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Original research article

Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990

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ABSTRACT

Insular Southeast Asian peatlands have experienced rapid land cover changes over the past decades inducing a variety of environmental effects ranging from regional consequences on peatland ecology, biodiversity and hydrology to globally significant carbon emissions. In this paper we present the land cover and industrial plantation distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 and analyse their changes since 1990. We create the 2015 maps by visual interpretation of 30 m resolution Landsat data and combine them with fully comparable and completed land cover maps of 1990 and 2007 (Miettinen and Liew, 2010). Our results reveal continued peatland deforestation and conversion into managed land cover types. In 2015, 29% (4.6 Mha) of the peatlands in the study area remain covered by peat swamp forest (vs. 41% or 6.4 Mha in 2007 and 76% or 11.9 Mha in 1990). Managed land cover types (industrial plantations and small-holder dominated areas) cover 50% (7.8 Mha) of all peatlands (vs. 33% 5.2 Mha in 2007 and 11% 1.7 Mha in 1990). Industrial plantations have nearly doubled their extent since 2007 (2.3 Mha; 15%) and cover 4.3 Mha (27%) of peatlands in 2015. The majority of these are oil palm plantations (73%; 3.1 Mha) while nearly all of the rest (26%; 1.1 Mha) are pulp wood plantations. We hope that the maps presented in this paper will enable improved evaluation of the magnitude of various regional to global level environmental effects of peatland conversion and that they will help decision makers to define sustainable peatland management policies for insular Southeast Asian peatlands.

1. Introduction

Insular Southeast Asia has faced rapid environmental changes over the past few decades and it is currently one of the global hotspot areas of deforestation, forest degradation, tropical peat fires and plantation development (Achard et al., 2002; Corlett, 2009; van der Werf et al., 2010; Miettinen et al., 2012a; Margono et al., 2014; Miettinen et al., 2014; Stibig et al., 2014). The intensity and rapidity of these changes, as well as the associated environmental problems, are perhaps best seen in the peatlands of the region (Miettinen et al., 2012b). Due to the difficult working conditions for heavy machinery, low agricultural potential and sufficient availability of land on mineral soils, the 25 Mha of peatlands in Southeast Asia (equal to 56% of all tropical peatland; Page et al., 2011) were left largely undeveloped until the 1980's. In their natural state, peat swamp forests form a carbon sink which has resulted in an immense carbon deposit (∼69 Gt) in the peatlands of the region

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(Page et al., 2011). In addition, peatlands support specialized flora and fauna, partially endemic to the region, play an essential role in hydrology by regulating the water flow and have significant societal values for local people (Giesen, 2004; Rieley and Page, 2005; Corlett, 2009).

However, since the 1980's the peatlands of insular Southeast Asia have been increasingly utilized (Silvius and Diemont, 2007), inducing significant ecological, hydrological and atmospheric effects. Extensive logging activities over the 1990's made peat swamp forests highly susceptible to fire (Siegert et al., 2001) and lead to catastrophic fire damage during the 1997–1998 El Niño season resulting in massive carbon emissions (Page et al., 2002). Due to very slow natural regeneration of burnt peat swamp forests, often hindered by dense ferns and recurrent fire activity (Langner and Siegert, 2009; Page et al., 2009; Blackham et al., 2014) the majority of the 1997–1998 burnt areas remained as degraded peatlands. Drainage and conversion of peatland areas to plantations and agriculture gained momentum over the first decade of the new millennium, leading to remarkable expansion of fire prone peatland areas with lowered water table levels. Aerobic conditions in the upper peat profile, often combined with change in vegetation cover and use of fertilizers, result in increased carbon emissions from peat oxidation (Hooijer et al., 2012, 2014; Jauhiainen et al., 2012, 2014; Hirano et al., 2014; Sakata et al., 2015) and make the top layers of peat vulnerable to fires (van der Werf et al., 2008; Gaveau et al., 2014). Carbon emissions associated with peatland drainage and cultivation (Couwenberg et al., 2010; Hooijer et al., 2010; Miettinen et al., 2012a) as well as with recurrent peat fires (Page et al., 2002; van der Werf et al., 2008, 2010; Gaveau et al., 2014) make Indonesia one of the top emitters of greenhouse gases in the world and directly affect global climate change.

Peatland deforestation, drainage and conversion to agriculture drastically changes peatland ecosystems and may jeopardize the existence of plant and animal species endemic to Southeast Asian peatlands (see e.g. Giam et al., 2012). The region is one of the biodiversity hotspots in the world but is currently experiencing high levels of extinctions (Myers, 1988; Wilcove et al., 2013). Peatlands serve increasingly as refuge for endangered animal species (e.g. orangutan, Sumatran tiger and Sumatran rhino) which are losing their habitats in mineral soils (Giesen, 2004; Morrogh-Bernard et al., 2003; Meijaard et al., 2012). Furthermore, peatland drainage causes fluvial runoff of carbon from the peat domes, easily leads to flooding in nearby areas and may have feedback effects on local and regional climate patterns due to changes in evapotranspiration (Rieley and Page, 2005; Evans et al., 2014).

By 2007, forest cover in the peatlands of Peninsular Malaysia, Sumatra and Borneo had decreased to 42% (Miettinen and Liew, 2010) and deforestation rates remained high (Miettinen et al., 2012b). Over a quarter of peatlands had been converted to managed land cover types (11% small-holder areas and 18% industrial plantations), with lowered water table levels, and further 23% of the peatland areas were covered by highly fire prone degraded fern, shrub and secondary regrowth (Miettinen and Liew, 2010). Deforestation and conversion to managed land cover types is expected to have continued since 2007 but the current land cover distribution in the peatlands of Southeast Asia is unknown.

Meanwhile, peatland deforestation and conversion taking place in insular Southeast Asia, and particularly the role of industrial plantation development in it, has become one of the most discussed topics in natural resource management and conservation (see e.g. Jewitt et al., 2014; Law et al., 2014 and Austin et al., 2015). Indonesia and Malaysia are constantly under international pressure to implement sustainable peatland management policies protecting the remaining peat swamp forests and improving management practices and rehabilitation efforts in deforested peatlands. Annual peatland fires with repeated transboundary haze episodes (see e.g. Gaveau et al., 2014) cause significant health problems and economic losses throughout the region, while the ecological, biodiversity and carbon emission effects of peatland conversion highlighted above have consequences in varying levels from local to global scale. Due to the broad and far reaching consequences of peatland management, current peatland policy discussion in Southeast Asia involves governmental, non-governmental and business stakeholders from all over the world with a common aim to find solutions to the pressing peatland management challenges in the region.

In order to provide information on the current status and recent change trends on peatlands to evaluate the effects of the changes and to support formulation and implementation of peatland management policies, we here present land cover and industrial plantation distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015. We analyse the 2015 maps together with fully comparable and completed land cover maps of 1990 and 2007 (Miettinen and Liew, 2010) as well as industrial plantation maps of 1990, 2000, 2007 and 2010 (Miettinen et al., 2012a). In our land cover change and industrial plantation expansion analyses we concentrate on previously unpublished changes since 2007 (and since 2010 for plantation extent) building on known peatland land cover change history 1990–2010.

2. Materials and methods

2.1. Study area

The study area covers 15.7 Mha of peatland (Fig. 1) as defined by the peatland maps used in the analysis. The peatland areas for Sumatra and Kalimantan (Indonesian part of Borneo Island), were extracted from the Wetlands International 1:700 000 peatland atlases (Wahyunto et al., 2003, 2004). For Malaysia, the European Digital Archive of Soil Maps (Selvaradjou et al., 2005) was used to outline peatland areas as described in Miettinen and Liew (2010). For Brunei, we could not find any existing maps of peatland extent. The peatlands in Brunei were manually digitized using the Landsat data described below, Shuttle Radar Topography Mission (SRTM) elevation product (Jarvis et al., 2006) and an image originally

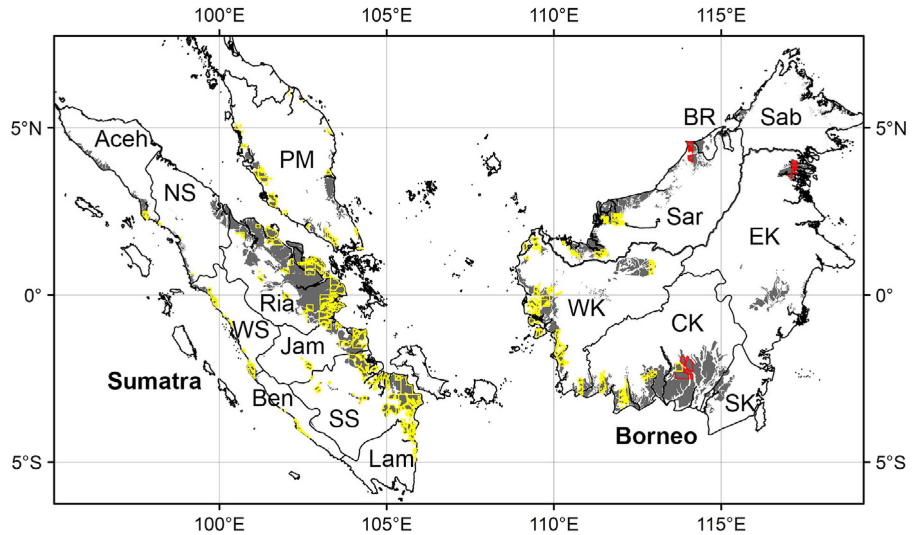

Fig. 1. Peatlands of the study area (dark grey). Accuracy assessment areas outlined in yellow (2015 very high resolution data) and red (2014 very high resolution data). Administrative area abbreviations: NS = North Sumatra, WS = West Sumatra, Ria = Riau, Jam = Jambi, Ben = Bengkulu, SS = South Sumatra, Lam = Lampung, WK = West Kalimantan, CK = Central Kalimantan, SK = South Kalimantan, EK = East Kalimantan, PM = Peninsular Malaysia, Sar = Sarawak, Sab = Sabah and BR = Brunei. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

published by Anderson and Marsden (1984), providing the extent of peat swamp forests in Brunei (available online at https://sites.google.com/site/peterengbersbrunei/brunei, accessed Oct 2015).

2.2. Satellite data

A 30 m spatial resolution composite image created with Landsat 7 ETM+ (Enhanced Thematic Mapper) and Landsat 8 OLI (Operational Land Imager) data was used in the 2015 land cover mapping. The composite image was created using the Google Earth Engine JavaScript Application Program Interface (https://developers.google.com/earth-engine/, accessed Sep 2015). The compositing script developed for this study utilized all available Landsat 7 and 8 data acquired between the 1st Jan 2015 and the 31st Aug 2015. Pixels were considered valid if the Top of the Atmosphere (TOA) reflectance in blue band was less than 0.2 and an additional criterion was valid. The additional criterion was dependent on vegetation greenness. (1) If NDVI was less than 0.6, the ratio between red and the 2.1 μm band needed to be less than 1.0. (2) If NDVI was greater than or equal to 0.6, the ratio between red and the 2.1 μm band needed to be less than 2.5. The first criterion masked out thick clouds, taking advantage of the sensitivity of the blue wavelength to clouds and haze. The idea behind the additional criterion is the high correlation between red and the 2.1 μm shortwave infrared (SWIR) band in cloud free conditions presented by Kaufmann et al. (1997). The ratio of red and the 2.1 μm is dependent on land cover, hence the separation into densely vegetated and sparsely vegetated or bare areas. A median value of all valid pixels was used for the composite image. The composite image contained three bands: 2.1 μm SWIR, near infrared (NIR) and red.

The rather limited observation period (eight months) was chosen (1) to limit the data acquisition to year 2015 in order to ensure inclusion of the latest land cover changes and (2) to minimize the inclusion of images with burned areas, thereby essentially creating a pre-fire land cover map for the exceptionally bad fire year of 2015. The quality of the composite was generally very good, with some limitations for the detection of the degradation level in peat swamp forests (see more below). The only area where classification could not be completed with the 2015 composite image due to missing data was the southern part of Riau province in Sumatra. For this area, a compositing period from the 1st Sep 2014 to the 31st Aug 2015 was used instead.

The satellite data used for the 1990 and the 2007 land cover maps are described in detail in Miettinen and Liew (2010). In short, the 1990 map was created using the 28.5 m spatial resolution GeoCover 1990 mosaic of Landsat 5 TM (Thematic Mapper) images acquired between 1987 and 1993 (MDA Federal, 2004). The 2007 map was created using 121 10–20 m resolution images from the SPOT (Satellite Pour l'Observation de la Terre) satellite, with acquisition dates varying from 2005 to 2008. And finally, two additional satellite image datasets were used for the industrial plantation mapping reported in Miettinen et al. (2012a) and referred in this study. The 2000 mapping was based on the 2000 GeoCover product composed of Landsat 7 ETM + images acquired between 1997 and 2003 (MDA Federal, 2004). The 2010 mapping was performed using 74 Landsat 7 ETM + images acquired between the 1st January 2010 and the 11th March 2011.

As described in Miettinen and Liew (2010) the 1990 and 2007 satellite image datasets did not allow full coverage mapping of the peatland areas due to clouds and missing data. The valid data proportions for the 1990 and 2007 maps were 90% and 82% respectively. During the 2015 mapping effort these missing areas were filled using Landsat composites created with the

Table 1
Description of land cover types.

Land cover type	Description
Water	Permanent water bodies. This class also includes fish and crab farming ponds.
Seasonal water	Areas that are inundated part of the year. Typically either extremely degraded areas or flood zones of rivers. This class also includes small-holder mining sites.
Pristine peat swamp forest (PSF)	PSF with no clear signs of human intervention.
Degraded PSF	PSF with clear signs of disturbance (e.g. logging), typically in the form of logging tracks and canals and/or opened canopy.
Tall shrub/secondary forest	Shrub land or secondary forest with average height above 2 m.
Ferns/low shrub	Ferns and grass or shrub land with average height less than 2 m.
Small-holder area	Mosaic of housing, agricultural fields, plantations, gardens, fallow shrubland etc. Note that the name of the class refers to the patchy land scape patterns, typical in small-holder dominated areas, but the actual land tenure of the areas is unknown.
Industrial plantations	Large scale industrial plantations assumed to have been already planted with the plantation species. Mainly oil palm and pulp wood.
Built-up area	Towns, industrial areas etc.
Clearance	Open area with no vegetation, including recently burnt areas.
Mangrove	Areas that were considered to be mangrove forest in the satellite image interpretation although they were located within the peatland maps used in this study.

same 2015 compositing approach described above. The 1990 additional composite images were built with Landsat 4 and 5 TM data acquired between the 1st Jul 1989 and the 30th June 1991. The 2007 additional composite images were produced with Landsat 5 TM and Landsat 7 ETM+ images acquired between the 1st Jul 2006 and the 30th Jun 2008.

2.3. Land cover classification

To maximize comparability with earlier results, the classification was performed using exactly the same approach as in Miettinen and Liew (2010). The classification was performed by visual inspection and on-screen digitizing of land cover features. The work was done using varying scales between 1:50 000 and 1:100 000, depending on the complexity of the area. The 2015 classification was performed by the same person who had done the 1990 and 2007 classifications. The interpreter has nearly 15 years of working experience with insular Southeast Asian land cover mapping and extensive experience on visual satellite image interpretation of tropical peatlands with high resolution images.

The classification scheme includes eleven classes (Table 1). The 'Degraded PSF'—class includes all areas where some sort of disturbance (most typically logging) has been detected at least once during the three rounds of classification. It essentially outlines those forest areas that are considered to be non-intact, as opposed to the intact forest areas where no disturbance has been detected in any of the mapping efforts. We considered to change the name of the class to better describe the reality of the classification, but finally decided to retain the old class names for consistency with previous publications. However, it is important to understand that the level of degradation varies within the class, from recovered logging areas where no signs of human disturbance can be seen anymore to areas which exhibit clear signs of recent selective logging. The 30 m Landsat composite images used for the 2015 mapping did not provide as detailed and sharp picture as the individual 10–20 m SPOT images used for the 2007 classification. Therefore, the 2007 classification of forest degradation level was used as the default for the 2015 forest degradation mapping, and changes to the 2007 classification were made only if clear signs of disturbance were noticed in the forest area.

2.4. Plantation classification and species identification

Industrial plantation areas were outlined as part of the 1990, 2007 and 2015 land cover classifications as described above. The same classification approach was used in the additional 2000 and 2010 industrial plantation classifications published in Miettinen et al. (2012a). Together these datasets enable analysis of the expansion of industrial plantations in the peatlands of Peninsular Malaysia, Sumatra and Borneo since 1990 in five time steps: 1990, 2000, 2007, 2010 and 2015.

Whenever possible, the plantation species identification was derived from the 2007 plantation map (Miettinen et al., 2012a), with some corrections of known identifications errors. The species had been originally identified using the 2007 SPOT satellite dataset described above. The species information for plantations established after 2007 was derived from the 2015 Landsat composite. The two main plantation species used in the peatlands of insular Southeast Asia, oil palm and pulp wood, have distinctly different appearance in 10–30 m spatial resolution satellite images, enabling reliable identification in most cases. In addition to the visual appearance (e.g. tone and texture), spatial arrangement of the plantation canals and roads, location, context, the interpreter's personal knowledge and available land use allocation information was used to support the decision making.

Three plantation species classes were used in the identification: 'Oil palm', 'Pulp' and 'Other/unknown'. The 'Other/unknown'-class was used for plantations which displayed characteristics not typical for either oil palm or pulp, or which were known to have other species. The same plantation species was assigned for each individual plantation in all of the time steps. This decision was assumed to be generally valid in the peatlands of insular Southeast Asia due to the relatively short period of existence for most of the plantations (predominantly less than 15 years) and the fixed infrastructure and plantation design needed for the two main plantation species found in the peatlands of the region.

2.5. Accuracy assessment

Very high resolution satellite images available in Google Earth were used in the accuracy assessment. Most of the images were acquired in 2015. A few images acquired in 2014 were also selected in order to get wider distribution of images over the entire study area (Fig. 1). The accuracy assessment areas covered 4.5 Mha or around 30% of the study area with 4.3 Mha covered by images acquired in 2015.

The sample plots were selected using stratified random sampling approach. Altogether 853 sample plots were used for the land cover accuracy assessment and 267 for the plantation species accuracy assessment. The 853 plots for the land cover accuracy assessment were composed of 800 basic plots (allocated based on the proportional areas of land cover types), and additional 53 plots to assure minimum of 20 plots for each class. The 267 sample plots for the plantation species accuracy assessment were composed of 250 basic plots with additional 17 plots in the 'Other/unknown'-class to reach the minimum of 20 sample plots.

The classes of 'PSF' and 'Degraded PSF', as well as the classes of 'Seasonal water', 'Fern/low shrub' and 'Clearance' were combined into two classes: 'Peat swamp forest' and 'Open undeveloped'. In the case of the 'Peat swamp forest'-class this was done since it was considered impossible to determine the correctness of the classification of the degradation level based on a single sample plot in a very high resolution image. This was partly due to the cumulative nature of the 'Degraded PSF'-class and partly due to the generalized delineation of logging areas, in most cases without any clear boundary in the forest. For the 'Open undeveloped'-class, the differences between the three combined classes are by definition somewhat ambiguous and they are easily interchangeable in short periods of time. It was thus not considered meaningful to evaluate the correctness of the classification of the three original classes separately using a single very high resolution image.

The visual interpretation of the very high resolution images was performed using a 300 × 300 m box as a sample plot, except for the 'Small-holder area'-class where the size of the plot was 500 × 500 m. The dominant land cover or plantation species within these boxes was recorded. The use of sample plots was considered more suitable than sample points (1) for the rather coarse manual classification approach used in the mapping, rarely resulting in polygons less than 10 ha in size and (2) for the mosaic nature of the 'Small-holder area'-class.

2.6. Analysis of land cover and industrial plantation distribution

With the new 2015 maps and the completed versions of the older maps combined, we now have a time series of comparable full coverage land cover maps for 1990, 2007 and 2015, as well as industrial plantation maps for 1990, 2000, 2007, 2010 and 2015. In this paper we concentrate on reporting the previously unpublished 2015 land cover and industrial plantation distribution, as well as their changes since the latest available maps (i.e. 2007 for land cover and 2010 for industrial plantations). However, we also refer to the older datasets to provide longer historical perspective. It is important to understand that the numbers presented in this paper may vary from the earlier publications. This is mainly due to the fact that both of the previous analyses (Miettinen and Liew, 2010; Miettinen et al., 2012a) have been based on incomplete samples, whereas in this study all the datasets have been completed to fully cover the peatlands of the study area.

For all the change analyses, the three classes of 'Seasonal water', 'Ferns/low shrub' and 'Clearance' are combined into one class of 'Open undeveloped' (exactly as in the accuracy assessment). The original three classes are easily interchangeable (e.g. due to changes back and forth to the 'Clearance'-class as a result of recurrent fire activity) without causing a significant change in the land cover/use from the perspective of this study. Therefore, it was not considered meaningful to analyse the changes between these classes. Please see more discussion on the problems related to the classification and analysis of these classes in the discussion section. Note, however, that the 'Tall shrub/secondary forest'-class was retained as a separate class also in the change analysis. Although the border between this class and the 'Open undeveloped-class (i.e. 2 m average height) is difficult to define in Landsat type data, and there are surely some misclassifications, the great majority of the 'Tall shrub/secondary forest'-class is considered to have canopy height over 5 m, in some cases even resembling primary forest in the Landsat images. Thereby, changes between these two classes from one time step to another may provide valuable information e.g. on the direction of change in the area (i.e. either natural regeneration or further degradation).

3. Results

3.1. 2015 land cover distribution with changes since 1990

The 2015 land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo (Fig. 2; Table 2) reveals that peat swamp forests cover 29% (4.6 Mha) of the study area, while 50% (7.8 Mha) of the peatlands are covered by managed land

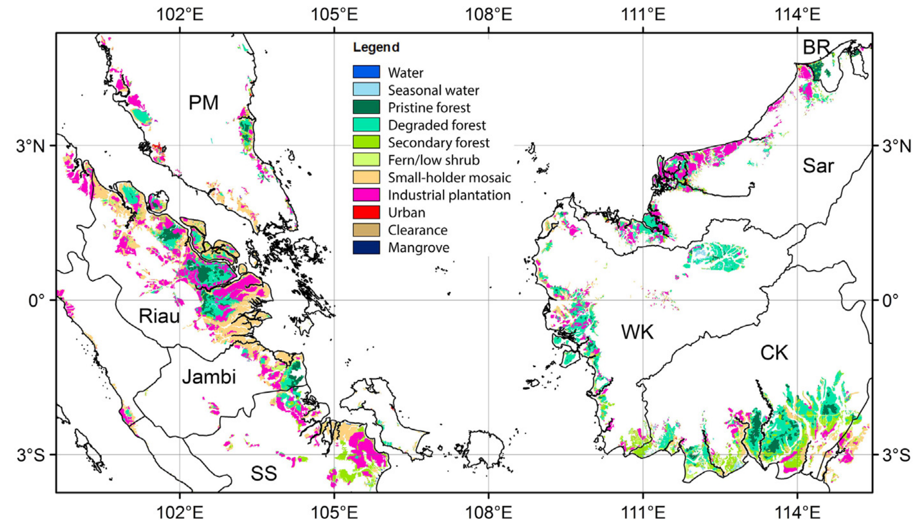

Fig. 2. Land cover 2015 in the major peat domes of the study area. Administrative areas referred in the text are identified as: PM = Peninsular Malaysia, Sar = Sarawak, BR = Brunei, SS = South Sumatra, WK = West Kalimantan and CK = Central Kalimantan.

Table 2
Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 (in 1000 ha and %).

	Water	Seasonal water	Pristine PSF	Degraded PFS	Tall shrub/ secondary forest	Ferns/ low shrub	Small-holder area	Industrial plantation	Urban	Clearance	Mangrove	Total
Peninsular Malaysia	9.84	3.06	41.15	152.17	48.91	34.02	267.13	279.35	24.68	30.01	1.38	891.70
	1.1	0.3	4.6	17.1	5.5	3.8	30.0	31.3	2.8	3.4	0.2	
Sarawak	1.73	1.31	7.60	383.44	152.27	12.70	141.02	725.09	10.38	8.64	5.25	1449.44
	0.1	0.1	0.5	26.5	10.5	0.9	9.7	50.0	0.7	0.6	0.4	
Sabah	0.96	0.97	3.40	43.25	21.20	22.30	25.74	66.20	2.03	2.31	2.53	190.89
	0.5	0.5	1.8	22.7	11.1	11.7	13.5	34.7	1.1	1.2	1.3	
Brunei	0.44	1.06	81.97	19.06	11.74	2.89	2.67	0.03	2.26	0.81	0.00	122.93
	0.4	0.9	66.7	15.5	9.5	2.3	2.2	0.0	1.8	0.7	0.0	
Riau	3.20	20.31	294.98	686.26	86.55	131.83	1501.98	1209.53	3.03	102.27	22.48	4062.42
	0.1	0.5	7.3	16.9	2.1	3.2	37.0	29.8	0.1	2.5	0.6	
Jambi	0.08	3.55	71.86	100.43	27.23	42.92	241.04	178.09	0.69	5.67	0.02	671.57
	0.0	0.5	10.7	15.0	4.1	6.4	35.9	26.5	0.1	0.8	0.0	
South Sumatra	12.03	12.21	11.03	76.88	315.01	117.22	271.74	618.16	0.04	20.52	1.95	1456.79
	0.8	0.8	0.8	5.3	21.6	8.0	18.7	42.4	0.0	1.4	0.1	
Total Sumatra	27.81	38.45	435.96	956.53	468.54	330.24	2392.65	2405.49	7.73	137.88	28.97	7230.24
	0.4	0.5	6.0	13.2	6.5	4.6	33.1	33.3	0.1	1.9	0.4	
West Kalimantan	0.86	63.40	69.43	766.28	154.69	94.38	198.41	351.93	0.10	46.96	6.05	1752.49
	0.0	3.6	4.0	43.7	8.8	5.4	11.3	20.1	0.0	2.7	0.3	
Central Kalimantan	2.36	95.92	326.86	1058.14	672.66	279.07	304.07	243.99	1.77	57.46	0.00	3042.31
	0.1	3.2	10.7	34.8	22.1	9.2	10.0	8.0	0.1	1.9	0.0	
South Kalimantan	0.17	4.10	0.00	7.73	39.21	23.77	143.91	83.27	1.02	0.14	0.00	303.32
	0.1	1.4	0.0	2.5	12.9	7.8	47.4	27.5	0.3	0.0	0.0	
East Kalimantan	1.38	57.09	29.66	177.73	166.07	46.68	34.64	130.71	0.90	23.84	14.89	683.59
	0.2	8.4	4.3	26.0	24.3	6.8	5.1	19.1	0.1	3.5	2.2	
Total Kalimantan	4.77	220.52	425.95	2009.88	1032.64	443.90	681.04	809.90	3.78	128.41	20.94	5781.72
	0.1	3.8	7.4	34.8	17.9	7.7	11.8	14.0	0.1	2.2	0.4	
Total study area	45.54	265.36	996.05	3564.32	1735.30	846.05	3510.41	4286.07	51.08	308.06	59.06	15 667.30
	0.3	1.7	6.4	22.8	11.1	5.4	22.4	27.4	0.3	2.0	0.4	

cover types (22.4% small-holders and 27.4% industrial plantations). Furthermore, the great majority of the remaining forest areas have been selectively logged, with only 6% of peatlands showing no signs of human influence since 1990. Currently one fifth (20%; 3.2 Mha) of the peatlands in the study area are covered by open undeveloped areas and secondary regrowth (i.e. the classes of 'Seasonal water', 'Fern/low shrub', 'Clearance' and 'Tall shrub/secondary forest').

Peninsular Malaysia, Sarawak and Sumatra have the highest proportions of peatland converted to managed land cover types (60%–66%), while (apart from Brunei) West and Central Kalimantan have retained the highest proportions of peat swamp forest (48% and 46% respectively). The largest areas of open undeveloped peatland and secondary regrowth can be found in South Sumatra, Central Kalimantan and East Kalimantan provinces (30%–40%), perhaps still at least partly as

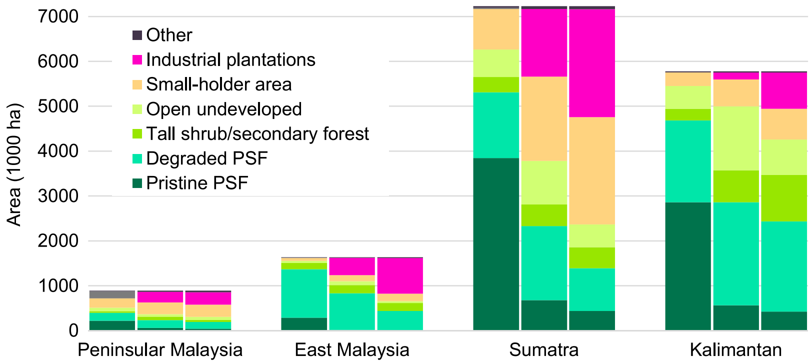

Fig. 3. Development of land cover distribution 1990–2007–2015 (left–centre–right) in the major sub-regions of the study area. East Malaysia contains Sarawak and Sabah. The 'Open undeveloped'-class includes the original classes of 'Seasonal water', 'Fern/low shrub', 'Clearance'.

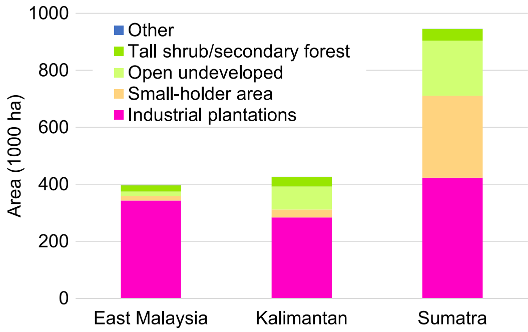

Fig. 4. 2015 land cover in areas deforested between 2007 and 2015.

a reminder of the 1997–1998 El Niño fires. The small country of Brunei stands out with a distinctly different peatland management strategy: 82% of the peatlands are still forested in 2015 and no industrial plantations have been established in peatland in the country.

Comparison of the 2015 land cover distribution to the situation in 1990 and 2007 highlights continued deforestation and conversion of peatland areas in the region (Fig. 3). Overall, the peatlands of the study area lost around 1.8 Mha of peat swamp forest between 2007 and 2015. This is around 28% of the peat swamp forest extent in 2007 and corresponds to an average yearly deforestation rate of 4.1%/a between 2007 and 2015. The three biggest contributors to the forest loss were Riau (692 000 ha), Sarawak (389 000 ha) and West Kalimantan (276 000 ha), which together accounted for around 1.36 Mha deforestation or 75% of all forest loss in the study area. The yearly deforestation percentages for these three administrative areas were 6.5%/a, 8.3%/a and 3.5%/a respectively.

By far the fastest expanding land cover type from 2007 to 2015 was industrial plantations (Fig. 3). Together with small-holder area, these two managed land cover types expanded 2.6 Mha since 2007, industrial plantations nearly doubling their area from 2.3 Mha in 2007 to 4.3 Mha in 2015. Figs. 2 and 3 also illustrate the largest remaining proportion of peat swamp forest in Kalimantan, the high importance of small-holder activities in Sumatra and the small extent of open undeveloped areas and secondary regrowth in East Malaysia. The small area of 'Open undeveloped' and 'Tall shrub/secondary forest'-classes in East Malaysian peatlands (Fig. 3) may be largely due to the small number of peatland fires, which have destroyed vast areas of logged peat swamp forests in Sumatra and Kalimantan over the past two decades converting them into fern, shrub and secondary forest.

Analysis of the 2015 land cover type in areas deforested since 2007 (Fig. 4) shows that 90% of all areas deforested in East Malaysia (i.e. Sarawak and Sabah) were classified as managed land cover types in 2015 (86% industrial plantations and 4% small-holder areas). Similarly, in East and West Kalimantan provinces over 70% of areas deforested since 2007 had been turned into industrial plantations by 2015, resulting in an overall proportion of 67% for the entire Kalimantan. The majority of the rest of the deforested peatland in Kalimantan remained as open undeveloped area (i.e. the classes of 'Seasonal water', 'Fern/low shrub' and 'Clearance'). In Sumatra, on the other hand, 30% of all areas deforested since 2007 had been taken over by small-holder mosaic by 2015, again highlighting the significance of small-holder activities on the island.

One of the most striking differences in land cover change patterns between the administrative areas is the distribution of land cover types in 2007 in areas converted to plantations by 2015 (Fig. 5). Six administrative areas together contain 85% of all new industrial plantations established between 2007 and 2015. But among the six administrative areas, three have clearly higher percentages of new plantations on areas covered by peat swamp forests in 2007: Sarawak 84%, Riau 77%

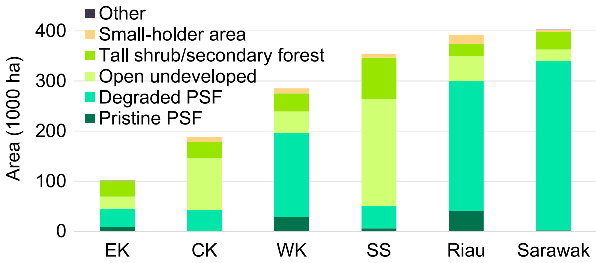

Fig. 5. 2007 land cover in areas converted to industrial plantations between 2007 and 2015. EK = East Kalimantan, CK = Central Kalimantan, WK = West Kalimantan and SS = South Sumatra.

Table 3
Industrial plantation distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015.

	Oil Palm		Pulp		Other/unknown		Total	
	1000 ha	% of plantations	1000 ha	% of plantations	1000 ha	% of plantations	1000 ha	% of peatland
Peninsular Malaysia	275.68	98.7	0.00	0.0	3.67	1.3	279.35	31.3
Sarawak	717.83	99.0	3.54	0.5	3.72	0.5	725.09	50.0
Sabah	66.00	99.7	0.00	0.0	0.20	0.3	66.20	34.7
Riau	591.22	48.9	602.95	49.8	15.37	1.3	1209.53	29.8
Jambi	115.47	64.8	62.62	35.2	0.00	0.0	178.09	26.5
South Sumatra	209.44	33.9	408.73	66.1	0.00	0.0	618.16	42.4
Total Sumatra	1315.83	54.7	1074.29	44.7	15.37	0.6	2405.49	33.3
West Kalimantan	309.32	87.9	41.38	11.8	1.23	0.4	351.93	20.1
Central Kalimantan	243.99	100.0	0.00	0.0	0.00	0.0	243.99	8.0
South Kalimantan	76.53	91.9	0.00	0.0	6.74	8.1	83.27	27.5
East Kalimantan	100.91	77.2	11.93	9.1	17.87	13.7	130.71	19.1
Total Kalimantan	730.75	90.2	53.32	6.6	25.84	3.2	809.90	14.0
Total study area	3106.10	72.5	1131.15	26.4	48.79	1.1	4286.04	27.4

and West Kalimantan 69%. This is in stark contrast to South Sumatra (14%) and Central Kalimantan (22%), where industrial plantation have mainly been established in open undeveloped and secondary regrowth areas.

3.2. 2015 industrial plantation distribution with changes since 1990

In total, industrial plantations cover 4.3 Mha (27%) of peatlands in Peninsular Malaysia, Sumatra and Borneo in 2015 (Table 3). The great majority of these are oil palm plantations (73%) while practically all of the rest (26%) are pulp plantations. Furthermore, the pulp plantations are heavily concentrated in Sumatra, where 45% of all industrial plantations are used for pulp wood production. Only recently (since 2007) pulp plantations have also been established in West Kalimantan and East Kalimantan provinces, where they cover around 10% of plantation area in 2015.

Within the past five years (2010–2015) industrial plantation area increased from 3.1 to 4.3 Mha, showing a 37% increase with an average annual new plantation area of around 235 000 ha (Table 3). This indicates a slight decrease in the new plantation establishment rate since the 2007–2010 period (278 000 ha/a). Five administrative areas together contained 79% (926 600 ha) of all new plantations established between 2010 and 2015: Riau 222 700 ha, Sarawak 205 800 ha, West Kalimantan 192 200 ha, South Sumatra 179 500 ha and Central Kalimantan 126 400 ha. Among the major sub-regions (i.e. Peninsular Malaysia, East Malaysia, Sumatra and Kalimantan), the most remarkable increase took place in Kalimantan, where industrial plantation area more than doubled (365 690 → 809 900 ha) between 2010 and 2015.

Overall, industrial plantation expansion has continued ceaselessly throughout the region since 1990 (Fig. 6). Peninsular Malaysia shows the most stable plantation areas since 1990, but even there industrial plantation in peatlands are expanding. East Malaysia and Sumatra has shown clear upward trend since 1990. In Kalimantan, industrial plantation expansion only properly started after the year 2000 and is current gaining momentum (20 200 ha/a, 70 000 ha/a and 88 900 ha/a for periods 2000–2007, 2007–2010 and 2010–2015 respectively). Due to the largest remaining areas of peat swamp forest as well as open undeveloped areas and secondary regrowth (Table 2; Fig. 3), it can be expected that Kalimantan will experience rapid plantation expansion in the near future.

3.3. Accuracy assessment

The accuracy assessment of the land cover map reveals an overall accuracy of 89% (Table 4). The major classes of 'Peat swamp forest', 'Industrial plantations' and 'Small-holder area' all have both user's and producer's accuracies near or above 90%. The worst accuracies can be found in the 'Tall shrub/secondary forest' and 'Open undeveloped' classes. This is understandable since not only is the separation between the two of them often very difficult on a Landsat image due to

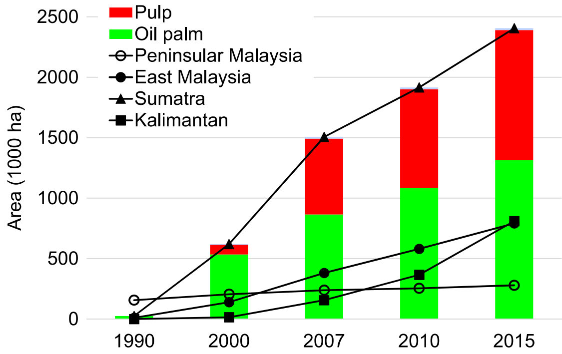

Fig. 6. Expansion of industrial plantations 1990–2000–2007–2010–2015 in the peatlands of Peninsular Malaysia, Sumatra and Borneo. Proportions of oil palm and pulp plantations in Sumatra are shown in red and green colours. In other areas nearly all plantations are oil palm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Error matrix for land cover classification.

	Reference									
	Water	All PSF	Tall shrub/secondary forest	Open undeveloped	Small-holder area	Industrial plantations	Urban	Mangrove	Total	User's acc.
Water	17	0	0	1	2	0	0	0	20	85.0
All PSF	0	219	7	5	0	2	0	0	233	94.0
Tall shrub/secondary forest	0	7	71	8	1	1	0	0	88	80.7
Open undeveloped	0	1	5	60	3	4	0	0	73	82.2
Small-holder area	0	5	5	8	158	3	1	0	180	87.8
Industrial plantations	0	1	3	8	5	201	1	0	219	91.8
Urban	0	0	0	4	1	0	15	0	20	75.0
Mangrove	0	0	1	0	1	0	0	18	20	90.0
Total	17	233	92	94	171	211	17	18	853	
Producer's acc.	100.0	94.0	77.2	63.8	92.4	95.3	88.2	100.0		89.0

Table 5
Error matrix for industrial plantation species identification.

	Reference				
	Oil palm	Pulp	Other/unknown	Total	User's acc.
Oil palm	173	3	5	181	95.6
Pulp	1	64	1	66	97.0
Other/unknown	0	4	16	20	80.0
Total	174	71	22	267	
Producer's acc.	99.4	90.1	72.7		94.8

the difficulty of defining the average height of the vegetation (i.e. below or above 2 m?), but both of the classes can also be easily confused with several other classes. The open undeveloped areas may be confused with newly established small-holder areas or industrial plantation. Likewise, it may be difficult to tell the 'Tall shrub/secondary forest'-class apart from small-holder plantations (e.g. rubber) or heavily degraded peat swamp forest.

The industrial plantation species identification has a very high overall accuracy of 95% (Table 5). This can be explained by the dominance of the two easily distinguishable plantation species (i.e. oil palm and pulp) in the peatlands of insular Southeast Asia. The classification errors were mainly due to (1) newly established plantations where the species could not be confirmed in the very high resolution image during accuracy assessment and which were categorized as 'Other/unknown' as a result and (2) plantation areas that were formed of two or more different plantations with different species, a fact which had gone unnoticed during the classification.

4. Discussion

The results of this study have revealed that peatland deforestation and conversion into managed land cover types have continued at high rate in the peatlands in Peninsular Malaysia, Sumatra and Borneo since 2007. In 2015, 29% (4.6 Mha) of the peatlands remain covered by peat swamp forest, with 6% (1.0 Mha) showing no signs of human influence. Managed land cover types (industrial plantations and small-holder areas) cover 50% (7.8 Mha) of all peatlands. Although not fully comparable due to the incomplete coverage and the coarse 250 m spatial resolution used for the 2000–2010 peatland deforestation estimates in Miettinen et al. (2012b), a comparison of the 2000–2010 estimates to the results obtained in this study suggests that peatland deforestation has continued roughly on the same level of magnitude during the 2007–2015 period (221 000 ha/a or 3.7%/a during 2000–2010 vs. 225 300 ha/a or 4.1%/a during 2007–2015). The main deforestation areas in the 2000–2010 period, Sarawak and Riau (41 000 ha/a or 8.1%/a and 93 600 ha/a or 5.0%/a respectively), have continued to experience high levels of deforestation during the 2007–2015 period (48 700 ha/a or 8.3%/a and 86 600 ha/a or 6.5%/a). Furthermore, deforestation in West Kalimantan has clearly increased from 22 300 ha/a (2.3%/a) in 2000–2010 to 34 600 ha/a (3.5%/a) in 2007–2015. These change comparisons need to be treated with caution since the absolute forest extent differs between the two studies, mainly due to the fact that heavily degraded forests (e.g. forest that have been selectively logged several times) are often classified into secondary forest in automated coarse resolution classification such as the one used for the 2000–2010 analysis in Miettinen et al. (2012b). Nevertheless, we believe that the change comparisons do give reasonable indications of the general trends of deforestation between the two epochs.

The plantation extent documented in this study agrees well with recently published World Resources Institute (WRI) plantation mapping (Petersen et al., 2016). Regardless of the fact that the plantation classes used by the WRI are not fully comparable to the ones used in this study, intersection of the two datasets revealed 91% agreement on the extent and location of large scale plantations (i.e. WRI 'Large industrial plantations' + 'Recent clearing for new plantations' vs. this study 'Industrial plantations'). The total areas of large scale plantation coverage in the peatlands of Peninsular Malaysia, Sumatra and Kalimantan were nearly identical (WRI 4.295 Mha vs. this study 4.286 Mha). However, it must be remembered that the WRI mapping was performed with datasets 1–2 years older than the mapping performed for this study, suggesting more conservative mapping approach used in this study, perhaps indicating some differences in the definition of plantation areas.

The rapidly decreasing forest cover and increasing area of managed land cover types drastically change peatland ecology and hydrology in the region, leading to tremendous changes in peatland functionality. Already at least half of all peatland areas are drained with varying intensity (industrial plantations and small-holder areas), in addition to an unknown proportion of the open undeveloped, secondary regrowth and degraded peatswamp forests. The increased human induced disturbances combined with very unsure natural regeneration of heavily degraded peatlands (Blackham et al., 2014; Cole et al., 2015) may be leading to a steady decline of Southeast Asian peat swamp forest ecosystems and eventual conversion to managed land cover types. The land cover change patterns in the peatlands of Peninsular Malaysia, Sumatra and Borneo since 1990 reported in this study (Fig. 3) resemble closely the progression of peatland degradation and conversion sequences documented by Miettinen et al. (2012c). In their study, they highlighted the role of degraded forests and open undeveloped areas as intermediary stages towards managed land cover types, creating a temporal buffer between pristine peat swamp forests and managed land cover types. Due to the steadily growing proportion of managed land cover types, the management practices used in the already converted peatlands are becoming an increasing important issue for the future of Southeast Asian peatlands. The majority of the peatlands in Peninsular Malaysia, Sumatra and Borneo are situated in lowlands close to sea level and are often found on highly acidic subsoils (i.e. the mineral soil underlying the peat layer; Rieley and Page, 2005). Due to the constant oxidation, runoff and subsidence of peat in drained and cultivated areas, it is uncertain how long agricultural activities can be continued on peat soils of the region before flooding or the exposure of the acidic subsoils will render the areas unsuitable for cultivation (see e.g. Hooijer et al., 2015).

The 2015 maps published in this paper are likely to be the last of their kind. Although we believe that it was important for this study to maintain comparability with the earlier land cover maps (1990 and 2007), it became clear during the 2015 classification that the changing land cover distribution is making the current classification scheme increasingly unsuitable. Firstly, due to the growing dominance of managed land cover types (already 50%), there is a need to provide more detailed information on the types and stages of vegetation development within the 'Industrial plantations' and 'Small-holder area'-classes. In conjunction with the accuracy assessment, land cover of each plot that fell into the 'Small-holder area'-class was further scrutinized in the very high resolution data. Excluding the 22 wrongly classified plots which were mainly undeveloped peatland with varying levels of regrowth or peat swamp forest, the land cover distribution of the 158 correctly classified plots turned out to be: 61% palm plantations (including oil palm and coconut), 16% agricultural fields, 13% other trees (e.g. house gardens or rubber plantations) and 10% fallow or unknown areas in early stages of development. Clearly, this distribution derived from a very small sample should be treated with extreme caution, but it does highlight the great variation of different land cover types found within this mosaic class. Furthermore, due to the rapidly increasing size of the small-holder farmers' holdings (especially in Sumatra), it is becoming ever more difficult to separate them from company owned large scale plantations. In future classifications the class separation primarily based on landscape pattern size used in this study would optimally be replaced by a unified managed area class with more detailed within class spatiotemporal land cover monitoring.

Secondly, it has become very difficult to separate the open undeveloped areas into the three classes used in the current classification: 'Seasonal water', 'Ferns/low shrub' and 'Clearance'. Due to the introduction of human induced degraded areas with low vegetation, it is often impossible to judge whether the area should be classified into permanently open 'Seasonal water' class or whether the area is merely in the early stages of development (i.e. 'Clearance') or even potential regeneration (i.e. 'Ferns/low shrub'). Thirdly, due to the cumulative nature of the 'Degraded peat swamp forest'-class, it currently contains a large variation of different degradation levels ranging from recovered former selective logging areas to heavily selectively logged forests designated for conversion to industrial plantations with the canal structure already visible. It would be important to describe this variation within the existing peat swamp forests in higher spatio-temporal detail in future classifications, using a quantitative parameter (e.g. canopy openness).

Regardless of the limitations discussed above, largely inherited from the earlier versions of the maps but retained to maintain consistency for change analyses, we hope that the maps presented in this paper will enable improved evaluation of the magnitude of the effects of peatland conversion in Southeast Asia. In addition, the dataset presented in this paper may be of use for evaluating the effects of peatland management policy decisions (e.g. Indonesia's forest moratorium; Murdiyarso et al., 2011) and the efficiency of protected area networks as well as identifying potential future hazards for the changing peatlands of insular Southeast Asia (e.g. changing fire regimes). The results of this paper highlighted substantial differences in current land cover distribution and recent change trends within the region. In light of these differences, the maps will hopefully support the ongoing and urgent process of policy formulation and implementation by helping to allocate the most suitable policy options in different parts of the region. The 1990–2010 maps used in this study have already been made publicly available at the Online Research Mapping Tool (ORMT; https://ormt-crisp.nus.edu.sg/ormt/Home/Disclaimer) maintained by the Centre for Remote Imaging, Sensing and Processing (CRISP) at the National University of Singapore (NUS). The 2015 maps will be made available on the same platform in due course after the official publication of the dataset.

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