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ORIGINAL PAPER

Towards sustainable management of Indonesian tropical peatlands

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Abstract Large areas of Indonesian peatlands have been converted for agricultural and plantation forest purposes. This requires draining with associated CO_2 emissions and fire risks. In order to identify alternative management regimes for peatlands, it is important to understand the sustainability of different peatland uses as well as the economic benefits peatlands supply under different land uses. This study explores the key sustainability issues in Indonesian peatlands, the ecosystem services supplied by peatlands, and potential responses to promote more sustainable peatland use. A literature review and spatial analysis were conducted. Based on predominantly government data, we estimate the amount of Indonesian peatlands that has been converted between 2000 and 2014. We quantify increases in oil palm and plantation forest crop production in this period, and we analyse key sustainability issues, i.e. peat fires and smoke-haze, soil subsidence and flood risk, CO_2 emissions, loss of habitat (in protected areas), and social conflicts that influence sustainability of Indonesian peatlands management. Among others we show that CO_2 emissions from peatlands in Indonesia can be estimated at between 350 and 400 million ton CO_2 per year, and that encroachment of oil palm and plantation forestry (acacia, rubber) has taken place on 28% of protected areas. However, as we examine, the uncertainties involved are substantial. Based on our findings, we distil several implications for the management of the peatlands.

Keywords Indonesia · Peatlands · Ecosystem services · Sustainability

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Introduction

In the last twenty years, large areas of Indonesian peatland have been converted, mainly into agricultural lands for estate crop production, and plantation forest areas for pulp production (Rehman et al. 2014; Gunarso et al. 2013; Miettinen et al. 2011; Koh et al. 2011; Murdiyarso et al. 2010). This conversion brought short-term economic gains, but poses major environmental and economic risks, resulting from health and economic damages due to peat fires, soil subsidence potentially leading to flooding of millions of hectares of coastal peat lands in the course of the next decades, the very large CO_2 emissions from burning and oxidising peat, and from the loss of globally significant biodiversity contained in natural peat swamp forests (Wösten et al. 2008; Page et al. 2011; Joosten et al. 2009; Turetsky et al. 2015; Hooijer et al. 2012). For instance, drained peatland in Indonesia contributes 58% of global peatland CO_2 emissions, with marked spike during El Nino years when emissions from fire are particularly high (Hooijer et al. 2006). In addition, a range of social issues have been related to peat conversion such as the loss of access to land of traditional forest users (Thorburn and Kull 2013; Sumarga et al. 2016).

A number of Indonesian national policies aim to enhance peatland management, for instance the Ministry of Agriculture Decree No. 14 year 2009 which prohibits oil palm establishment in peatlands with more than 3 m depth. The Indonesian government has also established a strict moratorium on peat conversion since 2011. Yet, this decree is often not effective because of a lack of enforcement at the level where many of the land-use decisions are taken i.e. at village, district and provincial level (Boer et al. 2012). The national policy on peatland management has not yet been widely translated into sub-national regulation, in part due to the lack of knowledge of local policy makers on short and long-term economic, social, and environmental consequences of different land use types. Nevertheless, in recent years, the emerging insights in the consequences of peat degradation including burning (e.g. World Bank. 2016; Turetsky et al. 2015), a better understanding of the various benefits provided by peatland ecosystems and their links to the stakeholders (e.g. Suwarno et al. 2016; Sumarga and Hein 2015) as well as new payment mechanisms (e.g. REDD+) have influenced the Indonesian playing field for peatland management. This may increase the chance for a transition to sustainability.

Although the potential effects of changes in Indonesian peatlands are now increasingly well understood, there is still no consensus on the economic benefits provided by peatlands under different uses at the scale of the country. This is important also in view of the major differences in peat development between the three major islands of the country that contain peat i.e. Sumatra, Kalimantan and Papua. In order to establish the effectiveness of proposed new policies on peatlands, based upon presidential guidance (PP 71 year 2014) and more recently articulated policy instructions (the direction of the President Republic Indonesia, on forest and peatland fires in a coordination meeting on 18 January 2016) a baseline assessment is needed of the current status of peatlands and the trends in their use.

The objective of this study is to analyse peatland uses and the ecosystem services supplied, the key sustainability issues, and the potential response options to move towards sustainability. We conduct a literature review and conduct spatial analysis to analyse peatland use in the period 2000–2014 in the three main islands (Sumatra, Kalimantan, and Papua). We specifically discuss the uncertainties in the current datasets on peat, which is one of the main barriers for effective policy implementation. The novelty in our paper is in bringing out economic benefits and sustainability issues in Indonesian peatlands in one paper, and in the review we conduct of the often contradicting datasets on this issue. We also propose a basic framework for identifying peatland management options.

Materials and methods

Study area

We specifically focused on peatland areas covering Sumatra, Kalimantan, and Papua covering 16 provinces of in total 33 provinces in Indonesia. This includes 10 provinces in Sumatra (Aceh, North-Sumatra, West-Sumatra, South-Sumatra, Riau, Kepulauan Riau, Jambi, Kepulauan Bangka Belitung, Bengkulu, and Lampung), 4 provinces in Kalimantan (West-Kalimantan, Central-Kalimantan, South-Kalimantan, and East-Kalimantan), and 2 provinces in Papua (Papua, and West-Papua). These three main islands together comprise the large majority of Indonesian peatlands. We show that these islands experience entirely different trends in the conversion of peatlands.

Trends in peatland use and ecosystem services

We first analysed peatland cover and subsequently we link these changes in peatland use to changes in ecosystem services provided by peatlands. We overlaid the *Indonesia Land Cover Map* for year 2000, 2003, 2006, 2009, 2012, 2014 produced by the Ministry of Forestry Republic Indonesia (MoFRI 2014) with the 2011 *Indonesia Peatland Map Scale 1:250,000* produced by Balai Besar Sumber Daya Lahan Pertanian (BBSDLP) the Ministry of Agriculture Republic Indonesia (Ritung et al. 2011). The land cover map contains 23 land-cover classes; and for the purpose of this study the classes were reclassified into 10 land cover classes, namely undisturbed natural forest, disturbed natural forest, plantation forest, estate crop, degraded land, paddy field, dryland agriculture, urban, open water, and other uses. We considered all primary forest as 'undisturbed natural forest' class and all secondary forest as 'disturbed natural forest' class. In addition, dry shrub, wet shrub, savanna, grasses, and open swamps areas are presented as 'degraded land' class (based on Law et al. 2015). Agriculture areas for food crops are classified into 'dryland agriculture' class and 'paddy field' class, in which dryland agriculture class consist of pure and mixed dryland agriculture areas. The 'other uses' class is classified by aggregating fish pond/aquaculture areas, mining areas, port & harbour areas, and also cloud & no-data. In particular for analysing biodiversity habitat (protected areas), we overlaid this output with maps of protected areas produced by the Ministry of Forestry Republic of Indonesia. To analyse the trends in Indonesian peatland-use, we only considered peatland with the peat depth of at least 50 cm (Krisnawati et al. 2015) with an estimation of the total area around 14.9 million hectares (Ritung et al. 2011), although there is still uncertainty on the exact peat area and boundaries. We discussed uncertainty of the peatland data in the "Discussion" section of our paper. All spatial analyses were done with help of ArcGIS 10.2.

Next, we quantified seven ecosystem services i.e. timber production, oil palm production, biomass production for pulp, paddy production, carbon sequestration, biodiversity habitat, and ecotourism. These selected services are the most relevant ecosystem services in Indonesian peatland (Law et al. 2015; Sumarga and Hein 2014). The performance indicators, sources of data, and assessment methods for quantifying the flow of the six selected ecosystem services (excluding carbon sequestration) are described in Table 1. Note that for oil palm plantation and plantation forest areas in Indonesian peatlands, we used data for the three islands recorded by various sources (see Appendices 3 and 4 Tables 8, 9). Note also that we only considered forested areas inside protected areas in analysing biodiversity habitat given the difficulties and the high potential uncertainty in identifying habitat outside protected areas. This latter restriction is also based on the assumption that most of the forest outside (and to some extend also inside, in particular in Sumatra and Kalimantan) the national parks have been moderately to severely degraded due to in particular timber harvesting and slash and burn cultivation (Biancalani and Avagyan 2014; Posa et al. 2011). We acknowledge that there are many more ecosystem services provided by Indonesian peatlands (see e.g. Suwarno et al. 2015) but due to a lack of data we focus on the aforementioned services. We discuss the implications of our limited selection of services in the "Discussion" section.

The quantification method for carbon sequestration requires further explanation. We quantified carbon sequestration (a service) and carbon emissions (a disservice) based on the net carbon (CO_2) flux of different types of peatland use, derived from several previous studies as listed in Appendix 1 (Table 6). The net carbon flux may be positive (sequestration higher than emissions) or negative (emissions higher than sequestration). We quantified the net carbon flux of eight peatland uses: undisturbed natural forest, disturbed natural forest, plantation forest (referred to acacia plantation), oil palm plantation, agricultural crops, shrubs (degraded lands), water, and other land uses (referred to degraded lands), with values ranging from −85 ton CO_2/ha/year (in oil palm plantation, assuming a drainage depth of 90 cm) (Hooijer et al. 2010) to 19 ton CO_2/ha/year (in undisturbed natural forest) (Suzuki et al. 1999). Except for undisturbed natural forest and water, we assumed that the areas are drained. As shown in Appendix 1 (Table 6), the net carbon fluxes are negative in most types of peatland use in Indonesia, indicating that what ecosystem provides in those land uses is a disservice. We multiplied the area of each peatland use with its net carbon flux data, and finally aggregated them all to derive the estimate of carbon sequestration at national level from 2000 to 2014.

Analysis of sustainability issues in peatland

Based on a literature review and supported by our spatial analysis, we analyse the key sustainability issues related

Table 1 The physical units of selected ecosystem services

Type of ES	Ecosystem service	Indicator	Sources data	Method
Provisioning services	Timber production	m^3/year	Statistics Indonesia (BPS 2000–2014) Sumarga and Hein (2014)	Timber produced (m^3/year) = area of natural forest in peatland * average timber harvesting since 2000 (excluding timber in protected area)
	Oil palm production	ton/year	Statistics Indonesia (BPS 2000–2014) Gunarso et al. (2013) Sumarga and Hein (2014)	Oil palm produced (ton/year) = area of oil palm plantation in peatland * average oil palm yields in peat since 2000
	Biomass production for pulp	ton/year	Statistics Indonesia (BPS 2000–2014) Krisnawati et al. (2011)	Biomass produced for pulp (ton/year) = area of plantation forest in peatland * average biomass production since 2000
	Paddy production	ton/year	Statistics Indonesia (BPS 2000–2014)	Paddy produced (ton/year) = area of paddy field in peatland * average paddy production since 2000
Regulating Services and Disservices	Carbon sequestration and emissions	ton CO_2/year	Several sources, see text	Emission and sequestration factors were considered for different land uses, see text below
Cultural Services	Ecotourism (Nature watching)	Number visitors/year	Statistics Indonesia (BPS 2000–2014) Forestry Statistics (MoFRI 2000–2014)	Nature watching = number of visitor to conservation areas in peatlands since 2000
	Biodiversity conservation (protected habitat)	ha	Conservation area map Protected forest map	Biodiversity habitat = area of peat swamp forests inside protected areas[a] that are not converted to other land uses since 2000[b]

[a] Indonesian protected areas consist of two main categories: conservation areas (including national park, recreation park, nature reserve and wildlife sanctuary) and protected forest

[b] The degraded peat swamp forests, for example due to fires, which are not converted to other land uses are included in the calculation of biodiversity habitat

to the current use of Indonesian peatlands. In particular, we include the following issues in our study: fires and smoke, peat soil subsidence and flood risks, CO_2 emissions (based on our analysis described above), loss of habitat, and social conflicts. We propose a general framework to order these sustainability issues. In this framework, we distinguish between four types of peatland condition: (1) forest use, drained; (2) forest use, no drainage; (3) agricultural use, drained; and (4) agricultural use, no drainage. With forest use is meant that the peatlands are not used for cropping systems including plantation crops or agroforestry and that they may be productive as forest systems with logging or supplying other ecosystem services (e.g. non-timber forest products, water regulation, carbon storage and sequestration), or that they may be degraded with little vegetation left. In the latter case the potential for rehabilitation to peat swamp forest exists, but rehabilitation may be hampered by recurrent fires that burn tree seedlings. The sustainability issues differ markedly for these categories as we will explore in our study. This has also repercussions for policy making, for example if peatlands are brought from the condition of productive use with drainage to non-productive use with drainage, for example because oil palm plantations are retired without subsequent peat rehabilitation including reducing drainage levels, this will not necessarily lead to sustainable peatland use. We also explore how these sustainability issues differ for the three islands that we consider.

Results

This section presents the results of our spatial analysis on peatland use and ecosystem services as well as our literature review on sustainability issues related to Indonesian peatlands. These sustainability issues are a consequence of the land use conversion to which the peatlands have been subject.

Indonesian peatland use

The distribution of the land cover in Sumatra, Kalimantan and Papua since 2000 reveals major changes in the use of Indonesian peatlands (see Table 2). Our study shows an ongoing, rapid conversion of natural forests to other land use in particular plantation crops (in particular but not only oil palm) and plantation forestry (in particular *Acacia crassicarpa* for pulp production). Indonesian tropical peatland occupied by disturbed and undisturbed natural forests decreased from about 9 million hectares in 2000 to about 6.4 million hectares in 2014. However, there is virtually no undisturbed peat swamp forest remaining in Sumatra and Kalimantan, i.e. all remaining undisturbed peat swamp forest is in Papua (where deforestation has been rapidly increasing in the last years). The fastest increase in land cover was related to expansion of oil palm plantations in Indonesian peatlands, which increased from about 700 thousands hectares in 2000 to almost 2 million hectares in 2014. Note that our figures are based on government data supplemented with data from industry for oil palm plantations. The figures are uncertain (see Appendices 2 and 3 Tables 7, 8 for more detailed assessment of uncertainties) and are likely to be conservative because new plantations are not immediately reflected in government statistics.

Our analysis also shows major differences in land conversion between the three islands. The highest conversion of natural peat swamp forest took place in Sumatra (Fig. 1). Natural peat swamp forest has decreased from 51% (of which only 6% is undisturbed forests) of Sumatran peatlands in 2000 to only 17% in 2014 (of which 4% undisturbed forests, all located in protected areas). Recent years also show conversion of protected areas to plantation crops including in for example substantial encroachment in Berbak National Park in Jambi, Sumatra. Kalimantan takes an intermediate position with conversion of peatland to plantations still ongoing. In Kalimantan there are also large areas of degraded peatland, drained but not covered by plantations. These areas increased from

Table 2 Peatland-use area (in thousands of hectares) based on land cover type in Indonesia since 2000 according to government data and various sources

Land cover type	Year					
	2000	2003	2006	2009	2012	2014
Undisturbed natural forest	3078	3086	2998	2829	2783	2745
Disturbed natural forest	6315	5832	5124	4589	4073	3685
Plantation forest (acacia)	49	68	264	425	803	1087[a]
Oil palm[b]	701	1106	1325	1544	1762	1908
Dryland agriculture	691	691	712	774	797	924
Paddy field	369	373	373	384	384	362
Urban	67	67	67	67	67	67
Open water	70	70	70	70	70	70
Other uses	19	20	20	18	17	18
Degraded land	3556	3602	3962	4215	4158	4049

[a] Industry data (see Appendix 4 Table 9)

[b] Gunarso et al. (2013) with regression (see Appendix 3 Table 8). Note that Gunarso et al. (2013) analysed oil palm on peat based on the Wetlands International map (Wahyunto and Suryadiputra 2008) which assumes a peatland area of 20.8 million ha. We renormalize to the 14.9 million ha of the BBSDLP MoARI map (Ritung et al. 2011) by adjusting the category disturbed forest based on the assumption that oil palm is in the large majority of cases developed in disturbed natural forest (Gunarso et al. 2013)

28% in 2000 to 35% of peatlands in 2014. As discussed in the next section, this has major repercussions for sustainability issues including peat fires. Most of the remaining peat swamp forests are in Papua. An issues is that data is particularly scarce and uncertain in Papua, for instance there are very few remote sensing based studies that we found with which we can compare government data. We compare our findings with other studies in the "Discussion" section, as well as in Appendices 2 and 3 (Tables 7, 8).

Ecosystem services provided by Indonesian peatland

Table 3 shows estimates of the dynamics of ecosystem services provided by Indonesian peatland since 2000. The details of the ecosystem services data used for this analysis are presented in Appendix 1 (Table 6). The conversion of natural peat swamp forests to oil palm and plantation forest led to an estimated almost 50% decrease of timber production within 14 years (2000–2014), and a significant increase of CPO production (almost threefold) and biomass production for pulp (more than 20-fold), followed by a 3% decrease of paddy production during that period. Carbon emissions from peat nearly doubled in the period 2000–2014, to 105 million ton C per year or 385 million ton CO_2 per year. This compares to emissions from other sources (e.g. households, industry) of around 595 million ton CO_2 per year for Indonesia (DNPI 2010). Peatland deforestation also leads to loss of protected habitat with an average annual loss of about 8.6 thousands hectares. This reflects illegal encroachment in the protected forest areas. In 2014, around 28% of the total protected areas in peatlands in Indonesia were converted already. This protected peat swamp forest areas cover 17% of total peatland areas in Indonesia. For ecotourism, we calculated the number of visitors who visit national parks and recreation parks in peat. Our analysis shows a 21% increase of total number visitors from 97 thousands people in 2000 (of which 1% foreigners); to approximately 117 thousands people in 2014 (of which 33% foreigners). This reflects only 3% of total number visitors to all conservation parks in Indonesia during this period—given the specific biodiversity of

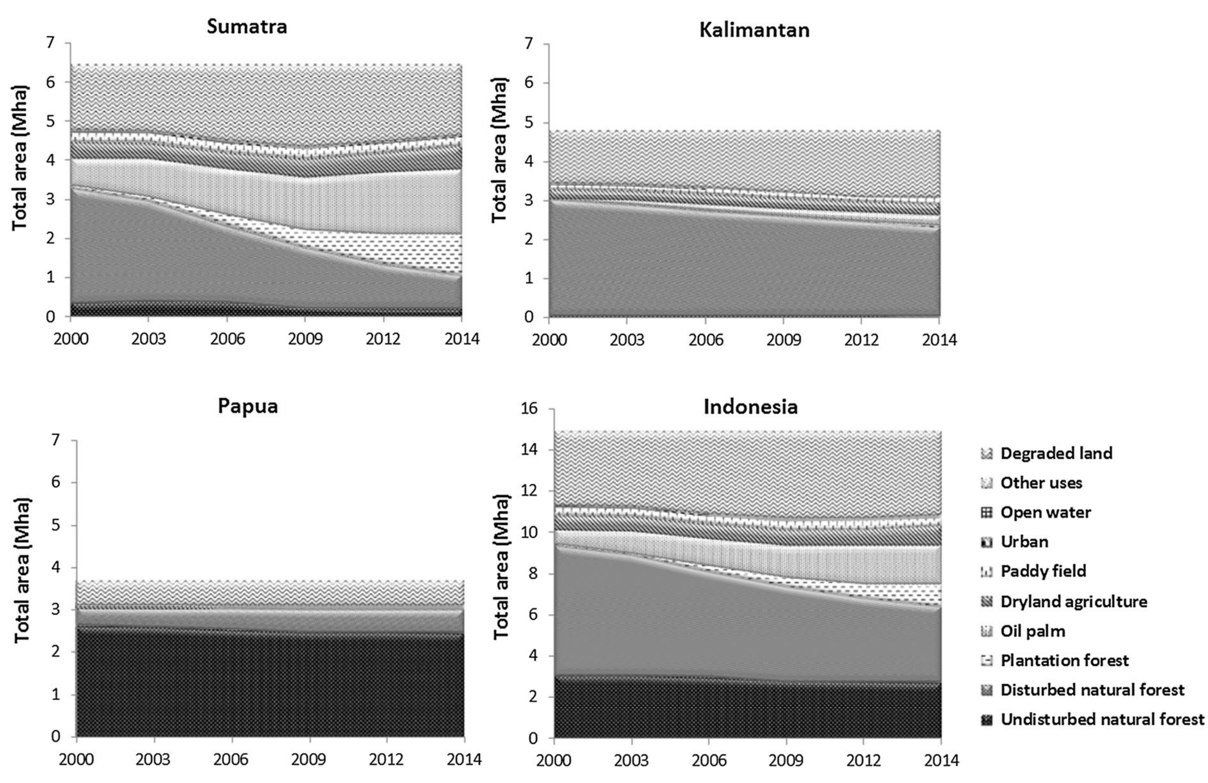

Fig. 1 Trends of peatland use in Indonesia since 2000 (based on government data and various sources)

Table 3 Ecosystem services provided by Indonesian peatland since 2000

Ecosystem services and disservices	Year					
	2000	2003	2006	2009	2012	2014
Timber production (1000 m3/year)	2272	2236	1955	1633	1430	1338
Oil palm production (1000 ton CPO/year)	1640	2518	3006	3494	3982	4307
Biomass production for pulp (1000 ton/year)	791	1102	4280	6889	13,025	17,631
Paddy production (1000 ton/year)	1336	1348	1350	1387	1386	1302
Nature watching (number of visitors in thousands/year)	97	15	41	178	65	117
Biodiversity habitat (1000 ha)	1728	1712	1690	1643	1634	1629
CO_2 emissions (million ton CO_2/year)	−210	−245	−278	−309	−352	−385

peatlands this is relatively low but it may be relate to a lack of tourism infrastructure in peat areas where such infrastructure (e.g. boardwalks) is expensive to construct and maintain.

Sustainability issues in Indonesian tropical peatland management

Table 4 summarizes the sustainability issues in Indonesian peatlands. Note that degradation may occur in under non-productive uses. Peatland areas with draining lead to abandoned areas, while peatland areas without draining remain as forest use areas. Shrubs, herbs, ferns or grasses are typically vegetation in abandoned areas which also categorized as degraded lands (Law et al. 2015) and having none of services and absent of Non Timber Forest Products (NTFPs). Peat swamp forest areas provide services like timber production and NTFPs, carbon stocks, biodiversity habitat, ecotourism, cultural services, etc. (Biancalani and Avagyan 2014).

Peatland areas under productive uses, with or without draining conditions, provide crop production services, including oil palm plantations, paddy fields, other horticultural lands (in drained areas); and paludiculture crops plantations (in non-drained areas) such as jelutung (*Dyera* spp.), sago palm (*Metroxylon sagu*), illipe nut (*Shorea* spp.), melaleuca, rattan, etc. Paludiculture is biomass cultivation in wet and or rewetted conditions (Biancalani and Avagyan 2014; Giesen 2013). Acacia plantations in peatlands are included as productive use with draining that provided biomass production for pulp service (Joosten et al. 2012).

Fires and smoke

Fire and smoke occur through the burning of drained peat. Fire may involve burning of both above ground biomass and below ground peat. Often, Indonesian peat fires are the result of deliberate or accidental human interventions (Glover and Jessup 2006; Harrison et al. 2009). Plantation companies as well as smallholder farmers may deliberately use fire to clear land with the associated benefit that the ashes increases the pH of the otherwise acidic peat soils (Islam et al. 2016). In some cases, fire may be started accidentally or spread beyond the areas in which it was ignited (Harrison et al. 2009). Once started, fires in drained peat can spread easily (Miettinen et al. 2012; Turetsky et al. 2015). Peat swamp forests and other lands with wet conditions seldomly burn (Turetsky et al. 2015). Peat fires have been reported on drained unused land, on drained peat used for wood pulp and paper (in particular in Sumatra) and on drained land used for oil palm plantations (Marlier et al. 2015b). Peat fires contribute strongly to CO_2 emissions and also cause smoke and haze (Marlier et al. 2015a; Heil et al. 2007). Because of often incomplete burning, the smoke contains a mixture of various gases including carbon monoxide, carbon dioxide, methane, ammonia, hydrogen cyanide, benzene, toluene, ethylbenzene, xylenes, formaldehydes, nitrous oxide, mono-nitrogen oxides, ethane, propone, butane, acrolein, acid gases, and particulate matter (PM or soot) (Stockwell et al. 2016; Gaveau et al. 2014; Heil et al. 2007). In the dry season, in particular during EL Nino years, smoke can cover major parts of Indonesia and even neighboring countries (Islam et al. 2016), with associated effects on

Table 4 Sustainability issues in Indonesian peatlands

Condition	Agricultural use		Non-productive or Forest use	
	Drained	Non-drained	Drained	Non-drained
Land cover	Plantation crops such as oil palm, rubber, acacia for pulp and paper, etc. and also food crops such as paddy and horticultural plants	Paludiculture crops such as jelutung, sago palm, illipe nut, etc.	Abandoned and degraded lands covered by herbs, ferns, or grasses	Ranging from degraded forest to peat swamp forest
Sustainability issues	(i) High fire risk, in particular in not well-managed plantations (ii) CO_2 emissions depending upon drainage depth (iii) Soil subsidence leading to flood risks affecting production of crops during wet season (iv) Habitat loss (v) Social issues, in particular loss of access of local people to forest and land	(i) Habitat loss (ii) Social issues may occur depending upon business models (large-scale vs small-scale, inclusive versus exclusive development model)	(i) Very high fire risk, often annual burning (ii) CO_2 emissions depending upon drainage depth (iii) Soil subsidence leading to flood risk depending upon drainage depth (iv) No income for local people	Ecosystems may be well preserved or degraded (but recovery through regeneration possible in many cases), ecosystems provide different ecosystem services (e.g. various non-timber forest products, water regulation)

human health. Reported impacts include negative health effects (acute and chronic), disruption on tourism, transport, and business, reduced enjoyment of life, contribution to the production of ozone, acid rain, and greenhouse gases, and reduced photosynthesis in plants by blocking some solar radiation (World Bank 2016). The cumulative impacts of (sequential) peatland fires, in combination with other disturbance factors such as forest conversion and peat subsidence, lead to the extinction and irreversible changes in forest species composition and vegetation structure and the disappearance of peat (Glover and Jessup 2006). Indonesia government data stated in World Bank (2016) indicated that during the fires from June to October 2015 about 2.6 million ha of land burned in Indonesia, of which 33% was peatlands. The total costs of the fires were estimated at IDR 221 trillion (USD 16.1 billion) (World Bank 2016). About 500 thousand people were hospitalized and other thousands people suffered including people in neighborhood countries Malaysia and Singapore.

Soil subsidence and flood risks

Soil subsidence occurs when peatlands are drained. Soil subsidence rates can be as high as 1.5 m in the first five years after the drainage and 3-5 cm in subsequent years as observed in drained peatland for acacia and oil palm plantation in Sumatera with a typical water table depth of about 70–90 cm (Hooijer et al. 2012). Subsidence is a consequence of both the physical drainage of the water (in particular in the first 5 years) as well as the chemical oxidation of dry peat. We assess (see Table 2) that there is about 4 million ha of drained peatland in Indonesia (in 2014), within the land cover types plantation forest, estate crops, dryland agriculture, paddy fields, and other uses. Other sources mention that about 7–12 million ha of peat is drained (Hooijer et al. 2010; Joosten et al. 2012; Miettinen et al. 2016). Consequently, soil subsidence leads to flood risks because many Indonesian peatlands are situated in coastal lowlands which will also be affected by sea-level rise because of climate change

(Dommain et al. 2011; Hooijer and Vernimmen 2013). Soil subsidence progressively affects the possibility to use peat for crop production (Sumarga et al. 2016). Although water management involving 40–60 cm drainage levels has been promoted as best practice (Lim et al. 2012), this still involves considerable and irreversible peat subsidence (Sumarga et al. 2016). Peatland uses that do not require drainage (e.g. paludiculture crops) substantially lower the risk of subsidence (Joosten et al. 2012). Note that our assessment indicates that drainage of peatlands is still ongoing on all three islands, since new crop (including oil palm and Hevea rubber) and forestry (including Acacia) plantations require drainage.

CO_2 emission

Carbon emission results from peat fires and peat oxidation (Hirano et al. 2007). Drained peat swamp forests for other peatland uses contribute to peat fires events and increasing peat oxidation that related to increase of CO_2 emission (Hooijer et al. 2010), while the increased frequency and duration of flooding will slow down the processes of oxidation and subsidence (Biancalani and Avagyan 2014). Our calculation for CO_2 sequestration in Table 3 shows that the historical emission from Indonesian peatland uses i.e. disturbed forests, plantation forests, oil palm plantations, agriculture crops (paddy fields and dryland agriculture areas), degraded lands, urban and other uses areas increased over time to almost 400 million ton CO_2 per year in 2014. Sumatra is still the biggest emitter, contributing around 70% of the total carbon emission from Indonesian peat.

Loss of forest in protected areas

Forests are recognized as habitats with high biodiversity. Conversion of peat swamp forests to other land uses is associated with habitat loss and fragmentation affecting a range of endemic animal and plants species (Miettinen et al. 2012; Posa et al. 2011; Yule 2010). Given that many lowland forests on mineral soils have been converted to other land uses, in particular to oil palm plantations (e.g. Sumarga and Hein 2015; Sumarga et al. 2016), peat swamp forests are the last remaining refugium for a range of species including the Sumatran tigers and rhino, and including species that occur in peat but prefer forests on mineral land such as the orangutan. Logging and fire are additional pressures on biodiversity. In our study area, there are about 2.6 million hectare of protected peat swamp forests (equal to 17% of total Indonesian peatland areas). Based on our analysis, plantation forests and crop areas are also found inside these protected areas covering about 28% of land designated as protected area in 2014 (Fig. 2), which we interpret to be the result of illegal forest encroachment. This occurs in particular in Sumatra and Kalimantan, such as in Sembilang and Danau Sentarum National Parks.

Social conflicts

In Indonesia, social conflicts related to land use are often triggered by overlapping land ownership or land use rights. This is the result of a lack of consistent national base map integrating cadaster information, land use, concessions applied for or granted, etc., in combination with sometimes opaque procedures involving a range of government agencies (Goldstein 2015; Galudra et al. 2011, 2014; Marlier et al. 2015b). Indonesia has about 8 sectoral maps of government agencies that have the authority to make their own sectoral maps for their own purposes (e.g. Ministry of Forestry with forestry maps for determining forestry areas, Ministry of Agriculture with maps of standard competence of agriculture human resources in order to support allocating land for agriculture purposes, etc.). We analysed maps from several government agencies and noted that they were indeed different, even though they covered the same subject matter such as forestry, conservation, mining areas, etc. The different outputs of these maps lead to conflicts between different companies but more often between companies and local residents whose traditional land use rights are often set aside by new permits and concessions. However, there are differences between the islands. For instance in Sumatra, there is increasing competition between companies (acacia and oil palm plantation) and local people (both transmigrants and indigenous) who also want to start or expand oil palm plantations (including on peat). This is related to the increasing scarcity of mineral land available for new plantations. On a specific occasion, local people protested outside the Regency Forest Agency until they were granted a concession to plant oil palm inside a protected area (Galudra et al. 2014). In Kalimantan, for instance, there are reports on conflicts between

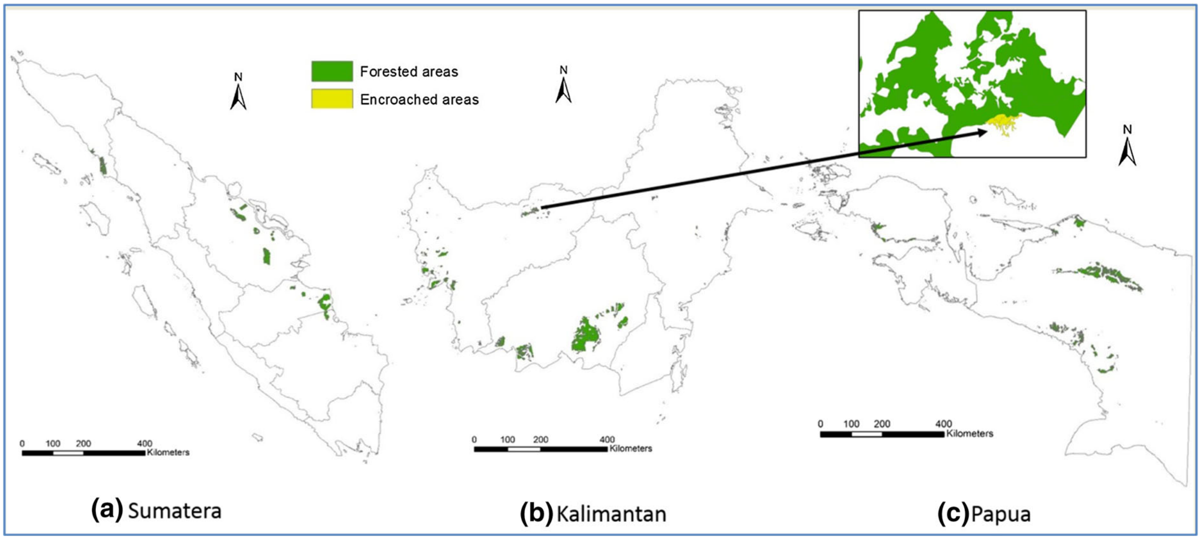

Fig. 2 Map of habitat inside protected areas in Indonesian peatlands in 2014 (insert area: Danau Sentarum National Park, West Kalimantan)

local communities who started to reclaim peatlands based on customary/tribal right, whereas the central and local governments used a different interpretation of the legality of different management regimes (Galudra et al. 2011; Suwarno et al. 2015). In Papua, conflicts on forestland utilization and concessions occurred due to overlapping regulations issued at the national level, provincial level, and district level leading to protests and human right violations against the local indigenous people (Hidayat et al. 2014). Hence, the pressure of land and the culture differ between the islands, but the lack of transparency in allocating land is a common factor.

Discussion

Uncertainties in baseline data

There is much uncertainty related to the occurrence of Indonesian peatland. The absence of common definitions, measurement techniques and other peatland-related information (forest status or intensive converted peatlands) leads to major differences in the various estimates of the area covered by Indonesian peatland. In this study, we considered peatland with at least 50 cm peat depth, however the lack of data on peat depth in many parts of the country means that this boundary is often highly uncertain. Studies reporting on the area covered by Indonesian peatlands, provide a considerable range from 12 to 26.4 million ha (see Appendix 2 Table 7). There are also substantial differences in the maps of peatland distribution in Indonesia, including the maps published by BBSDLP Ministry of Agriculture (Ritung et al. 2011), Wetlands International (Wahyunto and Suryadiputra 2008), and the Ministry of Environment (MoEFRI 2015). These different maps reflect the potential uncertainty related to estimation of both Indonesian peatland area and its spatial distribution (see Appendices 2–4 Tables 7, 8, 9), and the uncertainty propagates when it is combined with other sources of data, for example to estimate ecosystem services provided by multiple uses of peatland as analysed in this study.

We estimate ecosystem services supply based on data on land use in peatlands from a range of sources but in particular from Indonesian government data. Estimates of visitors to national parks, forest production, paddy production, acacia production are from the Indonesian government, and are generally based on survey and census data. The area covered by oil palm was analysed using remote sensing (Gunarso et al. 2013) in a study for the RSPO and we believed this to be more up-to-date than Indonesian government data. We were not able to map the spatial diversity of the supply of these services, for example forest timber production will not be equally spread over the different peat swamp forests but depend upon forest quality and species composition. Given the status of Sumatran and Kalimantan lowland forests (MoFRI 2014) it is likely that currently the majority of timber production takes places in Papua. We may also underreport the supply of specific services. For instance, oil palm productivity in Indonesia ranges from 4 to 8.6 ton Crude Palm Oil (CPO)/ha/year according to World Growth (2011) whereas census data from BPS (2000–2014) indicates an average yield of between 3 and 4 ton CPO/ha/year (depending upon the year).

The uncertainty in peat cover, and in particular in peat depth and the current land use on peat makes the implementation of policies at the local level very difficult. The various government agencies involved in evaluating applications for concessions sometimes lack accurate and up-to-date information on peat location, peat depth, existing concessions and pending concessions applications. By preparing an updated national peat map, the current One-Map policy by Indonesia government may improve the basic data as a basis for decision making (Wibowo and Giessen 2015).

Policy recommendations

The Indonesian government has voluntary pledged in 2009 to reduce GHG emissions nationally 26% by its own efforts, and up to 41% with international assistance in 2020. A more ambitious target was unveiled in 2015, specifically GHG emissions reduction up to 29% by 2030 (INDC 2015). To support these targets, the Indonesian government published government regulation PP number 71 year 2014 on the protection and management of peat ecosystems. This regulation mandated a maximum water drainage in peat of 0.4 m where appropriate. This has the potential to reduce emissions by around 60 tonnes of CO_2/ha/year if applied, however the challenge is that in practice it is extremely difficult to maintain the water level in large areas, year round, at this level. The level is also very close to when crops will start experiencing flood damages, and hence it may be very difficult for plantations in peat to implement this water level. In addition, even a drainage of 0.4 m still leads to soil subsidence. Hence, we believe that whereas this is a welcome initiative, it will not be sufficient to safeguard peat from fires and soil subsidence. Our analysis of Indonesian peatland conditions points to four main potential approaches for Indonesian peatland use depending upon their condition (Table 5).

Paludiculture crops (e.g. jelutung, sago palm, etc.) are crops that do not require drainage and therefore pose much lower fire risks, CO_2 emissions and enable cropping over the long-term given that there is no soil subsidence. However, currently they are less financially attractive compared to oil palm and rubber productions (Giesen 2013; Joosten et al. 2012; Sumarga et al. 2016) and therefore their cropping will depend upon policies and regulations that limit growing the crops that require drainage in peat. We also note that the 'traditional' crops such as oil palm have benefitted from a long period of breeding and value chain development, which is still in its infancy for the paludiculture crops. From an economic perspective, i.e. when the costs of externalities such as CO_2 emissions, health effects, soil subsidence and loss of productive land in the longer term are considered (e.g. World Bank 2016), paludiculture crops such as jelutung already are more profitable than oil palm and Hevea rubber on peat (Sumarga et al. 2016).

Conclusion

Indonesian peatlands have increasingly been converted for agricultural and plantation forest purposes in particular for oil palm, acacia and rubber. In the process, ecosystem services provided by peat swamp forest (e.g. carbon sequestration, biodiversity conservation) have been replaced by the production of agricultural commodities. The highest conversion of natural peat swamp forest took place in Sumatra. In Kalimantan conversion started later, and some peat swamp forest is still remaining—but the island is undergoing rapid land use change at the moment. Most of the remaining peat swamp forests are in Papua, where unfortunately there is also the largest lack of reliable information on forests and peatlands. On the positive side, this has led to major increases in palm oil production (nearly a factor 3 increase in production on peatlands between 2000 and 2014) and biomass production for pulp (a factor 20 increase in the same period). On the negative side, these production levels are not sustainable since progressive soil subsidence will lead to seasonal flooding of the drained plantations in the coming decades ensuring that they will

Table 5 Policy priorities for sustainable peatland uses in Indonesia

Condition	Agricultural use	Non-productive and Forest use
Drained	Productive uses with paludiculture crops, phase out oil palm and plantation crops that require drainage over time	Protect remaining forests
	Withdraw strategically located areas where drainage has major effects on surrounding, non-drained areas	Rehabilitate and rewet peatlands by blocking drainage canals
	Fire control	Fire control
Non-drained	Stop new drainage	Protect remaining forests
	Promote productive uses with paludiculture crops	In degraded forests: reforestation
	Fire control	Fire control
All areas and uses	Improve monitoring of the condition of peat areas, including land cover, land use and drainage	
	Improve monitoring of the local implementation of peat related policies	
	Improve enforcement of peat related policies	

need to be taken out of production (e.g. Sumarga et al. 2016). In addition there are significant externalities related to peat fires and health problems, CO_2 emissions and loss of habitat. To move towards sustainability, alternative peat development scenarios should be developed, which should involve a gradual phasing out of oil palm and other drained crops on peat and replacing them by crops that do not require drainage in combination with forestry including timber and non-timber forest production.

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Appendix

See Tables 6, 7, 8, and 9

Table 6 Ecosystem services data used for assessing changes of ecosystem services

Ecosystem services	Ecosystem services data	Sources
Timber production[a] (m^3/ha/year)	0.49 (Sumatra); 0.29 (Kalimantan); and 0.12 (Papua)	BPS Statistics Indonesia (2000–2014)
Oil palm production (ton CPO/ha/year)[b]	2.80 (Sumatra); 2.20 (Kalimantan); 2.06 (Papua)	BPS Statistics Indonesia (2000–2014)
Biomass production for pulp (ton/ha/year)[c]	16.22	Krisnawati et al. (2011)
Paddy production (ton/ha/year)	4.14 (Sumatra); 3.54 (Kalimantan); 3.83 (Papua)	BPS Statistics Indonesia (2000–2014)
Carbon sequestration (ton CO_2/ha/year)[d]	19 (undisturbed natural forest), −17 (disturbed natural forest), −81 (plantation forest, referred to acacia plantation), −85 (oil palm plantation), −48 (agricultural crops), −15 (shrubs/degraded lands), 0 (water), −15 (others land uses, referred to degraded lands)	Suzuki et al. (1999), Hooijer et al. (2006, 2010), Hirano et al. (2007), Jauhiainen et al. (2012)

[a] Timber productivity is referred to BPS data

[b] Oil palm productivity is referred to BPS data for Crude Palm Oil (CPO)

[c] Referred to biomass production of acacia plantation

[d] +indicates sequestration, −indicates emissions

Table 7 Comparison data of peatland distribution in Indonesia as reported by various sources

Source (year)	Peat distribution based on region					Highlight
	Sumatra	Kalimantan	Papua	Others	Total	
Polak (1952)*	n.a.	n.a.	n.a.	n.a	16.5	Unit: Mha
Driessen (1978)*	9.7	6.3	0.1	n.a	16.1	Unit: Mha
Pusat penelitian tanah (1981)*	8.9	6.5	10.9	0.2	26.5	Unit: Mha
Euroconsult (1984)*	6.84	4.93	5.46	0	17.2	Unit: Mha
Sukardi and Hidayat (1988)*	4.5	9.3	4.6	<0.1	18.4	Unit: Mha
Deptrans (1988)*	8.2	6.8	4.6	0.4	20.1	Unit: Mha
Subagyo et al. (1990)*	6.4	5.4	3.1	n.a	14.9	Unit: Mha
Deptrans (1990)*	6.9	6.4	4.2	0.3	17.8	Unit: Mha
Nugroho et al. (1992)*	4.8	6.1	2.5	0.1	13.5	Unit: Mha
Radjagukguk (1993)*	8.25	6.79	4.62	0.4	20.1	Unit: Mha
Dwiyono and Racman (1996)*	7.16	4.34	8.40	0.1	20.0	Unit: Mha
Wetlands International (2002–2006)*	7.21	5.83	7.8	n.a	20.8	Unit: Mha
Koh et al. (2011)	5572,443	6,668,629	n.a.	n.a	12,241,072	Unit: Ha
BBSDLP MoARI-Ritung et al. (2011)	6,436,649	4,778,004	3,690,921	n.a	14,905,574	Unit: Ha
Miettinen et al. (2012)	7,234,069	5,769,036	n.a.	n.a	13,003,105	Unit: Ha
Kementerian Lingkungan Hidup dan Kehutanan/MoEFRI (2015)	9,646,459	8,786,009	7,997,038	48,214	26,477,720	Unit: Ha (Kesatuan Hidrologi Gambut/Peat Hydrological Unit)
Miettinen et al. (2016)	7,230,230	5,781,720	n.a	n.a	13,011,950	Unit: Ha

n.a not available; * Data are taken from Wahyunto and Suryadiputra (2008)

Table 8 Comparison data of palm oil plantation distribution in Indonesian peatland since 2000 as reported by various sources

Year	Assumed peat area	Palm oil plantation areas in peatlands (Ha)				Source	Limitation
		Sumatra	Kalimantan	Papua	Indonesia		
1990	Indonesia: 20.8 Mha Sumatra 7.21 Mha Kalimantan: 5.83 Mha Papua: 7.8 Mha	250,000	821	0	250,821	Gunarso et al. (2013)	Exclude most independent smallholders
	Indonesia: 13,003,105 Ha Sumatra: 7,234,069 Ha Kalimantan: 5,769,036 Ha Papua: n.a	17,985	0	n.a	17,985	Miettinen et al. (2012)	Except Papua. Resolution: 250-m
2000	Indonesia: 20.8 Mha Sumatra 7.21 Mha Kalimantan: 5.83 Mha Papua: 7.8 Mha	438,864	16,415	0	455,279	Tropenbos (2011)	Assumed that in 1990 there was no palm oil on peatlands Not published document
	Indonesia: 20.8 Mha Sumatra 7.21 Mha Kalimantan: 5.83 Mha Papua: 7.8 Mha	700,000	1000	0	701,000	Gunarso et al. (2013)	Exclude most independent smallholders
	Indonesia: 13,003,105 Ha Sumatra: 7234,069 Ha Kalimantan: 5769,036 Ha Papua: n.a	512,341	15,982	n.a	528,323	Miettinen et al. (2012)	Except Papua Resolution: 250-m

Table 8 continued

Year	Assumed peat area	Palm oil plantation areas in peatlands (Ha)				Source	Limitation
		Sumatra	Kalimantan	Papua	Indonesia		
2005	Indonesia: 20.8 Mha Sumatra 7.21 Mha Kalimantan: 5.83 Mha Papua: 7.8 Mha	1,447,158	35,776	1278	1,484,212	Tropenbos (2011)	Assumed that in 1990 there was no palm oil on peatlands Not published document
	Indonesia: 20.8 Mha Sumatra 7.21 Mha Kalimantan: 5.83 Mha Papua: 7.8 Mha	1,200,000	50,000	1500	1,251,500	Gunarso et al. (2013)	Exclude most independent smallholders
2007	Indonesia: 13,003,105 Ha Sumatra: 7,234,069 Ha Kalimantan: 5,769,036 Ha Papua: n.a	821,949	111,414	n.a	933,363	Miettinen et al. (2012)	Except Papua. Resolution: 250-m
2010	Indonesia: 20.8 Mha Sumatra 7.21 Mha Kalimantan: 5.83 Mha Papua: 7.8 Mha	2,842,196	304,537	1726	3,148,459	Tropenbos (2011)	Assumed that in 1990 there was no palm oil on peatlands. Not published document
	Indonesia: 20.8 Mha Sumatra 7.21 Mha Kalimantan: 5.83 Mha Papua: 7.8 Mha	1,400,000	308,000	1700	1,709,700	Gunarso et al. (2013)	Exclude most independent smallholders
	Indonesia: 13,003,105 Ha Sumatra: 7,234,069 Ha Kalimantan: 5,769,036 Ha Papua: n.a	1,026,922	258,299	n.a	1,285,221	Miettinen et al. (2012)	Except Papua. Resolution: 250-m
2011	Indonesia: 12,241,072 Ha Sumatra: 5,572,443 Ha Kalimantan: 6,668,629 Ha Papua: n.a	464,553	43,184	n.a	507,737	Koh et al. (2011)	Only closed canopy oil palm plantations included. Resolution: 250-m. Except Papua
2015	Indonesia: 13,011,950 Ha Sumatra: 7,230,230 Ha Kalimantan: 5,781,720 Ha Papua: n.a	1,315,830	730,750	n.a	2,046,580	Miettinen et al. (2016)	Only industrial plantations Exclude smallholders Except Papua. Resolution: 30-m

n.a not available

Table 9 Comparison data of plantation forest areas for biomass production (pulp and other derivate) provided by Indonesian peatland since 2000 based on government data and other sources

Year	Assumed peat area (Ha)	Plantation forest areas for biomass production in peatlands (Ha)				Source	Limitation
		Sumatra	Kalimantan	Papua	Indonesia		
1990	Indonesia: 13,003,105 Ha Sumatra: 7,234,069 Ha Kalimantan: 5,769,036 Ha Papua: n.a	306	0	n.a	306	Miettinen et al. (2012)	Resolution: 250-m Only closed Acacia plantations included Except Papua
2000	Indonesia: 13,003,105 Ha Sumatra: 7,234,069 Ha Kalimantan: 5,769,036 Ha Papua: n.a	80,176	250	n.a	80,426	Miettinen et al. (2012)	Resolution: 250-m Only closed Acacia plantations included Except Papua
	Indonesia: 14,915,135 Ha Sumatra: 6,457,740 Ha Kalimantan: 4,777,398 Ha Papua: 3,679,998 Ha	48,342	0	453	48,796	Indonesian Government data Land cover from MoFRI (2014) Peat areas from BBSDLP MoARI - Ritung et al. (2011)	Without specific type of plant plantation. Resolution: 250-m
2003	Indonesia: 14,915,135 Ha Sumatra: 6,457,740 Ha Kalimantan: 4,777,398 Ha Papua: 3,679,998 Ha	67,490	13	453	67,956	Indonesian Government data Land cover from MoFRI (2014) Peat areas from BBSDLP MoARI - Ritung et al. (2011)	Without specific type of plant plantation. Resolution: 250-m
2007	Indonesia: 13,003,105 Ha Sumatra: 7,234,069 Ha Kalimantan: 5,769,036 Ha Papua: n.a	671,919	9,780	n.a	681,699	Miettinen et al. (2012)	Resolution: 250-m Only closed Acacia plantations included Except Papua
2009	Indonesia: 14,915,135 Ha Sumatra: 6,457,740 Ha Kalimantan: 4,777,398 Ha Papua: 3,679,998 Ha	423,112	1131	453	424,697	Indonesian Government data Land cover from MoFRI (2014) Peat areas from BBSDLP MoARI - Ritung et al. (2011)	Without specific type of plant plantation. Resolution: 250-m
2010	Indonesia: 13,003,105 Ha Sumatra: 7,234,069 Ha Kalimantan: 5,769,036 Ha Papua: n.a	874,921	22,797	n.a	897,718	Miettinen et al. (2012)	Resolution: 250-m Only closed Acacia plantations included Except Papua

Table 9 continued

Year	Assumed peat area (Ha)	Plantation forest areas for biomass production in peatlands (Ha)				Source	Limitation
		Sumatra	Kalimantan	Papua	Indonesia		
2012	Indonesia: 14,915,135 Ha Sumatra: 6,457,740 Ha Kalimantan: 4,777,398 Ha Papua: 3,679,998 Ha	790,475	12,082	453	803,010	Indonesian Government data Land cover from MoFRI (2014) Peat areas from BBSDLP MoARI - Ritung et al. (2011)	Without specific type of plant plantation. Resolution: 250-m
2014	Indonesia: 14,915,135 Ha Sumatra: 6,457,740 Ha Kalimantan: 4,777,398 Ha Papua: 3,679,998 Ha	871,753	29,793	453	901,999	Indonesian Government data Land cover from MoFRI (2014) Peat areas from BBSDLP MoARI - Ritung et al. (2011)	Without specific type of plant plantation Resolution: 250-m
2014	Indonesia: 20.8 Mha	610,000 + 427,000 (948,000 *0.45) = 1,037,000	50,000	n.a	1,087,000	Industry data: APP (Sustainability Report) 2014 PM.Haze (APRIL Tour Report) 2015	Only total number Except Papua
2015	Indonesia: 13,011,950 Ha Sumatra: 7,230,230 Ha Kalimantan: 5,781,720 Ha Papua: n.a	1,074,230	53,320	n.a	1,127,550	Miettinen et al. (2016)	Pulp wood plantations (*Acacia* sp.) Except Papua Resolution: 30-m

n.a not available

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