Remotely sensed forest cover loss shows high spatial and temporal variation across Sumatera and Kalimantan, Indonesia 2000–2008

Mark Broich1, Matthew Hansen1, Fred Stolle2, Peter Potapov1, Belinda Arunarwati Margono1 and Bernard Adusei1

1 South Dakota State University, Brookings, SD 57007, USA
2 World Resources Institute, Washington, DC 20002, USA

Abstract
The Indonesian islands of Sumatera and Kalimantan (the Indonesian part of the island of Borneo) are a center of significant and rapid forest cover loss in the humid tropics with implications for carbon dynamics, biodiversity conservation, and local livelihoods. The aim of our research was to analyze and interpret annual trends of forest cover loss for different sub-regions of the study area. We mapped forest cover loss for 2000–2008 using multi-resolution remote sensing data from the Landsat enhanced thematic mapper plus (ETM+) and moderate resolution imaging spectroradiometer (MODIS) sensors and analyzed annual trends per island, province, and official land allocation zone. The total forest cover loss for Sumatera and Kalimantan 2000–2008 was 5.39 Mha, which represents 5.3% of the land area and 9.2% of the year 2000 forest cover of these two islands. At least 6.5% of all mapped forest cover loss occurred in land allocation zones prohibiting clearing. An additional 13.6% of forest cover loss occurred where clearing is legally restricted. The overall trend of forest cover loss increased until 2006 and decreased thereafter. The trends for Sumatera and Kalimantan were distinctly different, driven primarily by the trends of Riau and Central Kalimantan provinces, respectively. This analysis shows that annual mapping of forest cover change yields a clearer picture than a one-time overall national estimate. Monitoring forest dynamics is important for national policy makers, especially given the commitment of Indonesia to reducing greenhouse gas emissions as part of the reducing emissions from deforestation and forest degradation initiative (REDD+). The improved spatio-temporal detail of forest change monitoring products will make it possible to target policies and projects in meeting this commitment. Accurate, annual forest cover loss maps will be integral to many REDD+ objectives, including policy formulation, definition of baselines, detection of displacement, and the evaluation of the permanence of emission reduction.

Keywords: tropical forest, deforestation, REDD+, deforestation drivers, remote sensing, Landsat, MODIS

1. Introduction
Carbon emissions from deforestation and forest degradation are the second largest source of anthropogenic carbon emission (Intergovernmental Panel on Climate Change 2007, Le Quere et al 2009, van der Werf et al 2009). Considered a cost effective way to mitigate anthropogenic greenhouse gas emissions, the reducing emissions from deforestation and
forest degradation in developing countries (REDD+) policy framework plans to financially compensate developing tropical nations for reducing their deforestation and forest degradation (Gullison et al. 2007, Baker et al. 2010). For the first time, the 16th Conference of the Parties (COP16) formally established a REDD+ mechanism under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC). Based on the COP16’s decisions, developing countries are encouraged to contribute to their reduction of emissions from deforestation and forest degradation (REDD), conservation of forest carbon stocks, sustainable management of forest, and enhancement of forest carbon stocks (REDD ‘+’). Developing countries are further encouraged to develop a robust and transparent national forest monitoring system to evaluate the above-mentioned activities (COP16/CMP6 2010).

Indonesia has the third largest extent of the world’s remaining humid tropical forests, extensive forested peatlands, and a high rate of deforestation (Achard et al. 2002, FAO 2005, Mayaux et al. 2005, Hansen et al. 2009, Forest Watch Indonesia/Global Forest Watch 2002), which makes the country highly significant in the context of REDD+. Indonesia’s forests are rich in biological diversity and provide ecosystem goods and services such as watershed protection and erosion prevention. Indonesian tropical forests also play a critical role for the livelihood of local communities and the national economy (Forest Watch Indonesia/Global Forest Watch 2002). In recognition of the importance of carbon sequestration and other important ecosystem services, a new REDD+ initiative, the ‘Norway–Indonesia REDD+ Partnership’ aims at reducing emissions from deforestation and degradation in Indonesia³. For Indonesia, the lack of timely, spatially and temporally detailed information on forest cover loss rates hampers forest management and governance (Fuller 2006, Hansen et al. 2009), posing a challenge in meeting the objectives of REDD+. A monitoring system that fits the objectives of REDD+ to calculate greenhouse gas emissions requires two inputs: activity data and emissions factors (Intergovernmental Panel on Climate Change 2003, 2006). Activity data quantify the area of forest land cover classes that have been converted to non-forest land cover classes. Emissions factors refer to emissions of greenhouse gases per unit area of a given forest class that was converted to a non-forest class. Quantifying activity data is critical for the formulation and evaluation of REDD+ policy, including the specification of deforestation baselines, quantification of displacement of deforestation, and evaluation of persistence of reduced deforestation rates (Miles and Kapos 2008). For example, deforestation has been displaced to Indonesia from countries that have slowed their deforestation rates or increased their forest area (Meyfroidt et al. 2010). Annual updates of forest change are a REDD+ objective (Baker et al. 2010) that has not been met in Indonesia.

Our overall objective of this research was to quantify and interpret interannual gross forest cover loss trends at the island and regional level from 2000 to 2008. While ‘deforestation’ implies a permanent conversion to non-forest, we use the term ‘forest cover loss’ to refer to areas that have been converted from a forest cover to a non-forest cover class within the study interval. The quantification of high spatial and temporal variations in forest cover loss trends, as they have been documented for the Brazilian Amazon (INPE 2010), requires detailed annual maps. Previous work quantifying Indonesian forest cover loss provided multi-year average maps (Government of Indonesia/World Bank 2000), sample-based estimates (e.g. Hansen et al. 2009), and annual maps for specific regions (Gaveau et al. 2009a, 2009b, 2009c, Uryu et al. 2008, van der Werf et al. 2008). Large area national-scale efforts to map forest cover loss at moderate spatial resolution⁴ and at annual time steps are missing (Sanchez-Azofeifa et al. 2009). Consequently, spatial and temporal variations in Indonesia’s forest cover loss trends have not been quantified in detail. Quantifying such trends is needed for targeting and evaluating policy aiming to reduce forest cover loss. Our analysis focuses on the island groups of Sumatera and Kalimantan (Indonesian Borneo), an area of ∼100 Mha and the primary area of recent forest clearing activities (Hansen et al. 2009, Mayaux et al. 2005, Curran et al. 2004, Fuller et al. 2004, Gaveau et al. 2009a, 2009c).

While other countries in the tropics, such as Brazil and India, produce periodic maps of deforestation at moderate spatial resolution (Forest Survey of India 2004, INPE 2010), a monitoring system for Indonesia has not yet been developed. Optical remote sensing-based deforestation monitoring in Indonesia is challenging due to persistent cloud cover. Annual monitoring using single best Landsat images during a local dry season, as applied for Brazil, is not feasible. For Indonesia, moderate spatial resolution Landsat images with low cloud cover were photo-interpreted to map forest cover and change for the 1985–1998 time intervals (Government of Indonesia/World Bank 2000). Yet, data gaps due to clouds adversely impact the reliability of deforestation estimates (Ministry of Forestry Indonesia 2003b) derived from this most recent (1985–1998) Landsat-based multi-year average map for Indonesia. Coarse spatial resolution remote sensing data streams, such as those provided by MODIS, have a higher observation frequency than moderate resolution data streams, therefore providing more frequent cloud-free observations (Global Observation of Forest and Land Cover Dynamics 2009). However, MODIS data are considered inadequate for accurate estimation of deforestation area as most deforestation occurs at subpixel scale (Global Observation of Forest and Land Cover Dynamics 2009, Morton et al. 2005, Sanchez-Azofeifa et al. 2009, Hansen et al. 2008a). Moderate spatial resolution data are recommended for quantifying deforestation area (Global Observation of Forest and Land Cover Dynamics 2009). For Indonesia, Broich et al. (2011) showed that even when combining cloud-free data from large numbers of Landsat 7 imagery, annual, gap-free forest cover loss maps over large areas cannot be derived. However, accurate, internally consistent, large area maps of forest cover loss based on Landsat 7 time-series data over a multi-year interval are feasible (Broich et al. 2011). Freely available Landsat

³ Letter of Intent between the Government of the Kingdom of Norway and the Government of the Republic of Indonesia, http://www.norway.or.id/.

⁴ Moderate spatial resolution is defined in Global Observation of Forest and Land Cover Dynamics (2009) as 10–60 m.
images represent the most complete remotely sensed dataset at moderate spatial resolution for the past decade.

Here we quantified forest cover loss trends by disaggregating Landsat-based moderate spatial, coarse temporal resolution maps, which represent forest cover loss area over a multi-year interval, to individual years. We used annual forest cover loss indicator maps derived from high temporal, coarse spatial resolution MODIS data\(^5\) to disaggregate Landsat-based forest cover loss maps to individual years. This data integration was needed to produce annual maps of forest cover loss over large areas that cannot be derived solely from Landsat or MODIS data. We investigated the following research questions using multi-source satellite and forest land use data to improve current understanding of Indonesian forest cover loss dynamics:

1. What was the spatio-temporal variation in forest cover loss for Sumatera and Kalimantan from 2000 to 2008?
2. What amount of forest cover loss occurred in land allocation zones where clearing is restricted or prohibited (Ministry of Forestry Indonesia 2008)?

2. Methods

2.1. Definitions

Forest was defined as >25% canopy cover of trees ≥5 m in height. Forest cover loss was measured without regard to forest land use, and included plantation and palm estate change dynamics. Using the above definition of forest, forest cover loss was defined as the conversion of forest to non-forest, and represents a stand-replacement disturbance at a 60 m spatial resolution. By using the term forest cover loss, we emphasize that we did not differentiate between a temporary loss of forest and a permanent conversion to a non-forest land cover. Consequently, ‘forest cover loss’ represents gross rather than net area and rate. Selective logging, defined as tree harvesting that does not result in conversion of forest to non-forest, was not part of our forest cover loss definition and was not mapped. Throughout this research, the term ‘trend’ is used to describe a ‘general tendency’. The term, as used here, does not refer to a ‘statistical trend’, as the small sample size of eight observations (2000–2008) precluded the robust identification of statistically significant trends.

2.2. Data

We utilized data from the Landsat 7 enhanced thematic mapper plus (ETM+) and MODIS sensors and digital elevation data from the Shuttle Topography Radar Mission (SRTM). Landsat 7 data were downloaded from USGS/EROS (WWW1) and resampled to 60 m × 60 m spatial resolution. MODIS 16 day composites of the MODIS land bands (Vermote et al. 2002) and the thermal bands (10 780–11 280 nm) were obtained for 2000–2008 (WWW2). SRTM-obtained digital elevation data (Rabu et al., 2003, USGS 2006) were downloaded for the study area (WWW3).

\(^5\) Coarse spatial resolution is defined in Global Observation of Forest and Land Cover Dynamics (2009) as 250–1000 m.

The latest update of the Digital Map of Indonesian Forest Land Use vector\(^6\) dataset was obtained from the Ministry of Forestry Indonesia (2008). Indonesia has three official function-based ‘forest’ land allocation zones, which include production forest (including regular production, limited production, and conversion), watershed protection forest, and biodiversity conservation forest\(^7\) (Law Republik Indonesia 1999). Selective logging and permanent forest clearing are allowed in conversion forests. Selective logging and restricted forest clearing are allowed in limited production forests (Ministry of Forestry Indonesia 2003a). Selective logging and clearing are also legal outside the forest zone on ‘other use\(^8\)’ lands that are not under the jurisdiction of the Ministry of Forestry. However, clearing is prohibited in watershed protection forest and biodiversity conservation forest (Ministry of Forestry Indonesia 2003a). For our analysis, we used the following six land uses zones: conversion forest, regular production forest, limited production forest, watershed protection forest, biodiversity conservation forest, and other use (figure 1).

2.3. Annual forest cover loss mapping

For this study, we used the method described in Broich et al. (2011) to automatically map forest cover loss at 60 m × 60 m spatial resolution, for the 2000–2008 time interval, using Landsat ETM+ and MODIS imagery as inputs. Due to persistent cloud cover and limited acquisitions per year, multiple years of Landsat 7 imagery have to be combined to derive complete cloud-free forest cover loss maps (Broich et al. 2011). Landsat images were first radiometrically normalized using MODIS-mapped dark forest as a reference (Broich et al., 2011, Hansen et al. 2008b). A radiometric normalization was required to allow the application of generic per-pixel classification algorithms. Each pixel in each Landsat image was automatically flagged as being influenced by clouds or assigned a probability of the pixel being forest. Forest probability classification was based on the Landsat bands and normalized differences of bands, which have long been known to partially compensate for the effect of rugged terrain (Vincent 1973, Cheng et al. 2004). Clear surface observations, acquired over multiple years, were assembled into per-pixel forest probability time series. These time series were then classified into either forest cover loss or no change. Cloud-free Landsat images are rare over Indonesia and clouds cannot be flagged with absolute certainty. As a consequence, individual observations are unreliable and the accurate, spatially explicit characterization of forest cover loss, as demonstrated by Broich et al. (2011), relies on multi-year per-pixel trajectories. All characterization models were based on supervised decision tree

\(^6\) ‘Peta Pemanjakan Kawasan Hutan’ in Indonesian.

\(^7\) ‘Hutan Produksi Tetap (HP), Hutan Produksi Terbatas (HPT), Hutan Produksi Konversi (HPK), Hutan Lindung (HL), and Hutan Konservasi (HK)’ are the Indonesian terms for regular production, limited production, conversion, watershed protection, and biodiversity conservation forests, respectively.

\(^8\) ‘Areal Penggunaan Lain (APL)’ in Indonesian.
algorithms (Breiman 1996, Prasad et al 2006) that have been previously used to successfully characterize remote sensing data (Michaelsen et al 1994, Hansen et al 1996, Friedl et al 1999, Hansen et al 2003).

MODIS data were classified with a decision tree algorithm following the approach of the standard vegetation continuous field product of the MODIS land science team (Hansen et al 2003) resulting in annual maps of per cent forest cover per 250 m × 250 m pixel. Pixels that lost more than 70% of their forest cover in subsequent years were identified for producing annual forest cover loss maps.

We disaggregated forest cover loss mapped at 60 m × 60 m spatial resolution for the 2000–2008 time interval, by year, using the annual MODIS detections. Each 60 m × 60 m forest cover loss pixel overlapping with a 250 m × 250 m MODIS forest cover loss pixel was allocated to the year of the MODIS detection. MODIS-mapped forest cover loss pixels or parts of such pixels that did not overlap with Landsat-mapped forest
Figure 3. Temporal disaggregation of the moderate spatial resolution forest cover loss map for Riau province, Sumatera. Landsat band 5 is displayed in grayscale with dark tones representing forest cover. Colors mark the year of MODIS-detected forest cover loss.

Figure 4. Forest cover loss, 2000–2008 for Sumatera and Kalimantan.

3. Results

3.1. Spatio-temporal variation in forest cover loss

Forest cover loss for Sumatera and Kalimantan mapped at moderate spatial resolution for the 2000–2008 interval was 5.39 Mha, 5.3% of the land area, and 9.2% of the year 2000 forest cover (figure 2). An example of the temporal disaggregation of the moderate spatial resolution map using annual MODIS-mapped forest cover loss for Riau province, Sumatera is shown in figure 3.

The overall trend of forest cover loss of the two islands groups increased until 2006 and decreased thereafter. The individual trends for Sumatera and Kalimantan are different from the overall trend (figure 4). Forest cover loss on Sumatera increased almost monotonically until 2005 and decreased thereafter, whereas forest cover loss exhibited peaks in 2002–2003 and 2005–2007 in Kalimantan.

The analysis of per province forest cover loss revealed that the combination of Central Kalimantan and Riau provinces totaled 46% of all forest cover loss. On an annual basis, these two provinces accounted for a minimum of 40% of all forest cover loss (2000–2001) and a maximum of 55% of all forest cover loss (2004–2005) for the study area. Riau province had the highest rates of forest cover loss in the study area, except for 2002–2003 and 2006–2007 when Central Kalimantan exceeded Riau's rate (figure 5).

3.2. Forest cover loss in different land allocation zones

The analysis of forest cover loss within the official land allocation zones showed that 79.9% of all mapped forest cover loss occurred in land allocation zones that permit permanent or temporary clearing (table 1). However, 6.5% of forest cover loss occurred in zones where clearing is prohibited, with 4.4% occurring in watershed protection zones, and 2.1% in biodiversity conservation zones. An additional 13.6% of forest cover loss occurred in limited production forests, where clearing is restricted.
Table 1. Area, forest area, and forest cover loss area within the official land allocation zones on Sumatera and Kalimantan (zones according to the Ministry of Forestry Indonesia 2008, Ministry of Forestry Indonesia 2003a).

| Land allocation zone               | Legal clearing               | Area (Mha) | Forest area 2000 (Mha) | Area of forest cover loss (Kha) | % of all forest cover loss | % of forest cover loss in forest use zones |
|-----------------------------------|------------------------------|------------|------------------------|--------------------------------|--------------------------|-------------------------------------------|
| Biodiversity conservation forest  | No                           | 8.7        | 7.3                    | 112.2                          | 2.1                      | 8.9                                       |
| Watershed protection forest       | No                           | 12.5       | 10.3                   | 237.3                          | 4.4                      | 18.7                                      |
| Limited production forest         | Restricted clearing          | 15.3       | 12.1                   | 734.2                          | 13.6                     | 72.4                                      |
| Conversion forest                 | Yes                          | 10.3       | 4.6                    | 890.8                          | 16.5                     |                                            |
| Regular production forest         | Temporary clearing           | 21.0       | 12.9                   | 1952.6                         | 36.1                     |                                            |
| Other use                         | Yes                          | 32.1       | 10.6                   | 1475.0                         | 27.3                     |                                            |

Figure 5. Forest cover loss trends 2000–2008 for Riau and Central Kalimantan provinces.

Clearing in watershed protection and biodiversity conservation forests did not show a distinct trend except for a year of maximum clearing in 2005 (figure 6). Clearing in limited production forests generally increased over the 8-year period of the study. As much as 27.3% of all forest cover loss occurred outside the official forest zone (table 1), where a generally increasing trend in clearing was observed (figure 6).

4. Discussion

4.1. Spatio-temporal variation in forest cover loss

Our results extend those of Hansen et al. (2009), who identified a near-monotonic increase in forest cover loss from 2000–2005. Our results reveal a peak in forest cover loss in 2006 followed by a gradual reduction thereafter, and provide a spatio-temporally explicit quantification of forest cover loss in Sumatera and Kalimantan.

Forest cover loss within Sumatera and Kalimantan is a largely a function of clearing within Riau and Central Kalimantan provinces, respectively. Forest cover loss within Riau and Central Kalimantan provinces accounts for nearly half of the total forest cover loss in the study area; their proportion of total change did not increase or decrease over time. The individual trends for Sumatera and Kalimantan were different and reflected the dynamics of Riau and Central Kalimantan provinces, respectively. The trend for Central Kalimantan corresponds to van der Werf et al.’s (2008) MODIS-derived deforestation trend for South Borneo that has been linked to fire and El Niño droughts (van der Werf et al. 2008). Dry season precipitation in Sumatera is spatially more variable than that of Borneo, and interannual variation in Sumatera’s precipitation is less distinct (van der Werf et al. 2008). Field et al. (2009) identified differences in the relationship between drought and fire for Sumatera and Kalimantan before the 1980s and attributed them to differences in population growth and transition to large plantations. Catastrophic El Niño fires have been interpreted as people using the opportunity of anomalous climatic conditions to clear forests via fire (Fuller et al. 2004, Casson 2000), an effect that possibly occurs when population density and the landscape proportion of large plantations reach a certain level.

The deforestation curve for Riau province, as published by Uryu et al. (2008), shows similar patterns to the trend we derived for the same area. Riau province has the largest pulp mill capacity in Indonesia (Uryu et al. 2008). Relatively low deforestation rates have been interpreted by Uryu et al. (2008) as a consequence of Riau’s pulp and paper industry defaulting on its debt in the early 2000s and a large police investigation concerning illegal logging in Riau in 2007. In the interim period, our results illustrate Riau’s rapid and extensive forest cover clearing. Variation in governance from one district to another has been debated as a region-specific deforestation driver (Smith et al. 2003, McCarthy 2002). Variation in governance increased with Indonesia’s decentralization after the years of the Suharto regime and has been held responsible for an increase in illegal logging (Casson and Obidzinski 2002, Smith et al. 2003).
4.2. Forest cover loss in different land allocation zones

Our analysis showed that the majority of all mapped forest cover loss (79.9%) occurred in land allocation zones that permit permanent or temporary clearing, while 20.1% occurred where clearing is either prohibited or restricted. Effective enforcement of existing biodiversity conservation, watershed protection, and limited production forest land use designations could significantly reduce forest cover loss. Furthermore, the increasing trend in forest cover loss in the limited production zone is of concern as clearing within this zone is restricted (Ministry of Forestry Indonesia 2003a). The trend within this zone mirrored that of the regional total, reflecting increased exploitation of limited production forests. We also found that a large and increasing proportion of forest cover loss occurred outside the official forest zone, an area that we mapped as 40% forest covered in 2000. Based on visual inspection of composite imagery, we interpreted forest clearance activity in this zone as replacement of oil palm plantation and small scale agriculture.

Both conversion and regular production forest zones exhibited a general increasing trend over the study period, with production forests having a higher overall rate of increase compared to conversion forests. Commercial forest land uses, such as timber plantations, are allowed within both production and conversion forests. Thus, while forest cover loss within biodiversity conservation and watershed protection zones implies the loss of intact forest, such a determination is not possible in this study for conversion and regular production forests.

4.3. Quantifying activity data in support of REDD+

Annual quantification of activity data is considered an important objective under REDD+ (Baker et al 2010). For Indonesia, annual maps of forest cover loss have not been previously provided. For Sumatera and Kalimantan, our results illustrate an interannual forest cover loss dynamic similar to that found in the Brazilian states of Mato Grosso and Para (INPE 2010). However, our estimate includes all forest cover loss, not just intact forest loss as with INPE’s product. Given the identified high spatial and temporal variation in forest cover loss trends, annual change estimates will be needed for determining baselines and evaluating policy impacts, more specifically quantifying the displacement of forest cover loss and permanence of forest cover loss reduction. While the specific integration of our annual map products into the policy process is yet to be determined, we believe that using maps with lower temporal resolution (multi-year averages) would lead to an inaccurate evaluation of policy impacts. Total mapped forest cover loss from 2000–2008 was derived from Landsat imagery. The temporal disaggregation of this total was based on annual detections of a MODIS forest cover loss product. Small and isolated Landsat-mapped forest cover loss patches could not be clearly allocated using the coarse spatial resolution MODIS product. Instead, those areas were allocated to individual years proportional to the temporal distribution of clearly allocated forest cover loss. We assume that the Landsat-derived totals and the inter annual trend per province, which was driven by industrial-scale clearing, closely approximated reality. However, the trends within certain forest land uses, for example watershed protection forests that are located mostly in uplands and characterized by small clearing patches, were less certain.

In this work, we did not differentiate the type of forest that has been cleared. The results of this study quantify the dynamics of all forest cover that has been lost between 2000 and 2008 for the study area including old growth, degraded, and secondary forest as well as timber plantations and oil palm estates. Differentiating forest types is important in determining emissions factors in a carbon accounting framework, but also critical in quantifying other ecosystem goods and services such as biodiversity conservation. Remote sensing-based identification of forest type is technically more challenging than forest cover loss mapping and is the subject of ongoing research.

5. Conclusion

The integrated use of multi-resolution remote sensing data is required for monitoring forest cover loss in many humid tropical forest zones with highly variable loss rates. Cloud contamination and restricted image acquisition strategies limit annual monitoring based only on Landsat 7 data for many humid tropical regions. However, Landsat 7-based maps over multi-year time steps are feasible. To date, annual forest cover loss maps have not been available for Indonesia, a country second only to Brazil in terms of area of humid tropical forest cover loss. Quantifying the spatial and temporal variation of forest loss ‘activity data’ within Indonesia is necessary in light of the ambitious goals of the Norway–Indonesia REDD+ Partnership.

Previous work quantifying Indonesian forest cover loss provided multi-year average maps (Government of Indonesia/World Bank 2000), sample-based estimates (e.g. Hansen et al 2009), and annual maps for specific regions (Gaveau et al 2009a, 2009b, 2009c, Uryu et al 2008, van der Werf et al 2008). Our method is the first to map gross forest cover loss at moderate spatial resolution annually for Sumatera and Kalimantan, Indonesia. For Sumatera and Kalimantan, a large and rapidly changing area in Indonesia, the combined use of spatially detailed Landsat data with temporally detailed MODIS data allowed the disaggregation of Landsat-mapped forest cover loss to individual years. This was possible due to the predominance of industrial-scale forest clearing in Sumatera and Kalimantan. The analysis of our annual spatially explicit datasets based on multi-resolution optical remote sensing data revealed large variations in the spatio-temporal trends of forest cover loss. The high observed fraction of forest cover loss in zones where clearing should be restricted, or where clearing is prohibited, points towards a significant potential for reducing forest cover loss in Indonesia via the effective enforcement of existing forest land use designations. The results of such enforcement should be verified using remotely sensed data sets. Operational satellite monitoring of national-scale forest dynamics will also provide information for the detection of displacement and the assessment of
permanence in response to changes in forest governance. Annual monitoring is required to identify the impact of new policy and law enforcement in an environment characterized by high spatial–temporal variations in forest cover loss rates. Results from this study illustrate the value and important contribution of multi-source approaches to forest monitoring.

Acknowledgments

Funding from the National Aeronautics and Space Administration supported this research under grant NWX08AL99G managed under the NASA Land Cover Land Use Change program (manager: Dr Garik Gutman).

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

Baker D J et al 2010 Achieving forest carbon information with higher certainty: a five-part plan Environ. Sci. Policy 13 249–60

Breiman L 1996 Bagging predictors Mach. Learn. 24 123–40

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

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))

Casson A and Obidzinski K 2002 From new order to regional autonomy: shifting dynamics of ‘illegal’ logging in Kalimantan, Indonesia World Dev. 30 2133–51

Cheng K S, Wei C and Chang S C 2004 Locating landslides using multi-temporal satellite images Adv. Space Res. 33 296–301

COP16/CMP6 2010 16th Conf. Parties (COP) and the 6th Conf. Parties Serving as the Mtg Parties to the Kyoto Protocol Decisions adopted by COP 16 and CMP 6. Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention (available at http://unfccc.int/meetings/cop_16/items/5571.php)

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 1000–3

FAO 2005 State of the World’s Forests (Rome: Food and Agriculture Organization of the United Nations)

Field R D, van der Werf G R and Shen S S P 2009 Human amplification of drought-induced biomass burning in Indonesia since 1960 Nat. Geosci. 2 185–8

Forest Survey of India 2004 State of Forest Report 2003 (Dehra Dun, India: Ministry of Environment and Forest)

Forest Watch Indonesia/Global Forest Watch 2002 The State of the Forest: Indonesia (Bogor, Indonesia: Forest Watch Indonesia) (Washington, DC: Global Forest Watch)

Friedl M A, Brodley C E and Strahler A H 1999 Maximizing land cover classification accuracies produced by decision trees at continental to global scales IEEE Trans. Geosci. Remote Sens. 37 969–77

Fuller D O 2006 Tropical forest monitoring and remote sensing: a new era of transparency in forest governance? Singapore 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

Gaveau D L A, Epting J, Lyne O, Linkie M, Kumara I, Kanninen M and Leader-Williams N 2009a Evaluating whether protected areas reduce tropical deforestation in Sumatra J. Biogeogr. 36 2165–75

Gaveau D L A, Linkie M, Suyadi Levang P and Leader-Williams N 2009b Three decades of deforestation in southwest Sumatra: effects of coffee prices, law enforcement and rural poverty Biol. Conserv. 142 597–605

Gaveau D L A, Wich S, Epting J, Juhn D, Kanninen M and Leader-Williams N 2009c The future of forests and orangutans (Pongo abelii) in Sumatra: predicting impacts of oil palm plantations, road construction, and mechanisms for reducing carbon emissions from deforestation Environ. Res. Lett. 4 034013

Global Observation of Forest and Land Cover Dynamics 2009 A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emission and removals caused by deforestation, gains and losses of carbon stock in forests remaining forest, and forestation GOFC-GOLD Report Version COP15-1

Government of Indonesia/World Bank 2000 Deforestation in Indonesia: A Review of the Situation in 1999 (Jakarta: Government of Indonesia/World Bank)

Gullison R E et al 2007 Tropical forests and climate policy Science 316 985–6

Hansen M, DeFries R S, Townshend J R G, Carroll, M, Dimiceli C and Kohlbarg 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 1–15

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

Hansen M, Roy D, Lindquist E, Adusei B, Justice C and Altstatt 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, Shimabukuro Y E, Potapov P and Pittman K 2008a Comparing annual MODIS and PRODES forest cover change data for advancing monitoring of Brazilian forest cover Remote Sens. Environ. 112 3784–93

Hansen M, Stehman S V, Potapov P V, Arunarwati B, Stolle F and Pittman K 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

INPE (Instituto Nacional de Pesquisas Espaciais) 2010 Deforestation Estimates in the Brazilian Amazon (São José dos Campos: INPE) (available at (http://www.obt.inpe.br/prodes/)

Intergovernmental Panel on Climate Change 2003 Good Practice Guide for Land Use, Land-Use Change and Forestry (LULUCF) (available at (http://www.ioccc-nggip.iges.or.jp)

Intergovernmental Panel on Climate Change 2006 Guidelines for National Greenhouse Gas Inventories vol 4 Agriculture, Land Use and Forestry (AFOLU) (available at (http://ipcc-nggip.iges.or.jp)

Intergovernmental Panel on Climate Change 2007 Climate Change 2007—The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report Law Republik Indonesia 1999 UURI 41/1999; P.32/1999

Le Quere C et al 2009 Trends in the sources and sinks of carbon dioxide Nat. Geosci. 2 831–6

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

McCarthy J F 2002 Turning in circles: district governance, illegal logging, and environmental decline in Sumatra, Indonesia Soc. Natur. Res.: Int. J. 15 867–86
Meyfroidt P, Rudel T K and Lambin E F 2010 Forest transitions, trade, and the global displacement of land-use *Proc. Natl Acad. Sci. USA* **107** 20917–22

Michaelsen J, Schimel D S, Friedl M A, Davis F W and Dubayah R C 1994 Regression tree analysis of satellite and terrain data to guide vegetation sampling and surveys *J. Vegetat. Sci.* **5** 673–86

Miles L and Kapos V 2008 Reducing greenhouse gas emissions from deforestation and forest degradation: global land-use implications *Science* **320** 1454–5

Ministry of Forestry Indonesia 2003a MoF 88/2003; P61/2003

Ministry of Forestry Indonesia 2003b *Rekalkulasi Sumber Daya Hutan Indonesia Tahun (Forest Resource Recalculation)* Forest Planning Agency

Ministry of Forestry Indonesia 2008 *Digital Forest Land Use Map*

Morton D C, DeFries R S, Shimabukuro Y E, Anderson L O, Espirito-Santo F D B, Hansen M and Carroll M 2005 Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data *Earth Interact.* **9** 1–22

Prasad A M, Iverson L R and Liaw A 2006 Newer classification and regression tree techniques: bagging and random forests for ecological prediction *Ecosystems* **9** 181–99

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

Sanchez-Azofeifa G A, Castro-Esau K L, Kurz W A and Joyce A 2009 Monitoring carbon stocks in the tropics and the remote sensing operational limitations: from local to regional projects *Ecol. Appl.* **19** 480–94

Smith J, Obidzinski K and Subaru Suramenggala I 2003 Illegal logging collusive corruption and fragmented governments in Kalimantan, Indonesia *Int. Forestry Rev.* **5** 293–302

Uryu Y et al 2008 Deforestation, Forest Degradation, Biodiversity Loss and CO2 Emission in Riau Technical Report (Indonesia, Jakarta: WWF Indonesia)

USGS 2006 *Shuttle Radar Topography Mission, 3 Arc Second, Filled Finished-A, 2.0, Global Land Cover Facility* (College Park, MD: University of Maryland)

van der Werf G R, Morton D C, DeFries R S, Olivier J G J, Kasibhatla P S, Jackson R B, Collatz G J and Randerson J T 2009 CO2 emissions from forest loss *Nat. Geosci.* **2** 829 (correction)

van der Werf G R et al 2008 Climate regulation of fire emissions and deforestation in equatorial Asia *Proc. Natl Acad. Sci. USA* **105** 20350–5

Vermote E F, El Saleous N Z and Justice C O 2002 Atmospheric correction of MODIS data in the visible to middle infrared: first results *Remote Sens. Environ.* **83** 97–111

Vincent R K 1973 Spectral ratio imaging methods for geological remote sensing from aircraft and utilization of remotely sensed data *Proc. American Society of Photogrammetry, Management and Utilization of Remote Sensing Data Conf. (Sioux Falls, South Dakota)* ed A Anson (Virginia: American Society of Photogrammetry) pp 377–97

WWW1, available: http://landsat.usgs.gov/

WWW2, available: http://modis.gsfc.nasa.gov/

WWW3, available: http://ftp.glcf.umd.edu/