# ABSTRACT

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| Title of Document: | ADVANCING INDONESIAN FOREST RESOURCE MONITORING USING MULTI-SOURCE REMOTELY SENSED IMAGERY |
| | Belinda Arunarwati Margono, Doctor of Philosophy, 2014 |
| Directed By: | Professor, Matthew C Hansen, Department of Geographical Science |

Tropical forest clearing threatens the sustainability of critically important global ecosystems services, including climate regulation and biodiversity. Indonesia is home to the world's third largest tropical forest and second highest rate of deforestation; as such, it plays an important role in both increasing greenhouse gas emissions and loss of biodiversity. In this study, a method is implemented for quantifying Indonesian primary forest loss by landform, including wetlands. A hybrid approach is performed for quantifying the extent and change of primary forest as intact and degraded types using a per-pixel supervised classification mapping followed by a GIS-based fragmentation analysis. The method was prototyped in Sumatra, and later employed for the entirety of Indonesia, and can be replicated across the tropics in support of REDD+ (Reducing Emissions from Deforestation and forest Degradation) initiatives. Mapping of Indonesia's wetlands was performed using cloud-free Landsat image mosaics, ALOS-PALSAR imagery and topographic indices derived from the SRTM. Results quantify an increasing rate of primary forest loss over Indonesia from 2000 to 2012. Of the 15.79 Mha of gross forest cover loss for Indonesia reported by Hansen *et al.* (2013) over this period, 38% or 6.02 Mha occurred within primary intact or degraded forests, and increased on average by 47,600 ha per year. By 2012, primary forest loss in Indonesia was estimated to be higher than Brazil (0.84 Mha to 0.47 Mha). Almost all clearing of primary forests (>90%) occurred within degraded types, meaning logging preceded conversion processes. Proportional loss of primary forests in wetlands increased with more intensive clearing of wetland forests in Sumatra compared to Kalimantan or Papua, reflecting a near-exhaustion of easily accessible lowland forests in Sumatra. Kalimantan had a more balanced ratio of wetland and lowland primary forest loss, indicating a less advanced state of natural forest transition. Papua was found to have a more nascent stage of forest exploitation with much of the clearing related to logging activities, largely road construction. Loss within official forest-land uses that restrict or prohibit clearing totaled 40% of all loss within national forest-land, another indication of a dwindling resource. Methods demonstrated in this study depict national scale primary forest change in Indonesia, a theme that until this study has not been quantified at high spatial (30m) and temporal (annual) resolutions. The increasing loss of Indonesian primary forests found in this study has significant implications for climate change mitigation and biodiversity conservation efforts.

# ADVANCING INDONESIAN FOREST RESOURCE MONITORING USING MULTI-SOURCE REMOTELY SENSED IMAGERY

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Advisory Committee:
Professor Matthew C Hansen, Chair
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Dr. Fred Stolle
Professor Marla McIntosh

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Belinda A Margono,
College Park, March 2014

*To my late mother: Dra. Soekilah Margono MA, who inspires me to walk this far*

*And to all who value their life by taking challenging opportunities to live their life!*

(Journey's poem)

*The Road goes ever on and on*
*Down from the door where it began*
*Now far ahead the Road has gone,*
*And I must follow, if I can,*
*Pursuing it with eager feet,*
*Until it joins some larger way*
*Where many paths and errands meet*
*And whither then? I cannot say.*

*The Road goes ever on and on*
*Out from the door where it began.*
*Now far ahead the Road has gone,*
*Let others follow it who can!*
*Let them a journey new begin,*
*But I at last with weary feet*
*Will turn towards the lighted inn,*
*My evening-rest and sleep to meet*

*(Lord of the Rings)*

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# Chapter 1: Rationale and Dissertation layout

The overall goal of this research is to advance national scale forest monitoring in Indonesia, including the quantification of forest disturbance dynamics, across space and through time with outputs appropriate for sustainable forest management and carbon accounting objectives. The entirety of this research is included in this dissertation, which is composed of five chapters. Chapter one contains the introduction to the research, background, study area, research objectives, structure of the research design, and dissertation layout. Chapters two, three, and four explain the sequential work flow to develop, test and complete the research work for the entire study area, subsequently concluded in Chapter five.

## Introduction

The extent of forest cover is essential knowledge for effectively managing forest resources, especially primary forests, which contain high carbon stocks and biodiversity richness. As such, quantifying the extent and loss of primary forest is valuable information for carbon accounting and biodiversity modeling efforts. Wetland cover is another significant classification type for carbon accounting, particularly for peat sub-types. Quantifying dynamic forest extent and disturbances across space and through time, throughout various forest landscapes such as *terra-firma* lowland, wetland, upland and montane forests, would further enhance assessments of forest carbon and biodiversity. Such information would help to facilitate monitoring, reporting, and verification (MRV) needs for programs that require carbon data (GOFC-GOLD 2010), including the Reducing Emission from Deforestation and Forest Degradation (REDD) and REDD+ initiatives of the United Nations Framework Convention on Climate Change (UNFCCC). To date, such information has not been readily available for Indonesia.

Remote sensing data have been applied widely to provide spatially and temporally explicit information for monitoring forest extent and disturbance (Holmes 2000, Woodcock *et al* 2001, Hansen *et al* 2003, 2009, Olander *et al* 2008). A reasonable cost and long-term availability of data are key characteristics in selecting remote sensing data for monitoring purposes, especially in developing countries such as Indonesia. Data from the Landsat suite of sensors fit these requirements (Tucker *et al* 2004) and are used to map forest cover and loss for Indonesia in this study. Landsat is a medium spatial resolution sensor with collected imagery of the earth's surface since 1972 (Wulder *et al* 2012). Landsat data are considered appropriate for accurate forest cover loss area estimation (GOFC-GOLD 2010, Hansen and Loveland 2012) and are used in Indonesia at the national scale for official mapping of forest cover (MoF 2008a, 2008b). Landsat has been used for mapping in Indonesia since the 1990s (Revilla and Liang 1989). Mining the Landsat 7 ETM+ and Landsat 5 TM archives is possible for Indonesia (Potapov *et al* 2012, Hansen and Loveland 2012) given the change in Landsat data policy, as the United States Geological Survey (USGS) has made Landsat data freely available over the internet since 2008 (Wulder *et al* 2008, 2012, Roy *et al* 2010). The free availability of the archive is critical in overcoming cloud cover within tropical regions such as Indonesia (Hansen *et al* 2009).

Consistent methodologies implemented repeatedly over time are a fundamental requirement for national-scale forest monitoring using remotely sensed data (DeFries *et al*

2007, Hansen and Loveland 2012). The conventional method appropriate for monitoring forest cover disturbances is visual interpretation of aerial photograph or satellite imagery. Such an approach is labor intensive, especially at a national scale (e.g. Revilla and Liang 1989, Skole and Tucker 1993, Holmes 2000). Another approach is digital image processing and mapping using either sample or wall-to-wall mapping approaches (Achard *et al* 2002, Hansen *et al* 2003, Hansen and DeFries 2004, DeFries *et al* 2007, Hansen *et al* 2008, Hansen and Loveland 2012). Sample approaches include an approach based on the stratification of low spatial resolution imagery to target Landsat samples (Hansen *et al* 2009, Broich *et al* 2011), high spatial resolution satellite imagery such as IKONOS/GeoEye-1 (Miettinen *et al* 2012), or systematic sampling grids using Landsat data (Stibig *et al* 2014).

In this research, a product made using a wall-to-wall approach and Landsat data (Potapov *et al* 2012) to map forest extent and loss is integrated with other data to quantify primary forest loss. Additionally, data from the Shuttle Radar Topography Mission (SRTM) (Bwangoy *et al* 2010) and the Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) (Bwangoy *et al* 2013, Margono *et al* 2014) were also used to characterize landforms, including wetlands (Zedler and Kercher 2005, Gong *et al* 2010). The aim of this research is to create spatial information required for forest management and carbon monitoring in Indonesia. This was achieved by utilizing multi-source remotely sensed imagery, of both passive and active sensors, as a data source for quantifying primary forest extent and disturbance.

***Background***

Warnings of climate change due the increase of greenhouse gases (GHG) emissions in the atmosphere have been ongoing since the end of the 20th Century, but only truly began to garner global attention after the release of the Stern Review in 2006 (Tol and Yohe 2006). The Stern Review (2006) highlighted the role of land use changes, primarily deforestation, as a major source of GHG in driving climate change. After the publication of the Stern Review, the Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC), a leading international body under the United Nations Environment Program (UNEP), escalated global attention to climate change by reporting deforestation and forest degradation as the second leading contributor to anthropogenic greenhouse emissions following fossil fuel combustion, contributing over 17 percent of global carbon dioxide ($CO_2$) emissions (IPCC 2007). The IPCC Report stated that 75 percent of the emissions have been from developing countries containing large extents of tropical forest, including Brazil, Indonesia, Papua New Guinea, Malaysia, Gabon, Costa Rica, Cameroon, Republic of Congo and the Democratic Republic of the Congo (IPPC 2007, MoF 2008b).

The reports encourage development of global initiatives under the United Nation Framework Convention on Climate Change (UNFCCC), introduced as REDD and REDD+, as part of climate change mitigation actions post Kyoto Protocol. REDD emphasizes efforts towards developing financial support through valuation of stored carbon in forests; and offering incentives to the developing countries to reduce emissions from deforestation and forest degradation; as well as promising developed countries (Annex 1 parties of the UNFCCC) a low carbon path-way to support a more sustainable type of development. REDD+ takes this a step further than REDD, and includes sustainable forest management, conservation and enhancement of forest carbon stocks. Global initiatives such as this require comprehensive documentation of timely and spatially explicit information for natural forest extent and disturbances, particularly at the national scale (DeFries *et al* 2007, Olander *et al* 2008, GOFC-GOLD 2010, Hansen and Loveland 2012), especially for Indonesia, the world's third largest emitter of greenhouse gases (WB-PEACE 2007).

Tropical peatland is one of the largest near-surface reserves of terrestrial organic carbon, and has enormous implications for climate change mitigation (Page *et al* 2002). Environmental changes to these ecosystems, such as drainage and forest clearing (Page and Rieley 1998, Uryu *et al* 2008), can intensify vulnerability and be a link to fire susceptibility. Indonesia is estimated to have 39.6 Mha of wetlands, 90 percent (35.8 Mha) distributed largely on the islands of Sumatra, Kalimantan and Papua (Margono *et al* 2014), which 58 percent (20.6 Mha) of peat types (Wahyunto *et al* 2003, 2004, 2006). National concern of these wetlands grew significantly following the extensive smoke pollution from smoldering peatlands in Sumatra and Kalimantan in the late 1990s, and also captured the attention of scientists and politicians around the world due to the magnitude of carbon emissions released (Page *et al* 2002, 2007, Usup *et al* 2004, Jauhiainen *et al* 2005, MoF 2008b, and Jaenicke *et al* 2008).

Indonesia's projected emissions by 2020 from a business-as-usual (BAU) standpoint estimate forestry and peatland loss to contribute over 60 percent of the country's total $CO_2$ emissions (Indonesian's Second National Communication 2009). At the Group of Twenty (G-20) summit in Pittsburgh in 2009, the Government of Indonesia (GOI) pledged to reduce Indonesia's GHG emission below the BAU 2020 projection by 26 percent with only domestic financial sources and by 41 percent with international financial assistance (Leader's yearbook 2011) while maintaining annual economic growth at 7 percent.

Following the pledge, and part of a $1 billion Indonesia-Norway partnership on REDD+ (LOI 2010), on May 2011 the Indonesian President Susilo Bambang Yudoyono announced a two year forest moratorium on the issuance of new permits in utilizing primary natural forest and peatlands (Presidential Instruction 10/2011). Another decree was released on May 13 2013 (Presidential Instruction 6/2013), extending the first moratorium implementation for two additional years. Overall, Indonesia has shown a commitment to reducing emissions from deforestation and forest degradation. However the effectiveness of the activities resulting from that commitment requires from Indonesia a credible and exhaustive monitoring system including comprehensive data documentation and robust methodologies. This research aims to fill that demand.

***The study area***

Indonesia is the largest country archipelago in the world, and lies on the approximate latitude of $4^0$ N to $11^0$ S and longitude of $94^0$ to $140^0$ E, scattered along both equator sides. The major islands are Sumatra, Kalimantan/Borneo (shared with Malaysia and Brunei), Java, Sulawesi, group of Moluccas islands, group of Nusa Tenggara islands, and Papua/ New Guinea (shared with Papua New Guinea) (Figure 1.1). Geographically, Indonesia has a tropical climate that is suitable for plant to growth throughout the year. It has a fairly constant temperature range from $28^0$ Celsius on the coastal plains to $26^0$/$23^0$ Celsius on the inland and mountain areas. However as an archipelago, Indonesia is very vulnerable to climate change.

Indonesia’s land extent is 187 Mha ha or about seven times that of the US state of Texas, with 53 percent covered by forests (MoF 2008a). The forests account for 2.3 percent of global forest cover (UNFAO 2010) and represent 39 percent of South East Asia’s forest extent (Achard *et al* 2002). Indonesia straddles the Wallace line (Wallace 1958) and has a humid tropical climate. As a result, Indonesia's forests feature a tremendously high floral and faunal biodiversity (FWI/GWF 2002, MoF 2003), containing 10 percent of the world's plants, 12 percent of the world's mammals, 16 percent of the world's reptile-amphibians, and 17 percent of the world's bird species (RePPProT 1990, Whitten *et al* 1996, 2000, 2002, MacKinnon *et al* 1996, Monk *et al* 1997, Marshall *et al* 2007). The forest's high biodiversity also makes Indonesia one of the world's mega-diverse countries (Mittermeier *et al* 1997). Preserving this biodiversity would be an invaluable co-benefit to reducing deforestation and forest degradation.

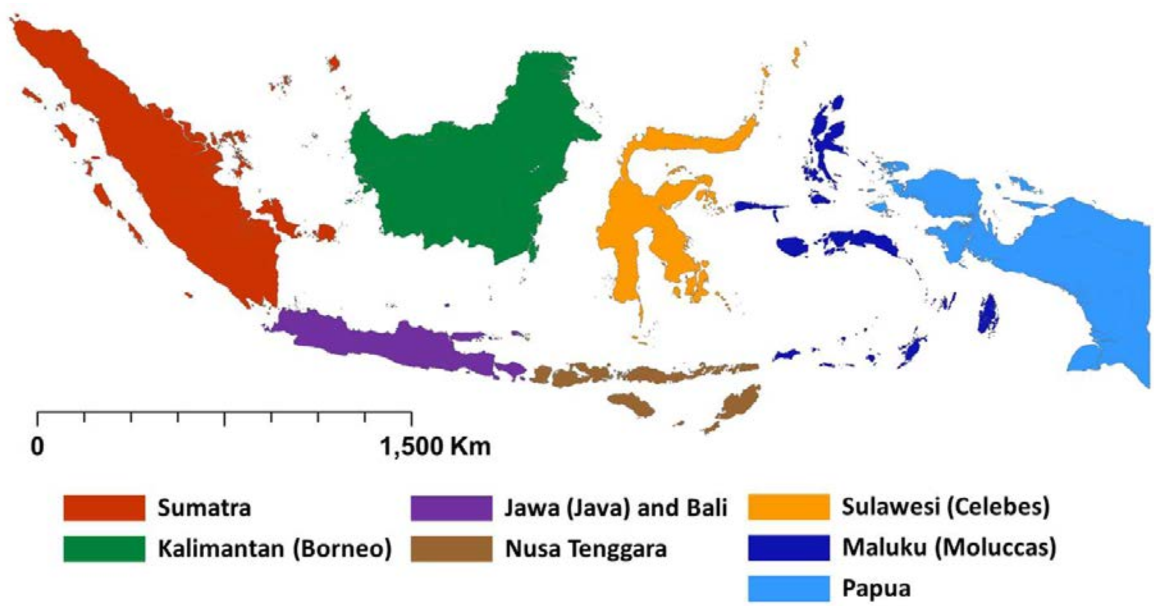


**Figure 1. 1.** Indonesia, an archipelago in South East Asia with the seven major islands / group of islands, representing general biogeographic regions that Indonesia encompasses

As a developing country with the 4th largest population in the world, (Indonesian central statistical agency 2012) almost 65 Mha or about 27 percent of Indonesia's population depends directly on these forests for their livelihoods (FWI/GWF 2002). Along with 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* 2008, 2009) with an estimated annual gross emission from deforestation of 502 Mha t $CO_2$ equivalents (MoF 2008b).

In an effort towards sustainable management of forests, the government of Indonesia (GOI) categorizes Indonesian forest-land use based on a consensus approach (Forestry Law 1999, MoF 2008a, 2011). Forest-land (*kawasan hutan*) is a land designation that indicates a use addressed for forestry with no regard to its actual land cover type. According to recent data (MoF 2012), Indonesia's forest-land covers 70 percent of the land, and is comprised of Protection forests (24.5 percent), Conservation forests (16.2 percent), and Production forests (59.3 percent). Of Production forests, 17.4 percent are designated as Limited Production forests, 26 percent as Regular Production forests, and 15.9 percent as Convertible Production forests (MoF 2013). Each forest-land use has a different type of management practice which affects the types of forest disturbance, as well as legal aspects of forest cover change dynamics. Slope, rainfall and soil type were initially used for setting up the forest-land use classification (RePPProT 1990), but it was performed only at a *reconnaissance* scale, and focused on soil susceptibility to erosion, excluding soil carbon organic matter which is important for carbon accounting purposes.

***Indonesia's forest resource monitoring***

Documenting forest dynamics through space and time is urgently needed. In Indonesia this kind of information, particularly the location of deforestation and forest degradation, at the national scale is not well understood. Problems exist due to complex and sometimes conflicting definitions for land cover classification, or due to lack of adequate data, robust methodologies, and insufficient infrastructure to perform work at a national scale. In addition, most work to date has focused on the project level (e.g. province, district levels, or smaller area capture), with the exception of the national land cover map of the Ministry of Forestry of Indonesia (MoF 2003, 2005, 2008b, 2010).

Initially, the Ministry of Forestry of Indonesia (MoF) developed forest resource monitoring through the National Forest Inventory (NFI) of Indonesia, established on 1989. The NFI project ran for seven years under collaboration between the GOI and Food and Agriculture Organization (FAO). Despite some limitations on data collection, the use of satellite imagery to produce a land cover map was introduced during that period and employed Landsat data (Revilla and Liang 1989, 1992). After the end of NFI project, the tasks were transferred to the Forest Planning Agency/Directorate General (DG) of Forest Planning of the MoF. The more systematic monitoring approach based on visual photo-interpretation techniques was first established in 2000. The system regularly produced a three year land cover map of Indonesia, provided 23 land classes including areas of cloud cover and no-data (MoF 2003, 2005, 2008b, 2010, SNI 2010). The workflow for establishing the Indonesian land cover map is illustrated in figure 1.2. This diagram is based on the author's work experiences in the mapping of Indonesia's land cover from 1999 to 2008, with additional observations from 2009 onwards.

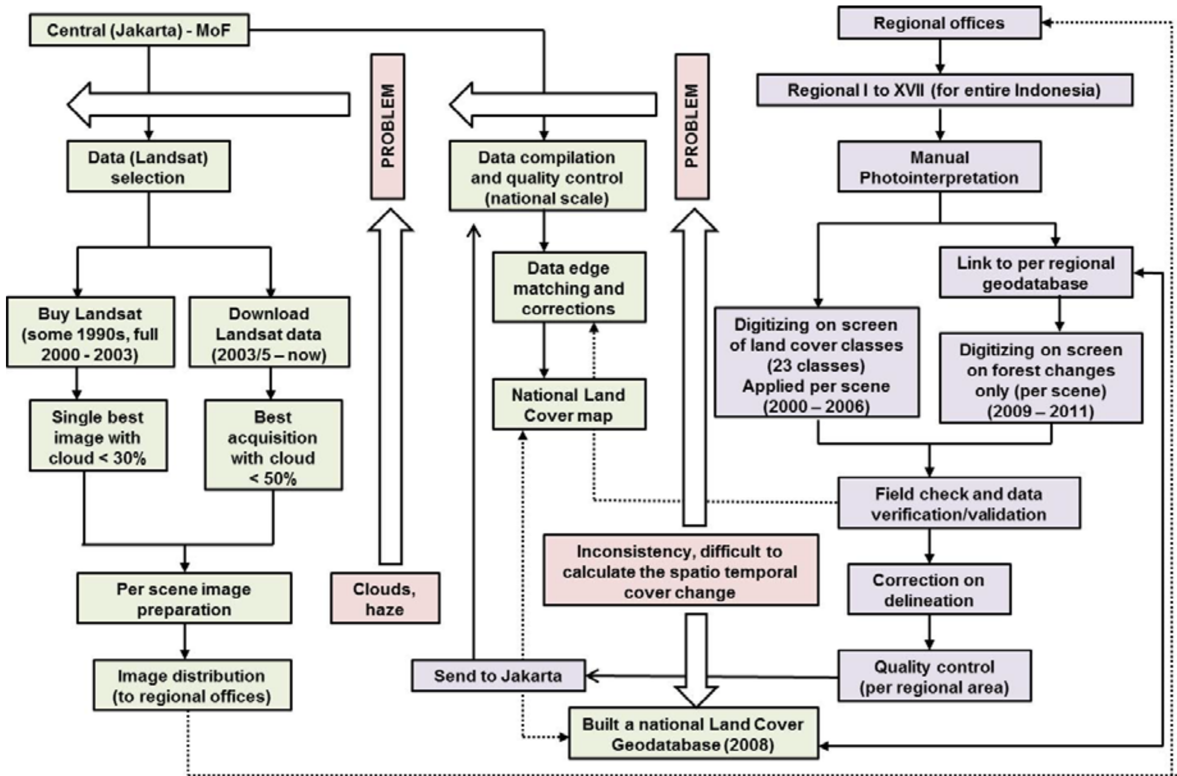


**Figure 1. 2.** General Indonesian Land Cover map workflow. Green color boxes represent activities in central office Jakarta; Purple color boxes represent activities employed in regional offices; Red boxes represent major related problems on the entire workflows. Improvements have been introduced in 2010/2011 onwards for delineating only the polygons of forest cover loss, and simultaneously improving the 23 classes through the Geodatabase establishment.

As illustrated in figure 1.2, the workflow is time consuming, labor intensive and subject to inconsistencies (Margono *et al* 2012). In 2012 and onward, the process in generating land cover classes as well as delineating polygons of forest disturbances was done only at the central office, without involving regional offices except for checking and validating the results. This decision shortens the work flow, but consequently adding work's volume at the central office. In general, three main problems exist: (i) presence of persistent clouds cover, (ii) inconsistency within the mapping processes, and (iii) inability to give near-real time information to match the dynamic recovery of vegetation disturbances. Clouds and haze are the major problems in using optical remotely sensed data in humid tropical regions like Indonesia (Hoekman 1997, Hansen *et al* 2008, 2009). Unlike Brazil, Indonesia does not have a seasonal cloud-free window (Broich *et al* 2011) which would offer an opportunity for capturing clouds-free images. The land cover map of the national forest monitoring system (NFMS) of the MoF is available online at http://nfms.dephut.go.id/ipsdh/, and at http://webgis.dephut.go.id/ for viewing.

## Relevance of the research

Improved methods using automatic data processing have been advantageous to overcoming the main obstacles of using optical passive remote sensing imagery in the tropics. Such methods however require mass data processing (Hansen *et al* 2009, 2013, Potapov *et al* 2011, 2012, Hansen and Loveland 2012), enabling an exhaustive wall-to-wall mapping approach. The study demonstrated here utilizes a wall-to-wall mapping approach for national-scale mapping of Indonesia.

### *Research objectives*

The following objectives and hypothesis are provided to achieve the overall research objective.

*Objective 1:* Characterize differences in natural primary forests in terms of primary intact and primary degraded forests

*Hypothesis 1:* By combining direct and indirect forest change characterization methodologies, an accurate quantification of the extent of primary intact and primary degraded forests and the change of such can be identified using Landsat time-series imagery

*Objective 2:* Establish a baseline of potential wetland of Indonesia for 2000

*Hypothesis 2:* Multi-source remotely sensed data inputs allow for characterization of wetlands at the national scale regardless of conversions of wetlands for other purposes

*Objective 3:* Quantify primary forest extent and loss from 2000 to 2012 in Indonesia by landform

*Hypothesis 3:* Primary forest loss in Indonesia is increasing, similar to estimates of gross forest cover loss for the period 2000 to 2012

Through these three objectives, a set of improved data and methods for national scale forest monitoring in Indonesia is demonstrated and established.

***Research Outline and dissertation layout***

The research is focused on three interrelated topics. Each topic is elaborated independently and integrated at the end of the research, as illustrated in figure 1.3. Work on each topic will be subsequently explained in three following chapters as well as presented in three different papers for independent publication.

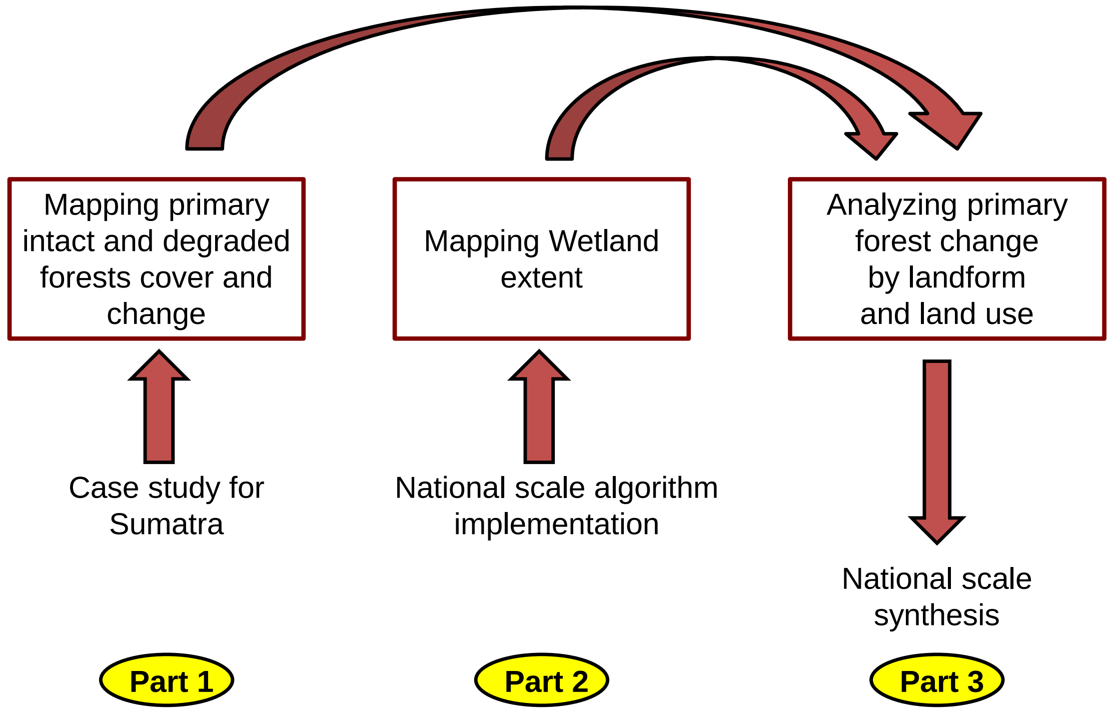


**Figure 1. 3.** Research outline in simultaneously integrated steps of three independent interrelated topics

Part one introduces the mapping of natural primary forests in the form of intact and degraded types, including the associated forest disturbances. Part two explains the mapping of wetlands in which the peat swamp is one of the important sub-types. Part three concludes a comprehensive analysis of natural primary intact and primary degraded forests and disturbances within different landform categories:  lowland *terra-firma*, wetland, upland and montane for the entirety of Indonesia. A comprehensive analysis of geographical and political subdivisions such as island groups and forest-land use are performed accordingly for each topic. In addition, though not included in this research, the work aims to develop an online Indonesian Atlas of all results.

***Characterize primary forests in the form of intact and degraded***

Part one demonstrates a method for mapping primary intact and degraded forests for Sumatra. Sumatra was selected as the research site since the island experiences the most dynamic forest cover change in the country. The works aims to provide a response to each of the following research questions:

1. What is the extent of primary intact and primary degraded forest in Sumatra?
2. What are the rates of primary forests cover loss, both stand-replacement disturbance and forest degradation in Sumatra?
3. In what official forest land use zones of Sumatra have these forests changes occurred?

The work employed a hybrid approach to distinguish two different forest structures: intact and degraded form. A per-pixel mapping approach is implemented for primary forest extent and stand-replacement disturbance, but such an approach is not viable in Indonesia for mapping degradation after logging. Instead, a second procedure emplying a Geographical Information System (GIS)-based fragmentation and buffering analysis was selected to map all human impacts on forest landscapes – roads, villages, etc. Results were evaluated using LIDAR Geoscience Laser Altimeter System (GLAS) data to verify that the hybrid methodology differentiated primary intact and degraded forests.

The work intentionally focuses on assessing the second D in REDD, degradation. The methods are straightforward and repeatable at the national scale. Details of this work are presented in chapter two and are also presented in a peer-reviewed paper entitled "*Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010*". The paper is published in IOP Science Journal: Environmental Research Letters, Volume 7 Number 3 (16pp), 2012, doi:10.1088/1748-9326/7/3/034010. The authors are Belinda A Margono, Svetlana

Turubanova, Ilona Zhuravleva, Peter P Potapov, Alexandra Tyukavina, Alessandro Baccini, Scott Goetz and Matthew C Hansen.

***Establishing a baseline of the potential wetland of Indonesia***

Part two is applied at the national-scale. The related research questions for this study are as follows:

1. How accurate is an algorithm-driven national-scale map compared to heritage photo-interpreted maps?
2. What spectral or spatial inputs enable the mapping of wetland extent in Indonesia?

This work demonstrates the mapping of wetlands in Indonesia, in a single thematic class including peat lands, freshwater wetlands and mangroves. Expert-interpreted training data were used to identify wetland landform including areas of likely past wetland extent that have been converted to other land uses. Topographical indices (SRTM-derived) and optical (Landsat) and radar (PALSAR) image inputs were used to build a topographical model based on earth's surface characteristics in order to generate a national-scale map of potential wetland.

The results represent a synoptic algorithmic application for mapping wetlands extent at the national scale for Indonesia. An internally consistent algorithm-derived national wetland extent map can be used to quantify changing rates of forests conversion inside and outside the wetlands. The work is elaborated in chapter three as well as in a peer-reviewed paper entitled "*Mapping wetlands in Indonesia using Landsat data and PALSAR data sets and derived topographical indices*". The paper is published in Taylor & Francis Journal: Geo-spatial Information Science, Volume 17 Issue 1, 60-71, 2014, doi:

10.1080/10095020.2014.898560. The authors are Belinda A Margono, Jean-Robert B Bwangoy, Peter P Potapov and Matthew C Hansen.

***Indonesia's primary forest and disturbance, 2000 to 2012, on major landform***

Part three is an extension and synthesis of Indonesia's forest cover dynamic based on methods developed and tested in the first and second parts of the thesis. The work responds to the following research questions:

1. What extent of Indonesia's primary forests remains in wetland, lowland *terra firma*, upland, and montane forest landforms?
2. What is the size distribution and pattern of forest cover loss by landform category?
3. What are the trends of primary intact forest clearing versus primary intact forest degradation versus primary degraded forest clearing by landform category?

In this work, the global forest loss data of Hansen *et al* (2013) and an extension of the work of Margono *et al* (2012, 2014) were combined to disaggregate total forest cover loss by primary/non-primary status for the entirety of Indonesia. We further investigate the primary forest extent and loss in terms clearing and degradation by landform. Montane, upland and lowland landform are disaggregated using a different threshold of elevation and slope, with wetland landforms mapped separately.

The results provide national baseline information for the study period primary forest loss. Results are suitable to support global climate change mitigation objectives, biodiversity assessments and national forest management strategies. Details of the work are described in chapter four with an additional sub-chapter analyzing the effectiveness of the first year of the logging moratorium in Indonesia. Two independent papers have been written: "*Primary forests cover loss in Indonesia, 2000 to 2012*", which is submitted to

Nature Climate Change Journal on December 23rd 2013. The authors are Belinda A Margono, Peter Potapov, Svetlana Turubanova, Fred Stolle and Matthew C Hansen. The second paper is still in progress and entitled "*Effectiveness of Indonesia's Forest Moratorium to reduce Deforestation*". The authors are Belinda A Margono, Matthew C Hansen, Svetlana Turubanova, Peter Potapov, Kemen Austin, and Fred Stolle.

**General terminology used**

With the use of remote sensing as a data source for mapping, several unique terms and associated definitions were introduced and adjusted. For this study, "forest" is defined as tree cover with a minimum height of 5 meters and canopy cover density of at least 30 percent at the Landsat pixel scale (referring to FAO 2005, FAO-GFRA 2006, MoF 2008a, GOFC-GOLD 2010, Hansen *et al* 2013). The term "primary forest" is used to define all mature forest stands that retain their "natural" composition, structure, and have not been completely cleared and re-planted in recent history (at least 30 years in age). Due to the spatial resolution of the remote sensing data used, which is Landsat 30 meters resolution, the primary forests were mapped using a minimum mapping unit of 5 ha (GOFC-GOLD 2010). The "non-primary forest" class, as opposed to primary forest, consists of two different sub-classes: "non-primary forest areas - with tree cover" (or other tree cover subclass); and "non-primary areas - without tree cover" (or non-tree cover subclass). The "non-primary forest area - with tree cover" includes timber and pulp plantations, agricultural and mixed tree crops, as well as old coppices. A consistent disaggregation of "primary forest" from "non-primary forest areas - with tree cover" across the globe at the

Landsat pixel scale is unavailable at present and both are presented as tree cover (Hansen *et al* 2013). The "non-primary forest" class, both with and without tree cover, is a theme in this study. The analysis focuses only on "primary forest cover".

The primary forests were disaggregated into two different types: intact (undisturbed type), and degraded (disturbed type). "Intact primary forest" has a minimum area unit of 500 $km^2$ with the absence of detectable signs of human-caused alteration or fragmentation, and refers to the Intact Forest Landscape definition of Potapov *et al* (2008). The "degraded primary forest" is a primary forest that has been fragmented or subjected to forest utilization, e.g. by selective logging or other human disturbances, which have led to partial canopy loss and altered forest composition and structure (ITTO 2002, Margono *et al* 2012). Corresponding to the official national land cover data sets available in the country, a product comparison is enabled. The terms "primary intact forest" and "primary degraded forest" used in this study refer to the primary (undisturbed) forest class and secondary forest class, respectively, from the land cover classification of *Standar Nasional Indonesia* (SNI) 7654 (2010) employed by the Ministry of Forestry of Indonesia (MoF), as well as in Indonesian UNREDD documentation (2013). In the SNI and UNREDD documentation, the secondary forest class of Indonesia is not described as a forest experiencing a successional process after clearing, or secondary regrowth (Chokkalingam and De Jong 2001, Wilcove *et al* 2013). Secondary forest according to the official definitions has been described as disturbed, principally by logging activities and has not experienced stand-replacement disturbance. Primary forest cover loss refers to primary forests of both intact and degraded types which experience a stand replacement disturbance; while primary forest that experience a transition from intact to degraded type refers to forest degradation. The mapping of primary forests by type is further elaborated in Chapter two.

The term forest formation is commonly used as a category to express the floristic, structural complexity and physiognomy of the stands (Grubb *et al* 1963, Whitmore 1984, Allaby 2004) and is highly associated with climatic, edaphic, and physiographic factors (Richard *et al* 1940, Clark *et al* 1999,). This variation will be a substantial input for biomass estimation (Clark and Clark 2000, Laumonier *et al* 2010) and biodiversity protection (Wilcove *et al* 2013). In this study, visible major landforms such as lowland, wetland, upland and montane, were employed to express physical forms of the surface that representing forest formations in disaggregating primary forest cover dynamic. The wetlands landform was defined as temporary or permanently inundated lands having a water table at or near the land surface (Cowardin et al 1979, Middleton 1999). Wetlands mapping is elaborated in Chapter three. The major non-wetland landforms include lowlands, uplands and montane and were mapped based on broad physiographic features with details presented in Chapter four.

Wetland primary forest formations include inundated primary forest, either permanently or seasonally, such as peat swamp forest, brackish-water forest, freshwater swamp forest, and mangrove forest (Whitmore 1984). Non-wetland primary forest (lowland forest formation) refers to dry-land rainforest (Whitten 1984), which are forests growing on well-drained mineral soils. Previous studies introduced this lowland primary forest formation as non-swampy lowland forests (Holmes 2000), dry lowland forest (Holmes 2002), non-swamp forests (Laumonier 2010), and lowland forests (Kinnaird *et al* 2002, Curran *et al* 2004, Miettinen *et al* 2011). For this work, it is simply named lowland (*terra firma*[1]) forest. Montane forest formations are primary forests growing in the biogeographic zone with relatively moist cool upland slopes up to the tree line. The forest is a *microphyll* dominated forest with relatively flat canopy surfaces of slender trees, usually trees with limbs and very dense sub-crowns (Whitmore 1984). Montane forests are grouped into upper-montane and lower-montane forests. Upland forest formation is the lower montane forest with *mesophyll* dominated forest and taller trees, while compare to the upper montane forests. The upland forests usually spread along a broad ecotone between montane and lowland *terra firma* forests.  Upland forests were distinguished from the upper montane forests as they are commonly utilized for slash and burn agriculture (e.g. Fearenside 1997) by smallholders; montane forests are not used as such and are often set aside for protection and conservation purposes.

[1] *Terra firma* is a phrase mostly used for Amazon Basin forests and not commonly used in South East Asia. However, the term *terra firma* comes from a Latin meaning “solid earth” and refers to the dry land mass on the earth’s surface, regardless of geographical position.

# Chapter 2: Mapping and monitoring deforestation and forest degradation using Landsat time series datasets from 1990 to 2010: a case study for Sumatra (Indonesia) [2]

## Introduction

Forest ecosystems, notably primary forests of the humid tropics, shelter a major portion of terrestrial biological diversity (MacKinnon 1997) including an estimated 80 percent of all terrestrial species (Carnus *et al* 2006), and contain 70-90 percent of terrestrial aboveground and belowground biomass (Houghton *et al* 2009). However, 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) that greatly reducing forest biodiversity and carbon storage of forest biomass. Sumatra is one of Indonesia's island experiences a very dynamic forests cover change (Hansen *et al* 2009, Broich *et al* 2011b, Margono *et al* 2012), including rapid land use conversion in support of agro-industrial development (Miettinen *et al* 2012) that 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). Meanwhile, the forests ecosystem of Sumatra are incredible, home to over 10,000 plants species, 201 mammal species, and 580 avifauna species (Whitten *et al* 2000, MoF 2003).

Besides deforestation, forest degradation has been another major attention within the international forestry community, including the United Nations Forum on Forest

[2] The content of this chapter already published in IOP Science Journal: Environmental Research Letters, Volume 7 Number 3, 2012 (16pp), doi:10.1088/1748-9326/7/3/034010.

(UNFF), and the 2010 Target of the Convention on Biological Diversity (CBD) (Simula 2009). Defining and mapping forest degradation is less mature as compare to deforestation and arriving at a common standard is a challenge (Simula 2009). This 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).

The two problems exist in working with optical remotely sensed data in humid tropical forest environments (Asner 2001, Hansen *et al* 2008, 2009). Those are cloud cover and the quick recovery of forest cover. The periodic forest monitoring performed by the Ministry of Forestry of Indonesia (MoF) was employed Landsat imagery only on a single best image (least cloud-affected) basis (MoF 2008b, 2011) and presented in a three-year monitoring update approach due to a lack of cloud-free images at annual time intervals (MoF 2008b). With such intervals, there is little to no detections of deforestation in the region, since most clear cuts regrow rapidly converted into mixed tree crops, timber plantations or palm oil estates. For example, fast growing tree species (e.g. *Acacia mangium*) used for local 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, especially for monitoring forest degradation.

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 include those of Asner *et al* (2005) and Souza *et al* (2003), which 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.  Canopy recovery is quick in the humid tropics and the temporarily visible indications of forest disturbance due to logging are quickly obscured (Souza *et al* 2003).  For regions with persistent cloud cover (Hoekman 1997), such as Indonesia especially Sumatra, timely data for mapping degradation using such direct methods is not viable.

The official three-yearly land cover map of Indonesia is made via photo interpretation methods (MoF 2011), and broadly classified forest 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 (SNI 7645, 2010). Boundaries between primary and secondary/degraded forests are manually delineated by multiple operators, which compromise inconsistency to the output map. Regardless, the accuracy of the forest cover classes is reported to be high (>90 percent), based on field verification and local knowledge of the operators (MoF 2011).

The work intended to map the extent and disturbances of the primary forests of Sumatra Island (Indonesia) in term of forests cover loss and forest degradation, from 1990 to 2010, by employing a hybrid approach of a per-pixel direct mapping method coupled with a Geographic Information System (GIS)-based fragmentation analysis of the detectable disturbances such as roads, settlements and other signs of human landscape alterations.

## Material and methods

### *Rationale*

FAO-GFRA (2006) defined an area of trees that covering land more than 0.5 hectares, and reach a minimum height of 5 meters *in situ* with a canopy cover of at least 10 percent, as forests. For forest management purposes, Indonesia's forest is defined as an area of trees with a minimum mapping unit of 0.25 hectares that is covered by trees higher than 5 meters with a canopy cover of more than 30 percent (MoF 2008a). For this study, the forest definition used in Indonesia with 30 percent threshold were employed, and with a focus on forests composed of indigenous tree species and lacking near-term evidence of stand-replacement disturbance (FAO 2005), introduced as "primary forests". Forest timber and pulp plantations, oil palm estates, mixed tree crops, and secondary (regrowth) forest were excluded from the analysis.

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 method and coupled with a fragmentation analysis using the Intact Forest Landscape (IFL) method of Potapov *et al* (2008). The difference in the extent of primary forest and intact forest landscape is the area 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.

***Data***

Satellite data inputs included Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 5 Thematic Mapper (TM) imagery downloaded from the U.S. Geological Survey National Center for Earth Resources Observation and Science (EROS-USGS) 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 percent for 37 Landsat scene footprints covering Sumatra were selected and downloaded. In total, 3,129 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 meters 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 as a normalization target over pseudo-invariant land cover features.

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 each time interval) reflecting surface reflectance change within analyzed time intervals were generated, as previously described by Potapov *et al* (2011). Due to incomplete cloud-free coverage for 1990, all but 7.4 percent 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, LiDAR (light detection and ranging) data from the GLAS (Geoscience Laser Altimetry System) instrument onboard the IceSat-1 satellite was used. GLAS was launched in January 2003 and collects laser pulses in an ellipsoidal footprint of approximately 65 meters, spaced about 172 meters 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 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).

Ancillary data such as official provincial boundaries (figure 2.1a), forest-land use, and land cover digital maps of Sumatra were obtained from the Ministry of Forestry of Indonesia (MoF 2010). A summary of the Indonesian forest-land use is shown in table 2.1 along with a map of Sumatran forest land use zones in figure 2.1b.

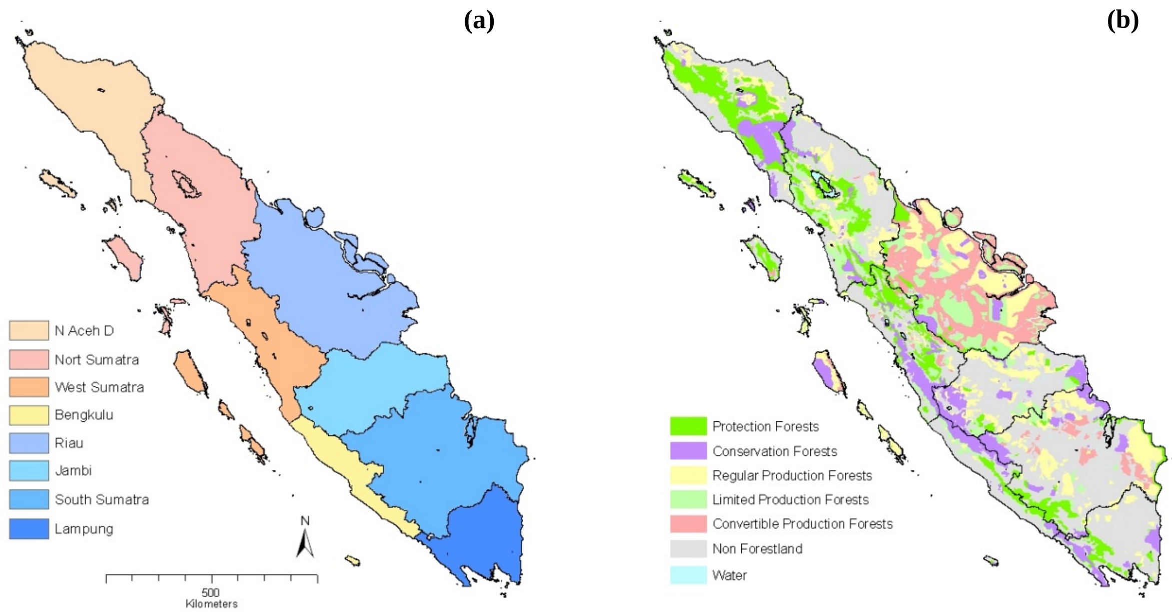


**Figure 2. 1.** a) Eight provinces of Sumatra (Nanggroe Aceh Darussalam, North Sumatra, West Sumatra, Bengkulu, Riau, Jambi, South Sumatra, and Lampung). b) Forest land use zones for Sumatra. Noted that eastern islands of Sumatra of Kepulauan Riau province is excluded from the analysis

**Table 2. 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) |
|---|---|---|---|---|---|
| **Forest land** | | 59.2 | Designed as a forest land | 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 life support system to control the water cycle and water catchment, prevent flood, 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 | Forest production | Dynamic deforestation |

| | | | | | |
|---|---|---|---|---|---|
| | | | mainly from timber extraction | | and forest degradation |
| Limited Production Forest | **HPT** | 9.0 | Low intensity logging (due to topographical condition) | Limited logging<br>Very selective logging<br>Very limited clear cutting<br>Post-logging silvicultural treatments | Forest degradation |
| Regular Production Forest | **HP** | 15.5 | Logging<br>Forest plantations | Selective logging<br>Post-logging silvicultural treatments<br>Clear cutting | Temporary deforestation<br>Forest degradation |
| Convertible Production Forest | **HPK** | 11.1 | Logging<br>Agriculture estate<br>Other uses | Clear cutting | Permanent and temporary deforestation<br>Forest degradation |
| **Non-forest land** | **APL** | 40.8 | Outside forest land and designated for other uses (agriculture land, settlements etc) | | Permanent deforestation<br>Forest degradation<br>Reforestation |

***Methodological approach***

Mapping of primary forest cover employed Landsat composites and metrics as data input and performed using a two-step supervised classification. The first step included mapping areas with tree canopy cover of 30 percent and above for the 1990 and 2000 reference years. A decision tree algorithm, a hierarchical classifier was used to split independent data (Landsat inputs) into more homogenous subsets regarding class membership (Breiman *et al* 1984). To map trees cover, training data were created using photo-interpretation of the circa 1990 and 2000 image composites, respectively. The resulting trees 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 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. Reference data from GoogleEarth[tm] and local knowledge were used to create classification training data and to perform post-classification manual primary forest mask corrections for obvious commission and omission errors. The 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.

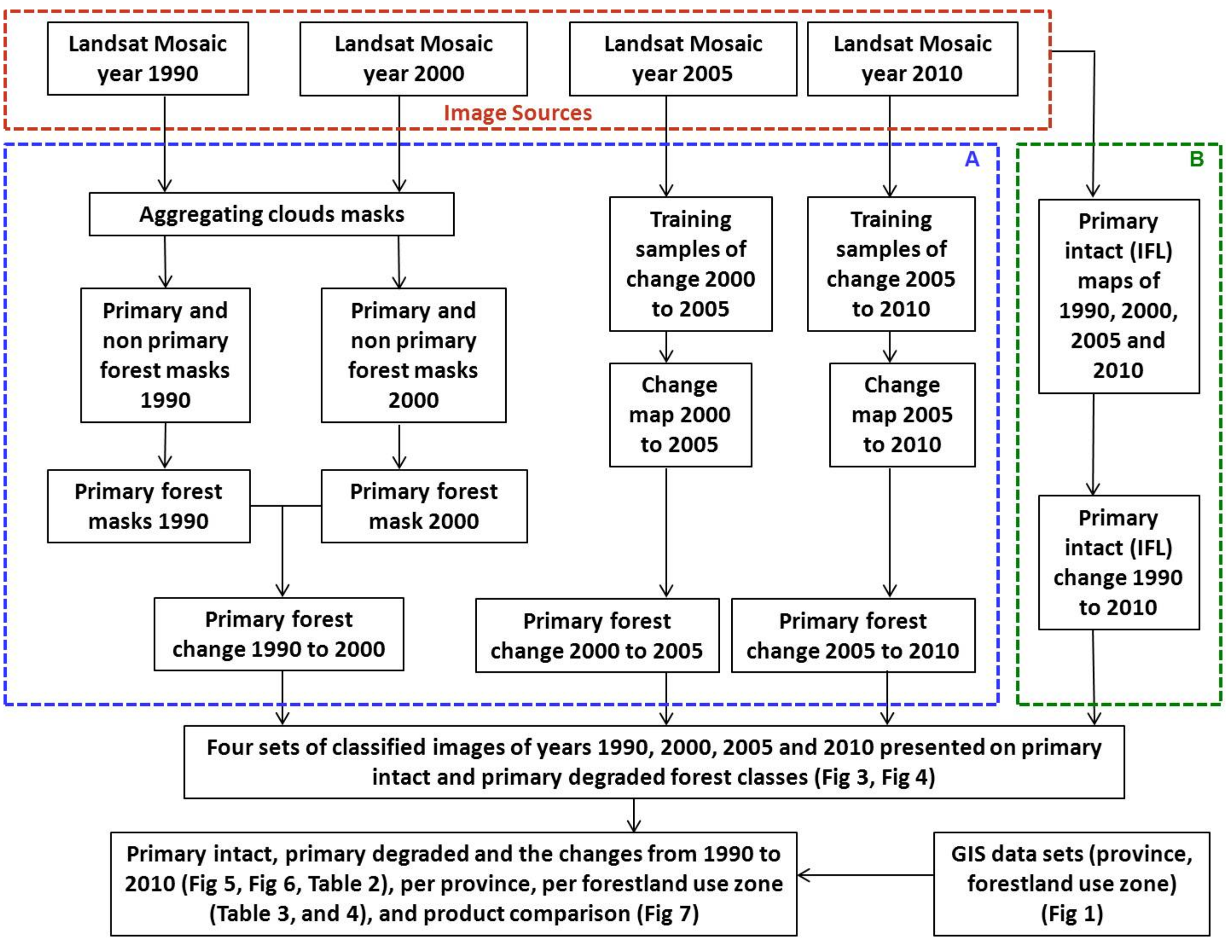


**Figure 2. 2.** Scheme of methodology used to map the primary forests, including primary intact and primary degraded forests, and its change in terms of deforestation and forest degradation from 1990 to 2010; Box A is the approach of per-pixel mapping of primary

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.

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 training sites manually created and applied to the multi-temporal metrics of the 2000-2005 and 2005-2010 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 (Arvidson and Gasch 2001) 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 percent 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 to 2010 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 2000-2005 and 2005-2010 intervals was subtracted to create the primary forest maps of 2005 and 2010. In figure 2.2, per-pixel mapping of primary forest extent and forest cover loss is shown in the box labeled (A).

The IFL map 2000 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 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. 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) were used 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 2.2, box (B).

Two different approaches were incorporated 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 2.3 illustrates the primary (intact and degraded) forests maps for a subset of Riau and Jambi provinces.

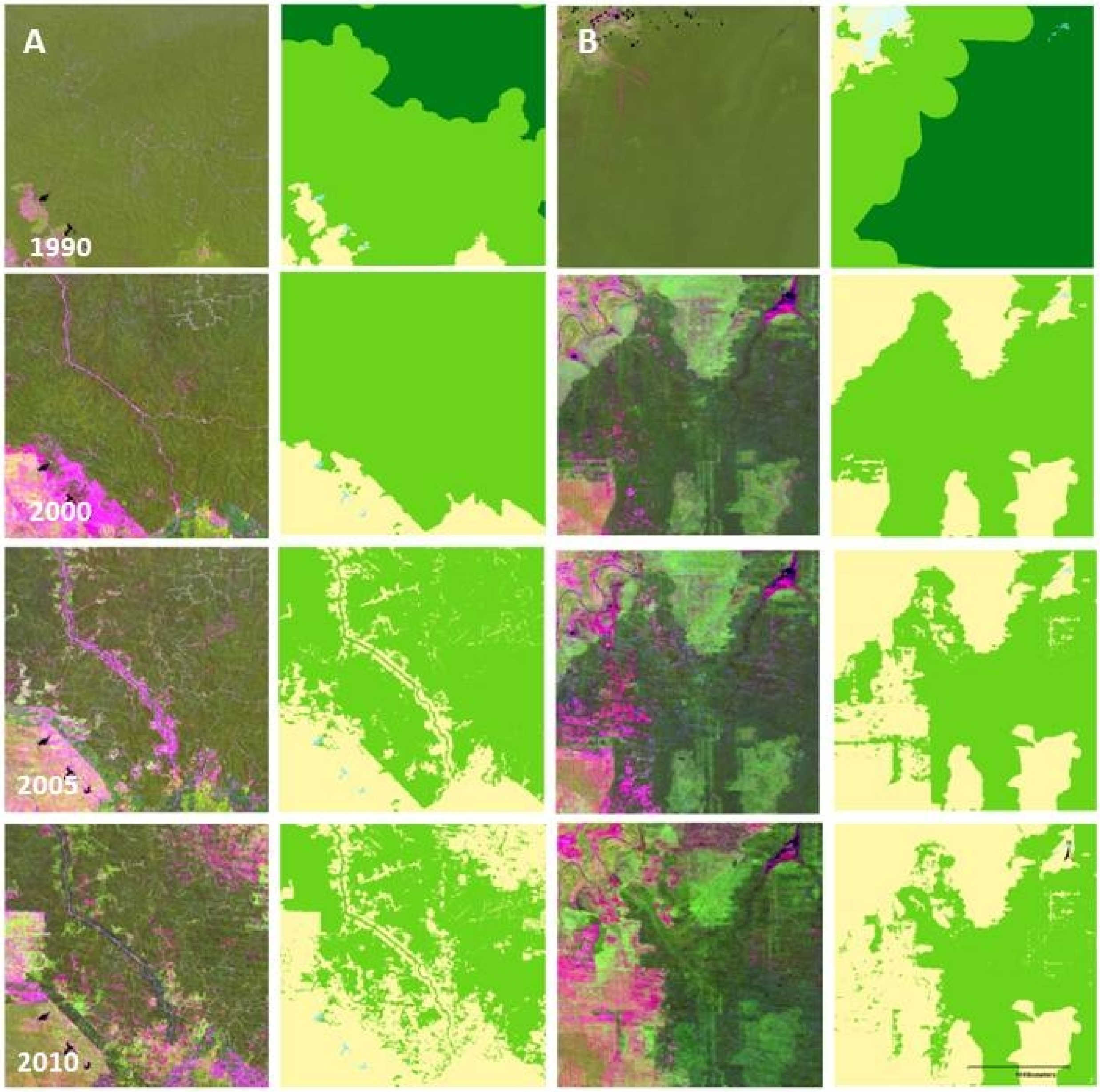


**Figure 2. 3.** Landsat TM and ETM+ image composites for circa year 1990, 2000, 2005 and 2010, with a 5-4-3 spectral band combination (left); and classification results (right). Classes: primary intact forest (dark green), primary degraded forest (light-green), non-primary forest land (light yellow), and no data/clouds (light grey). 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)

Four sets of primary forest maps of years 1990, 2000, 2005 and 2010 were produced (figure 2.4). 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, 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 were examined.

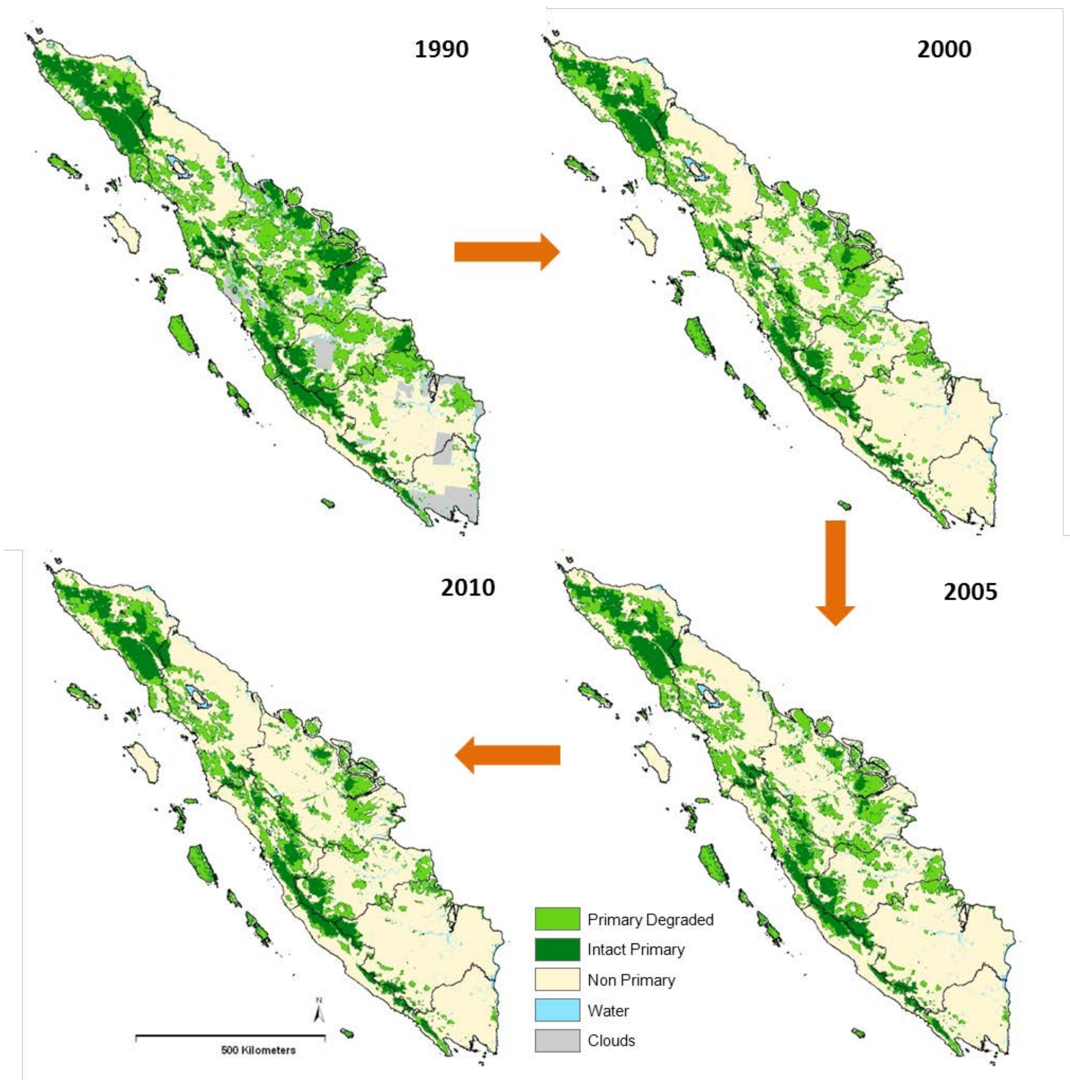


**Figure 2. 4.** Four depictions of Sumatra primary forest extent and change for 1990, 2000, 2005 and 2010.

**Results**

Sumatra primary forest extent for 1990, 2000, 2005, and 2010 is shown in table 2.2 and figures 2.4-2.6. 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 percent of the total land area. Primary forest extent was nearly halved over the 20-year study period.

**Table 2. 2**. Primary forests extent, land cover types, and the forest cover change in Sumatra for two decades from year 1990 to 2010.

| **Dominant forests and land cover types** | **Area (Mha hectares)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Year 1990** | **Forest Change (1990 – 2000)** | | **Year 2000** | **Forest Change (2000 – 2010)** | | **Year 2010** | **Forest Change (1990 – 2010)** | |
| | | **Forest Loss** | **Forest Degra dation** | | **Forest Loss** | **Forest Degra dation** | | **Forest Loss** | **Forest Degra dation** |
| 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 areas are presented in Mha of hectares and numbers were rounded

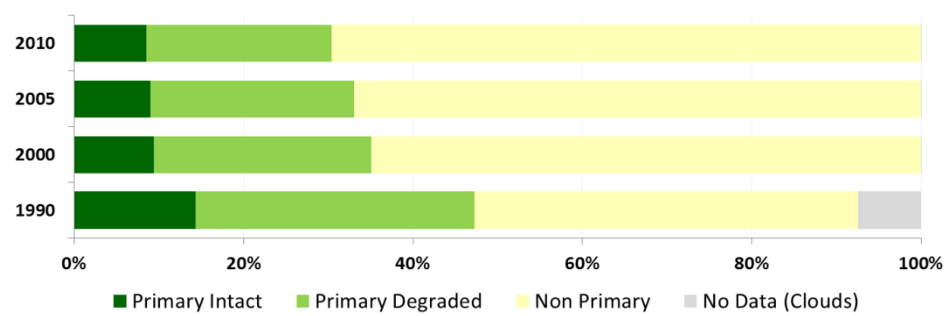


**Figure 2. 5.** The expanse of primary intact forest, primary degraded forests and non-primary of Sumatra from year 1990 to 2010; about 7.4 percent of the data year 1990 was not available.

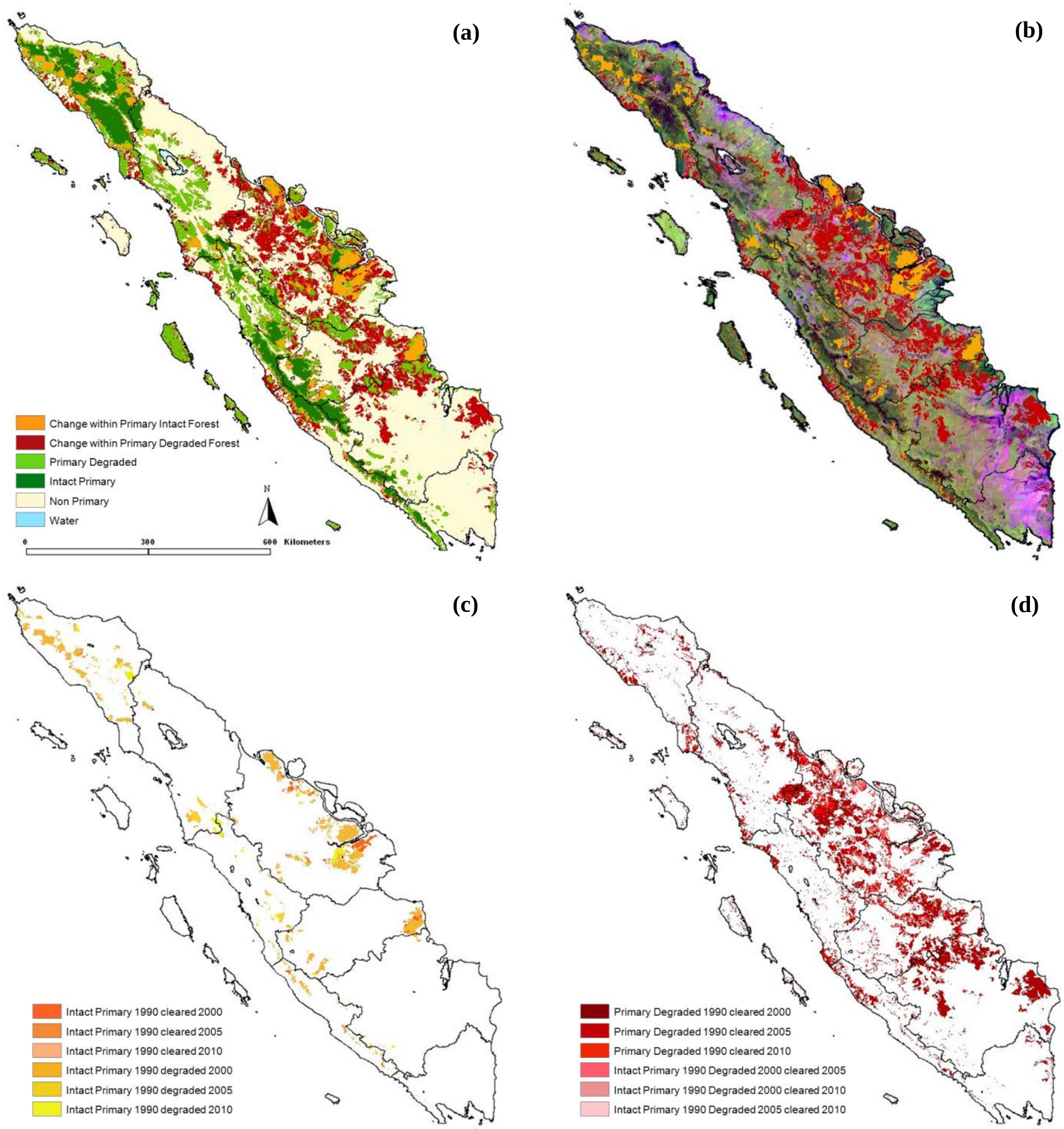


**Figure 2. 6.** Sumatra forest cover change from year 1990 to 2010. a) Total 1990 primary intact forest loss shown in orange and total 1990 primary degraded forest loss in red; b) Same change dynamics on top of Landsat ETM+ circa 2010 image composite with 5-4-3 spectral band combination; c) Change dynamics 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 6b illustrates the existence of both non-treed other tree cover types, such as oil palm, within the non-primary forest class.

As summarized in table 2.2, 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 percent of 1990 primary forest area. An additional 11 percent of 1990 primary intact forest was degraded. In total, nearly half (47 percent) of 1990 Sumatran primary forest was either cleared or degraded during the study period. Primary forest cover loss in the 1990s was far greater 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 Mha to 0.02 Mha).

For the entire study period, the rate of forest loss was 0.38 Mha per year, and the rate of forest degradation was 0.12 Mha per year. The first decade of analysis (1990-2000) contributed 72 percent of forest loss and 83 percent of forest degradation. The rate of loss was about 0.54 Mha per year and comparable to the estimated rate of forest cover loss for Sumatra from 1985 to 1997 of 0.56 Mha per year (Holmes 2000a, 2000b). The second decade (2000-2010) accounted for 28 percent of forest loss and 17 percent of forest degradation for the two-decade study period. The rate of forest loss was 0.21 Mha per year, less than half of the rate of the 1990s.

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, Kettering *et al* 1999). Additionally, in 2000 Indonesia applied a new decentralization policy (Seymour and Turner 2002) providing regional autonomy (Law No 22/1999) and authority to provinces and districts in sharing revenue from land use fees and taxes (Law No 25/1999). The decentralization policy provides a rationale for quantifying provincial-scale information pertinent to forest management.

The primary forest cover loss over two decades for eight provinces in Sumatra was summarized in table 2.3. The percent primary forest loss for the provinces of Riau and South Sumatra exceeded 50 percent of their 1990 primary forest extent; the province of Jambi experienced a primary forest loss in excess of 40 percent. 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 percent of all primary intact forest loss in Sumatra. Riau contributed 46 percent of total Sumatran forest degradation, followed by Nanggroe Aceh Darussalam/Aceh (23 percent) and Jambi provinces (12 percent). For all provinces, there was a dramatic decline in primary intact forest loss between 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 percent that of the 1990s. Remaining primary intact forest in 2010 was located largely in Aceh (40 percent), West Sumatra (15 percent), and Bengkulu (12 percent) 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 percent 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 2.1). 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.

**Table 2. 3**. Primary forests extent and its change in eight provinces of Sumatra for two decades from year 1990 to 2010

| Province | Area (Mha hectares) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Primary Forests (Year 1990) | | | Forest change (1990 – 2000) | | | Primary Forests (Year 2000) | | | Forest change (2000 – 2010) | | | Primary Forests (Year 2010) | | |
| | | | | Forest Loss | | For. Deg. | | | | Forest Loss | | For. Deg. | | | |
| | Tot | PD | PI | PD | PI | | Tot | PD | PI | PD | PI | | Tot | 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); Tot: Total, PD: Primary Degraded Forest, PI: Primary Intact Forest; For. Deg.: Forest Degradation

The primary forest change over the two decades for each forest land use zone in Sumatra was quantified (table 2.4). 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 percent, 17.1 percent and 15.8 percent of the total loss, respectively. For primary intact forest, about 50 percent 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* 2011b).

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 percent to 29 percent 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 percent of primary forests were located in the outside forest land use (APL); 96 percent of these forests were degraded. By 2010, outside forest land use (APL) accounted for 8.7 percent of Sumatran primary forest.

**Table 2. 4.** Primary forests extent and its change in forest land use zone of Sumatra for two decades from year 1990 to 2010 (see table 2.1 for forest land use zones in code).

| Forest land Use Zone (in code) | Area (Mha hectares) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Primary Forests (Year 1990) | | | Forest change (1990 – 2000) | | | Primary Forests (Year 2000) | | | Forest change (2000 – 2010) | | | Primary Forests (Year 2010) | | |
| | | | | Forest Loss | | For. Deg. | | | | Forest Loss | | For. Deg. | | | |
| | Tot | PD | PI | PD | PI | | Tot | PD | PI | PD | PI | | Tot | 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; Tot: Total, PD: Primary Degraded Forest, PI: Primary Intact Forest; For. Deg.: Forest Degradation

Within the forest land uses, production forests as a whole (HP, HPT and HPK) accounted for 65.8 percent of the total primary forest cover loss, comparable to 5 percent of protection forests (HL), and 4 percent of conservation forests (HK). These data demonstrate 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).

*Product comparison and accuracy assessment*

For assessment of the results, we employed the Ministry of Forestry of Indonesia (MoF) land cover maps year 2000 (figure 2.7b) 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 percent for all 23 land cover classes and 98 percent for forest and non-forest classes (MoF 2011). We regrouped the classes of the MoF map into primary intact forest, primary degraded forest, and non-primary forest classes. The overall agreement of total primary forest (combined primary degraded and primary intact forest) for year 2000 was 92 percent (producer's agreement 86 percent and user's agreement 93 percent). When treating primary degraded and primary intact forest classes separately, the overall agreement was 79 percent (producer's agreement 56 percent, user's agreement 71 percent for primary intact class, and producer's agreement 90 percent, user's agreement 82 percent for primary degraded class).

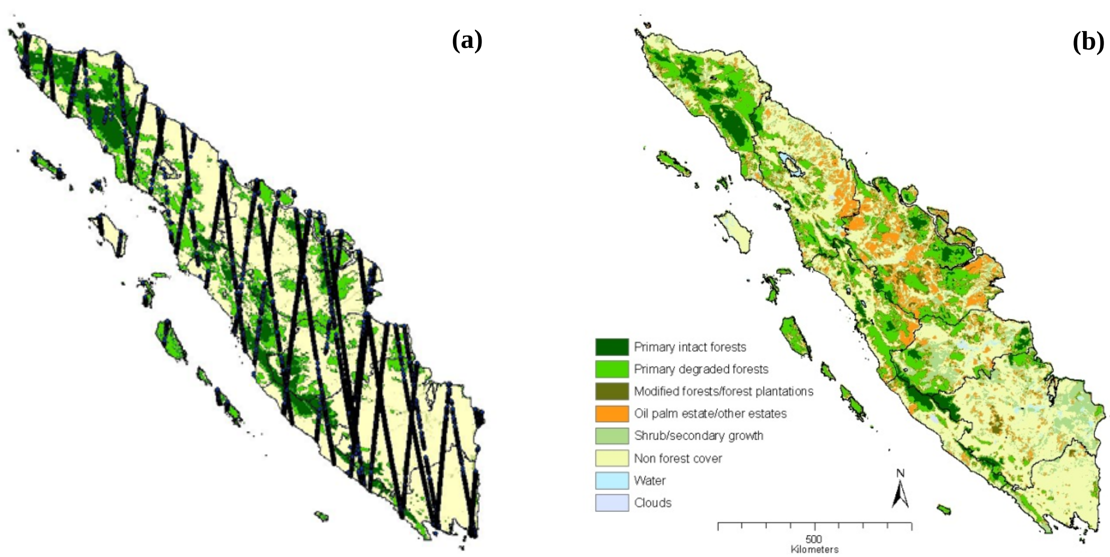

**Figure 2. 7.** Data used for product evaluation: a) GLAS L1A and L2 (year 2006) shots in black dots on top of Sumatra primary forests extent for 2005; b) The land cover map of the Ministry of Forestry of Indonesia year 2000, presented in eight classes from an original 23 classes. For product comparison, the last six classes (except clouds) were regrouped as the non-primary forest class.

The GLAS data set (figure 2.7a) was also employed to evaluate the 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 28m $\pm$ 8.7m), primary degraded forests (19m $\pm$ 8.2m), and non-primary forest covered with trees/other tree cover (13m $\pm$ 5.2m), as characterized using the combination of primary forest mapping and the IFL buffering of forest near human infrastructure (figure 2.8). A t-test with 95 percent 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.

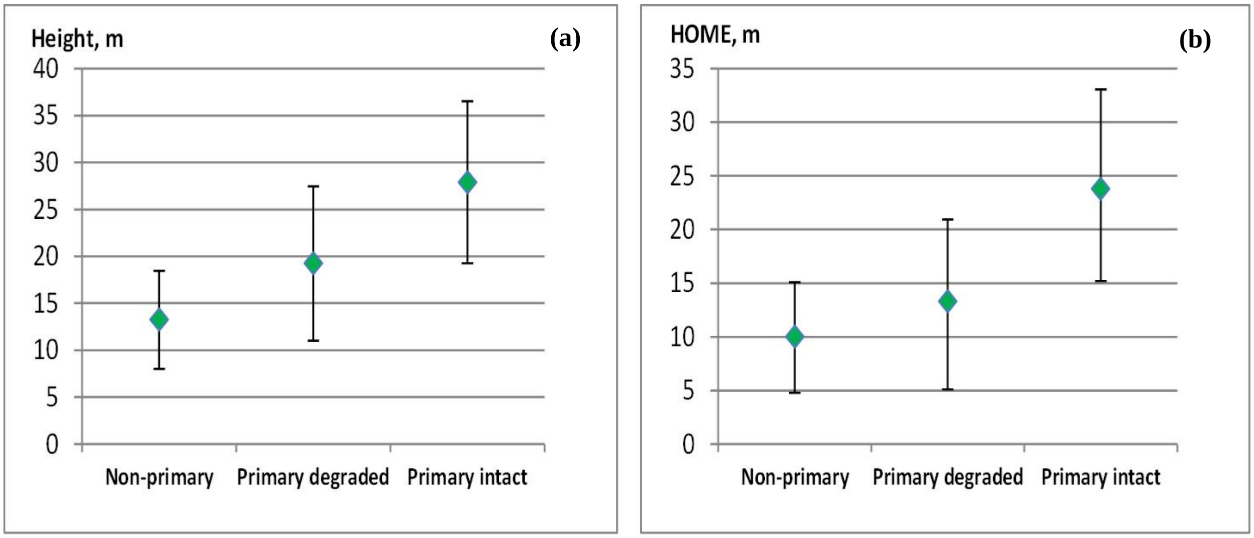


**Figure 2. 8.** Mean and standard deviation values for GLAS metrics of a) Tree height and b) HOME from 2006 GLAS L1A and L2 shots within non-primary, primary degraded and primary intact forests of Sumatra. Summary t-tests with the following degrees of freedom each yielded p-values of <<0.000 for the 95 percent confidence interval: 24,423 for non-primary/primary degraded; 16,834 for non-primary/primary intact; 9,299 for primary degraded/primary intact.

## Discussion

This work produced a new set of maps quantifying the extent of primary degraded and primary intact forests in Sumatra over a twenty year 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 showed 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 *et al* 2001) facilitated mapping for the 2000 to 2010 epoch, while a traditional post-classification approach with expert intervention was required to map the comparatively data poor 1990 to 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 above-ground carbon stock dynamics and ecosystem services and co-benefits for forest conservation (Stickler *et al* 2009).

Over the past 60 years, Sumatra has experienced intensive industrial forestry and agricultural development that has significantly reduced the area of natural forest. In 1950, forest covered 71.2 percent of Sumatra (Hannibal 1950 as reported by FWI/GWF 2002), which was reduced to 49 percent by 1985 and to 35 percent by 1997 (Holmes 2000a). We estimated that remaining 1990 primary forest extent covered 47 percent of Sumatra, which was reduced to 33 percent by 2000 and to 30 percent 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 60 years in Sumatra is provided in table 2.5. 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 2.4). 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 (Seymour and Turner 2002), and the inability of provincial governments to adequately enforce forest codes (Nawir *et al* 2007, Uryu *et al* 2008).

**Table 2. 5**. A Summary for illustrating the primary forest change drivers in Sumatra over years.

| Periods | Main drivers of forest cover loss | Other drivers of forest cover loss | Main drivers of forest degradation |
|---|---|---|---|
| Before our time frame for analysis | | | |
| 1950 – 1970 | • Agriculture expansion notably rice cultivation<br>• Smallholder clearance for rubber and coffee<br>• Shifting cultivation | | |
| 1970 – 1990 | • Large-scale commercial logging concessions<br>• Large-scale forest plantations | • Transmigration programs for tree crops (rubber, cocoa and coffee) and labor for timber industry<br>• Fires 1982 – 1983 | |
| During our time frame for analysis | | | |
| 1990 – 2000 (The first decade of analysis) | • Agriculture expansion mainly oil palm estate<br>• Establishment of pulp-paper and sawn-timber plantations | • Fires 1997 – 1998<br>• Transmigration programs<br>• Spontaneous trans migrants activities<br>• Smallholder clearance for tree crops | • Uncontrolled and controlled selective logging within forest logging concession<br>• Illegal logging |
| 2000 – 2010 (The second decade of analysis) | • Agriculture expansion mainly oil palm estate<br>• Expansion of pulp-paper and sawn-timber plantations | • Transmigration programs Spontaneous trans migrants activities<br>• Limited fires | • Illegal logging |

Sources: summarized from Tomich and van Noorwijk 1995, Kettering *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* 2008, Laumonier *et al* 2010

**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 2.6, 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 *terra firma* 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 percent 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/Inpres 10/2011, Murdiyarso *et al* 2011). Under the moratorium, no clearing or logging outside of pre-existing concessions should occur within 2011-2013. However, it must be noted that of primary forest in 2010 located within moratorium-designated lands, over half exists in already protected status HL and HK forest land uses (56.8 percent). Another 17.0 percent exists in already established concessions with exemptions for logging and forest plantations. A total of 8.7 percent is in other APL land uses, with licenses controlled by the National Land Authority (BPN). The remaining 17.5 percent 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.

# Chapter 3: Mapping wetlands in Indonesia using Landsat and PALSAR data sets and derived topographical indices [3]

## Introduction

As an ecotone between aquatic and terrestrial ecosystems, wetlands provide habitat for a variety of aquatic and terrestrial species. Wetlands provide numerous ecosystem services including the vital role of regulating water availability in watersheds through wet and dry seasons. Wetlands also act as a cleansing agent for water purification, filtering pollutants and sediments. Furthermore, wetlands are essential for animal migration and reproduction, including a spawning zone for many species of fish, and provide a vital habitat for innumerable endangered, threatened or vulnerable plant and animal species.

Tropical wetlands maintain high rates of primary productivity as well as anaerobic soil conditions that slow decomposition (Brinson *et al* 1981, Neue *et al* 1997, Murdiyarso *et al* 2009). As a result, wetlands represent one of the largest terrestrial biological carbon pools (Zedler and Kercher 2005). Wetlands are often unsuitable for agricultural land uses and in many places remain largely intact (Murdiyarso *et al* 2009). However, when land use intensification options are limited, wetlands often become a site of land use change, for example the development of agro-industrial plantations in Indonesia (Miettinen *et al* 2012). In Indonesia, most non-wetlands lowland forests have been allocated for forest logging concessions since the 1960s (Government regulation 21/1970 and 18/1975). As more non-

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wetlands lowland forests have been used in logging operations, forestry activities have moved into wetlands. Since then, wetland conversion and degradation have accelerated.

The loss and degradation of wetlands reduce the watersheds capacity to maintain biodiversity, water quality, flood deterrence and carbon sequestration (Zedler and Kercher 2005). National concern for Indonesia's wetlands has grown intensively following the magnitude of carbon emissions released from smoldering peatlands in Sumatra and Kalimantan islands (e.g. Page *et al* 2002, 2007, Usup *et al* 2004, Jauhiainen *et al* 2005, MoF 2008, and Jaenicke *et al* 2008). Indonesia, largely due to emissions from peatland soils, is second to only Brazil in greenhouse gas emissions for tropical countries. The exceptional carbon storage and potential emissions from land use change within wetlands have implications for global climate change (Hadi *et al* 2005, Murdiyarso *et al* 2009). For many policy initiatives, such as the United Nations Framework Convention on Climate Change (UNFCCC) Reducing Emissions from Deforestation and forest Degradation (REDD) program, the monitoring of wetland land use change is of critical importance.

Remote sensing data have been applied widely to monitor land cover change, mostly in terms of deforestation and forest degradation (e.g. Achard *et al* 2002, Souza *et al* 2003, Currant *et al* 2004, Hansen *et al* 2008b, Hansen *et al* 2009, Miettinen and Liew 2010, Broich *et al* 2011, Margono *et al* 2012). At the same time, remote sensing has also been used to map wetland extent (e.g. Zedler and Kercher 2005, Silva *et al* 2008, Lowry *et al* 2009, Bwangoy *et al* 2010, Melack and Hess 2010). For many monitoring applications, the quantification of wetland extent is required. To date, a number of national-scale wetland mapping products using photo-interpretation have been generated. Available maps of wetlands distribution include the national land cover map developed by the Ministry of

Forestry of Indonesia (MoF) and a peatlands distribution map from collaboration between Wetlands International and the Ministry of Agriculture of Indonesia (WI/MoAg). More systematic methods using digital image processing and characterization at the national-scale have not been implemented. In this study, such an approach was applied and compared to the existing maps and available ancillary data.

The objective of this research was to map wetlands in Indonesia using passive optical, Landsat, and active radar PALSAR, data sets and elevation-derived topographical indices. The topographical indices were derived from data from the Shuttle Radar Topography Mission (SRTM) and were employed to represent landform and hydrological condition.

## Materials and methods

### *Study area*

In the Koppen-Geiger climate classification, Indonesia is categorized as Af (tropical wet) with $\geq$ 60 mm precipitation during the driest month (Peel *et al* 2007). Given the fairly consistent temperatures, the most influential variable on climate is rainfall. The dry season occurs principally from June through September, and the rainy season from December through March. On average, throughout the year, rainfall ranges from 125 to 280 mm per month (NOAA 1997, Hendon 2003), and precipitation always exceeds evapotranspiration (Tan 2008) causing a relative humidity ranging from 70-90 percent. As a result, given suitable geomorphology, Indonesia has an abundance of water resources to support wetlands formation.

***Characteristic and rationale***

Wetlands defined as "lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water" (Cowardin *et al* 1979, Middleton 1999). The presence of wetlands is a function of climate and landform and wetlands often have characteristic flora and soils (Cowardin *et al* 1979, Tiner 1999). This approach to digital mapping posits that water presence, landform and vegetation type can be observed using multi-source data sets. Such data sets, processed consistently over large areas, enable the delineation of wetlands at national scales. Specifically, Landsat imagery capture floristic differences that can be associated with wetland status, as well as water extent and leaf moisture content, both indicators of possible wetland status. Topographical indices capture landforms more likely to retain water. The different interactions of microwave data (PALSAR) with surface water compared to vegetation enable the improved discrimination wetlands. All three data sources have complementary characteristics that warrant their combined use in characterizing wetland extent (Li and Chen 2005, Bankanza *et al* 2010).

***Data and methods***

Landsat data inputs included Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat Thematic Mapper (TM) imagery, downloaded from US Geological Survey National Center for Earth Resources Observation and Science (http://glovis.usgs.gov/). A cloud-free mosaic for year 2000 was generated. Year 2000 was selected due to its temporal proximity to the Shuttle Radar Topography Mission (SRTM) acquisition date of 2000. All Landsat input images were re-projected to a sinusoidal project and resampled to a 60 meters spatial resolution. The raw digital numbers (DN) were converted to top of atmospheric reflection (TOA) (Chander *et al* 2009) to minimize differences in ETM+ values that resulted from sensor calibration, sun-earth distance and sun elevation. Each pixel was subsequently screened for clouds/haze/shadows/water per the method of Potapov *et al* (2012), resulting in a set of quality-assessed land observations. Radiometric normalization was conducted using top of canopy reflectance MODIS data in order to remove residual atmospheric contamination and surface anisotropy (Hansen *et al* 2008a). A single composite image, using nearest quality-screened observation to January 1, 2000, for the following Landsat bands was created: red (630-690 nm), near-infrared (760-900 nm), and short-wave infrared (1550-1750, 2080-2350 nm).

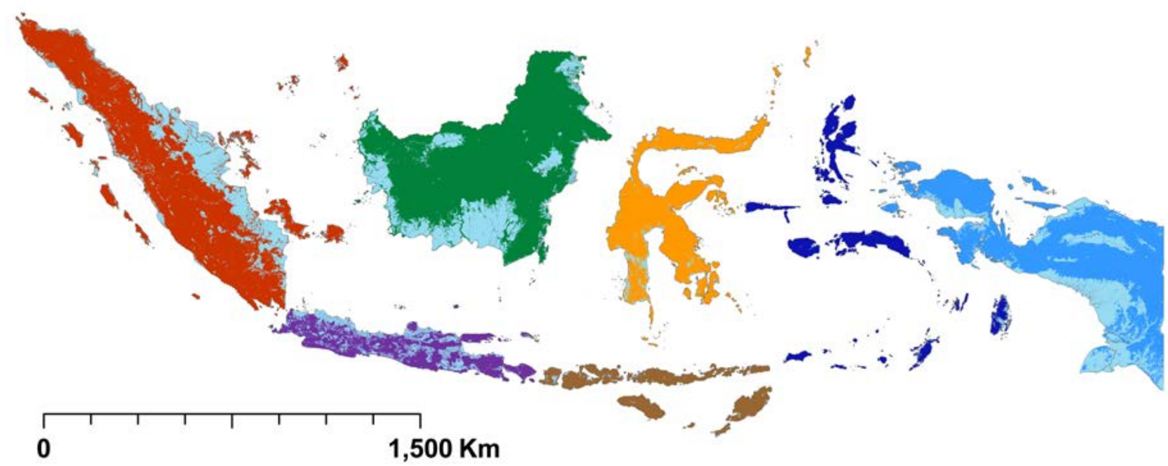



**Figure 3. 1.** The seven largest islands of Indonesia and the approximate distribution of potential wetlands from image-interpretation, obtained from combined a land cover map of Indonesia for year 2000 (MoF) and an Indonesian peatland distribution map for 2011(WI/MoAg).

The digital elevation data used for this research was derived from the Shuttle Radar Topography Mission (SRTM) flown on-board the shuttle Endeavour for eleven days in February 2000 (Rabus *et al* 2003). The DEM was derived from a single pass interferometric synthetic aperture radar (InSAR) (Stofan *et al* 1995, Rosen *et al* 2000) at spatial resolution levels of 3 *arc* seconds (approximately 92 meters) (Rabus *et al* 2003, Hamilton *et al* 2007). The data are available to the public at US Geological Survey's Earth Resources Observation System (EROS) Data Center for FTP download.

The radar data used in this study were from the phased array L-band synthetic aperture radar, (PALSAR), onboard the Advanced Land Observing Satellite (ALOS). The data are delivered as 50 meters spatial resolution orthorectified mosaics provided by The Kyoto and Carbon (K&C) Initiative led by Japan's Aerospace Exploration Agency (JAXA). From the available 72 alternatives fine-beam (FB) modes in PALSAR, the single polarization HH and dual polarization HH+HV have been selected for operational use (Lowry *et al* 2009). These modes yield a 70 km swath width and 10 x 10 and 10 x 20 m ground resolution in HH and HH+HV respectively (Rosenqvist and De Grandi 2009). The ALOS PALSAR mosaic tiles were acquired from June to October, 2009 for Sumatra, Kalimantan, Java, Nusa Tenggara, Sulawesi, and Maluku islands; and from May to October 2008 for Papua. A total of 21 PALSAR tiles covering Indonesia for HH and HH+HV polarizations were used as independent variables for mapping the wetlands.

Several ancillary datasets were used for data validation, product comparison and analysis. A digital peatlands distribution map produced by the Ministry of Agriculture and Wetlands International (WI) (MoAg 2011) was obtained from the Ministry of Agriculture of Indonesia (MoAg). A land cover map for 2000, obtained from the Ministry of Forestry of Indonesia (MoF), includes wetland-related land cover classes. Both reference wetland maps were generated using on screen photointerpretation and are displayed in figure 3.1. The WI/MoAG map had an additional input of field survey data of substrate (physicochemical features)/soils types in determining peatland soil types and depth. For comparison purposes, the following MoF land cover classes were aggregated to create a generic wetland class: primary swamp forests, secondary swamp forests, primary mangrove forests, secondary mangrove forests, swampy shrub, paddy field, fish pond, and open swamp (grassy swamp). The reported accuracy of the MoF land cover map is 88 percent (MoF 2011a, Margono *et al* 2012). The estimated accuracy of the WI/MoAg map land is 70-80 percent (MoAg 2012 personal communication). The reference wetland layer consisted of areas where either the WI/MoAg peatland or MoF wetland maps indicated wetland land covers.

Field data from the Indonesian National Forest Inventory (NFI) obtained from the MoF were employed to further evaluate the derived wetland map. The NFI data were collected from a systematic sampling grid of 20km x 20km (UTM zone) for all forest lands/state forests below 1000m altitude (Revilla and Liang 1989, 1992). Permanent sample plots (PSP) are 100m by 100m in extent and are measured every 3-5 years, including wetland/dryland status. In total 427 PSPs from Sumatra and 881 PSPs from Kalimantan collected between 1995 and 2000 were used to compare with the output wetland map. Of the PSP data, 138 plots (32.3 percent) and 156 plots (17.7 percent) were recorded as wetlands for Sumatra and Kalimantan, respectively.

***Methodological approach***

The approach of Bankanza *et al* (2010) in deriving a set of topographical indices was employed to be used as inputs to the wetland mapping task. A number of metrics that quantify the effects of topography on hydrological processes were derived from digital elevation data including first and second order derivatives of elevation (e.g. slope and curvature) (Wood, 1996, Wolock and McCabe, 1999). The derivatives were generated by fitting a quadratic function to the digital elevation model. A quadratic function is a successful compromise between a number of data points required to uniquely model the surface and the fidelity in which the model fits the true surface (Wood 1996). Quadratic coefficients were generated by an ordinary least squares (OLS) fitting of 9 neighboring DEM pixels. In addition, the root mean square error of the OLS fitting was calculated to indicate quality of the fit, and subsequently employed as an independent variable.

Finally, five metrics describing relative height with respect to variously defined support area/catchment sizes were calculated. The hydrological topology was defined using the D8 method to compute flow direction, the upslope contributing area (flow accumulation), and catchment (O'Callaghan and Mark 1984, Jenson and Domingue 1988, MacMillan *et al* 2000, Lang *et al* 2012). Drainage channels were extracted at all points with accumulated areas above a threshold defined by a support area parameter; all cells having at least as many cells flowing to them as the threshold value are determined to be "streams". Each stream catchment was then used to calculate a relative elevation per pixel by subtracting actual elevation from the minimum elevation of the defined catchment. The five relative elevations were calculated for 1,000, 5,000, 10,000, 15,000, and 20,000 SRTM 90m grid cell support areas (Bankanza *et al* 2010).

A flowchart of the overall methodology is shown in Figure 3.2. A systematic pixel-wide grid of 100km x 100km in X and Y directions was used to derive training data and to estimate the proportion of land covered by wetlands. Each pixel along all transects was labeled as either wetland or non-wetlands via image interpretation of the 2000 image composite. In total, 1,286,943 training pixels were collected in this manner, of which 263,419 (20.5 percent) were labeled wetlands. The systematic sample provided an estimate of the actual class proportions, similar to prior probabilities. However, such sampling does not ensure a high-fidelity map output due to the complexity of landscapes and input variable features. Consequently, additional, non-systematically collected training data were added to the initial training by image interpreters in iterating the product. The 20.5 percent estimate of wetland extent was used as a reference in guiding the derivation of the final wetland map. Decision trees have been widely used to characterize tropical wetlands using either passive or active remotely sensed data sets (e.g. Hess *et al* 1995, Simard *et al* 2002, Li *et al* 2005, Hui *et al* 2009). Using an entropy or deviance measure, decision trees classify each pixel by splitting on independent variables (e.g. Landsat bands) in order to create more homogeneous subsets regarding class membership (Breiman *et al* 1984). A single classification tree, terminated when a given node captured 0.1 percent of the training data's total deviance, was generated and applied to the entire national-scale data set.

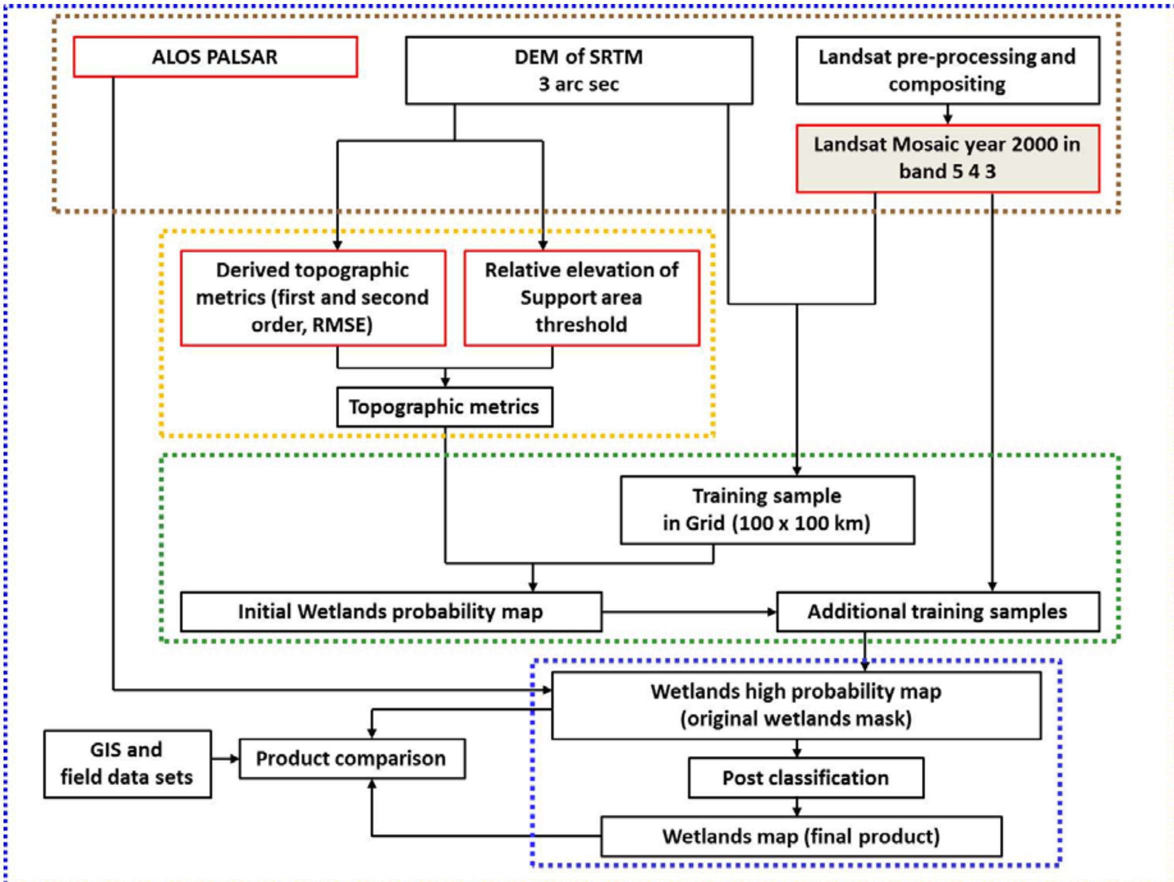



**Figure 3. 2.** Scheme of methodology for classifying the Indonesian wetlands using Landsat mosaic 2000 band 5-4-3, ALOS PALSAR data in HH and HH+HV polarization, ten topographical parametric and five relative elevation of different area threshold as independent variables.

## Results

### *Independent variables for mapping wetlands*

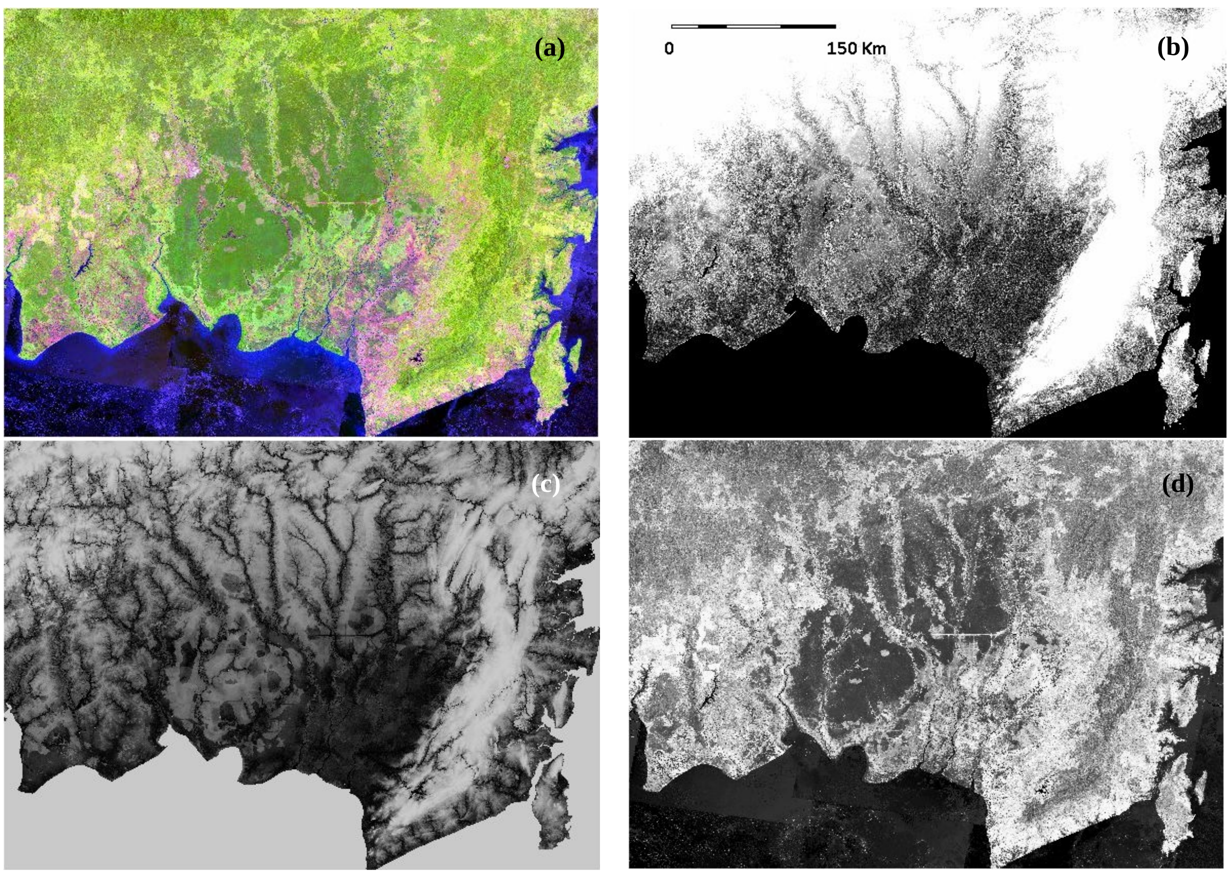
Among the number of independent variables applied for classification, the most influential are root mean square error (RMSE), Landsat band 5, and relative elevation of 121.5 $km^2$

(15,000 support area) catchments (Table 3.1, figure 3.3b, 3.3c, 3.3d, and 3.3e). Various curvature and convexity derivatives, excepting plan convexity, did not contribute to the decision tree. As an independent variable, the RMSE of the fitted model indicates how well the quadratic describes the digital elevation model. Low RMSE values indicate closer agreement between the model and the actual topography, and are indicative of flat areas suitable for water inundation. Higher RMSE values are found in areas of high relief, areas less likely to retain surface water. The RMSE variable accounted for nearly half of the model's reduction in deviance. Landsat band 5 contributed 14.5 percent and is the second highest contributor to the classification. Landsat band 5 is useful for identifying wetlands due to its ability to distinguish vegetation types as well as leaf and soil moisture content (Ozesmi and Bauer 2002). The relative elevation based on a 121.5 $km^2$ (15,000 support area) catchment area was third overall in contributing to wetland characterization, followed by 162.0$km^2$ (20,000 support area) and 40.5$km^2$ (5,000 support area) catchment sizes. Relative elevation is an indicator of catchment slope and the possible presence of wetlands. While SAR data have also been renowned as a valuable tool for wetlands mapping (Hess *et al* 1995, Silva *et al* 2008), the PALSAR dual and single polarized data contributed only 3.95 percent for HH+HV polarization and 1.96 percent for HH polarization of deviance reduction.

**Table 3. 1**. Significant contribution from independent variables to map per-pixel wetland probability

| Metric name | Deviance | Percent contribution (%) |
|---|---|---|
| Root mean square error (RMSE) | 46,564.14 | 48.44 |
| Landsat band 5 of mosaic 2000 | 13,940.20 | 14.50 |
| Relative elevation 15,000 grid (121.5 $km^2$) | 8,572.26 | 8.92 |

| | | |
|---|---|---|
| Relative elevation 20,000 grid (162.0 km$^2$) | 6,973.09 | 7.25 |
| Relative elevation 5,000 grid (40.5 km$^2$) | 4,126.33 | 4.29 |
| ALOS PALSAR HH+HV polarization | 3,795.92 | 3.95 |
| Slope | 3,096.79 | 3.22 |
| Landsat band 4 of mosaic 2000 | 2,368.02 | 2.46 |
| Landsat band 3 of mosaic 2000 | 2,340.08 | 2.43 |
| ALOS PALSAR HH polarization | 1,883.93 | 1.96 |
| Relative elevation 1,000 grid (8.1 km$^2$) | 1,111.42 | 1.16 |
| Relative elevation 10,000 grid (81.0 km$^2$) | 573.24 | 0.60 |
| Aspect | 482.35 | 0.50 |
| Plan convexity | 300.86 | 0.31 |



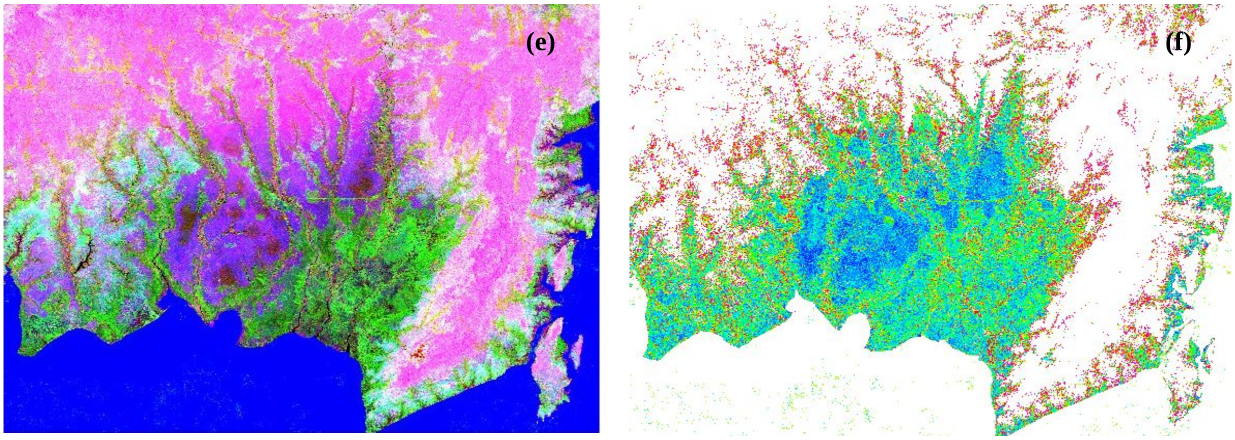



**Figure 3. 3.** (a) Landsat image with 5-4-3 spectral combination; (b) fit of the model represented by the RMSE; (c) relative elevation of 121.5 $km^2$ catchments; (d) Landsat band 5; (e) false-color r-g-b of (b), (c) and (d); (f) the initial resulting wetland map as a probability layer where blue is high probability and white low probability, for the part of Central Kalimantan Province (centered approximately at $114^0$10'24.86E $2^0$22'53.54S).

***Post classification***

An objective of this study was to depict naturally occurring wetlands, even for areas that previously experienced land use conversion.  As such, we delineated wetland training on a number of land uses, such as oil palm estates, that had been introduced to wetland landscapes. Our per-pixel mapping method was found wanting for a number of these areas and required a post classification procedure to minimize errors of omission regarding recent historical land use conversions.

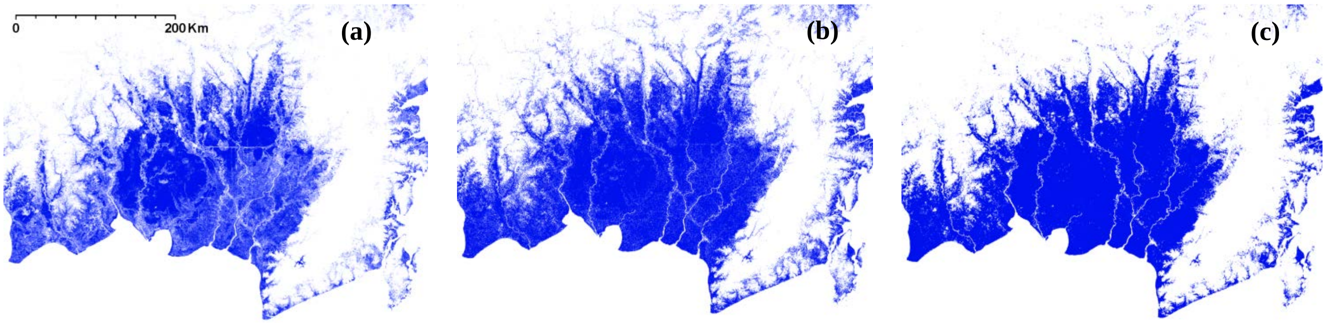



**Figure 3. 4.** Post classification steps to refine original wetlands mask from noise. This example is given from Central Kalimantan Province (centered approximately at $114^0$10’24.86E $2^0$22’53.54S); (a) a per-pixel original wetland mask; (b) a map produced by buffering the per-pixel original wetland mask; (c) a final wetlands map produced by smoothing map b.

Two post classification procedures were performed and are illustrated in figure 3.4. The per pixel classified map in Figure 3.4a represents the original wetlands map created from the decision tree classification. Figure 3.4b is the first post-classification step derived using a DEM-based buffer. Any non-wetland pixels within 5 pixels of a wetland pixel and having an elevation difference of less than or equal to 2 meters was relabeled a wetland. Figure 3.4c illustrates the final result based on a second post classification process, a filtering of (b) to clean up all polygons smaller than 20 pixels threshold. Both steps removed noise in the product, particularly related to land uses within wetlands, resulting in a more generalized depiction of wetland extent.

*Product comparison*

The WI/MoAg peatland map (figure 3.5a) and the wetland land cover classes of the MoF map (figure 3.5b) were combined to create a reference map (figure 3.5c) for comparison to the wetland classification from this study. Both the per-pixel and post-classification versions of the produced map (figure 3.4a and figure 3.4c) were evaluated against the reference map (figure 3.5c) for the entirety of Indonesia (table 3.2). The produced map was also compared to the NFI field data sets for Sumatra and Kalimantan (figure 3.6). In this work, non-wetland (dry) land or wetland status per PSP was utilized. Results in table 3.3 include a comparison of PSPs with the existing image-interpreted map. The PSPs were measured at various times from 1995 to 2000. The existing image-interpreted map has high agreement (Table 3.3). Disagreements are mostly along rivers or in the boundary of wetlands and non-wetlands. The final wetland map significantly improves the overall and producer's accuracy when compared to the PSPs, though there is a minor increase in commission error.

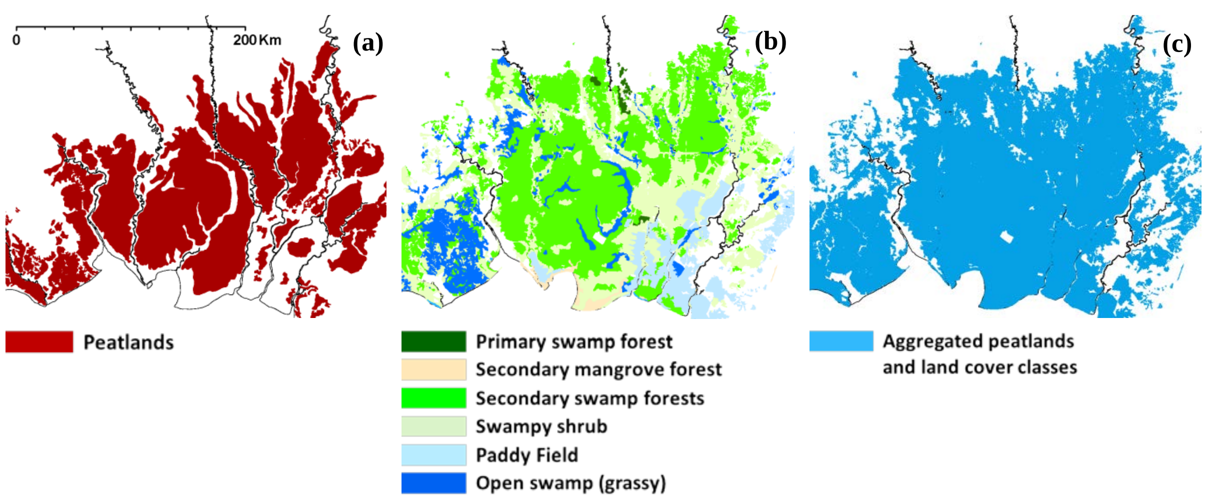



**Figure 3. 5.** The existing image-interpreted map for the part of Central Kalimantan Province centered at approximately $114^{0}10'24.86E$ $2^{0}22'53.54S$; (a) peatlands distribution

map; (b) land cover map; (c) the aggregated map of map (a) and map (b) as the available image-interpreted map.

**Table 3. 2**. Product comparison of wetland original mask, wetland final product post classification, and the available image-interpreted map for the entire country

| Assessment of agreement | Wetlands | |
|---|---|---|
| | Original per pixel map (%) | Final wetlands map (%) |
| Overall agreement | 86.1 | 89.2 |
| Producer's agreement | 54.2 | 73.1 |
| User's agreement | 76.2 | 77.1 |
| Kappa statistic | 55.0 | 68.0 |

**Table 3. 3**. Product comparison of original wetlands mask, final wetlands map, available image-interpreted map and the NFI field plots of Sumatra and Kalimantan

| Assessment for agreement | Wetlands | | | | | |
|---|---|---|---|---|---|---|
| | Sumatra | | | Kalimantan | | |
| | Original per pixel map (%) | Final wetlands map (%) | WI/MoAg/ MoF map (%) | Original per pixel map (%) | Final wetlands map (%) | WI/MoAg/ MoF map (%) |
| Overall agreement | 86.4 | 91.1 | 94.6 | 89.9 | 90.7 | 94.5 |
| Producer's agreement | 64.2 | 83.2 | 89.1 | 67.9 | 80.1 | 91.0 |
| User's agreement | 90.7 | 88.4 | 93.8 | 73.6 | 71.4 | 80.7 |
| Kappa statistic | 66.0 | 79.0 | 87.0 | 65.0 | 70.0 | 82.0 |

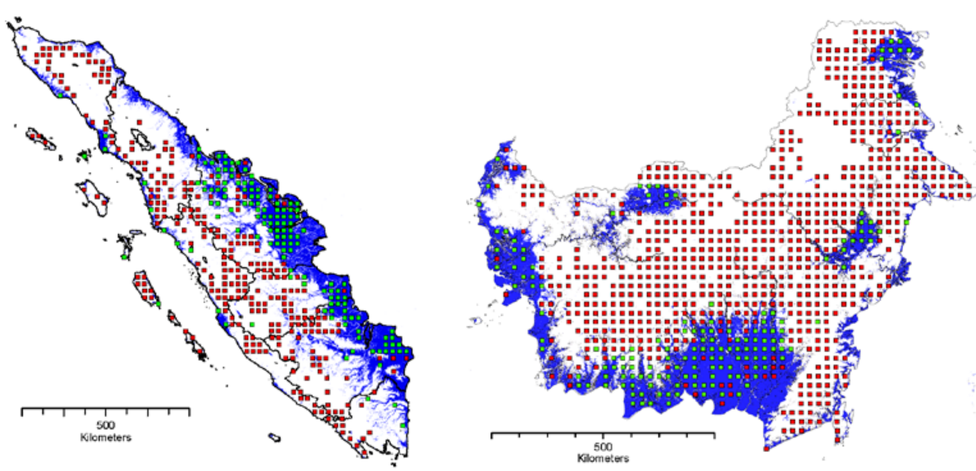


**Figure 3. 6.** (a) The permanent sample plot (PSP) of NFI data for Sumatra over the Sumatra wetlands; (b) The PSPs of NFI data for Kalimantan over the Kalimantan wetland. Wetland final product is in blue, PSPs with wetland category are in green, and PSPs with non-wetland category (dry-land) are in red.

The produced map was also compared to the available data and provides an agreement and disagreement assessment. Examples of product agreement with existing maps are illustrated for areas of Papua for inland wetlands, and Sumatra for riparian wetlands (Figure 3.7). Disagreements are largely related to the mapping methods, specifically the more detailed per pixel digital approach compared to the heritage photo-interpreted method. Greater detail depicted by the algorithmic approach is found inside and outside of the general wetland features delineated by the interpretation method.

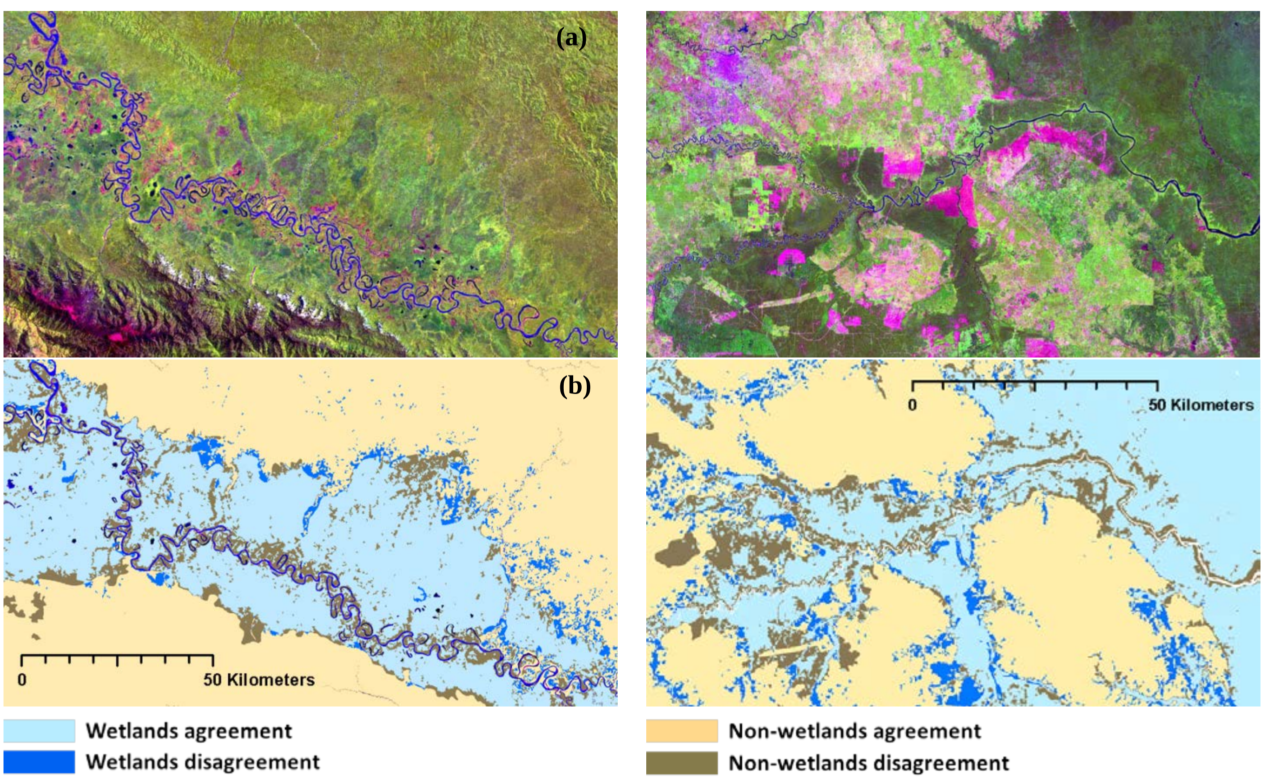


**Figure 3. 7.** The map for agreement/disagreement for the inland wetlands in part of West Papua Province (centered at $138^0$59’30.02E $3^0$10’50.18S) on the left, and part of South Sumatra Province (centered at $103^0$26’20.4”E $1^0$56’45.6”N) for riparian wetlands on the right; for (a) Landsat image with 5-4-3 spectral band combination; (b) The wetlands/non-wetlands agreement and disagreement

***National wetlands: the extent and its distribution***

The extent of Indonesia’s wetlands (figure 3.8) is estimated to be 21 percent of the total land area, totaling 39.6Mha. Detailed assessment of the original wetland mask derived from the decision tree classification and the final wetland map is shown in table 3.4. Indonesian wetlands consist of peat swamps, freshwater swamps, mangrove swamps, woodlands swamps (sago palm/*Metroxylon sagu* and pandan/*Pandanus amaryllifolius*), herbaceous swamps, grass swamps and savannas (Scott 1989, Silvius 1989). As summarized in table 3.4, wetlands are distributed primarily in Sumatra (30.1 percent) or 25.2 percent of Sumatra’s land; Kalimantan (30.8 percent) or 22.9 percent of Kalimantan’s land; and Papua (29.9 percent) or 28.9 percent of Papua’s land.

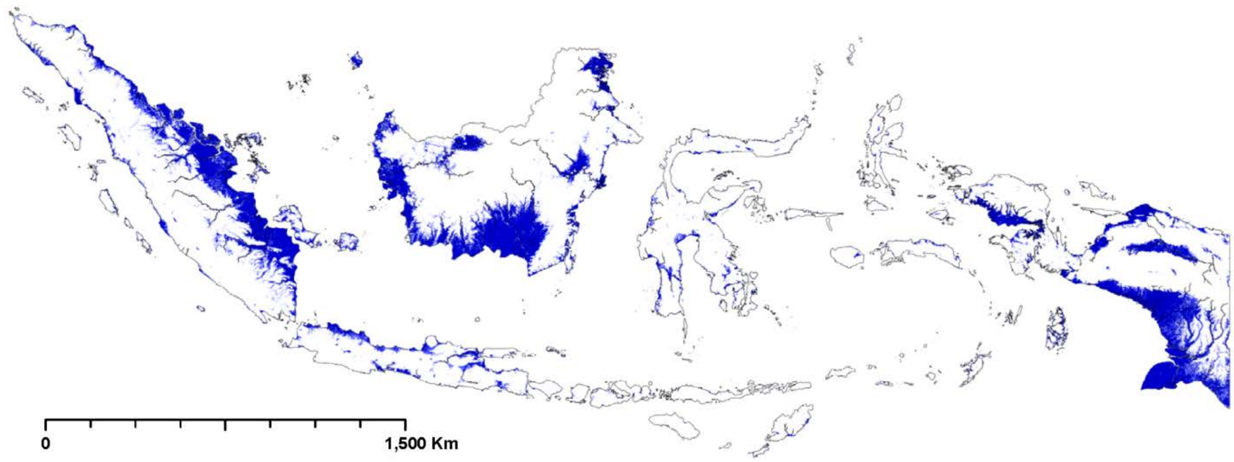



**Figure 3. 8.** The national wetlands map of Indonesia.

**Table 3. 4**. The Indonesian wetlands area extent and its distribution per each major island

| Island | The wetlands | | | | | | |
|---|---|---|---|---|---|---|---|
| | Area extent (Mha) | | Area increase | Percentage to the total area wetlands (%) | | Percentage to the corresponding island (%) | |
| | Original mask | Post classification | Percent (%) | Original mask | Post classification | Original mask | Post classification |
| Sumatra | 8.7 | 11.9 | 37.0 | 29.3 | 30.1 | 18.4 | 25.2 |
| Kalimantan | 9.4 | 12.2 | 29.4 | 31.7 | 30.8 | 17.7 | 22.9 |
| Java | 1.2 | 1.9 | 51.4 | 4.2 | 4.7 | 9.3 | 14.1 |
| Sulawesi | 0.9 | 1.2 | 33.2 | 3.0 | 2.9 | 4.7 | 6.3 |
| Maluku | 0.4 | 0.5 | 08.7 | 1.5 | 1.2 | 5.6 | 6.0 |
| Banusra *) | 0.1 | 0.2 | 21.3 | 0.5 | 0.4 | 1.9 | 2.3 |
| Papua | 8.9 | 11.8 | 33.0 | 29.9 | 29.9 | 21.7 | 28.9 |
| Total | 29.7 | 39.6 | 33.4 | | | 15.8 | 21.0 |

*) Bali and Nusa Tenggara

The directory of Asian Wetlands (Scott 1989, Scott and Jones 1995), which includes an inventory of Indonesia's wetlands (Silvius 1987), estimated Indonesia's freshwater swamp to be roughly 11.6 Mha and woodland swamp to be about 8 Mha. Peatland swamps, particularly in Sumatra, Kalimantan and Papua, were estimated to cover 20.7 Mha (Silvius 1987, Wahyunto *et al* 2003, 2004, and 2006, Page *et al* 2011). Mangroves have been nationally estimated at 3.8 to 4.2 Mha (Darsidi 1984, Silvius 1987, Soemodihardjo 1987). From these ancillary databases, Indonesia's natural wetlands are estimated to cover appoximately 44Mha. The WI/MoAg/MoF wetlands map totals 41.2 Mha. The produced map is a more conservative representation of 39.6Mha of wetland extent.

## Discussion

### *Independent variables and wetlands discrimination*

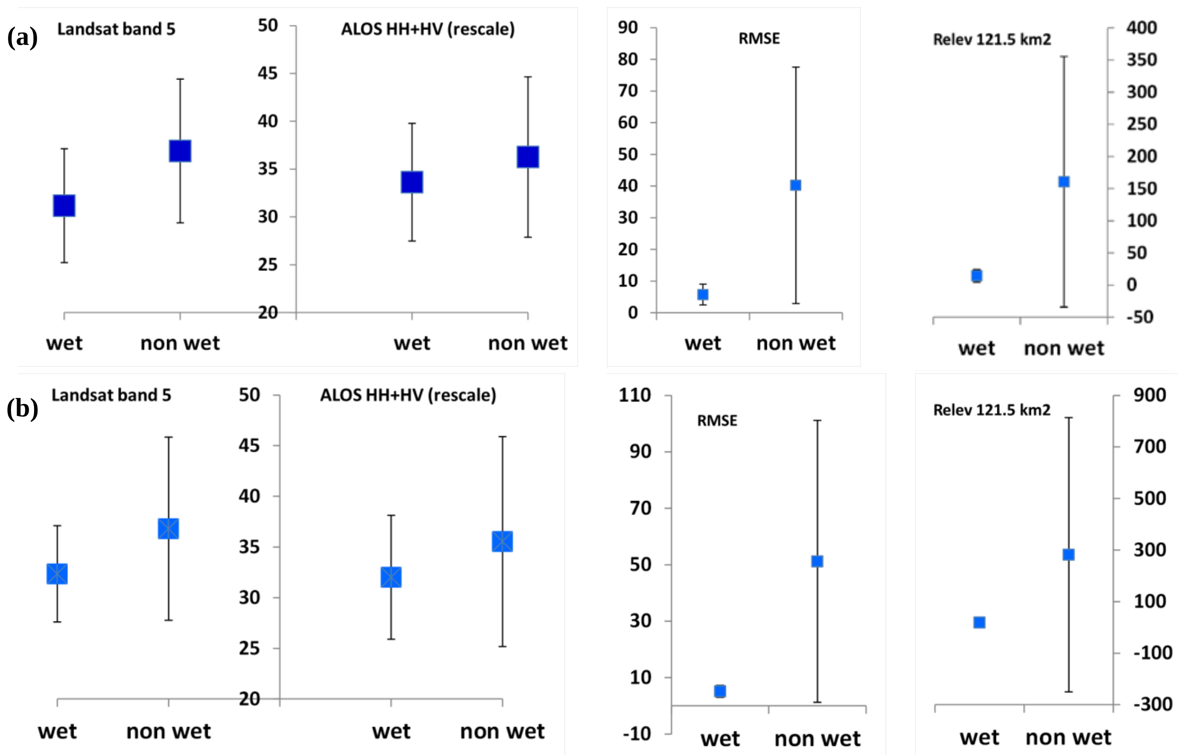



**Figure 3. 9.** The mean and standard deviation of four of the most important independent variables (RMSE, Landsat band 5, relative elevation of 121.5 km$^2$ catchments, and ALOS PALSAR HH+HV polarization) for the original wetlands mask sampled for existing NFI data, for (a) Kalimantan,105 wetlands plots and 679 non wetlands plots; and (b) Sumatra, 86 wetlands plots and 280 non-wetlands plots. The t-test summary yielded a p value of

<<0.000 with 95 percent confidence with respect to the degrees of freedom of 780 for Kalimantan and 362 for Sumatra.

Topographical indices such as RMSE and relative elevation of 121.5 $km^2$ catchment area are the first and third most important discriminators of wetlands (Table 3.1). Figure 3.9 shows the mean values for these two variables, all significantly different for wetlands and non-wetlands classes. Additionally, Landsat band 5 and PALSAR polarization indices, useful for observing vegetation and soil moisture content (e.g. Hess *et al* 1995, Ozesmi and Bauer 2002, Silva *et al* 2008), were found to be significantly different for the two classes. However, of the respective topographical, passive optical and active microwave information sources, it is clear that landform information based on topographical modeling is the most useful information for mapping wetlands.

***Original wetlands mask versus post classification product***

The dynamic forest cover change in Indonesia posed a challenge for mapping wetlands. While a number of wetlands have been drained and converted to agro-industrial land uses, the objective of the exercise was to delimit potential natural wetland extent. This is different from the wetland map of Bankanza *et al* (2010) for the Democratic Republic of the Congo, where almost no conversion of natural wetlands has occurred (Bankanza *et al* 2012). The mapping of potential wetland without regard to current land use led to a greater use of topographical indices in the characterization of Indonesian wetlands. For example, Landsat spectral responses of existing peatland forest, cleared peatland forest, or subsequent oil palm estate, could all be labeled as wetland in this exercise. As a result, the topographical data became the clear driver of the mapping algorithm. Flat areas with low relative elevation across various catchment sizes indicated potential wetland more readily than the Landsat or PALSAR inputs. However, the Landsat bands and PALSAR (figure 3.9) data were important, contributing more than 25 percent of the deviance reduction in mapping wetlands (table 3.1). Post classification was deemed necessary to overcome limitations in more completely mapping converted wetlands. The post classification process increased wetland extent by 33 percent overall (table 3.4). Per island group, Java had the highest increase (51.4 percent), followed by Sumatra, Sulawesi, Papua and Kalimantan. Post-processing improved final map agreement by 3.1 percent overall, 18.9 percent for producer's accuracy, 0.9 percent of user's accuracy, and 13 percent of Kappa.

***Wetlands and its spatial distribution for major islands***

Sumatra, Kalimantan and Papua contain roughly 30 percent of Indonesian wetland area totaling 35.8 Mha (table 3.4), close to the area of the WI/MoAg/MoF map (34.8 Mha). Greatest areal disagreements are found where artificial wetlands are present. Indonesian has extensive artificial wetlands from agriculture and aquaculture land uses (Silvius 1987, Whitten *et al* 1989, 1996, Scott 1989, Finlayson *et al* 2002) found largely in Java, Sulawesi and some parts of Sumatra. Many artificial wetlands, for example terraced rice paddies, are not depicted in the map made for this study. However, they are part of the combined WI/MoAg/MoF map. Figure 3.10 illustrates this disagreement for Java, where extensive artificial wetlands are indicated as errors of omission in the new wetlands map. Java alone captures more than 20 percent of non-wetland disagreement. For island groups with less artificial wetlands, there is less disagreement between the map and reference data sets.

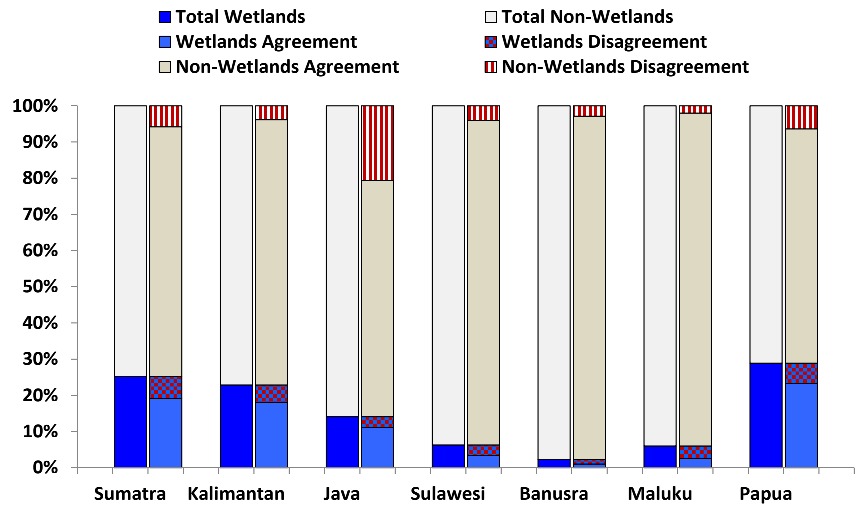



**Figure 3. 10.** The percentage of wetlands and non-wetlands extent, including agreement/disagreement for each major island group for the derived map and the WI/MoAg/MoF product

## Conclusion

Topographical indices (SRTM-derived), optical (Landsat) and radar (PALSAR) image inputs were used to implement a supervised classification of Indonesia's wetlands as a single thematic class encompassing peatlands, mangroves, and other freshwater wetlands. The results agree with existing image-interpreted products from Indonesia's Ministries of Forestry and Agriculture and Wetlands International (WI/MoAg/MoF), as well as with forest inventory data from the Ministry of Forestry. Overall agreement when compared with forest inventory data indicates slightly lower, but comparable accuracies with the image-interpreted WI/MoAg/MoF map.

A significant challenge in establishing a land use history for Indonesia is the quantification of past wetland extent. This study attempted to create a baseline wetland extent map, upon which recent land use change can be mapped. Such a product can be used to estimate rates of forest change, both inside and outside of wetlands, as an input to carbon emissions models, and in support of biodiversity assessment efforts. The presented map was implemented at the national-scale using a systematic, algorithmic approach. As such, it represents an internally consistent quantification of Indonesian wetland extent, suitable for science and policy applications related to wetland ecosystem services and their change over time.

# Chapter 4: Spatially and temporally quantifying primary forest cover loss and primary forest degradation, 2000 to 2012 [4]

## Introduction

Quantifying primary forest cover loss, particularly within wetlands, is important for greenhouse gas accounting efforts. Primary forests are the largest aboveground carbon stores in the world and peatlands are the largest reservoirs of soil carbon (Page *et al* 2002, 2007, Zedler and Kercher 2005, Houghton *et al* 2009). The high rates of forest cover change, in term of forest loss and degradation, coupled with the high carbon stocks in aboveground and belowground pools has made Indonesia the third largest global emitter of $CO_2$ (WB-PEACE 2007).

In fact, current understanding of primary forest cover loss within Indonesia lacks consensus, and to date no substantive reports on forest degradation exist. The United Nations Food and Agricultural Organization's (UNFAO) Forest Resource Assessment 2010 reported the rate of forest loss in Indonesia to be 0.31 Mha per year from 2000 to 2005 and 0.69 Mha per year from 2005 to 2010 (FAO 2010a, 2010b). Indonesia's second communication to the United Nations Framework Convention on Climate Change in 2009 reported a forest loss rate of 1.1 Mha per year from 2000 to 2005 (MoF 2008a, MoE 2010). A more recent estimate of 0.40 Mha per year of forest loss from 2009 to 2011 was reported by the Indonesian Ministry of Forestry (MoF 2013). Lack of consensus on quantification of primary forest cover change is hampering Indonesia's ability to meet the country's

[4] The content of this chapter is accepted on Nature Climate Change journal (dated May 8th 2014) and under process of publication

commitment to implement, and thus to benefit from, global initiatives on Reducing Emissions from Deforestation and Forest Degradation (REDD) and REDD+ and furthermore is preventing effective monitoring, reporting, and verification (MRV), an essential component of REDD+.

Brazil, for years, had experienced the highest rate of deforestation, which Indonesia was the second (FAO 2001, 2006a, Hansen *et al* 2008, 2009). Brazil replied this challenge by establishing a system named PRODES (*Monitoramento do desmatamento das formações florestais na Amazônia Legal*) that especially designed to monitor the dynamic forest change within Amazon (Shimabukuro *et al* 2013). The forest class of PRODES is defined as dense tropical forest and dense savanna woodland (*cerradao*) (INPE 1992). The Brazil's PRODES forest mask represents intact and degraded natural forest, which is annually reduced in extent as these forests are cleared and converted to other land uses. The Brazil's PRODES forest is equaled to the primary forest term used in this study.

Figure 4.1 depicts Indonesian primary forest loss totals by year from this study compared to official Indonesia government data (MoF 2008a, MoE 2010, MoF 2013), UNFAO data for Indonesia (FAO 2010a, 2010b), and Brazil's PRODES deforestation data (INPE 2013), with all data sets estimating primary forest cover loss (see Chapter one for detailed definition and terminology used). The estimates and comparison on figure 4.1 points to the need for thematic consistency and improved spatio-temporal data for Indonesia in bringing transparency to this important land change dynamic.

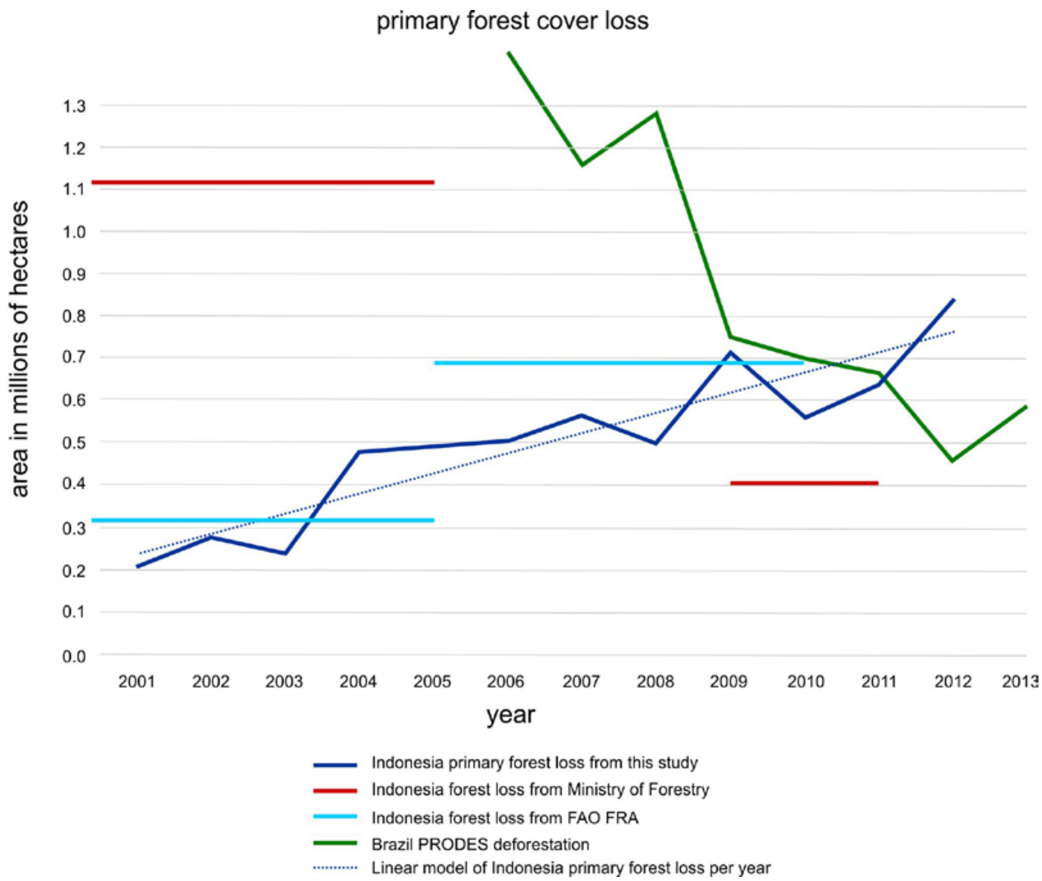



**Figure 4. 1.** Estimates of annual primary forest loss for Indonesia and Brazil

The Indonesia's natural forest cover extent varies from place to place (Van Steenis 1957, Corlett 2005), depending on the climatic, edaphic, and physiographic features (Richard *et al* 1940, Clark *et al* 1999), and later by the degree and types of human activity on forests (Gupta 2005). Terms of forest formation is used, and commonly employ information on stand floristic, structural complexity and physiognomy (Richard *et al* 1940, Allaby 2004), which are often based on landform, such as lowland forests, wetland/swamp forests, and montane forests (Whitmore 1984). For Indonesia, the state of the forests, as well as levels of intensity in utilizing the forests are associated with forest formations. For example: Indonesia's lowland forests, particularly to the west of Wallace Line (Wallace 1859), are species rich and include the famous lowland *Dipterocarps* forests (Whitmore 1984, Ashton 1992, Manokaran 1995, Appanah 1998) and one of the most species-rich ecosystems in the world. For years, these lowland forests have long been threatened by various anthropogenic disturbances that lead to deforestation and forest degradation (Holmes 2000, Curran *et al* 2004, Beukema *et al* 2007, Hansen *et al* 2009, Broich *et al* 2010, Margono *et al* 2012). In contrast, wetland forests in Indonesia have historically remained largely intact (Murdiyarso *et al* 2010). However, the conversion of wetland forests, including peatlands, to agro-industrial land uses has increased during the last two decades (Murdiyarso *et al* 2010, Uryu *et al* 2008, Koh *et al* 2011, Stibig *et al* 2014). Unlike lowland and wetland forests, upland and montane forests are less disturbed, and the rate of forest loss is reported to be less significant compared to that of the lowlands (Whitten *et al* 1996, Li 1999, Holmes 2000). However though the rate of forest loss is less, unlike other parts of the world, forest disturbances in upland tropical forests still occur (Mackie *et al* 1987, Armitage 2004) and are vulnerable to fire (Corlett 2005). As a consequence, estimating and mapping forest extent and loss within different forest formations is highly demanded, not only for carbon monitoring purposes but for maintaining biodiversity, habitat loss and species extinctions.

A recent study providing spatially explicit maps of globally gross forest cover change found Indonesia to be the country with the highest rate of increasing forest cover loss from 2000 to 2012 (Hansen *et al* 2013). However, the results were based on forests, defined by tree cover, and included commercial forestry dynamics in the quantification of forest loss. In other words, the clearing of pulp plantations and oil palm estates as well as primary forest was included in tabulating forest cover loss. In the context of climate change, it is critical to know the context of forest disturbance, whether of a high biomass natural forest or a short cycle plantation of an *acacia spp*. In addition, Indonesia poses a particular challenge in the context of tropical deforestation. Deforestation, as defined by the replacement of natural forest by non-forestry related land uses, does not typically occur in Indonesia. Natural forest cover is more often replaced by commercially managed forest cover, resulting in a complicated landscape of forest cover change.

Improved documentation on primary forest cover loss is a challenge. The objective of the presented study is to improve the context of understanding of this Indonesian forest cover change dynamic by quantifying the portion of gross forest cover loss that occurred within primary forests from 2000 through 2012, including a disaggregation by landforms. Additionally, a review of primary forest loss within the first phase of Indonesian deforestation moratorium period (2011-2012) is reported as an initial assessment on the effectiveness of the moratorium.

## Material and Methods

### *Rationale*

Landforms all around the world are the combined result of plate tectonics, other geomorphic processes, and anthropogenic modification of the landscape (Gupta 2005). Landforms are commonly defined by conspicuous physical attributes such as elevation and slope. A benefit of using landforms as a basis for mapping units is their timeless character that remains relatively constant as land use and cover change (Desaunettes 1977). In this study visible major landforms such as lowland, wetland, upland and montane were employed to assess the changes in extent over time of primary intact and degraded forests.

Lowland is an informal, generic, imprecise term for an extensive region of low-lying land, often near a coast and including extended plains lying not far above tidal level (USDA 2008). Lowland could be either permanently dry or water logged/temporary and/or permanently covered by a water layer, which categorized wetlands. Upland is a core of hilly to mountainous landscapes of rolling and steeply inclined surfaces, including table lands and plateaus lying at higher elevation; is not flood-irrigated and is not found in the immediate coastal fringe, estuarine or within alluvial plains or other wetlands (Li 1999). Montane refers to a mountainous biogeographic zone below the tree line.

***Data sets***

This research utilized multiple data sets originating from several sources. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat Thematic Mapper (TM) with standard pre-processing of Potapov *et al* (2011, 2012) were used as the main inputs to create national scale of Indonesia's time-sequential image composites. These composites were used to update the IFL 2000 (Potapov *et al* 2008) to create IFL 2005, 2010 and 2012. The annual change map 2000-2012 of Indonesia, a subset of the gross forest cover change map of Hansen *et al* (2013), was subsequently examined using the time-sequential image composites. Indonesia's wetlands map of Margono *et al* (2014) was generated from topographical indices derived from 90m elevation data from the Shuttle Radar Topography Mission (SRTM), optical (cloud-free Landsat image mosaics) and radar (ALOS PALSAR) image inputs, previously elaborated in Chapter three. Other landforms were defined using STRM elevation data. Various ancillary datasets were used for data validation and product comparison. Land cover data for Indonesia for the year 2000 and a forest-land use map 2000-2005 periods, were obtained from the Ministry of Forestry of Indonesia (MoF).

Indicative moratorium maps were downloaded from Indonesian REDD+ taskforce website (http://www.satgasreddplus.org/).

***Methodological approach***

As a whole, the works of this study are divided into four independent parts, which are (a) mapping the primary forests loss; (b) mapping the primary forests extents in the form of intact and degraded types; (c) mapping wetlands; and (d) mapping major landforms and forest formation. Those independent but interrelated parts are illustrated in figure 4.2.

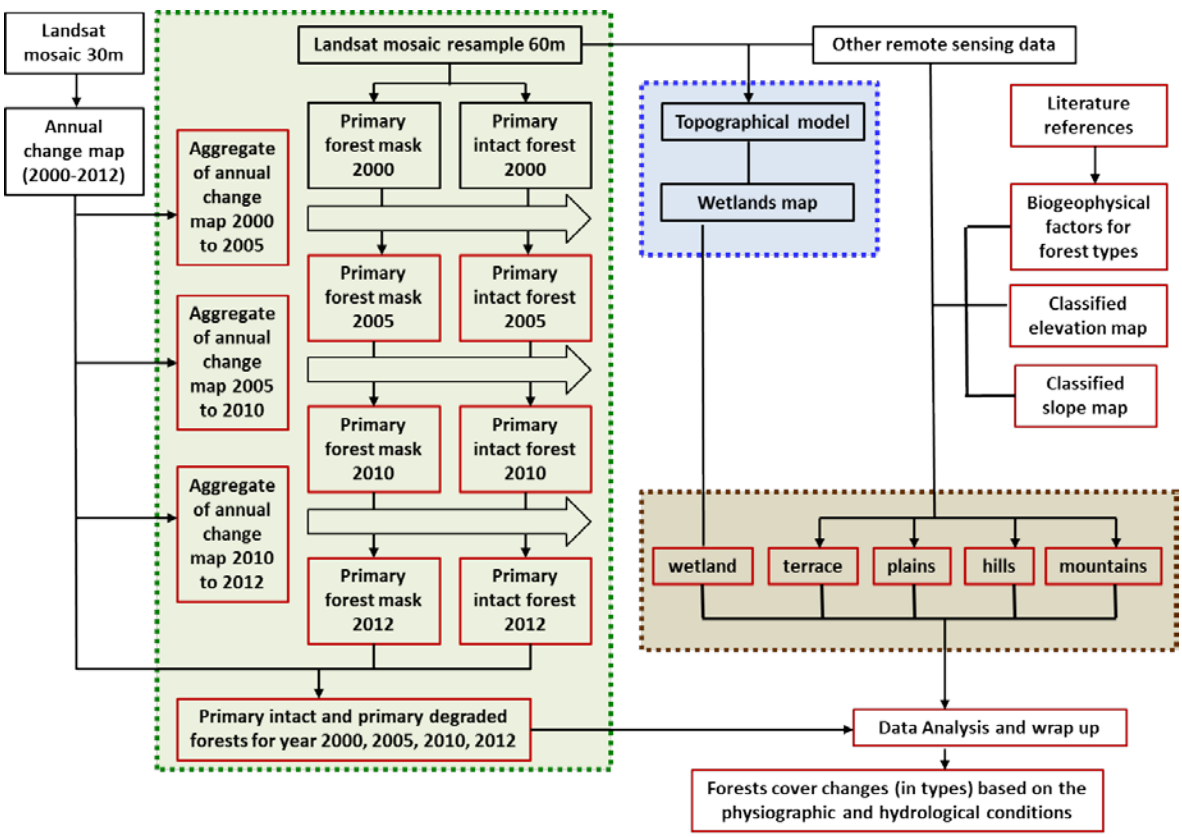



**Figure 4. 2.** The workflow to map the primary forest and timely disturbances on major landforms; the green box is the method used for sub setting primary forest loss and mapping primary intact and primary degraded forests, representing step (a) and (b); the

blue box performs the method applied in mapping Indonesia's wetland (c); the brown box illustrates method to map landforms, step (d); and the red boxes indicate the work employed particularly for this work.

In general, this work combines the gross forest loss data of Hansen *et al* (2013) with an extension of the work of Margono *et al* (2012, 2014) in disaggregating total forest cover loss 2000-2012 by primary/non-primary status and landform for all of Indonesia. Primary forest loss data were a subset of the global product that employed a data mining approach of the Landsat 7 archive to quantify annual gross forest cover loss. This global forest change map was created by applying a decision tree model of forest and non-forest cover loss training data to multi-temporal metrics for the 2000-2012 intervals; subsequently, gross loss was disaggregated using annual Landsat-derived percent canopy data, as described in Hansen *et al* (2013). The annual gross global change was overlain with the Indonesia primary forest mask 2000 to map the primary forests loss from 2000 to 2012. The mapping of the primary forest base map 2000 was initially demonstrated in Sumatra (Margono *et al* 2012), and extended to the entirety of Indonesia for this work.

The primary forests were disaggregated into intact and degraded sub-classes, by employing a hybrid approach (Margono *et al* 2012) using a per-pixel supervised classification mapping followed by a Geographic Information System (GIS)-based fragmentation analysis to delineate Intact Forest Landscapes (IFL) of Potapov *et al* (2008). To create the IFL layers, buffers of roads, settlements and other signs of human landscape alteration were used (Potapov *et al* 2008) to identify degraded areas within zones of primary forest cover. A cloud-free composite of Landsat imagery for the year 2000 was used to generate the reference primary forest extent map. IFL layers employed 2005, 2010 and 2012 cloud-free Landsat mosaics to map changes in primary intact forest extent. The stand's structure of primary intact and degraded sub-classes has a significant difference as demonstrated using GLAS data in Chapter two. The primary intact and primary degraded forest map corresponds to the Indonesia Ministry of Forestry's map classes of primary and secondary forest (see Chapter one for detail explanation). Table 4.1 and figure 4.3 illustrate the agreement across these classes in assessing the accuracy of primary forest extent 2000 from this study.

**Table 4. 1**. Product comparison of primary forests (intact and degraded form)/non-primary forests 2000, and the disaggregated classes of primary intact/primary degraded, versus the MoF land cover map of forest/non-forest 2000, and the disaggregated classes of primary/secondary

| Assessment for agreement | Primary forests (intact & degraded) | Non-primary forests | Primary intact forest | Primary degraded forest |
|---|---|---|---|---|
| Overall agreement | 90.2 | 90.2 | 70.4 | 70.4 |
| Producer's agreement | 90.0 | 90.4 | 58.2 | 84.5 |
| User's agreement | 91.4 | 88.9 | 81.2 | 63.7 |
| Kappa statistic | 80.0 | 80.0 | 42.0 | 42.0 |

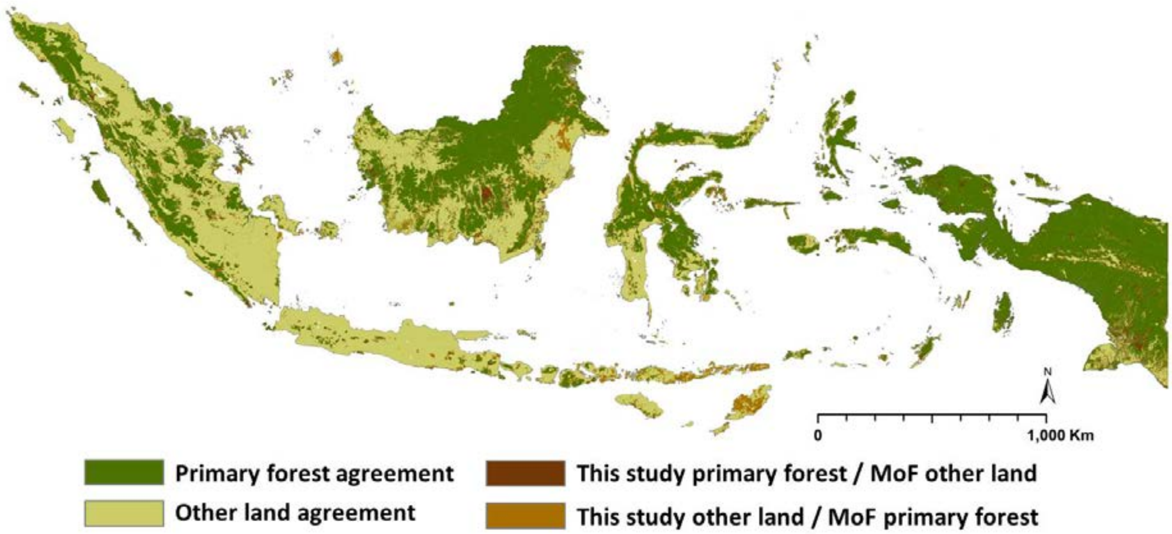



**Figure 4. 3.** Map of agreement and disagreement for the primary forest / other land classes of this study versus the primary forest / other land classes of the Ministry of Forestry of Indonesia, both for year 2000.

Mapping the wetlands (Margono *et al* 2014) is elaborated in Chapter three, combined with criteria for mapping the non-wet landforms, and employed further to map lowland *terra firma*, upland and montane forest formations. In general, although mountains are a conspicuous element of the landscape (Spehn *et al* 2010), setting up the mountains range to distinguish it from lowland plains is not a simple task. Kapos *et al* (2000) applied elevation and slope combinations to define the six major classes of global mountain area, which used to distinguish mountains from lowland plains. However, forest formations based on the elevation gradients of Van Steenis as cited in Whitmore (1984) do not precisely fit the mountain classification of Kapos (Table 4.2), so predominant physiographic features were used (Table 4.3), and generated to map the major landforms using criteria in table 4.4.

**Table 4. 2**. Mountains range and forest formation based on elevation gradient

| Global mountain (Kapos et al. 2000, Korner-Ohsawa 2005) | | | Tropical forest formation (Whitmore 1984 based on Van Steenis 1950) | | |
|---|---|---|---|---|---|
| | **Classes for $23^0$N-$19^0$S** | **Elevation, local variation, slope** | | **Forest formation** | **Elevation** |
| 1. | Class 1 | >4,500 meters | 1. | Tropical subalpine forests | (>3,000 meters to tree line (for only biggest mountains |
| 2. | Class 2 | 3,500 to 4,499 meters | 2. | Tropical upper montane forests | 1,500-3,000 meters |
| 3. | Class 3 | 2,500 to 3,499 meters | 3. | Tropical lower montane forests | 1,200-1,500 meters |
| 4. | Class 4 | 1,500 to 2,499 meters if it slopes more than $2^0$ | 4. | Tropical lowland evergreen forests | <1,200 meters |
| 5. | Class 5 | 1,000 to 1,499 meters if it slopes more than $5^0$; or has a local elevation range of 300 meters or more | | | |
| 6. | Class 6 | 300 to 999 meters if it has local elevation range of 300 meters or more; and 0-1,000 m at the equator | | | |

Elevation gradient and slope classes were generated from SRTM data to define relief and micro-relief in mapping landforms (Desaunettes 1977). The representation of relief and micro-relief correspond to the DEM spatial resolution. The SRTM data have an absolute vertical accuracy of 9-16 m (Farr *et al* 2007), and an approximate 92 meter spatial resolution (Rabus *et al* 2003, Hamilton *et al* 2007), adequate for *reconnaissance* scale mapping of broad physiographic features. In this work, broad physiographic features are grouped into plains, terraces, hills and mountains. Plain (*dataran*) refers to any flat terrain, either large or small that has few or no prominent hills or valleys but sometimes has considerable slope; plains are present as lowlands or plateaus at higher elevations. Terraces (*teras/undak*) are a step-like landform, usually along a river bed or shoreline. A hill (*bukit*) is a landform that rises above the surrounding terrain but with a lower elevation and less slope than a mountain (*gunung*) (Desaunettes 1977). Table 4.3 represents a matrix used to integrate elevation gradient, slope classes, and relief and micro-relief category to demonstrate the predominant physiographic features in Indonesia. The major non-wet landforms, including lowlands, uplands, and montane, as well as wetlands of Margono *et al* (2014), were determined and mapped based on the physiographic features and criteria introduced in table 4.4. Figure 4.4 is the graphical display of forest formations presented in primary intact and degraded forest types.

**Table 4. 3**. Matrix used to demonstrate the predominant physiographic features in Indonesia, adopted and generated from several studies on landform and forest formation in Indonesia (Desaunettes 1977, RePPProT 1990, Whitmore 1984, Holmes 2000, 2002, Kapos *et al* 2000, Korner and Ohsawa 2005).

| Slope classes | Classified elevation to match tropical forest formation | | | | |
|---|---|---|---|---|---|
| | Productive Lowlands (0-1000m) | Upper Lowlands (1000-1200m) | Lower Montane (1200-1500m) | Upper Montane (1500-3000m) | Subalpine (3000-4000m) |
| **Flat (0-3$^0$)** | Plains | Terraces | Hills | Mountains | Mountains |
| **Gently undulating (3-8$^0$)** | Plains | Terraces | Mountains | Mountains | Mountains |
| **Undulating (8-15$^0$)** | Terraces | Hills | Mountains | Mountains | Mountains |
| **Rolling (15-25$^0$)** | Hills | Hills | Mountains | Mountains | Mountains |
| **Moderately steep (25-40$^0$)** | Hills | Hills | Mountains | Mountains | Mountains |
| **Steep (>40$^0$)** | Hills | Hills | Mountains | Mountains | Mountains |

**Table 4. 4**. Criteria used to determine major landforms based on predominant physiographic features (sources, summarized from Desaunettes 1977, Whitmore 1984, RePPProT 1990, Holmes 2000, Kapos *et al* 2000, Korner and Ohsawa 2005)

| Major Landforms | Broad physiographic features | Criteria of elevation and slope classes | Forest formation |
|---|---|---|---|
| **Lowland** | Plains and terraces | elevation 0-1000 m with slope 0-15$^0$<br>elevation 1000-1200 m with slope 0-8$^0$ | Dry-lowland forests |
| **Upland** | Hills | elevation 0-1000 with slope >15$^0$<br>elevation 1000-1200 m with slope >8$^0$ | Upland forests (lower montane) |

| | | | |
|---|---|---|---|
| | | elevation 1200-1500 with slope 0-$3^0$ | |
| **Montane** | Mountains | elevation 1200-1500 with slope >$3^0$ and elevation >1500m | Montane forests (upper montane) |
| **Wetlands** | Water logged, and temporary or permanently inundated | elevation > 0 m with water table is at or near the surface | Wetland forests (Peat swamp forest, freshwater swamp forest, and mangrove forest) |

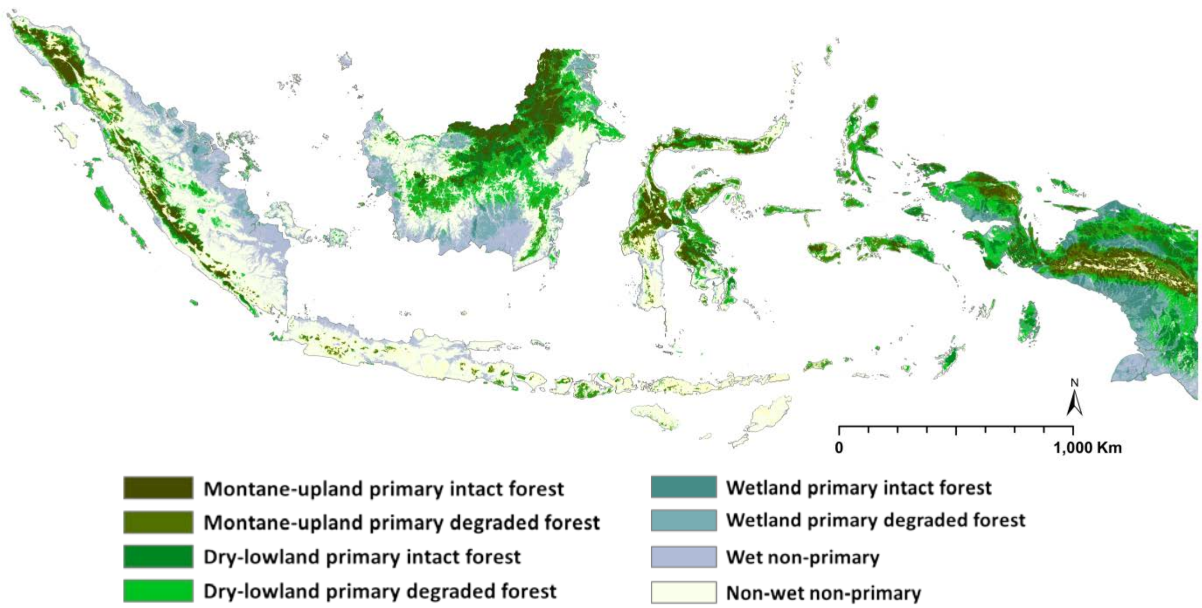



**Figure 4. 4.** Indonesia's forest formation 2013 of lowland, wetland, upland and montane forests, with primary intact and degraded forest types within each formation

In the presented study, primary forests were mapped for the reference year 2000, and the loss quantified through 2012. The results were disaggregated by landforms of wetland, lowland, upland and montane, to map wetland, lowland *terra firma*, upland, and montane forest formations. The two primary forest classes, four landforms (of forest formations) and annual forest cover loss data were overlain to generate the spatio-temporal estimate of loss within Indonesia's primary forest cover.

## Results and analysis

### *Indonesia's primary forests cover loss*

Of the 15.79 Mha of gross forest cover loss for Indonesia reported by Hansen *et al* (2013), for the period 2000-2012, 38 percent or 6.03 Mha occurred within primary intact or degraded forests. The 62 percent or 9.56 Mha of the loss occurred within non-primary forest. The annual disaggregation of primary forest and non-primary forest cover loss is in figure 4.5. The loss of non-primary forest cover includes the clearing (harvesting) of pulp plantations, oil palm estates and other tree crops. Quantifying forest loss of non-primary forests class is critically important, both in the contexts of carbon monitoring and forest management, in order to distinguish the loss of high biomass and high biodiversity natural forests, and that of previously established monoculture tree plantations. Figure 4.6 presents a map of Indonesia's primary and non-primary forest extent and loss, from 2000 to 2012, where "forest" is defined as 30 percent or greater tree canopy cover.

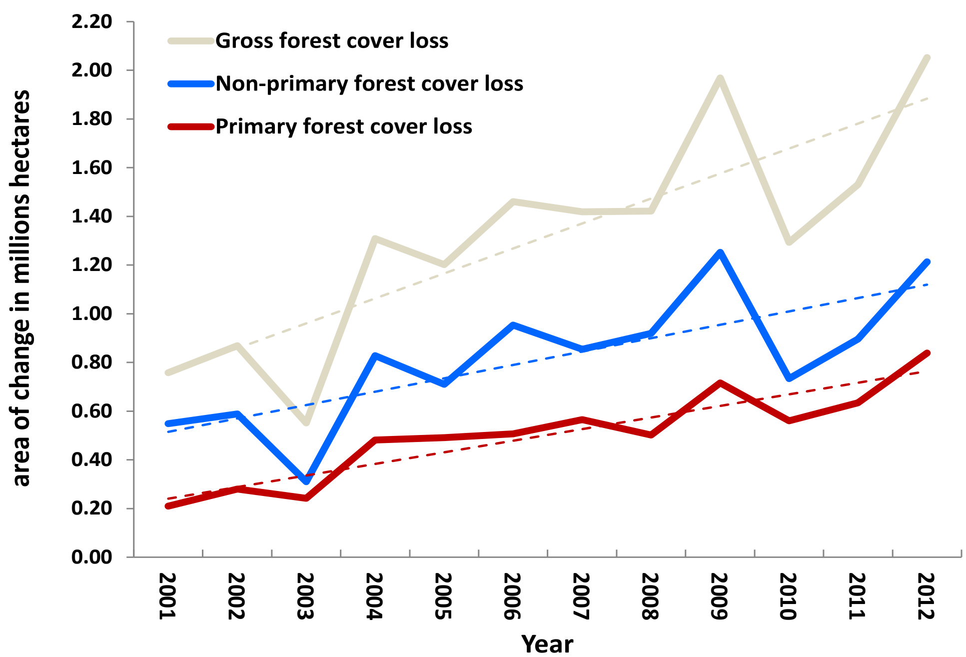


**Figure 4. 5.** Gross forest cover loss for Indonesia (grey-line), disaggregated into national primary forest cover change (red-line), and non-primary forest cover change (blue-line); dashed lines with different color represent linear model of each corresponding loss

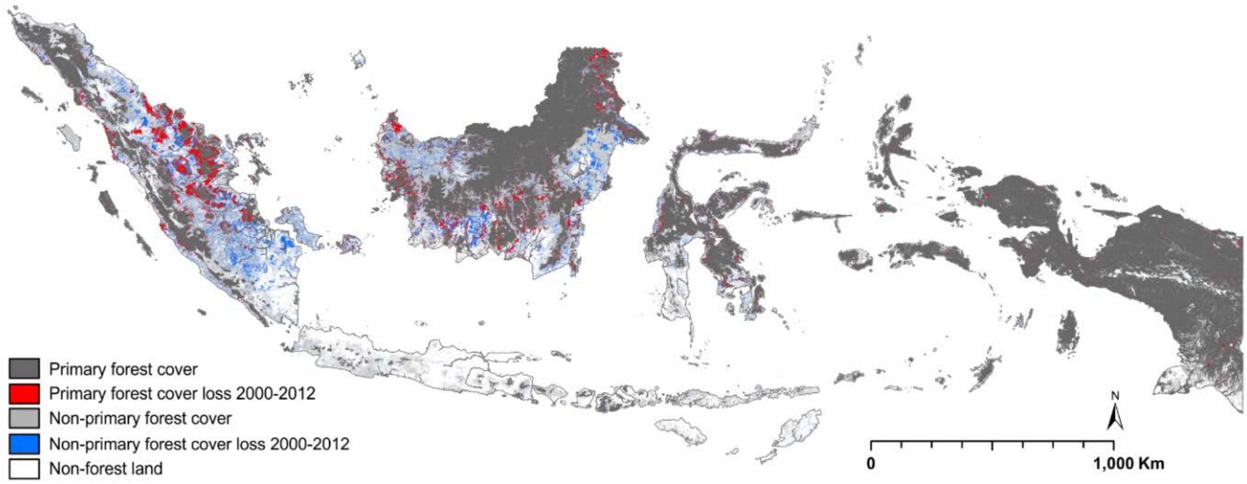



**Figure 4. 6.** Map of Indonesia primary and non-primary forest extent and loss, 2000 to 2012, where forest is defined as 30 percent or greater tree canopy cover. Primary forest includes both intact and degraded (selectively logged) types

About 56 percent of Indonesia's land is dry lowland with 43 percent (45.3 Mha) covered by primary forests in 2000. Wetland covers 21 percent of the land, and in 2000, 50 percent (19.8 Mha) was covered by primary forest. Upland covers about 16 percent of the land, and in 2000 75 percent (22.2 Mha) was covered by primary forest, and montane only occupies 7 percent but as of 2000, 83 percent (11.1 Mha) was covered by primary forest (figure 4.7a). The year 2000 was determined as a baseline for the extent of primary forest, with the loss and extensive reduction were further disaggregated based on landforms within three epochs of 2000-2004, 2005-2008, and 2009-2012 (figure 4.7b). Lowland and wetland primary forests are more dynamic throughout the time; while upland and montane demonstrate a relatively stable forest cover within each epoch.

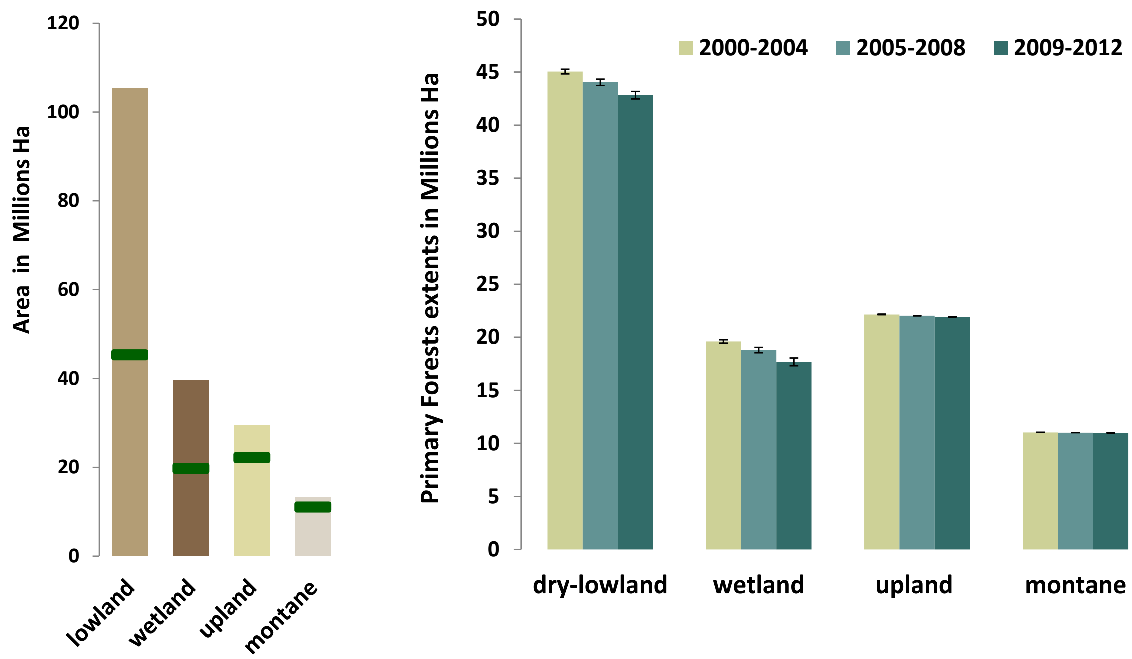



**Figure 4. 7.** Indonesia's interior: (a) extent of primary forest cover in 2000 (green marked) within the four major landforms; (b) Dynamic primary forests extents for 2000-2004, 2005-2008, 2009-2012 epochs within four major forest formations of lowland *terra firma*, wetland, upland, and montane forests

In total annual primary forest cover loss increased over the study period (Table 4.5) with the highest total primary forest cover loss having occurred in 2012, the last year of the study. Primary forest loss in 2012 totaled 0.84 Mha, more than the reported forest loss of Brazil (0.47 Mha) (PRODES 2013), the historical leader in the clearing of tropical forests. Results from this study show that Indonesia experienced an average annual increase of

47,600 ha of primary forest cover loss, which is more than any other tropical country's increase in annual gross forest cover loss from the study of Hansen *et al* (2013).

Several studies have reported a high rate of primary forests cover loss on the islands of Sumatra and Kalimantan (Fearenside 1997, Kettering *et al* 1999, Holmes 2000, 2002, FWI/GWF 2002, Lambert and Collar 2002, Curran *et al* 2004, Gaveau *et al* 2007, Uryu *et al* 2008, Hansen *et al* 2009, Broich *et al* 2011), and are supported by the findings of this study as depicted in figure 4.8. Among the seven major islands, Sumatra and Kalimantan exhibit the highest amount of primary forest cover loss from 2000 to 2012. Sumatra exhibits a more intensive forest cover loss over the twelve years of this study and a greater annual increase in forest loss compared to that of Kalimantan. Based on the annual trend, prior to 2005 Indonesia's primary forests loss was mainly from Sumatra's loss, but post 2005, the national loss was driven by both Sumatra and Kalimantan.

**Table 4. 5**. Annual primary (intact and degraded) forests cover loss for each landform of lowland, wetland, and aggregated upland-montane, for Indonesia and the islands of Sumatra, Kalimantan and Papua

| Year | Primary (intact and degraded) forest cover loss (Thousand Ha) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Indonesia | | | | Sumatra | | | Kalimantan | | | Papua | | |
| | **Tot** | **Low Land** | **Wet Land** | **Up Mon*** | **Low land** | **Wet land** | **Up Mon*** | **Low land** | **Wet Land** | **Up Mon*** | **Low Land** | **Wet Land** | **Up Mon*** |
| 2001 | 209 | 132 | 59 | 19 | 62 | 41 | 6 | 46 | 15 | 3 | 7 | 2 | 1 |
| 2002 | 280 | 156 | 93 | 30 | 47 | 59 | 5 | 61 | 28 | 4 | 14 | 5 | 2 |
| 2003 | 242 | 112 | 104 | 27 | 32 | 29 | 5 | 50 | 70 | 3 | 8 | 3 | 2 |
| 2004 | 481 | 251 | 192 | 38 | 87 | 141 | 7 | 104 | 44 | 5 | 16 | 3 | 3 |
| 2005 | 491 | 241 | 224 | 26 | 110 | 175 | 8 | 97 | 44 | 4 | 10 | 3 | 2 |
| 2006 | 504 | 297 | 169 | 38 | 118 | 94 | 10 | 121 | 69 | 5 | 15 | 3 | 3 |
| 2007 | 565 | 248 | 290 | 27 | 94 | 117 | 10 | 119 | 167 | 4 | 14 | 3 | 3 |
| 2008 | 501 | 281 | 192 | 29 | 116 | 114 | 15 | 137 | 72 | 5 | 11 | 3 | 2 |
| 2009 | 716 | 377 | 295 | 45 | 153 | 157 | 17 | 168 | 126 | 7 | 16 | 5 | 5 |
| 2010 | 560 | 238 | 295 | 28 | 96 | 204 | 12 | 108 | 84 | 4 | 16 | 4 | 5 |
| 2011 | 635 | 288 | 317 | 29 | 114 | 180 | 13 | 130 | 128 | 6 | 19 | 7 | 2 |
| 2012 | 839 | 423 | 374 | 42 | 175 | 218 | 16 | 191 | 142 | 9 | 26 | 12 | 4 |
| **Total** | 6,024 | 3,044 | 2,602 | 378 | 1,205 | 1,529 | 123 | 1,331 | 987 | 59 | 173 | 54 | 34 |

*) Up-Mon: Upland and Montane landform

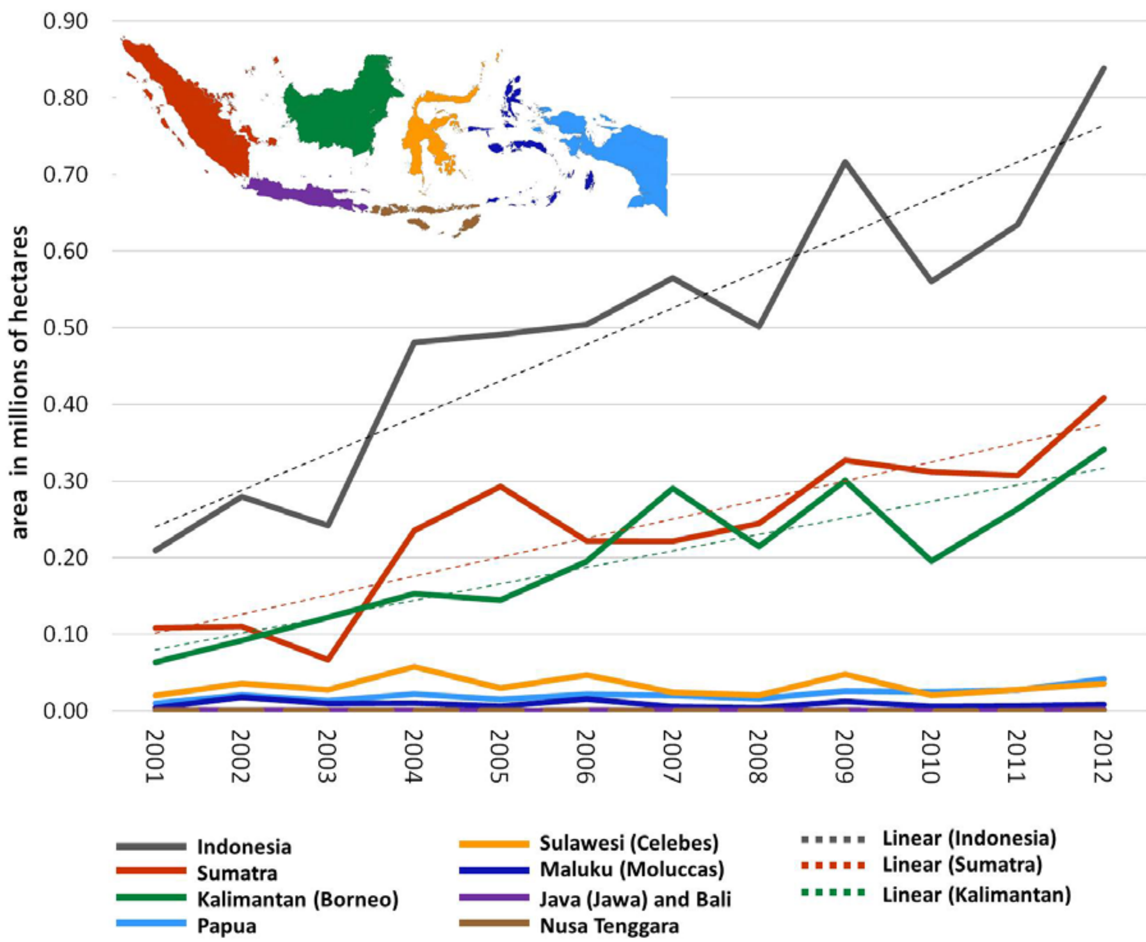



**Figure 4. 8.** Annual primary forest cover loss, 2000-2012 for the seven major islands (group of islands) of Indonesia (Sumatra, Kalimantan, Papua, Sulawesi, Maluku, Java, and Bali-Nusa Tenggara; with a dashed line only for Sumatra and Kalimantan representing linear model of the loss of Sumatra in red and of Kalimantan in green

Disaggregating the primary forest loss by landform, 3.04 Mha, or 51 percent of total primary forest cover loss occurred in lowland landforms, while 2.60 Mha, or 43 percent occurred in wetland landforms (table 4.5). However, the overall trend demonstrates increasing wetland primary forest loss compared to lowland primary forest cover loss (figure 4.9), with 25,700 ha occurred in wetlands and 20,900 ha in adjacent dry lowlands. The ratio of lowland to wetland forest loss was 2.3 in 2001 and 1.1 in 2012. The annual primary forest cover loss of lowland is nearly the highest within the twelve year interval, except for 2007, 2010, and 2011. Those years are where the primary forests cover loss within wetlands exceeds the loss of lowland, driven by wetland primary forest loss of Kalimantan in 2007, and of Sumatra in 2010 and 2011 (figure 4.8). Wetland primary forest cover loss of Sumatra and Kalimantan is significant for the country, as the wetlands are largely distributed throughout Sumatra, Kalimantan, and Papua (Margono *et al* 2014) and are primarily of the peat swamp sub-type (Wahyunto *et al* 2003, 2004, 2006).

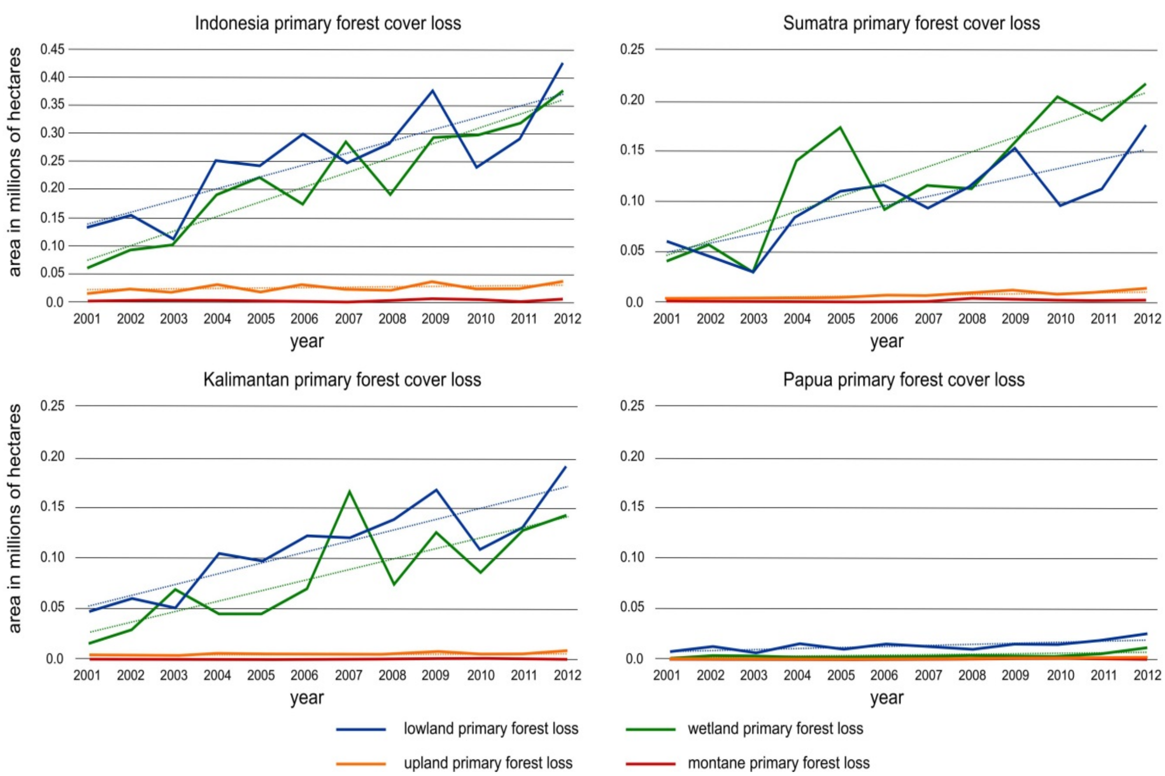



**Figure 4. 9.** Annual primary forest loss disaggregated by landform for Indonesia as a whole, and the island groups of Sumatra, Kalimantan and Papua

More intensive appropriation of wetland landform is found in Sumatra compared to Kalimantan or Papua, possibly reflecting a near-exhaustion of easily accessible lowland forests in Sumatra (Figure 4.9). The results suggest that the island of Kalimantan may still be at an earlier stage of forest exploitation than where Sumatra is today, and this appears to be the case even more so for Papua. Primary wetland forest loss during the study period in Sumatra totaled 1.53 Mha, compared to 1.21 Mha in lowland forest. The annual increase of Sumatra's wetland forest loss totaled 14,600 ha compared to 9,200 ha of additional lowland forest loss. Maximum annual Sumatran wetland forest loss was 0.22 Mha in 2012. Kalimantan was more balanced in its ratio of wetland and lowland primary forest cover loss, reflecting an earlier stage of forest land conversion. Kalimantan's lowland primary forest loss during the study period totaled 1.33 Mha with an annual increase of 10,700 ha. Wetland primary forest loss of Kalimantan totaled 0.99 Mha with an annual increase of 10,400 ha. Papua is at a more nascent stage of forest exploitation. For lowland and wetland formations, primary forest loss of Papua totaled 0.17 Mha and 0.05 Mha, respectively. Papua's lowland forest loss grew by an average of 1,000 ha per year, while wetland loss grew annually by 500 ha. Large-scale conversion is not as prevalent in Papua, with much of the clearing related to logging activities, largely road construction.

In term of forest types, the IFL data for Indonesia for the years 2000, 2005, 2010 and 2012 served as the basis for examining rates of change within the primary intact and degraded forest types. Primary forest loss occurred almost exclusively within primary degraded forests (98 percent of total loss) (Table 4.6), meaning forests were typically logged preceding clearing (figure 4.10). Of the primary degraded forests cleared, 92 percent were found in lowland and wetland landforms. The annual rate of degraded forest clearing in lowlands per epoch was 174,000 ha per year, 282,000 ha per year and 345,000 ha per year (2000-05, 2005-10 and 2010-12, respectively). Wetland degraded forest clearing rose to meet the lowland loss rate from 132,000 ha per year to 246,000 ha per year to 342,000 ha per year for the respective epochs. Primary degraded forest extent increased in upland and montane landforms as logging roads were expanded during the period of study.

**Table 4. 6**. Primary forest extent in Indonesia for intact and degraded forms for 2000, 2005, 2010 and 2012, including the primary forest loss and forest degradation within those intervals

| **Dominant forests and land cover types** | **Area (Mha hectares)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Year 2000** | **Forest Change (2000 – 2005)** | | **Year 2005** | **Forest Change (2005 – 2010)** | | **Year 2010** | **Forest Change (2010 – 2012)** | | **Year 2012** |
| | | **Forest Loss** | **Forest Degra dation** | | **Forest Loss** | **Forest Degra dation** | | **Forest Loss** | **Forest Degra dation** | |
| **Lowland *terra firma*** | | | | | | | | | | |
| Primary Intact Forest | 13.96 | 0.02 | 0.69 | 13.24 | 0.03 | 0.77 | 12.44 | 0.02 | 0.25 | 12.18 |
| Primary degraded Forest | 31.39 | 0.87 | - | 31.21 | 1.41 | - | 30.57 | 0.69 | - | 30.13 |
| Total Primary Forests | 45.35 | 0.89 | 0.69 | 44.45 | 1.44 | 0.77 | 43.01 | 0.71 | 0.25 | 42.31 |
| **Wetland** | | | | | | | | | | |
| Primary Intact Forest | 4.60 | 0.01 | 0.11 | 4.48 | 0.01 | 0.19 | 4.29 | 0.01 | 0.03 | 4.26 |
| Primary degraded Forest | 15.18 | 0.66 | - | 14.63 | 1.23 | - | 13.58 | 0.68 | - | 12.92 |
| Total Primary Forests | 19.78 | 0.67 | 0.11 | 19.11 | 1.24 | 0.19 | 17.87 | 0.69 | 0.03 | 17.18 |
| **Upland and montane** | | | | | | | | | | |
| Primary Intact Forest | 16.73 | 0.01 | 0.37 | 16.35 | 0.01 | 0.51 | 15.82 | 0.01 | 0.09 | 15.72 |
| Primary degraded Forest | 16.52 | 0.13 | - | 16.76 | 0.15 | - | 17.12 | 0.06 | - | 17.15 |
| Total Primary Forests | 33.25 | 0.14 | 0.37 | 33.11 | 0.16 | 0.51 | 32.94 | 0.07 | 0.09 | 32.87 |
| **Indonesia (all forests formation)** | | | | | | | | | | |
| Primary Intact Forest | 35.29 | 0.04 | 1.17 | 34.08 | 0.05 | 1.47 | 32.56 | 0.03 | 0.37 | 32.16 |
| Primary degraded Forest | 63.09 | 1.66 | - | 62.60 | 2.80 | - | 61.27 | 1.44 | - | 60.20 |
| Total Primary Forests | 98.38 | 1.70 | 1.17 | 96.68 | 2.85 | 1.47 | 93.83 | 1.47 | 0.37 | 92.36 |

The primary forest cover loss occurred in both primary intact and degraded sub-classes, with additional forest degradation quantified only within primary intact, as depicted in subset areas of Kalimantan and Papua in figure 4.10. The trends of primary intact loss, primary intact degraded and primary degraded loss within lowland, wetland, upland and montane, are illustrated in Figure 4.11.

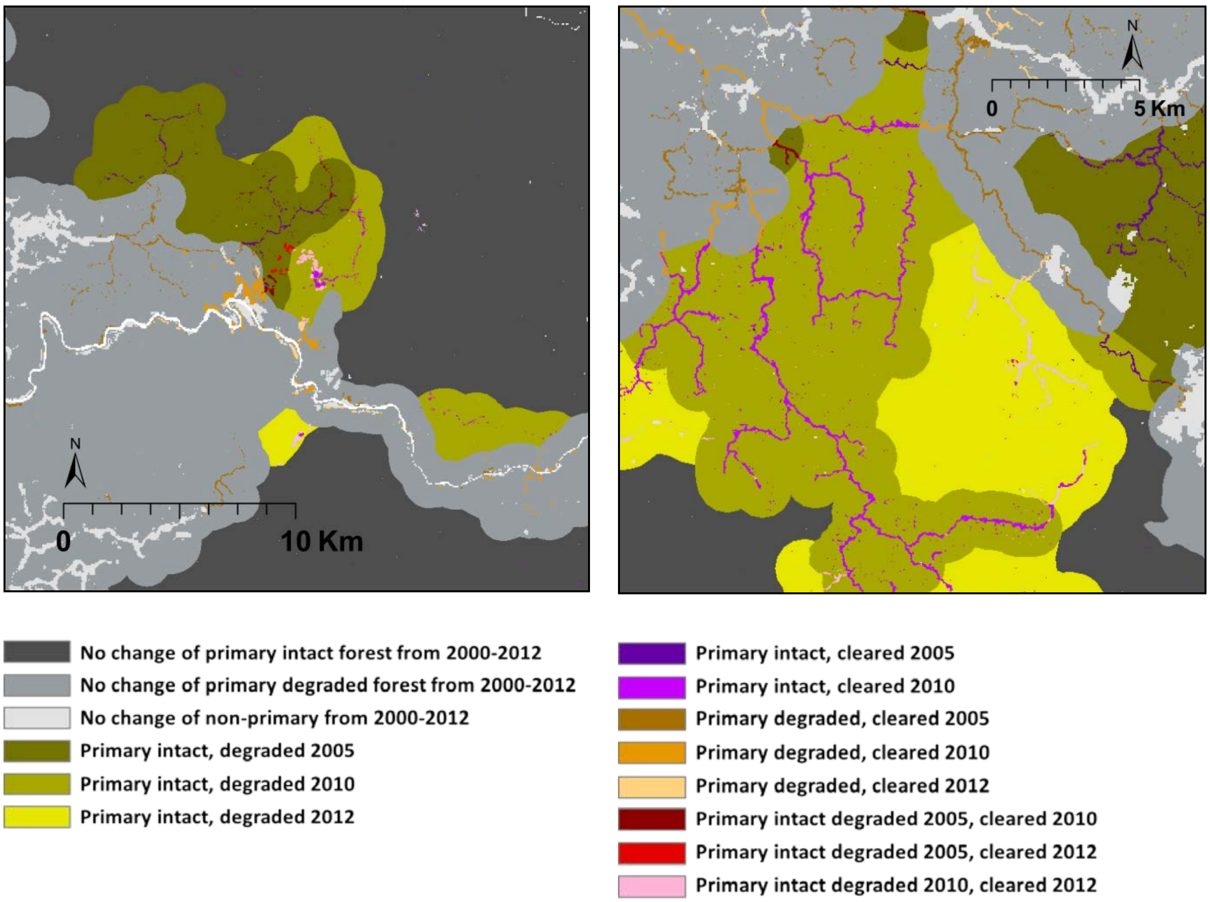



**Figure 4. 10.** Time-sequential primary forests cover loss and forest degradation from 2000 to 2012 for depicted area of Kalimantan (centered at approximately 0$^0$40’12”N/114$^0$15’28”) in the left; and Papua (centered at approximately 2$^0$55’16”S/133$^0$30’21”) in the right

Forest loss in wetlands and lowlands occurred almost exclusively within primary degraded forest. Typically the primary forests were logged preceding clearing, and the rate of forest degradation within primary intact forest of lowlands is high, compared to those in wetlands, likely due to management practices and accessible landform. Upland and montane exhibit different trends with high forest degradation and low forest cover loss, meaning the pattern of logging preceding clearing was not common in areas with high elevation and slope.

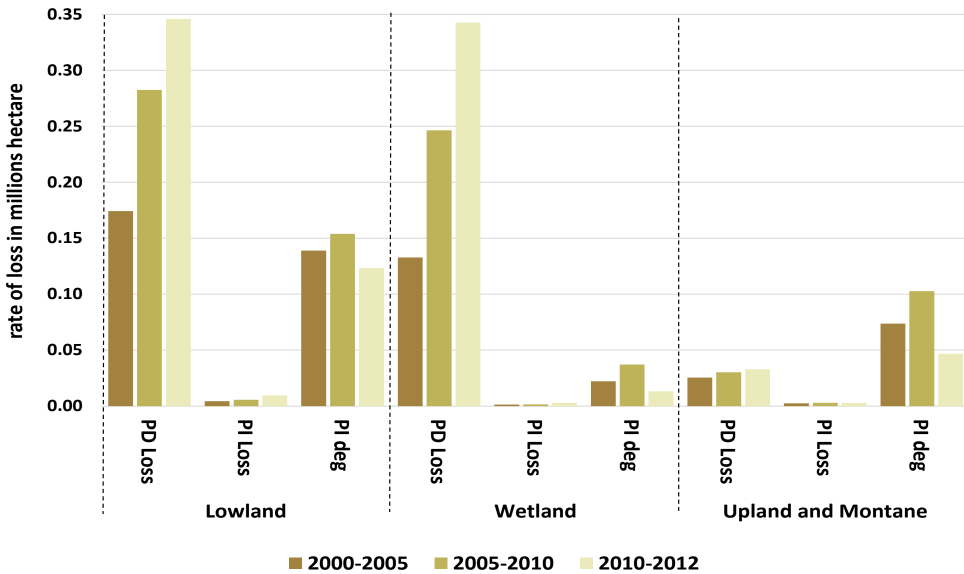



**Figure 4. 11**. Trend of primary intact forest clearing (PI loss), versus primary intact degraded (PI deg.), versus primary degraded forest clearing (PD loss), for dry-lowland, wetland, upland and montane forests per epoch of 2000-2005, 2005-2010, and 2010-2012

While maintaining within forest-land use (*kawasan hutan*), of the 6.03 Mha of primary forest cover loss 2000 to 2012, 69 percent or 4.15 Mha occurred within official forest-land use. Primary forest loss due to management practices were elaborated by quantifying the primary forest loss within each of the forest land use classes. Figure 4.12 illustrates primary forest loss by official forest land use.  Total primary forest loss within official forest land (*kawasan hutan*) was 2.2 times that outside of official forest land (*di luar kawasan hutan*) with an overall increasing trend in loss for both. Clearing of primary forest on official forest-land use is allowed in production and conversion forests, restricted within limited production forests, and prohibited in conservation and protection forests, as described in Chapter two.

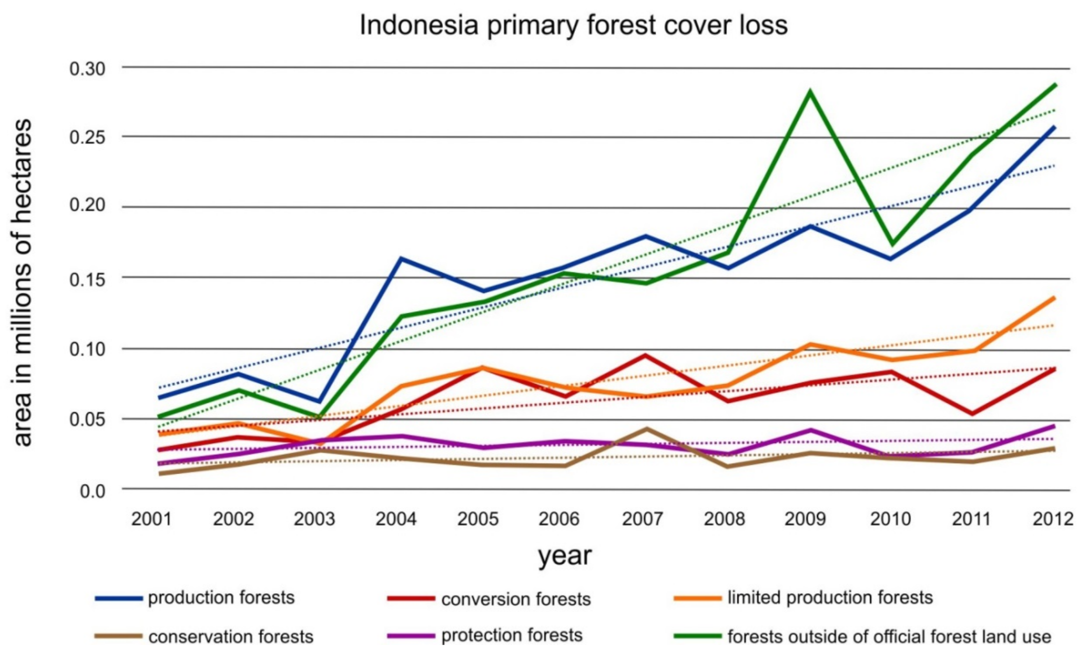



**Figure 4. 12**. Annual primary forest loss of Indonesia disaggregated by official forest land use; dashed line with similar colors represent linear model of primary forest loss per year within corresponding forest land use

Increasing primary forest loss was found mainly in production forests. An average of 27,000 additional ha of primary forest loss occurred per year over the study period, with 14,000 of this new loss within production forests. Limited production forest loss also increased over the study period (7,000 additional ha per year on average), due to rising rates of loss within lowland landforms. Almost 40 percent of total primary forest loss within national forest-land uses (*kawasan hutan*) occurred within land uses that restrict or limit clearing; 22 percent occurred in limited production forests that restrict clearing and 16 percent within conservation and protection forests that prohibit clearing. Annual primary forest loss for each of the forest land use classes of lowland and wetland respectively is illustrated in figure 4.13.

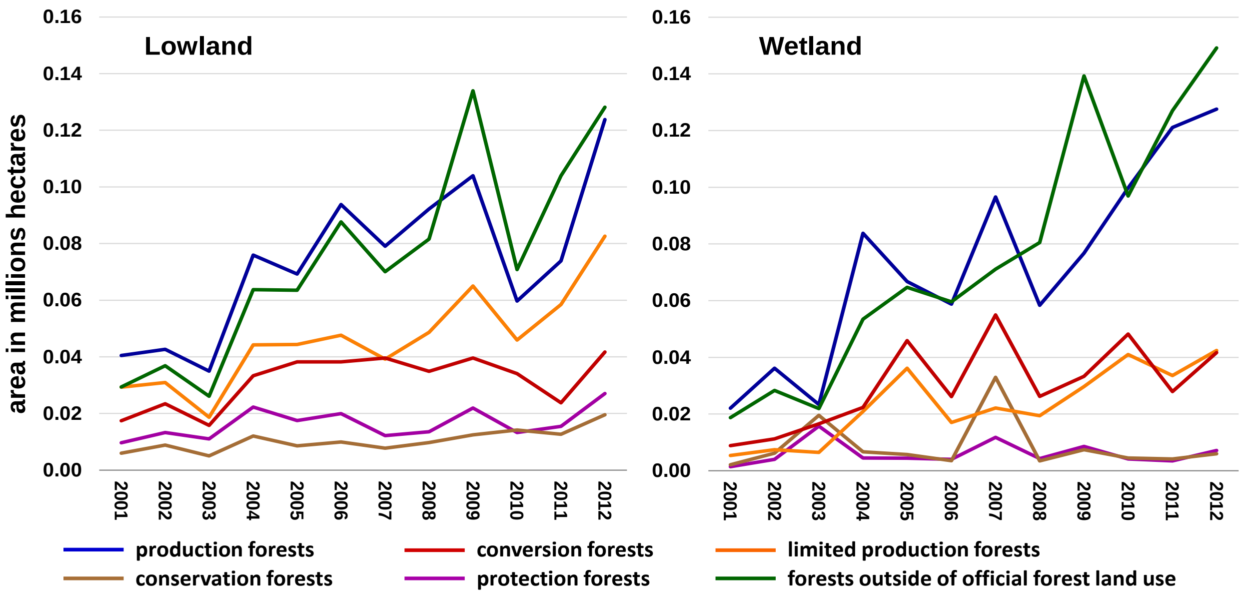



**Figure 4. 13**. Annual primary forest loss of Indonesia disaggregated by official forest land use, for lowland in the left, and wetland in the right

Nearly half of total lowland primary forest loss occurred within production and limited production forests. Production forest loss within lowlands and wetlands was comparable, while limited production forest loss within lowlands was twice that of wetlands. The increasing loss of forests within limited production areas on lowlands could indicate a changing management regime focused on greater conversion as other forest lands are exhausted within this landform. The high value of primary forest loss within conversion forest on wetland could be a sign of the high demand for agriculture expansion, particularly for oil palm, within the wetland. The annual primary forest loss of per forest land use classes of upland and montane respectively are illustrated in figure 4.14. Nearly half of upland primary forest loss occurred within protection and limited production forests.

Nearly half of montane primary forest loss occurred within protection forests. The increasing loss of primary forests on upland and montane within protection forests indicates a significant exhausted lowland forest resource.

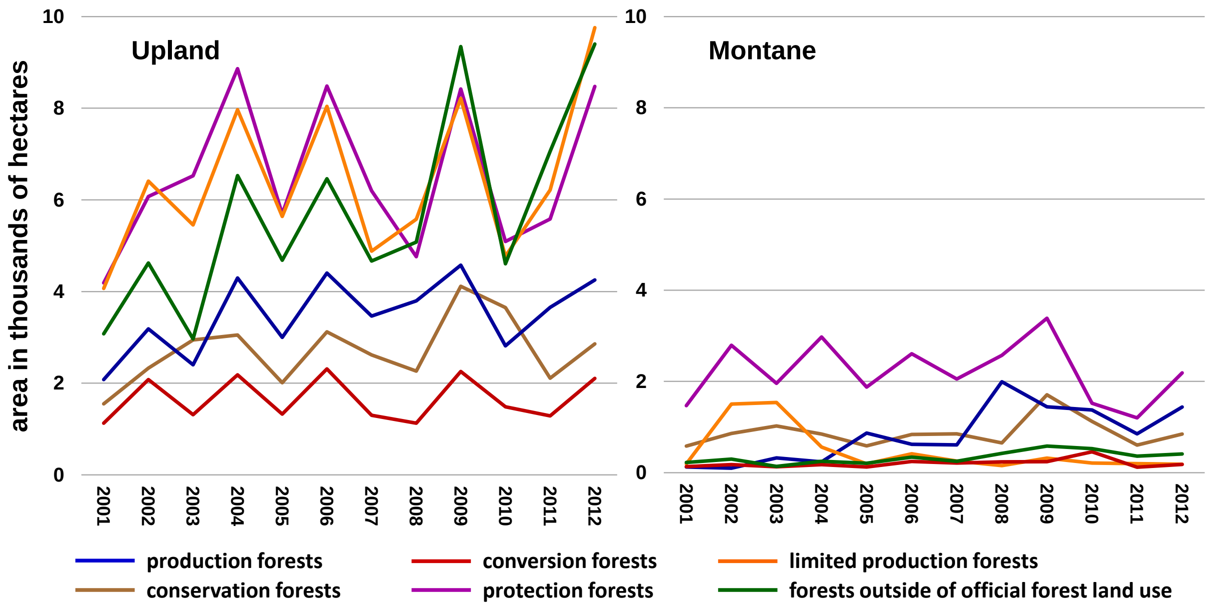



**Figure 4. 14**. Annual primary forest loss of Indonesia disaggregated by official forest land use, for upland in the left, and montane in the right

Primary forest loss on each landform was further analyzed for patch size by segmenting the annual forest cover loss data into unique polygons. This was done to assess clearing size within each landform. The segmentation defines primary forest cover loss clumps of each landform, including estimates the area's extent of each clump. Results for Indonesia are illustrated in figure 4.15 and table 4.7. Figure 4.16 describes mean value and standard error of primary forest cover loss patch size in three year epochs of 2000-04, 2005-08, and 2009-12 per lowland and wetland landform in the island of Sumatra, Kalimantan and Papua.

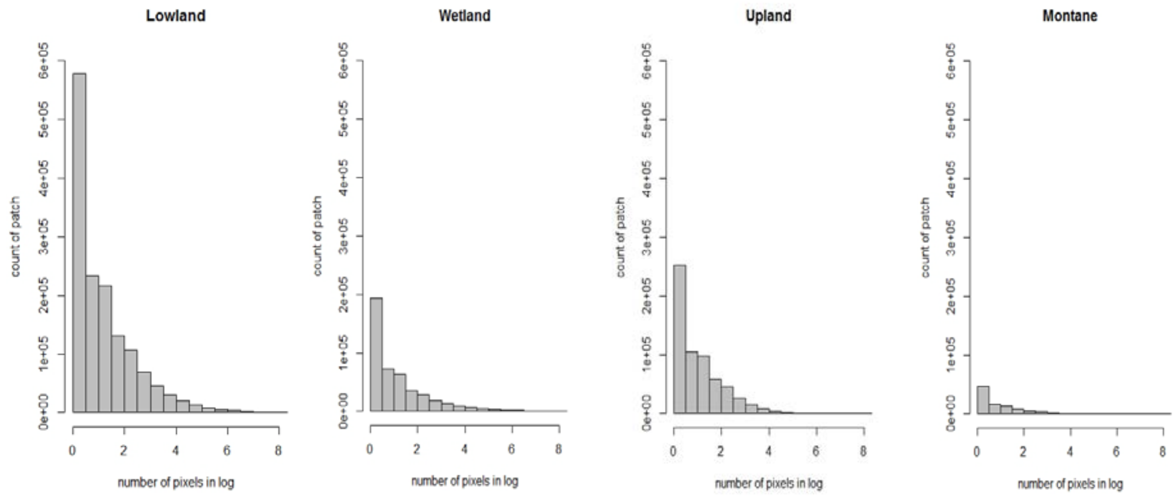



**Figure 4. 15**. Distribution of forest cover loss patch size for entire Indonesia for each landform of (a) Lowland forests, (b) Wetland forests, (c) Upland forests, and (d) Montane forests; data are presented in logarithmic form

**Table 4. 7**. Patch sizes analysis of primary forest cover loss 2000-2012 for each major landform of Indonesia

| Statistical nomenclature | Forest cover loss patch sizes (Ha) | | | |
|---|---|---|---|---|
| | Lowland | Wet-land | Upland | Montane |
| **1st quartile** | 0.0900 | 0.0900 | 0.0900 | 0.0900 |
| **Median** | 0.1800 | 0.1800 | 0.1800 | 0.1800 |
| **Mean** | 2.0800 | 5.7400 | 0.5204 | 0.6183 |
| **3rd quartile** | 0.5400 | 0.4500 | 0.4500 | 0.3600 |
| **Maximum** | 79,256.5200 | 69,299.7300 | 783.9900 | 1,464.1200 |
| **SD** | 115.5568 | 265.2168 | 2.5500 | 7.2151 |
| **CI left** | 1.8174 | 4.6462 | 0.5114 | 0.5537 |
| **CI right** | 2.3472 | 6.8296 | 0.5295 | 0.6829 |

Patch size analysis was also employed independently for Sumatra and Kalimantan, the islands that exhibit highest forest cover loss, as well as Papua, the island with the greatest remaining forests covers, for epochs of 2000-2004, 2005-2008, and 2009-2012. Instead of using decadal intervals, the annual primary forest cover loss was aggregated proportionally into four year epochs of 2000-2005, 2006-2010, and 2011-2012. Figure 4.16 illustrates the trends of primary forest loss patch size by landform for Sumatra, Kalimantan and Papua. The mean clearing patch size in wetland of Sumatra and Kalimantan is the largest of any landform. Those three islands have similar trends. These indicate wetland forest experiences bigger patches of primary forest loss rather than of lowland forests, and an increase for the recent year, with the exception of Papua where the largest patches were observed in the epoch 2005-2008.

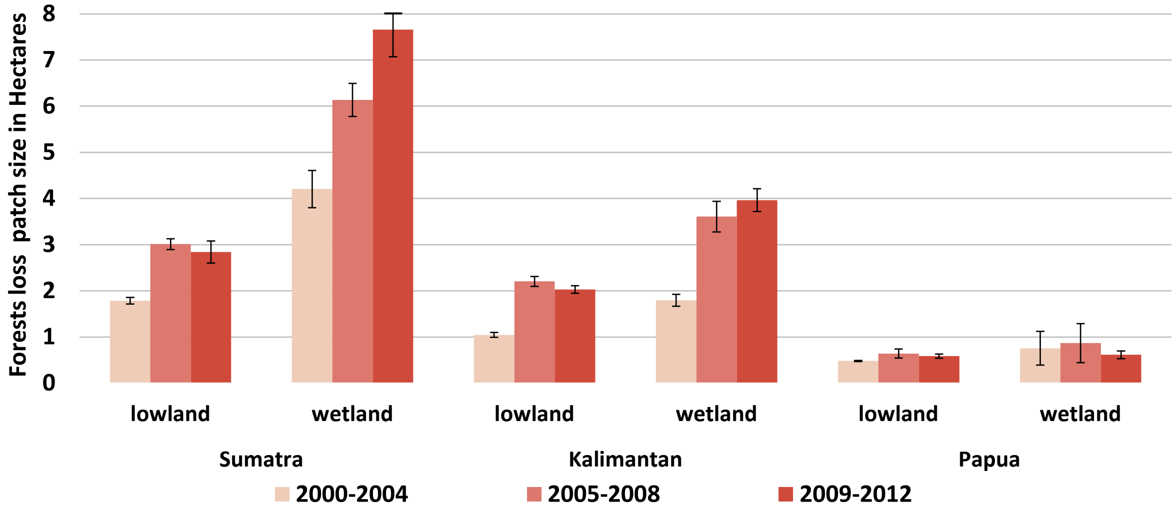



**Figure 4. 16**. The mean value and standard error of primary forest cover loss patch size by four year epoch of 2000-04, 2005-08, and 2009-12 and landform for the island groups of Sumatra, Kalimantan and Papua

***Deforestation moratorium***

The Indonesian moratorium on granting new licenses for logging and conversion of natural primary forest and peatland was intended to significantly contribute to Indonesia's goal of a 26 percent decrease in GHG emission, by reducing deforestation and its associated GHG emission. A 2-year moratorium went into effect on May 2011 and was extended on May 2013 for two additional years. As part of the moratorium process the government released a map that showed all lands that were included in the moratorium, the so called indicative moratorium map, IMM. The IMM illustrates zones for suspending new licenses, consisting of (a) natural primary forest of conservation, protection, production forests, and non-forest lands, as well as for (b) peatlands (figure 4.17).

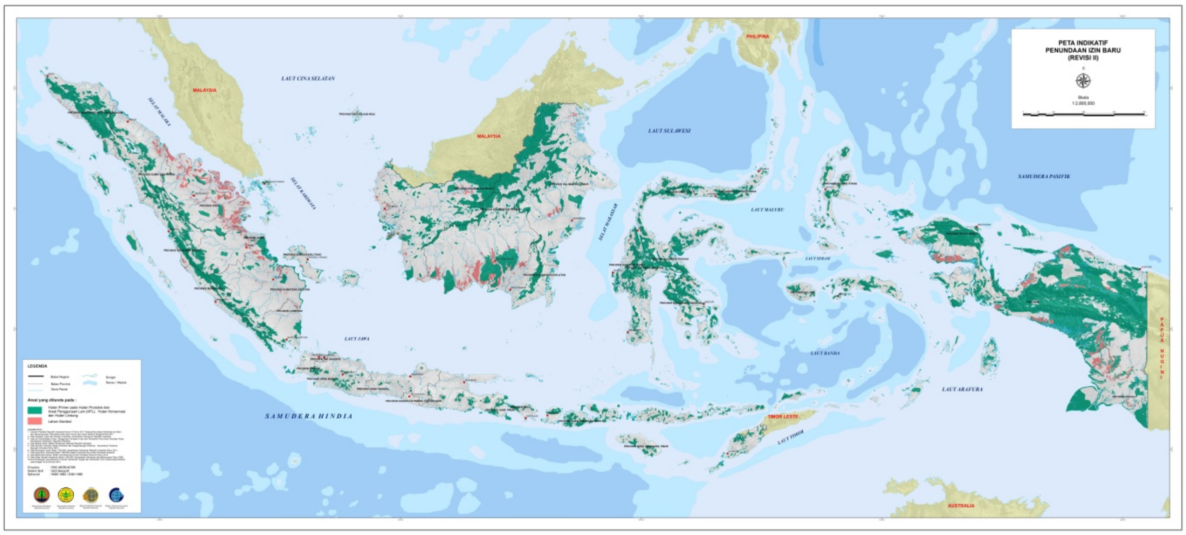



**Figure 4. 17**. The indicative moratorium map (IMM) version 2 displaying natural primary forest of conservation, protection, production forests, and non-forest lands in green, and peatlands in red (http://appgis.dephut.go.id/appgis/moratorium3/PIPIBINDONESIA2.jpg)

Here, the term natural primary forest in the IMM refers to undisturbed forest (Inpres 10/2011), which employed the land cover map of the MoF particularly the primary forest class, and corresponds to the primary intact forest type in this study. IMM is reviewed and updated every six months using updated information from field verification, subsequent coordination among institutions, and public inputs; aiming to adjust field reality to the existing map. In this study we used IMM version 2 (V2) with a spatial extent of $\pm$ 65.4 Mha, to match the year of primary forests cover change data sets.

Understanding how the moratorium was understood by stakeholders is important for further analysis. In fact, the moratorium instruction does not explicitly mention a “halt of clearing” of natural primary forest and peatland, but instructs to “prohibit the granting of new concessions for two years”. This formulation allows existing concessions to continue business-as-usual (BAU)’s activities, including clearing. Besides these sanctioned clearing activities several exceptions exit “allowing forest clearing”; for (a) areas vital for national development especially for geothermal, oil, natural gas, electricity, paddy production and sugar cane; (b) the renewal of forest concession’s.

With all exceptions included, the analysis concludes an increase of primary forests cover loss within the moratorium period of 2011(with only 7 months are part of the moratorium) to 2012 (figure 4.18). The total loss between 2010 and 2012 is 1.47 Mha, of which 1.24 Mha (84 percent) occur outside and 235,000 ha (16 percent) inside the IMM. Percent loss toward primary forests extent in 2010 outside/inside is 2.92 percent outside and only 0.46 percent inside the IMM. Of the loss inside the IMM, about 9,000 ha (4 percent) is on primary intact forest, and 226,000 ha (96 percent) on primary degraded forest.

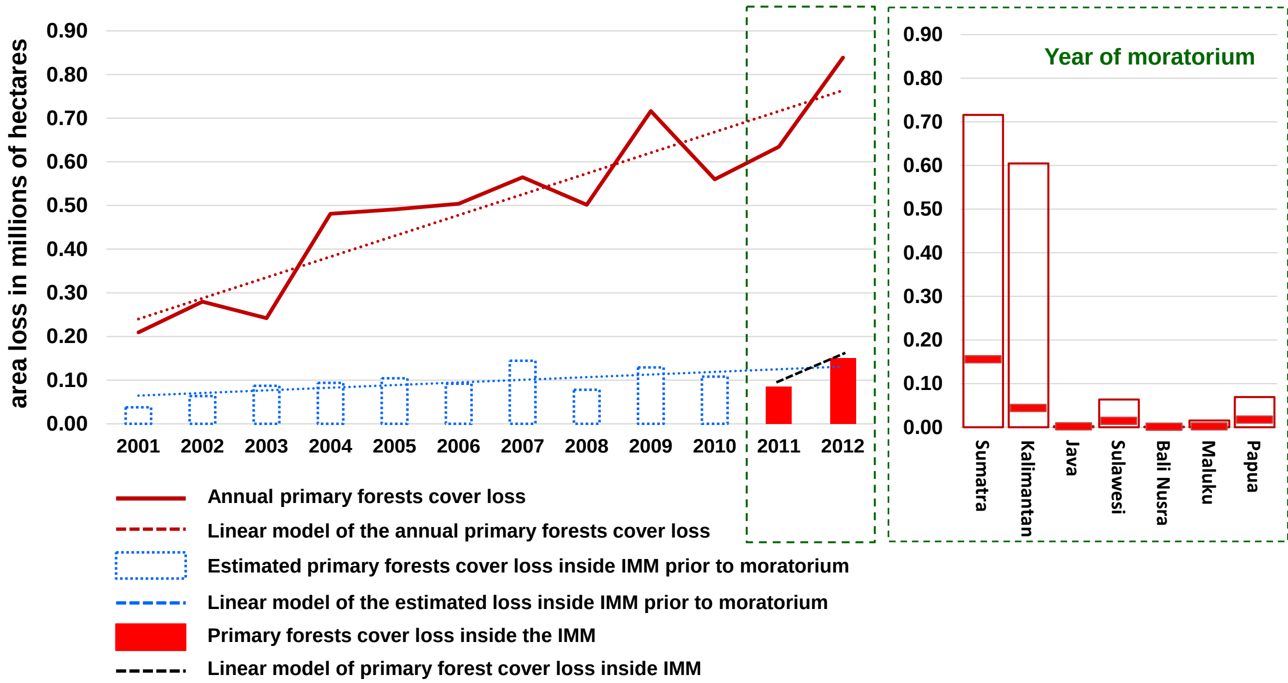



**Figure 4. 18**. Annual total Indonesia primary forest cover loss of intact and degraded types, 2000-2012 and primary forest loss inside IMM V2 for 2011 and 2012; estimated loss inside IMM V2 supposition for 2000 to 2010 (in the left); In the right is the total primary forest loss within the year of moratorium (2011 and 2012) for major islands and group of islands with proportion of loss inside the IMM in red marked

The blue line illustrated in figure 4.18 represents business-as-usual within the IMM, even though the IMM is not official until May 2011. A dramatic increase of primary forest loss within the IMM from 2011 to 2012 can be explained by intensification of clearing within the areas that have been granted concessions. Details of forest cover loss in term of wetland and non-wetland (lowland, upland and montane landforms) of intact and degraded forest types for Indonesia, and three major islands of Sumatra, Kalimantan and Papua where the peatlands are major types of the island’s wetlands are in table 4.8.

**Table 4. 8**. Primary forests cover loss for Indonesia as a whole, and the island groups of Sumatra, Kalimantan and Papua, in term of primary intact and primary degraded forests cover loss, of dryland and wetland, inside and outside moratorium

| Cover types | Primary forests extent 2010 (thousand ha) | | | Primary forest cover loss 2011 and 2012 | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Areas (ha) | | | | Percent (%) | |
| | | | | Inside | | Outside | | total | Total |
| | **Total** | **Inside** | **Outside** | **2011** | **2012** | **2011** | **2012** | **inside** | **Outside** |
| | | | | **Sumatra** | | | | | |
| Primary Intact | | | | | | | | | |
| • Non-wetland | 3,641 | 3,448 | 193 | 928 | 1,185 | 261 | 888 | 0.06 | 0.60 |
| • Wetland | 140 | 81 | 59 | 1 | 26 | 148 | 70 | 0.03 | 0.37 |
| Primary Degraded | | | | | | | | | |
| • Non-wetland | 7,321 | 3,897 | 3,424 | 23,335 | 39,752 | 102,396 | 149,208 | 1.62 | 7.35 |
| • Wetland | 2,966 | 1,410 | 1,556 | 30,240 | 59,790 | 150,027 | 157,709 | 6.38 | 19.78 |
| **Total Sumatra** | 14,068 | 8,836 | 5,232 | 54,505 | 100,753 | 252,833 | 307,875 | 1.76 | 10.72 |
| | | | | **Kalimantan** | | | | | |
| Primary Intact | | | | | | | | | |
| • Non-wetland | 9,201 | 6,736 | 2,465 | 497 | 1,181 | 1,495 | 2,720 | 0.02 | 0.17 |
| • Wetland | 130 | 84 | 46 | 3 | 16 | 66 | 87 | 0.02 | 0.33 |
| Primary Degraded | | | | | | | | | |
| • Non-wetland | 13,857 | 2,677 | 11,180 | 4,240 | 6,092 | 129,880 | 189,759 | 0.39 | 2.86 |
| • Wetland | 5,041 | 2,217 | 2,824 | 12,370 | 19,410 | 115,141 | 122,015 | 1.43 | 8.40 |
| **Total Kalimantan** | 28,229 | 11,714 | 16,515 | 17,111 | 26,699 | 246,583 | 314,581 | 0.37 | 3.40 |
| | | | | **Papua** | | | | | |
| Primary Intact | | | | | | | | | |
| • Non-wetland | 11,393 | 7,936 | 3,457 | 958 | 2,521 | 3,736 | 5,981 | 0.04 | 0.28 |
| • Wetland | 4,000 | 2,956 | 1,044 | 276 | 760 | 1,222 | 3,208 | 0.04 | 0.42 |
| Primary Degraded | | | | | | | | | |
| • Non-wetland | 14,695 | 8,061 | 6,634 | 2,930 | 6,878 | 13,127 | 14,539 | 0.12 | 0.42 |
| • Wetland | 5,161 | 2,854 | 2,306 | 816 | 1,971 | 4,351 | 6,020 | 0.10 | 0.45 |
| **Total Papua** | 35,249 | 21,808 | 13,441 | 4,981 | 12,129 | 22,437 | 29,746 | 0.08 | 0.39 |
| | | | | **Indonesia** | | | | | |
| Primary Intact | | | | | | | | | |
| • Non-wetland | 28,264 | 21,219 | 7,044 | 2,664 | 5,497 | 5,824 | 10,810 | 0.04 | 0.24 |
| • Wetland | 4,293 | 3,139 | 1,153 | 282 | 803 | 1,437 | 3,367 | 0.03 | 0.42 |
| Primary Degraded | | | | | | | | | |
| • Non-wetland | 47,693 | 20,359 | 27,334 | 37,776 | 62,631 | 271,107 | 386,041 | 0.49 | 2.40 |
| • Wetland | 13,581 | 6,673 | 6,908 | 44,004 | 81,582 | 271,477 | 288,232 | 1.88 | 8.10 |
| **Total Indonesia** | 93,830 | 51,390 | 42,440 | 84,727 | 150,513 | 549,845 | 688,451 | 0.46 | 2.92 |

Among the three islands during the moratorium from 2011 to 2012, Sumatra experienced the highest forest loss with proportionally 22 percent occurring inside and 78 percent outside the IMM. The dominant forest loss in Sumatra during the moratorium year is primary degraded type and mainly on wetlands. Kalimantan has the second highest forest loss, but with the proportion of forest loss inside IMM low (7 percent) compared to loss outside IMM (93 percent). However, just like Sumatra, the dominant forest loss is primary degraded forest on wetland formations. The average during the moratorium in Sumatra and Kalimantan respectively for primary forest loss is 0.28 Mha per year outside the IMM, with 77,600 ha loss per year inside the IMM for Sumatra, and 22,000 ha loss per year inside IMM in Kalimantan. Papua has the lowest forest loss in the year of moratorium, but proportionally experienced the highest percentage of the loss inside with 25 percent compared to 75 percent outside IMM. The dominant forest loss here is primary degraded forest type outside of wetlands.

The moratorium is criticized due the exclusion of primary degraded forest (Murdiyarso *et al* 2011, Edward and Laurance 2011, Austin *et al* 2012), and this class is called secondary forest in Indonesia. In fact 26.8 Mha of degraded primary forest was located in the IMM and 25 percent within wetlands. Indeed 96 percent of the loss inside IMM is of that primary degraded forest, particularly on wetlands. Primary degraded forests are still significant carbon stores (Berry *et al* 2010) as well as sites of high biodiversity (Wilcove *et al* 2013), and their exclusion is a significant loophole in the moratorium process. In addition to the significant loss of degraded forests, primary intact forest cover loss within conservation and protection forests almost doubled, from 18.9 Mha in 2011 to 34.9 Mha in 2012. Referring to the Forestry Law 41/1999, clearing within the conservation and protection forests are prohibited, regardless of the type of forest cover. It appears that the moratorium has not had its intended effect, with the most promising relative outcomes for Kalimantan. Regardless, for the first full year of this study within the moratorium period, 2012, Indonesia experienced the highest rates of non-wetland and wetland primary forest cover loss, including areas inside the IMM.

**Discussion and conclusion**

The new global gross forest cover change product 2000 to 2012 of Hansen *et al* (2013) provides a new approach to map global forest loss and gain. However the change was mapped based on forests defined by tree cover at 30 m spatial resolution, including *man-made* forests. Of the total gross forest loss for Indonesia 2000 to 2012, 38 percent occurred within primary forests. A terminology of primary forest is used in this study to define all forest stands that retain their natural composition, structure, and that have not been completely cleared in recent history (at least 30 years in age), nor re-planted. In other words, the terminology of primary forest was employed to distinguish natural stands from non-natural or *man-made* stands (FAO 2003). By this definition, 62 percent of the gross forest loss of Hansen *et al* (2013) for Indonesia 2000 to 2012 was of a harvesting cycle on timber and lumber plantations, oil palm estates and other tree crops.

Primary forest was analyzed separately and further disaggregated into intact and degraded types. While Indonesia has been reported to have one of the world's highest primary forest cover loss rates (deforestation), second only to Brazil (FAO 2001, 2006, Hansen *et al* 2008b, 2009), this study finds that by 2012 Indonesia had surpassed Brazil in area of primary forest cover loss. The primary forests extent 2000, 2012 and the forest cover loss for the twelve years (2000-2012) for major islands, is in table 4.9.

**Table 4. 9.** The primary forest extent 2000, 2012 and the forest cover loss for the twelve years on Major Island that also representing its unique biogeographic regions

| Island/group of islands – landforms | Total area extent | Primary forest extent 2000 | | | Primary forest loss 2000 – 2012 | | | Primary forest extent 2012 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mha | Mha | % * | % ** | Thousand Ha | % * | % ** | Mha | % * | % *** |
| **Sumatra** | | | | | | | | | | |
| Lowland | 26.8 | 5.7 | 21.1 | 12.0 | 1,205 | 21.3 | 7.43 | 4.5 | 16.6 | 9.4 |
| Wetland | 11.9 | 4.2 | 35.5 | 9.0 | 1,529 | 36.1 | 9.43 | 2.7 | 22.7 | 5.7 |
| Upland | 5.4 | 3.8 | 69.4 | 8.0 | 97 | 2.6 | 0.60 | 3.7 | 67.6 | 7.8 |
| Montane | 3.1 | 2.5 | 82.3 | 5.4 | 26 | 1.0 | 0.16 | 2.5 | 81.5 | 5.3 |
| Total | 47.2 | 16.2 | | 34.3 | 2,857 | | 17.63 | 13.4 | | 28.3 |
| **Kalimantan** | | | | | | | | | | |
| Lowland | 32.1 | 15.9 | 49.6 | 29.9 | 1,331 | 8.4 | 4.44 | 14.6 | 45.4 | 27.4 |
| Wetland | 12.2 | 5.9 | 48.3 | 11.1 | 987 | 16.8 | 3.29 | 4.9 | 40.2 | 9.2 |
| Upland | 7.8 | 7.1 | 90.1 | 13.3 | 59 | 0.8 | 0.20 | 7.0 | 89.4 | 13.2 |
| Montane | 1.1 | 1.1 | 99.9 | 2.1 | 0.3 | 0.0 | 0.00 | 1.1 | 99.8 | 2.1 |
| Total | 53.3 | 30.0 | | 56.3 | 2,378 | | 7.92 | 27.6 | | 51.9 |
| **Papua** | | | | | | | | | | |
| Lowland | 18.1 | 16.6 | 91.8 | 40.7 | 173 | 1.0 | 0.49 | 16.4 | 90.8 | 40.3 |
| Wetland | 11.8 | 9.2 | 77.8 | 22.5 | 54 | 0.6 | 0.15 | 9.1 | 77.3 | 22.4 |
| Upland | 5.3 | 5.1 | 96.2 | 12.4 | 21 | 0.4 | 0.06 | 5.0 | 95.7 | 12.3 |
| Montane | 5.6 | 4.6 | 81.7 | 11.3 | 13 | 0.3 | 0.04 | 4.6 | 81.5 | 11.2 |
| Total | 40.8 | 35.4 | | 86.9 | 261 | | 0.74 | 35.2 | | 86.2 |
| **Sulawesi** | | | | | | | | | | |
| Lowland | 9.3 | 3.5 | 37.5 | 1.8 | 247 | 7.1 | 0.25 | 3.2 | 34.9 | 1.7 |
| Wetland | 1.2 | 0.2 | 14.3 | 0.1 | 26 | 15.6 | 0.03 | 0.1 | 12.0 | 0.1 |
| Upland | 5.6 | 4.0 | 72.3 | 2.1 | 107 | 2.7 | 0.11 | 3.9 | 70.4 | 2.1 |
| Montane | 2.5 | 2.3 | 90.9 | 1.2 | 16 | 0.7 | 0.02 | 2.2 | 90.3 | 1.2 |
| Total | 18.5 | 9.9 | | | 396 | | 0.40 | 9.5 | | |
| **Maluku** | | | | | | | | | | |
| Lowland | 5.0 | 3.2 | 64.9 | 1.7 | 77 | 2.4 | 0.08 | 3.2 | 63.4 | 1.7 |
| Wetland | 0.5 | 0.3 | 56.6 | 0.1 | 6 | 2.2 | 0.01 | 0.3 | 55.3 | 0.1 |
| Upland | 2.2 | 1.7 | 80.4 | 0.9 | 26 | 1.5 | 0.03 | 1.7 | 79.2 | 0.9 |
| Montane | 0.2 | 0.1 | 97.4 | 0.1 | 0 | 0.3 | 0.00 | 0.1 | 97.1 | 0.1 |
| Total | 7.8 | 5.4 | | | 109 | | 0.11 | 5.3 | | |
| **Jawa and Bali** | | | | | | | | | | |
| Lowland | 9.7 | 0.2 | 2.2 | 0.1 | 6 | 2.7 | 0.01 | 0.2 | 2.1 | 0.1 |
| Wetland | 1.9 | 0.0 | 1.2 | 0.0 | 0 | 0.4 | 0.00 | 0.0 | 1.2 | 0.0 |
| Upland | 1.5 | 0.2 | 16.7 | 0.1 | 5 | 1.9 | 0.00 | 0.2 | 16.3 | 0.1 |
| Montane | 0.7 | 0.3 | 45.3 | 0.2 | 3 | 0.9 | 0.00 | 0.3 | 44.9 | 0.2 |
| Total | 13.8 | 0.8 | | | 13 | | 0.01 | 0.8 | | |
| **Nusa Tenggara** | | | | | | | | | | |
| Lowland | 4.4 | 0.3 | 5.9 | 0.1 | 6 | 2.1 | 0.01 | 0.3 | 5.8 | 0.1 |
| Wetland | 0.1 | 0.0 | 4.1 | 0.0 | 0 | 0.6 | 0.00 | 0.0 | 4.1 | 0.0 |
| Upland | 1.8 | 0.3 | 16.0 | 0.2 | 3 | 0.9 | 0.00 | 0.3 | 15.9 | 0.2 |
| Montane | 0.2 | 0.1 | 35.6 | 0.0 | 1 | 1.5 | 0.00 | 0.1 | 35.1 | 0.0 |
| Total | 6.6 | 0.6 | | | 9 | | 0.01 | 0.6 | | |
| **Total Indonesia** | | | | | | | | | | |
| Lowland | 105.3 | 45.3 | 43.0 | 24.1 | 3,044 | 6.7 | 3.09 | 42.3 | 40.2 | 22.5 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wetland | 39.6 | 19.8 | 49.9 | 10.5 | 2,602 | 13.2 | 0.64 | 17.2 | 43.4 | 9.1 |
| Upland | 29.6 | 22.2 | 75.0 | 11.8 | 318 | 1.4 | 0.32 | 21.9 | 73.9 | 11.6 |
| Montane | 13.4 | 11.1 | 82.8 | 5.9 | 59 | 0.5 | 0.06 | 11.0 | 82.3 | 5.8 |
| Total Indonesia | 187.9 | 98.4 | | 52.4 | 6,024 | | 6.12 | 92.4 | | 49.1 |

The sum and percentage are rounded
* ) percentage of each forest formations
** ) percentage to the total area of each island/group of island

Results from this study indicate increasing primary forest loss overall, and a greater proportion of that loss within wetlands, with significant implications for GHG emissions and attempts to mitigate climate change. Clearings on peat soil wetlands are often accompanied by draining the wetland with an impact on carbon emissions beyond the footprint of the actual development (Page and Rieley1998, Uryu *et al* 2008). The results were generated from a robust systematic method demonstrated for mapping the dynamic primary forests cover in Indonesia. Figure 4.19 illustrates two landscapes emblematic of this dynamic from 2000 to 2012. Increasing loss over time is shown as well as the location of more recent clearings within wetlands formation. The implications for carbon emissions are substantial given the known carbon stocks of both above ground primary forest and below ground peatland land covers.

Official forest land use when compared to primary forest loss brings into question the effectiveness of forest governance in Indonesia. Within official forest lands, 40% of clearing occurred within land uses that restrict or prohibit clearing. Such a result illustrates a lack of official policy implementation on the ground. Concerning the IMM, initial results from this study also bring into question the effectiveness of stated policies, although the IMM language has loopholes that could allow for clearing within the IMM. Combining policy domain knowledge with the spatially and temporally explicit data presented here on primary forest loss is required in order to assess policy effectiveness and remedies if required. Overall, results from this study highlight the importance of spatially and temporally explicit data in bringing transparency to an important land use dynamic. Such data are a prerequisite to establishing, implementing and evaluating policies designed to manage forests and slow emissions from deforestation and forest degradation.

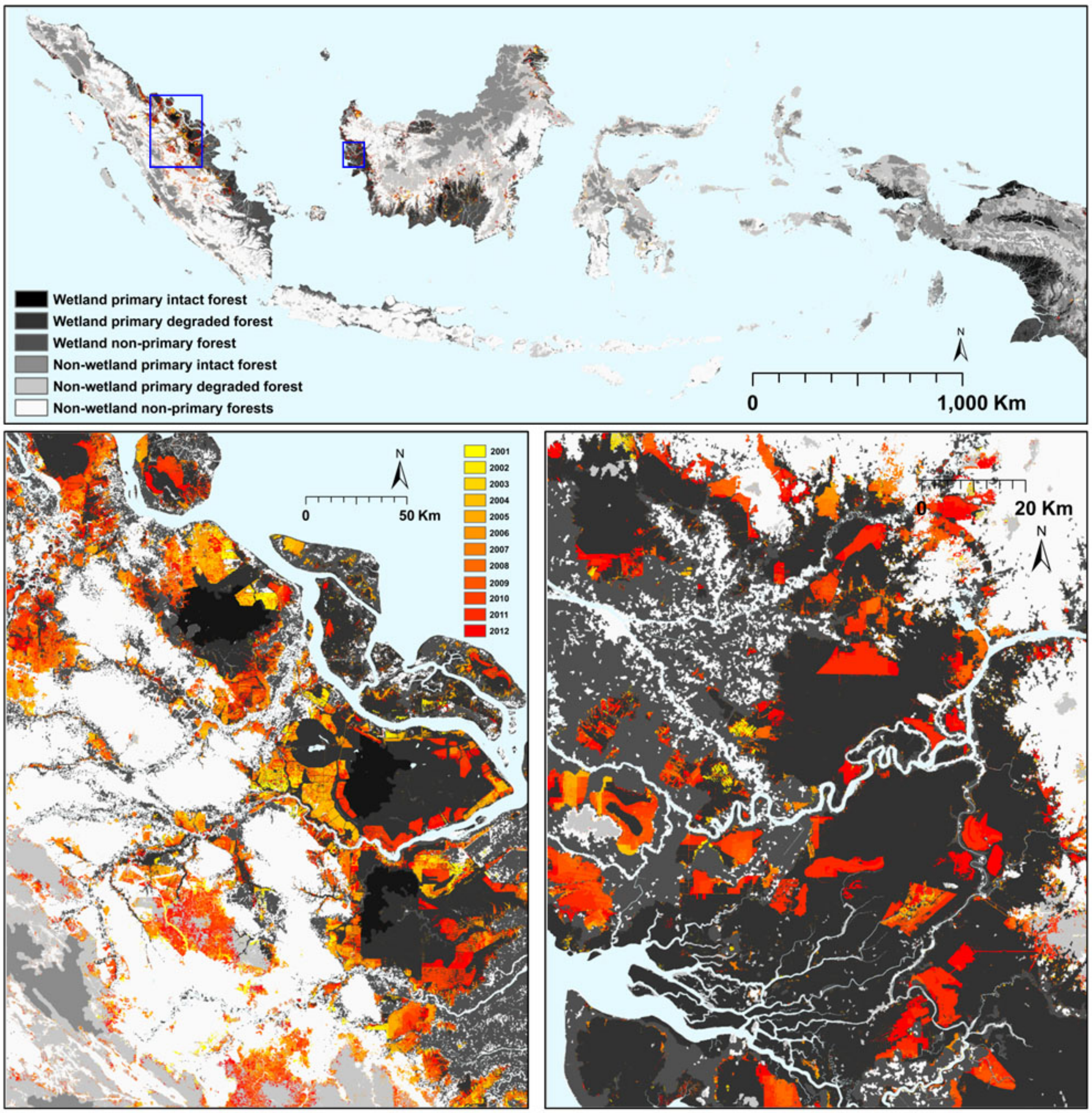



**Figure 4. 19**. Annual primary forest loss and landform for Riau province, Sumatra on left and West Kalimantan province, Kalimantan on right

# Chapter 5: Synthesis and conclusion

The overall goal of this study is to advance national scale forest monitoring in Indonesia, including the quantification of forest disturbance dynamics, across space and time with outputs appropriate for sustainable forest management and carbon accounting objectives. Three objectives were pursued to achieve the overall goal.

The first objective is to characterize differences in natural primary forests in terms of primary intact and primary degraded types using Landsat time-series imagery. The hybrid approach of the direct per-pixel mapping of primary forest extent and time-series stand-replacement disturbance, followed by GIS-buffering of observable anthropogenic disturbances, was implemented in providing an accurate time-series quantification of primary forest change in terms of intact and degraded types. Canopy structural differences based on LiDAR data were used to validate the primary forest types.

Sumatra, home to the most advanced forest cover change dynamic in Indonesia, was selected to investigate and test the hybrid approach, which was subsequently extended to the rest of Indonesia. The map of primary intact and degraded forests 2000 for the entirety of Indonesia agreed well when compared to the primary and secondary forests classes of the official land cover map of Indonesia of 2000 produced by the Ministry of Forestry of Indonesia. Primary intact and degraded forest extents for 2000 were then used as a reference for 2000 to 2012 forest cover loss evaluation. Sumatra was initially analyzed using a Landsat 5 image composite centered on 1990; however, limited Landsat observational coverage for circa 1990 led to more than 7 percent cloud cover in the composite.  At the national-scale, Landsat 7 data were used to create a cloud-free composite for 2000; the systematic acquisition strategy of Landsat 7 (Arvidson and Gasch 2001), which not implemented with Landsat 5, allowed for an improved reference for primary forest mapping.

Establishing a baseline of potential wetland extent for Indonesia was the second objective of this study. Quantification of wetland extent for 2000, similar to the primary forest extent layer, enables the analysis of forest change within the context of wet and non-wet (dry) landforms. The combination of topographical indices (SRTM-derived), optical (Landsat) and radar (PALSAR) image inputs employed using a systematic algorithmic allowed for the characterization of wetland extent at the national-scale. The result is a single thematic class of wetland encompassing peatlands, freshwater wetlands, and mangroves. Such a product can be used as an input for carbon estimation models and in support of biodiversity assessment efforts and is suitable for policy applications related to wetland ecosystem services and their change over time. The wetland map of this study agrees well with existing image-interpreted products from Indonesia's Ministries of Forestry and Agriculture and Wetlands International (WI/MoAg/MoF), as well as with forest inventory data from the Ministry of Forestry. However, compare to these existing image-interpreted products, the wetland map yielded a systematic algorithm and internally consistent approach that simply to replicate, especially when lack of ground measurements were taken place.

By completing the first and second objectives, the third synthesis objective of disaggregating forest disturbance by primary forest and landform within Indonesia from 2000 to 2012 was enabled.  A consistently-applied definition of forest type, landform and stand-replacement disturbance allowed for the transparent spatial and temporal characterization of an important land use dynamic. The overall results represent an exhaustive and a robust method in using remote sensing data sets for forest resource monitoring in Indonesia, which enable a credible measurement, reporting, and verification (MRV) (Breidenich and Bodansky 2009) of REDD+ applications in the country. The national-scale dynamic of forest extent and disturbance, in terms of natural/primary forests, across space and time, on various landforms, provides a valuable reference for activity data appropriate for MRV (GOFC GOLD 2010); when combined with ground-based forest inventory data (Gibbs *et al* 2007), a method for systematically assessing forest biomass and carbon content change over time is enabled.

In addition, the synthesis reveals information significant for forest management objectives, including forest extent and trends of primary forest loss in various forest formations, forest-land uses, and island groups (figure 5.1). Trends in Indonesia primary forest loss indicate the biophysical, economic, institutional and demographic factors which influence the spatio-temporal dynamic of natural forest appropriation. Figure 5.2 illustrates a model for appropriate forest land use by landform reflected in the results of this study. At the national scale, more than half primary forest loss occurred within accessible lowlands from 2000 to 2012. Wetlands account for an increasing share of the overall dynamic as the lowland forest resource is largely exhausted. This is most evident in Sumatra, where forest loss in wetlands is an increasing majority share of overall forest loss. Upland and montane forest formations are more preserved by topographical features, specifically slope and elevation, which result in more logging activities and less land use conversion.

The path of forest utilization within islands needs to be documented independently to track forest transitions as described in figure 5.1, especially for the three islands with the most extensive wetlands: Sumatra, Kalimantan and Papua (Margono *et al* 2014). Wetland sub-types on these three islands are predominantly peat swamps (Wahyunto *et al* 2003, 2004, 2006). Most lowland forests, including those in the protected areas of Sumatra and Kalimantan (Curran *et al* 2004, Gaveau *et al* 2007, 2012) are vanishing (Holmes 2000, Tomich *et al* 2001, Lambert and Collar 2002, Dennis and Colfer 2006, Hansen *et al* 2009).

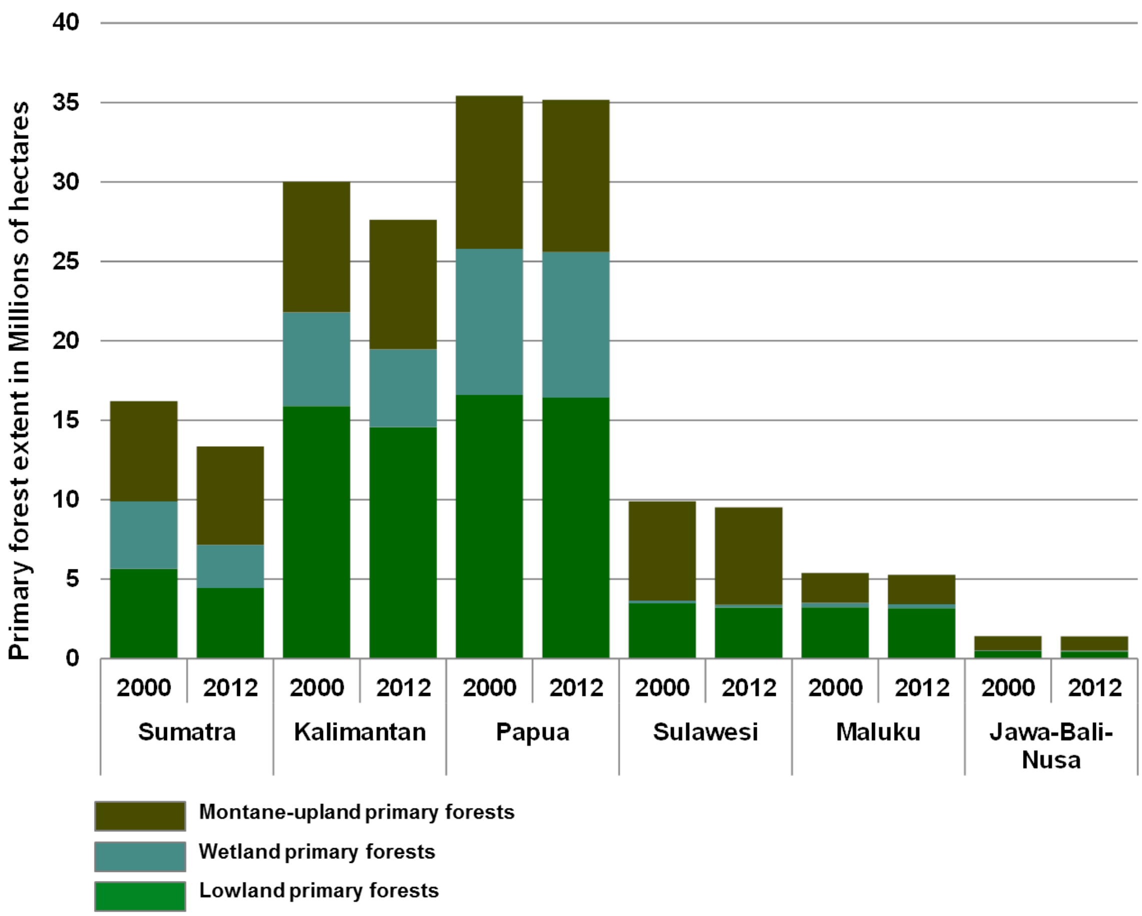



**Figure 5. 1.** Primary forest extent 2000 and 2012 respectively, for major island and group of islands in Indonesia, represented in a proportion of lowland, wetland and upland-montane forest formations

As illustrates in figure 5.1, Sumatra is the most advanced in terms of experiencing forest transition (Mather 1992, Rudel 1998, Perz 2008). The island was covered by natural forests almost evenly until the program of transmigration for resettling people to the outer islands from Java and Bali was initiated (Fearenside 1977, FWI/GWF 2002). Lowland forests were the first forests affected by anthropogenic disturbances with the lowland *terra firma* forests of Sumatra largely cleared prior to 2000 (Holmes 2000, Margono *et al* 2012). Clearing typically is preceded by commercial timber harvesting, which degrades the intact primary forest stands. Un-controlled logging practices make remaining degraded forests (Lambert and Collar 2002, Stolle *et al* 2003) prone to fire (Holmes 2000, Baber and Schweithelm 2000, FWI/GWF 2002, Tacconi 2003, Uryu *et al* 2008). The mass utilization of Sumatra's forests for agro-industrial plantations (Miettinen *et al* 2012) and tree crops (Koh *et al* 2011) followed the logging activities (Holmes 2000, Nawir *et al* 2007, Uryu *et al* 2008, Hansen *et al* 2008b, Broich *et al* 2011a, Margono *et al* 2012), spurred by policies supporting oil palm estate establishment in the outer islands of Indonesia (Casson 2000). Due to the near exhaustion of the lowland primary forest resource, wetland forests are increasingly targeted as lands for conversion. Sumatra's wetlands are at increased risk from controlled burning and wildfires (Kinnaird and O'Brien 1998, Lambert and Collar 2002) as a consequence of the use of fire for large-scale land clearing operations (Baber and Schweithelm 2000). The wetland primary forests exhibited the largest forest cover loss patch size, reflecting mechanical clearings for agro-industrial plantations and agriculture expansions. As primary forests on lowland are granted concessions to logging/plantations concessionaires, traditional smallholders move to upland sites, practicing slash and burn agriculture (*ladang*). By 2012 the island of Sumatra had less than 30 percent forest cover.

Referring to Forestry Law 41/1999 article 18 and Government Regulation 26/2008 article 7, at least 30 percent of total land must remain naturally forested.

Kalimantan is at an earlier stage of forest exploitation than Sumatra. However, the general pattern indicates a path similar to that of Sumatra, with nearly all primary intact lowland forest gone, increasing conversion of remaining primary lowland degraded stands and increasing clearing of wetland primary forests. Papua has the most extensive remaining forests in Indonesia, reflecting a more nascent stage of the forest transition. At this point, conserving Papua's forests should be a main concern of forestry management efforts, particularly given the fate of lowland and wetland forests in Sumatra and Kalimantan.

Results of this study provide a recent historical record of forest transition within Indonesia from 2000. From what was a traditional system of using native forests for hunting and food gathering (Mather 1992), swidden agriculture (Dennis and Colfer 2006), and smallholder cash cropping (Kettering *et al* 1999, Holmes 2000, 2002); a new utilization of forests for commercial wood production and economically productive forests and plantation crops (Holmes 2000, 2002, Uryu *et al* 2008, Hansen *et al* 2008) has ensued (figure 5.2). Evidence of the forest transition (Mather 1992, Rudel 1998) in Indonesia is at the level of decreasing natural forest and a corresponding expansion of *man-made* forest.

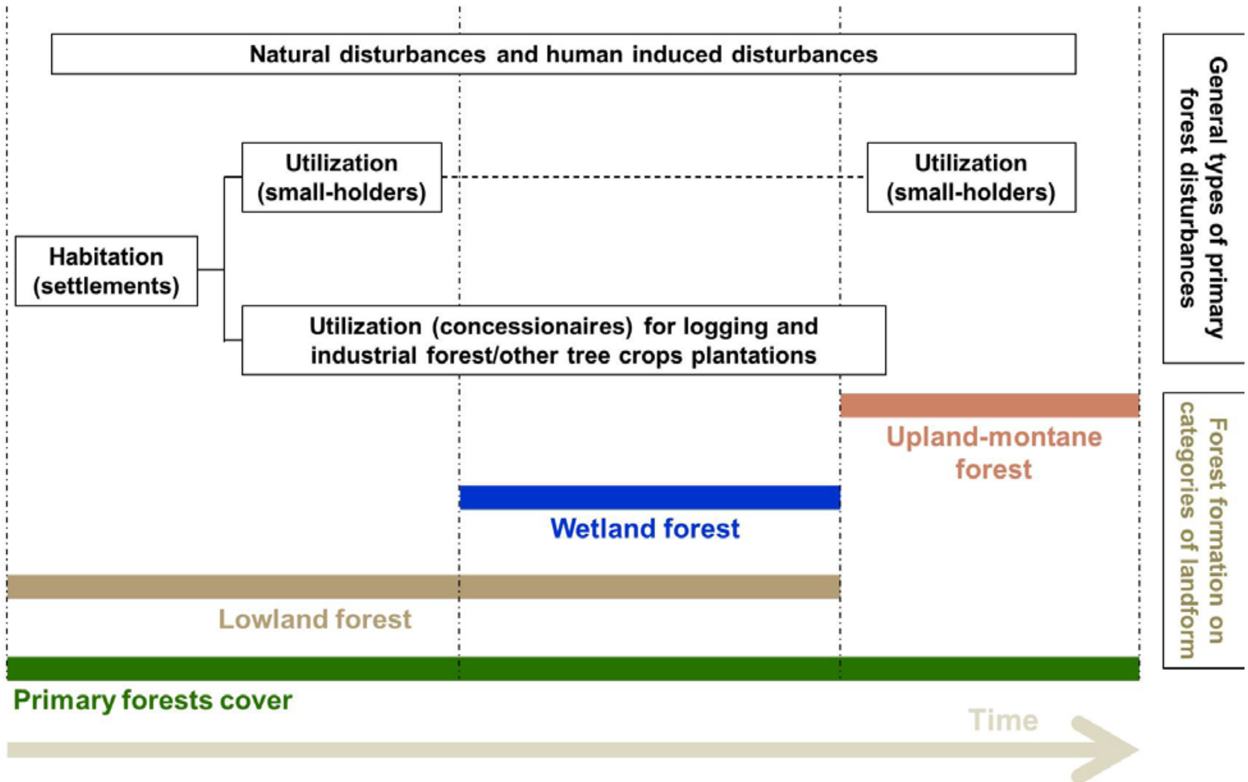



**Figure 5. 2**. Typical forest disturbances in Indonesia per forest formation, depicted as a function of landform categories, based on data analysis and literatures references (Fearenside 1977, Kinnaird and O'Brien 1998, Baber and Schweithelm 2000, Holmes 2000, Tomich *et al* 2001, Lambert and Collar 2002, FWI/GWF 2002, Tacconi 2003, Stolle *et al* 2003, Curran *et al* 2004, Dennis and Colfer 2006, Gaveau *et al* 2007, 2012, Uryu *et al* 2008, Hansen *et al* 2008, 2009) modelled for Sumatra Island

Of particular concern given the loss of natural forest cover is the unique biodiversity of each island group. Two blocks of distinctive tropical evergreen forests representing two different ecological zones are found within Indonesia (Whitmore 1984, Corlett 2005). The western block on the Sunda shelf is part of the *Indomalaya* ecosystem, home to *Dipterocarpaceae spp* within the lowland primary forests of Sumatra and Kalimantan

(Whitmore 1984, Ashton 1992, Manokaran 1995, Appanah 1998); the eastern block of *Australasian* flora on the Sahul shelf has unique indigenous commercial species of Matoa (*Pometia pinnata*) in Papua (Marshall and Beehler 2007). Given the within region floristic biodiversity, it is important to note that preserving one region, such as Papua, does not mean the preservation of all biodiversity. If the natural forests of Sumatra and Kalimantan are lost, Papua will not serve as a bank of the lost biodiversity.

Remote sensed imagery provides information for forest resource monitoring in Indonesia, particularly in the case of the Landsat record (Tucker *et al* 2004, Hansen and Loveland 2012). However, the timely acquisition of cloud-free imagery across the country still limits mapping efforts, particularly for conventional methods of labor intensive photo-interpretation employed by official agencies in-country.

Improved automatic data processing is required to overcome obstacles of using optical passive remote sensing imagery in Indonesia in order to meet the country's commitment to perform effective monitoring, reporting, and verification (MRV), an essential component of REDD+. Such policy initiatives require annual reporting, only possible through mass data processing (Hansen *et al* 2009, Potapov *et al* 2011, Hansen and Loveland 2012) that facilitate annual national-scale mapping updates. This study employed a generic forest cover loss product, one that captures all 'activity' data in terms of forest disturbance, whether the loss of natural forest or plantation forest cover. By mapping primary forest extent and landform, contextual information appropriate for REDD+ monitoring was applied to the generic forest cover loss data.

A key finding was that designated forest land use does not properly protect remaining forests from exploitations. 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. A government mandated restriction on new forest concessions, or moratorium (Inpres 10/2011), is expected to slow forest clearing. The method and results presented here are useful to verifying the potential effectiveness of the moratorium policy.

The moratorium was declared as a tool to reduce deforestation and its associated GHG emissions within areas where logging and conversion of natural primary forest are prohibited. However, the moratorium has several loopholes (Edwards and Laurance 2011) and does not prohibit the logging and forest conversion within existing concessions to continue business-as-usual's activities. Exceptions include "allowing forest clearing"; for (a) areas vital for national development especially for geothermal, oil, natural gas, electricity, paddy production and sugar cane; (b) the renewal of forest concessions, even if occurring within the designed area of moratorium.

The ambiguity of the moratorium language, specifically exceptions relate to national development and food-energy security objectives limit the potential effectiveness of the moratorium in reducing the loss of primary forest cover. Of further importance, terminology defining natural primary forest leads to the exclusion of degraded natural forests from the moratorium. This forest, which in official land cover of Indonesia is renowned as "secondary forest", are part of natural forest extent, and have potential benefits regarding REDD+ objectives.

Overall, Sumatra has passed the minimum 30 percent natural forest cover threshold (referring to Forestry Law 41/1999 article 18, Government Regulation 26/2008 article 7) and has forest cover loss within moratorium lands. Kalimantan has comparatively less primary forest cover loss within moratorium lands compared to outside of the moratorium. Papua has a higher percentage of primary forest cover loss inside the moratorium than outside. Further study of moratorium implementation is required.

Indonesia is challenging to monitor compared to other countries that experience true deforestation, or the conversion of natural forest cover to non-forest land uses. In Indonesia, deforestation, as defined by the replacement of natural forest by non-forestry related land uses, is not the typical forest loss dynamic in Indonesia. Natural forest cover is more frequently replaced by commercially managed forest/tree cover, such as forest plantations or oil palm estates. Brazil's dynamic is largely the conversion of primary forest in the Amazon Basin to pasture and cropland land uses and is depicted in the PRODES produce of the Brazilian Space Agency (INPE 2013). As such, the target for monitoring is more easily mapped than in Indonesia. The key to improved Indonesia carbon monitoring is the establishment of a PRODES-like natural/primary forest extent mask. The presented study achieves this objective and can contribute to national-scale carbon accounting efforts.

**The way forward**

Mass processing of archival satellite imagery (Hansen *et al* 2009, Potapov *et al* 2011, Hansen and Loveland 2012) for mapping forests cover loss is a valuable input to downstream monitoring applications, including carbon accounting (Gibbs *et al* 2007). This is particularly important for areas experiencing rapid forest conversion dynamics. The ability to reduce product latency by automating procedures has significant advantages over heritage photo-interpretative approaches (Hansen and Loveland 2012). Data available from both the Landsat 7 (Arvidson and Gasch 2001) and Landsat 8 (Gerace *et al* 2011) sensors enable annual updates of Indonesian forest cover. If implemented operationally, such a system would match the current standard for humid tropical forest monitoring systems: INPE's PRODES deforestation maps of Brazil (INPE 1992, 2003, 2013). Moving past annual updates is another option and an important line of inquiry in advancing the timeliness of forest disturbance monitoring.

The spatial and time-sequential products generated here are useful for a number of applications. First and foremost, they can be directly integrated with available forest carbon stock (e.g. Van Noordwijk *et al* 2002, Basuki *et al* 2009, Laumonier *et al* 2010) and other ancillary data (Koh *et al* 2011) in estimating emissions from deforestation and forest degradation. The products themselves can be a potential input or reference in developing a biomass data bases (e.g. Fazakas *et al* 1999, Houghton *et al* 2001, Luther *et al* 2006). Forest types, as in intact and degraded primary types, coupled with forest formations based on landform, can be used to generate strata for allocating forest field inventory plots appropriate for aboveground and belowground biomass measurements (Nelson *et al* 2000, Clark and Clark 2000, Houghton *et al* 2001, Houghton 2005, Gibbs *et al* 2007). Such an approach offers a strategic and effective sample design option, especially when destructive samplings are required (Houghton *et al* 2001, Basuki *et al* 2009). For example, more field effort could be assigned to primary wetland forest formations given the exceptional carbon storage and potential emissions from land use change within wetlands generally (Hadi *et al* 2005, Murdiyarso *et al* 2009) and peat soils in particular (Page *et al* 2002, 2007, Zedler and Kercher 2005, Murdiyarso *et al* 2009, Houghton *et al* 2009). The wetlands map as a single landform entity, regardless vegetation covers, combined with a very high resolution satellite data and appropriate field verification can be used to disaggregate the wetlands map into sub-types e.g. peat swamp, freshwater swamp and mangrove.

The presented work provides a set of activity data essential for carbon accounting objectives (GOFC-GOLD 2010). However for comprehensive carbon monitoring (e.g. Guo and Gifford 2002, Houghton 2005), the quantification of net forest change, i.e. including the mapping of forest gain, is needed. The forest gain theme would provide information valuable for evaluating the terms of “gross” and “net” deforestation (Ramankutty *et al* 2007). Given the importance of the forestry sector to the government of Indonesia, a more comprehensive monitoring system would be enabled (MoF 2011b). The forest gain class of Indonesia generated from global map of Hansen *et al* (2013) could provide evidence whether the forest cover loss within forest is followed by recovery according to designed growing cycles. Further, the comprehensive information on forest gain along with forest cover loss can be used to elaborate on the state of the forest transition within Indonesia (Perz 2008).

Another potential use of the produced maps is to target areas in need of improved enforcement of the official forestry regulations in support of biodiversity assessment efforts, especially in regard to designated forest-land uses. The proposed approach could significantly complement and act as a check on the official forest resource monitoring system in Indonesia (MoF 2008b). Governance, particularly the appropriate legal exploitation of the various official land uses, is lacking in Indonesia. Results of this study show significant forest exploitation in land uses where such exploitation is limited or prohibited by law. The detailed results of this study will be made available online for users to evaluate good forest governance and support the move towards improved transparency and forest management (Fuller 2006, Springate-Baginski and Wollenberg 2010, Kanowski *et al* 2011). Lastly, methods should be applied to earlier archives in establishing a more long-term baseline (DeFries *et al* 2007, Hansen and Loveland 2012), specifically from the beginning of the Landsat Thematic Mapper era in the 1980s.  The mapping of primary intact and degraded forest change was demonstrated in this study from 1990 to 2000 for Sumatra (Margono *et al* 2012); further work exploiting Landsat 4 and 5 archival data to mimic the products from the presented study will help establish a valuable record of forest extent and change in Indonesia.

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