickler C M, Nepstad D C, Coe M T, McGrath D G, Rodrigues H O, Walker W S, Soares-Filho B S and

Davidson E A 2009 The potential ecological costs and cobenefits of REDD: a critical review and case study from the Amazon region *Glob. Change Biol.* **15** 2803–24

Souza C Jr, Firestone L, Silva L M and Roberts D 2003 Mapping forest degradation in the Eastern Amazon from SPOT 4 through spectral mixture models *Remote Sens. Environ.* **87** 494–506

Sunderlin W D, Resosudarmo I A P, Rianto E and Angelsen A 2000 *The Effect of Indonesia's Economic Crisis on Small Farmer and Natural Forest Cover in the Outer Island* (Bogor: CIFOR)

Tacconi L 2003 *Fires in Indonesia: Causes, Cost and Policy Implications* (Bogor: CIFOR)

Tacconi L 2007 *Illegal Logging: Law Enforcement, Livelihoods and Timber Trade* (Trowbridge: Cromwell Press)

Tambunan T 2006 *Indonesian Crude Palm Oil: Production, Export Performance and Competitiveness* (Jakarta: Kadin Indonesia)

Tomich T P and Van Noorwijk M 1995 What drives deforestation in Sumatra *Regional Symp. on Montane Mainland Southeast Asia in Transition Chiang Mai Thailand* (Bogor: ICRAF)

Tomich T P, Van Noordwijk M, Budidarsono S, Gillison A, Kusumanto T, Murdiyarso D, Stolle F and Fagi A M 2001 *Agricultural Intensification, Deforestation and the Environment: Assessing Tradeoffs in Sumatra, Indonesia Alternatives to Slash-and-Burn Project* (Bogor: CIFOR)

Tucker C J and Townshend J R G 2000 Strategies for monitoring tropical deforestation using satellite data *Int. J. Remote Sens.* **21** 1461–71

Uryu Y *et al* 2008 *Deforestation, Forest Degradation, Biodiversity Loss and CO_2 Emission in Riau, Sumatra, Indonesia* (Jakarta: WWF Indonesia)

Whitten T, Damanik S J, Anwar J and Hisyam N 2000 *The Ecology of Sumatra* (*The Ecology of Indonesia Series* vol I) (Singapore: Periplus)