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Primary forest cover loss in Indonesia over 2000–2012

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Extensive clearing of Indonesian primary forests results in increased greenhouse gas emissions and biodiversity loss. However, there is no consensus on the areal extent and temporal trends of primary forest clearing in Indonesia. Here we report a spatially and temporally explicit quantification of Indonesian primary forest loss, which totalled over 6.02 Mha from 2000 to 2012 and increased on average by 47,600 ha per year. By 2012, annual primary forest loss in Indonesia was estimated to be higher than in Brazil (0.84 Mha and 0.46 Mha, respectively). Proportional loss of primary forests in wetland landforms increased and almost all clearing of primary forests occurred within degraded types, meaning logging preceded conversion processes. Loss within official forest land uses that restrict or prohibit clearing totalled 40% of all loss within national forest land. The increasing loss of Indonesian primary forests has significant implications for climate change mitigation and biodiversity conservation efforts.

Tropical deforestation from developing countries[1], including Indonesia[2,3], contributes to emissions of greenhouse gases, principally carbon dioxide, the primary driver of global warming[1,3]. Primary forest clearing also results in the loss of biodiversity due to the destruction of unique tropical forest habitats[4–6]. Present understanding of forest change within Indonesia lacks consensus. 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 (refs 7,8). 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 (refs 9,10). 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[11]. The variation in estimates points to the need for thematic consistency and improved spatio-temporal data in bringing transparency to this important land change dynamic.

A recent study that spatially explicitly mapped global gross forest cover change found Indonesia to be the country with the highest rate of increasing forest cover loss from 2000 to 2012 (ref. 12). However, the results were based on forests as 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 critically important to know the context of forest disturbance, whether of a high-biomass natural forest or a short-cycle plantation. Similarly, the clearing of natural forest versus managed forest has very different implications on the maintenance of biodiversity richness. Indonesia poses a particular challenge in the tropical deforestation context. Deforestation, as defined by the replacement of natural forest by non-forestry-related land uses, is widespread in Indonesia. However, natural forest cover is also frequently replaced by commercially managed forest/tree cover in the form of plantations or oil palm estates, resulting in a complicated landscape of forest cover change. The objective of the presented study is to bring improved context to the Indonesian forest cover change dynamic by quantifying the portion of gross forest cover loss that occurred within primary forests from 2000 through 2012.

Definitions and rationale

Our study combines the global gross forest loss data of ref. 12 with an extension of the work of refs 13,14 in disaggregating total forest cover loss by primary/non-primary status and landform for all of Indonesia. Primary forest is defined as mature natural forests of 5 ha or more[15] in extent that retain their natural composition and structure, and have not been completely cleared and re-planted in recent history, including both intact and degraded types[4,13]. Intact primary forests have no detectable signs of human-caused alteration or fragmentation and are delineated as per the Intact Forest Landscape method of ref. 16. Primary degraded forests are primary forests that have been fragmented or subjected to forest utilization, for example, by selective logging or other human disturbances that have led to partial canopy loss and altered forest composition and structure[13,17].

Primary forests, consisting of intact and degraded types, were mapped for the year 2000 and their loss quantified through the end of 2012 and disaggregated by landform, specifically wetland, and *terra firma* lowland, upland and montane formations. Primary forest cover loss in general and within wetlands in particular is important for greenhouse gas accounting efforts. Primary forests are the largest above-ground carbon stores in the world[18] and peatlands the largest reservoirs of soil carbon[19–21]. Indonesia's primary lowland forests have long been threatened by deforestation and forest degradation[5,22,23]. Easy access to lowland forest has made primary forests a target for logging and the subsequent conversion to higher value land uses[5]. Wetland forests in Indonesia have historically remained largely intact[24]. However, during the past two decades the conversion of wetland forests, including peatlands, to

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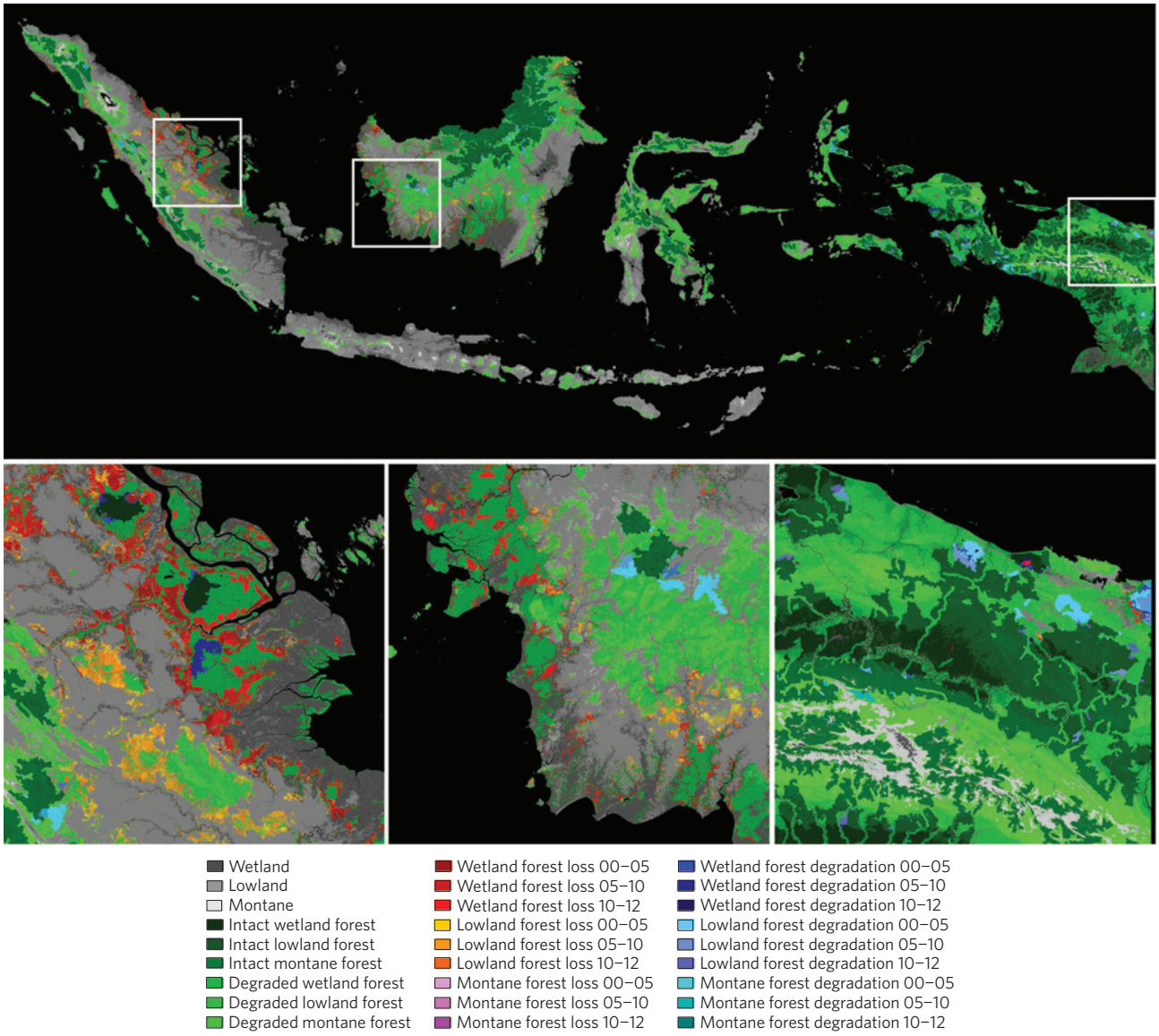

Figure 1 | Indonesian landform, intact and degraded primary forest extent and loss. Left to right subsets (360 km by 360 km) are for Riau province, Sumatra (left); West Kalimantan province, Kalimantan (centre); and Papua province, Papua (right).

agro-industrial land uses has increased[24–27]. The high rates of primary forest loss, including intact and degraded types[13], coupled with the high carbon stocks in above-ground and below-ground pools[18] has made Indonesia the third largest global emitter of carbon dioxide[3].

In addition, Indonesia's forests contain high floral and faunal biodiversity[28–30] including 10% of the world's plants, 12% of the world's mammals, 16% of the world's reptile–amphibians, and 17% of the world's bird species[31]. The forest's high biodiversity places Indonesia among the world's mega-diverse countries[32]; extensive clearing of Indonesian primary forest cover directly results in habitat loss and associated plant and animal extinctions[4,28]. Explicit characterization of the spatio-temporal variation of primary forest loss will inform biodiversity modelling efforts from national to local scales.

Key findings

Of the 15.79 Mha of forest cover loss for Indonesia reported in ref. 12 for the period 2000–2012, 38% or 6.02 Mha occurred within primary intact or degraded forests. Annual primary forest cover loss increased over the study period with the highest total primary forest cover loss having occurred in 2012, the last year of the study. Primary forest loss in 2012 totalled 0.84 Mha, more than the reported forest loss of Brazil (0.46 Mha; ref. 33), the historical leader in the clearing of tropical forest. Figure 1 illustrates the final results in map form. Figure 2 depicts annual primary forest loss for Indonesia as a whole and for its main island groups. Supplementary Fig. 1 depicts Indonesian primary forest loss totals by year from this study compared with official Indonesia government data[9–11], UNFAO data for Indonesia[7,8] and Brazil's PRODES deforestation data[33–36], with all data sets estimating primary forest cover loss (Supplementary Methods for definitions used as a basis for intercomparison). 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 forest cover loss from the study in ref. 12. Disaggregating the results by landform, 3.04 Mha, or 51% of total primary forest cover loss, occurred in lowland landforms, whereas 2.60 Mha, or 43%, occurred in wetland landforms. The overall trend in increasing wetland primary forest loss was greater than lowland primary forest cover loss. Of the annual increase in primary forest loss over the study

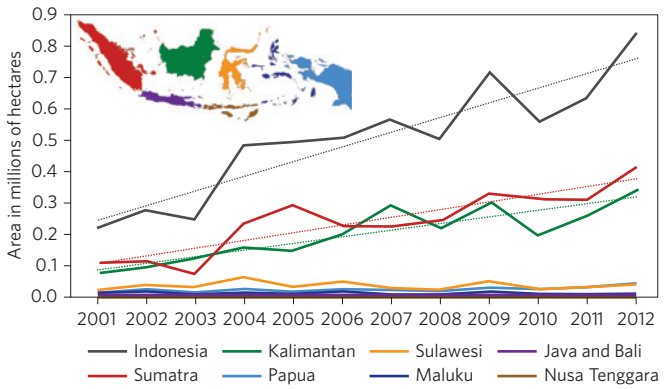

Figure 2 | Annual primary forest cover loss, 2000–2012, for Indonesia as a whole and by island group (Sumatra, Kalimantan, Papua, Sulawesi, Maluku, Nusa Tenggara and Java and Bali). Dashed lines are linear fits to the data.

period, 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.

More intensive appropriation of wetland landscapes is found in Sumatra compared with Kalimantan or Papua, possibly reflecting a near-exhaustion of easily accessible lowland forests (Fig. 3). Primary wetland forest loss during the study period in Sumatra totalled 1.53 Mha compared with 1.21 Mha in lowland forest. The annual increase of wetland forest loss totalled 14,600 ha compared with 9,200 ha of additional lowland forest loss. Maximum annual 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 conversion. Lowland primary forest loss during the study period totalled 1.33 Mha with an annual increase of 10,700 ha. Wetland primary forest loss totalled 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 totalled 0.17 Mha and 0.05 Mha, respectively. Lowland forest loss grew by an average of 1,000 ha per year, whereas 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. Data on primary forest extent and loss per island group are shown in Table 1 and Fig. 2, and Supplementary Table 2 and Fig. 3.

Primary forest loss at the national level occurred almost exclusively within primary degraded forests (98% of total loss; Supplementary Table 3), meaning forests were typically logged preceding clearing. The loss of primary degraded forests is important as they still contain significant carbon stores[37,38] and biodiversity richness[4,6]. Of the primary degraded forests cleared, 92% were found in lowland and wetland landforms. The annual rate of degraded primary 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 primary 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. Degraded primary forest extent increased in upland and montane landforms as logging roads were expanded during the period of study.

Discussion and concluding remarks

By the end of the study period, Indonesia had surpassed Brazil in area of primary forest cover loss, with an increasing proportion of loss having occurred within wetland formations. Figure 1 illustrates three landscapes emblematic of this dynamic. Increasing loss over time is shown as well as the location of more recent clearings within the wetlands of Sumatra and Kalimantan. The implications for carbon emissions are substantial given the known carbon stocks

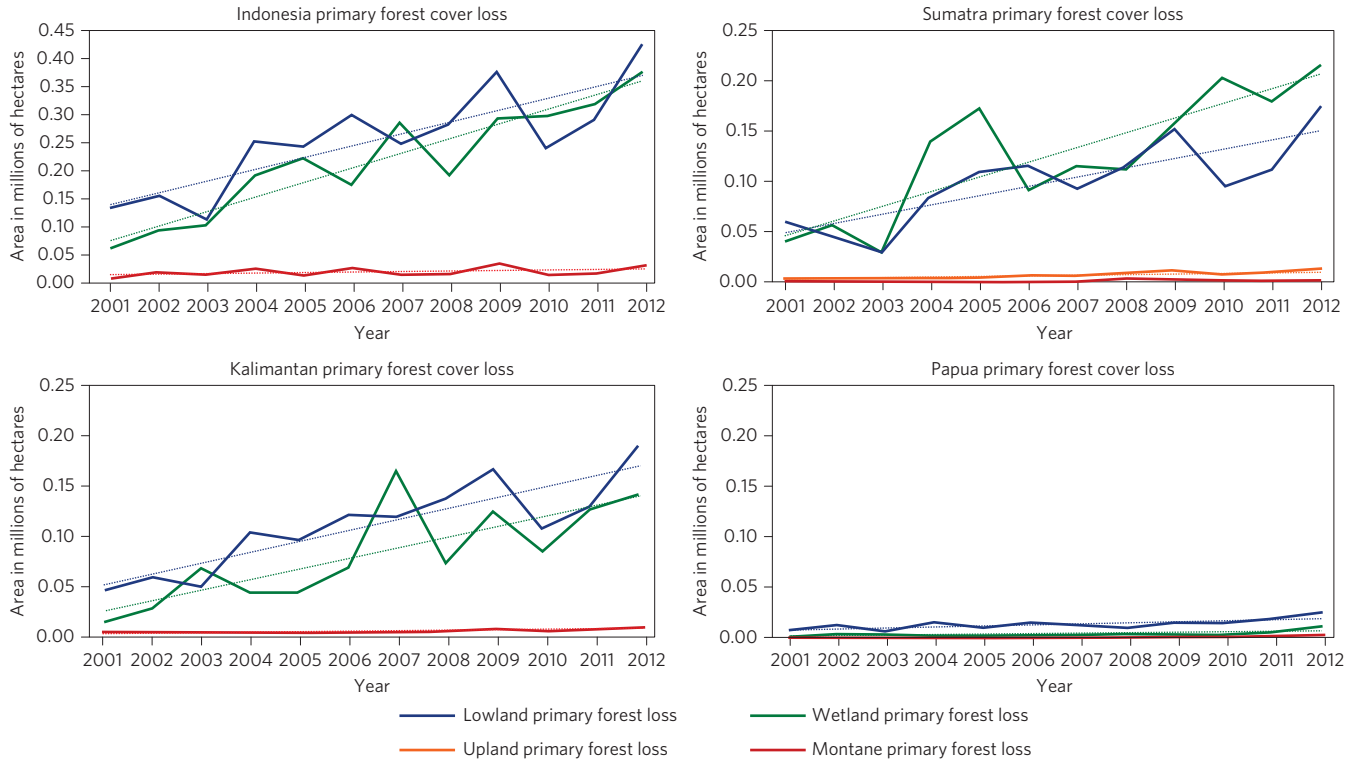

Figure 3 | Annual primary forest loss disaggregated by landform for Indonesia as a whole, and the island groups of Sumatra, Kalimantan and Papua. Dashed lines are linear fits to the data.

Table 1 | Primary forest extent for 2000 and primary forest cover loss from 2000 to 2012 for Indonesia and its main island groups.

Island/group of islands—landforms	Total area extent	Primary forest extent 2000			Primary forest loss 2000–2012			Primary forest extent 2012		
	Mha	Mha	%*	%†	kha	%*	%†	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		5.3	396		0.40	9.5		5.1
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		2.9	109		0.11	5.3		2.8
Java 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		0.4	13		0.01	0.8		0.4
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		0.3	9		0.01	0.6		0.3
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 landform by respective category. †Percentage of island/island group land area by respective category.

of both primary forest[37–39] and peatland land covers[19–21]. Large wetland clearings are probably not caused by small-holders, but by agro-industrial land developers[25–27]. These larger developments on peatlands are often accompanied by draining the wetland and an impact on carbon emissions beyond the footprint of the actual development[25,40]. Supplementary Table 5 reports mean clearing patch size by landform for Sumatra, Kalimantan and Papua; increasing large-scale clearing of wetlands in Sumatra and Kalimantan is evident and illustrated in the subsets of Fig. 1.

Supplementary Fig. 4 illustrates primary forest loss by official forest land use. Total primary forest loss within official forest land was 2.2 times that outside official forest land 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[13]. Increasing primary forest loss was found mainly in production forests. An average of 27,000 additional hectares of primary forest loss occurred per year within official forest land use 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 hectares per year on average), owing to rising rates of loss within lowland landforms. Nearly half of total lowland primary forest loss occurred within production and limited production forests. Production forest loss within lowlands and wetlands was comparable, whereas 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. Almost 40% of total primary forest loss within national forest lands occurred within land uses that restrict or limit clearing, 22% in limited production forests that restrict clearing and 16% within conservation and protection forests that prohibit clearing. 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.

Although Indonesia recently implemented an implicit deforestation moratorium[41], beginning in May 2011, it seems that the moratorium has not had its intended effect[42,43]. In fact, the first full year of this study within the moratorium period, 2012, experienced the highest rates of both lowland and wetland primary forest cover loss. Questions concerning the moratorium as a driver of increased deforestation are worthy of investigation. The spatial and temporal variation in primary forest loss documents the continuing appropriation of natural forests within Indonesia, including the increasing loss of primary forests in wetlands and in land uses meant to limit or prohibit clearing, with implications for accurate greenhouse gas emissions estimation. 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 slow emissions from deforestation and forest degradation and are made available at the following website: http://glad.geog.umd.edu/indonesia/data2014/index.html.

Methods

Forest was defined as tree cover with a minimum height of 5 m and canopy cover of at least 30% (ref. 2) at the Landsat pixel scale[12]. Primary forest consisted of mature natural forest cover that has not been completely cleared in recent history and consisted of a contiguous block of 5 ha or more[4,13,15]. Primary forest cover mapping employed Landsat composites and multi-temporal metrics as input data to a two-step supervised classification first prototyped for the island of Sumatra in ref. 13. The first step was a per-pixel classification of areas with tree canopy cover of 30% and above for the 2000 reference year. A second per-pixel classification procedure was performed to separate primary forest from other tree cover for 2000; contiguous areas of 5 ha and greater were retained as primary forest. A limited editing of this classification was performed to remove older plantations and adjust other forest formations that could not be identified using the per-pixel classifier, but could be identified in photo-interpretive contexts. Primary forests were subsequently characterized into primary intact and primary degraded subclasses using the GIS-based buffering approach of the Intact Forest Landscapes (IFL) of ref. 16. To create the IFL layer, buffers of roads, settlements and other signs of human landscape alteration were used to identify degraded areas within zones of primary forest cover. IFL mapping employed 2000, 2005, 2010 and 2012 cloud-free Landsat mosaics to quantify changes in primary intact forest extent. Forest degradation is defined as an area having experienced a transition from primary intact forest to primary degraded forest and was estimated using IFL change for the 2000–2005, 2005–2010 and 2010–2012 epochs (Supplementary Table 3). Our map of primary intact and primary degraded forest cover types corresponds to the Indonesia Ministry of Forestry's primary and secondary forest cover types[44,45]. Supplementary Table 1 and Fig. 2 illustrate the agreement across these classes in assessing the accuracy of our primary forest extent for 2000 reference.

Forest cover loss data were subset from a global product that employed a data mining approach and the Landsat 7 archive to quantify forest cover loss[12]. Forest loss within the year 2000 primary forest extent map was used to generate rates of change across the study period per primary forest type and landform. The forest loss data were employed at annual timescales. Wetlands were defined as temporary or permanently inundated lands having a water table at or near the land surface[46], and include various forests formations, including mangrove, fresh water and peatland[47]. Wetlands were mapped using cloud-free Landsat image mosaics, ALOS PALSAR radar imagery and topographic indices derived from 90 m elevation data from the Shuttle Radar Topography Mission[14] (SRTM). Other landforms were defined using SRTM elevation data. Supplementary Table 4 describes the criteria for landform delineation[31,47–50]. The two primary forest classes, four landforms and annual forest cover loss data were overlain to generate the spatio-temporal estimate of loss within Indonesia's primary forest cover over 2000–2012.

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Author contributions

B.A.M. designed and implemented workflow; performed data processing; characterized wetland extent, other landforms and primary forest; performed analyses and results synthesis; prepared the manuscript; M.C.H. assisted in study design and manuscript composition; P.V.P. assisted in study design, performed pre-processing of remote sensing data inputs and generated forest change data; S.T. performed data processing and led primary forest characterization; F.S. advised on policy consequences and overall thematic presentation.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.A.M.

Competing financial interests

The authors declare no competing financial interests.