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Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections

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Abstract

Tropical peatlands cover over 25 Mha in Southeast Asia and are estimated to contain around 70 Gt of carbon. Peat swamp forest ecosystems are an important part of the region's natural resources supporting unique flora and fauna endemic to Southeast Asia. Over recent years, industrial plantation development on peatland, especially for oil palm cultivation, has created intense debate due to its potentially adverse social and environmental effects. The lack of objective up-to-date information on the extent of industrial plantations has complicated quantification of their regional and global environmental consequences, both in terms of loss of forest and biodiversity as well as increases in carbon emissions. Based on visual interpretation of high-resolution (30 m) satellite images, we find that industrial plantations covered over 3.1 Mha (20%) of the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2010, surpassing the area of Belgium and causing an annual carbon emission from peat decomposition of 230–310 Mt CO_{2e}. The majority (62%) of the plantations were located on the island of Sumatra, and over two-thirds (69%) of all industrial plantations were developed for oil palm cultivation, with the remainder mostly being *Acacia* plantations for paper pulp production. Historical analysis shows strong acceleration of plantation development in recent years: 70% of all industrial plantations have been established since 2000 and only 4% of the current plantation area existed in 1990. 'Business-as-usual' projections of future conversion rates, based on historical rates over the past two decades, indicate that 6–9 Mha of peatland in insular Southeast Asia may be converted to plantations by the year 2020, unless land use planning policies or markets for products change. This would increase the annual carbon emission to somewhere between 380 and 920 Mt CO_{2e} by 2020 depending on water management practices and the extent of plantations.

Keywords: oil palm, peatland carbon emissions, peatland conversion, plantation development, pulp wood production, tropical peatland

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Introduction

Southeast Asia contains 25 Mha of peatlands, equal to 56% of all tropical peatland areas (Page *et al.*, 2011). These layers of organic soil with an average thickness of 5.5–7.0 m have been formed over thousands of years by accumulation of organic material in anaerobic and often acidic conditions of waterlogged lowlands (Rieley & Page, 2005; Page *et al.*, 2011). Peatlands in this region form a considerable surface carbon deposit containing 11–14% (69 Gt) of global peat carbon (Page *et al.*, 2011), equivalent to nearly eight times the annual amount of carbon released globally into the atmosphere by fossil fuel combustion in 2008 (9 Gt; Boden *et al.*, 2010). Peat swamp forest ecosystems are an important part of the region's natural resources supporting unique flora and fauna endemic to Southeast Asia (Rieley & Page, 2005; Corlett, 2009). In addition, they serve as a refuge for endangered animal species such as orangutan and Sumatran tiger, as well as performing hydrological and other ecosystem functions (Morrogh-Bernard *et al.*, 2003; Giesen, 2004; Rieley & Page, 2005).

Widespread human activities in peat swamp forests invariably set in motion ecosystem degradation. This affects the sensitive peat accumulation process which depends on the delicate balance between hydrology, ecology and landscape morphology (Page *et al.*, 1999).

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Agricultural activities on peatlands require lowered water table levels that lead to aerobic conditions in the upper peat profile (see, e.g. Hirano *et al*., 2007; Jauhiainen *et al*., 2012) resulting in enhanced peat oxidation and increased carbon emissions to the atmosphere (Couwenberg *et al*., 2010; Hooijer *et al*., 2010, 2012).

Recent assessments of peatlands in insular Southeast Asia have revealed a dramatic reduction of peat swamp forest cover since 1985 and projections suggest that forest cover on peatlands will be considerably reduced over coming decades (Hooijer *et al*., 2006; Miettinen & Liew, 2010; Fuller *et al*., 2011; Miettinen *et al*., 2011a). Conversion of peat swamps to industrial plantations is often seen as one of the major causes of deforestation (see, e.g. Sarvision, 2011). In particular, oil palm cultivation for biofuel production has caused much controversy (Stone, 2007; Venter *et al*., 2008; Sheil *et al*., 2009). However, the quantification of the regional and global environmental consequences of plantation agriculture on Southeast Asian peatlands, both in terms of loss of forest and biodiversity as well as increases in carbon emissions, has been greatly complicated by a lack of objective and up-to-date information on the extent of industrial plantations on peat soil.

The majority of all industrial plantations on peatlands are large-scale oil palm and pulp wood (*Acacia*) plantations. These types of plantations can be delineated using visual interpretation of high spatial resolution (<30 m) satellite images (Miettinen & Liew, 2010; Wahid *et al*., 2010). In addition to large-scale industrial plantations, smaller areas of oil palm, coconut, pineapple, sago palm, rubber and other plantations exist, often managed by small-holder farmers. However, the heterogeneous structure and small size of the plantations make it practically impossible to assess the extent of various plantation crops cultivated by small-holder farmers at the regional level using currently available remote sensing datasets.

In this study, we investigated the extent of oil palm, pulp and other types of large-scale industrial plantations on the peatlands of Peninsular Malaysia, Sumatra and Borneo (Fig. 1). We used visual interpretation of high-resolution (10–30 m) satellite data to map industrial plantations in the region with an unprecedented level of detail and accuracy. The objectives of this paper are (1) to report the extent and spatial distribution of industrial plantations in 2010, (2) to analyse the historical development trends of industrial plantation agriculture since 1990 and (3) to derive projections for near-future plantation expansion on the peatlands of insular Southeast Asia based on 'business-as-usual' scenarios.

Materials and methods

Peatland maps

Peatland areas in Sumatra and Kalimantan (Indonesian part of Borneo Island) were outlined using the Wetlands International 1 : 700 000 peatland atlases (Wahyunto *et al*., 2003, 2004). For Malaysia, information on the extent of peatlands was derived

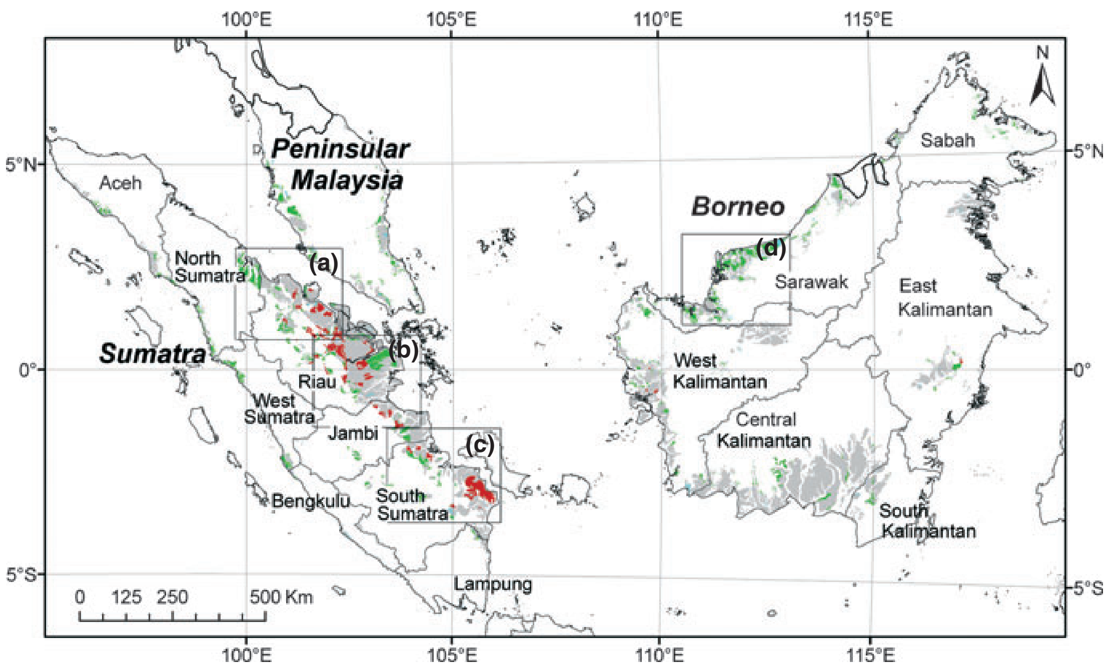

Fig. 1 Plantation distribution on the peatlands of the study area in 2010. Locations of insets presented in Fig. 2 are marked as black boxes. For colour legend please refer to Fig. 2.

from the European Digital Archive of Soil Maps (Selvaradjou *et al.*, 2005) as described in Miettinen & Liew (2010). The small country of Brunei, located in the northern coast of Borneo Island, was excluded from the analysis due to the unavailability of peatland maps.

Mapping of industrial plantations

For the 2010 mapping of industrial plantations, 100% of peatland areas were covered with 74 Landsat 7 ETM+ images acquired between 1 January 2010 and 11 March 2011. The images had 28.5 m spatial resolution. RGB band combination of 742 was used for on-screen viewing (band 7: 2.08–2.35 μm, band 4: 0.76–0.9 μm and band 2: 0.52–0.6 μm). Industrial plantations were manually delineated on screen based on visual interpretation of the images at a scale of 1 : 50 000.

For the historical analysis of the expansion of industrial plantations, the extent of plantation areas in 1990 and 2007 was derived from the land cover maps created earlier by Miettinen & Liew (2010) with Landsat and Satellite Pour l'Observation de la Terre (SPOT) data using the same visual interpretation-based mapping methodology described above. And finally, the 2000 plantation mapping was performed in the present study on the 2000 GeoCover product which is a 14.25 m resolution pansharpened mosaic of Landsat 7 ETM+ images acquired 1997–2003. The 2000 mapping was undertaken using the same methodology which had been used for all the above-mentioned mappings and the same RGB:742 used for the Landsat data in the 2010 mapping.

For consistency in the historical analysis, only areas covered by valid data (i.e. free of cloud cover, thick haze or other artefacts) in all four observations (1990–2000–2007–2010) were used. The overlapping valid data coverage over all observed time slices was 81% of peatlands in the entire study area. Lack of data coverage affected especially Peninsular Malaysia and East Kalimantan Province where only 52% and 36% of peatland areas were covered with valid data, respectively. This needs to be noted when assessing the results of the historical expansion of plantations in these provinces.

Plantation species identification

The plantation species identification was mainly performed on the set of SPOT images described by Miettinen & Liew (2010). Altogether 121 high spatial resolution (10–20 m) SPOT scenes were available. Due to the persistent cloudy weather conditions in this region, the data acquisition ranged over 3 years (2006–2008) with four additional images captured in 2005. Twenty seven of the images were captured in 2006, 58 in 2007 and 32 in 2008.

The plantation species identification was based on visual appearance (i.e. tone and texture) of the plantation areas, spatial arrangement of the plantation canals and roads, location, context, field knowledge of the interpreters and available land use allocation information. Plantations which could not be allocated to either oil palm or pulp due to lack of evidence or which were known to be of other plantation species were assigned to the 'other/unknown' class.

It was assumed that the plantation species did not change over the 20 year study period. This was considered to be a reasonable assumption since species suitable for industrial plantations on peatlands are very limited in number and infrastructure for palm oil and pulp processing remains in place for decades. We acknowledge that some sporadic exceptions to this rule may exist especially in those parts of the study area that have a long history of plantation development (e.g. Peninsular Malaysia and Sabah), but we believe that their effect on the results is marginal. Thus, the 1990 and 2000 plantation areas were assigned the same species as detected in 2007 in the specific locations. Species for new plantation areas established between 2007 and 2010 were determined by the location, appearance and spatial arrangement of the plantation area in the Landsat 7 ETM+ images together with personal knowledge and available land use allocation information.

Accuracy assessment

Very high-resolution satellite imagery acquired between 2004 and 2010 available in Google Earth was utilized to evaluate the accuracy of the methodology used in this study by comparing the very high-resolution samples to the 2007 map. The very high-resolution data available in Google Earth included images from the IKONOS and GeoEye-1 satellites operated by GeoEye as well as the Quickbird, WorldView-1 and WorldView-2 satellites operated by Digital Globe. These satellites have 0.5–1.5 m spatial resolution and enable accurate detection of industrial plantation areas including species identification.

The data used for the accuracy assessment covered 4% of the peatlands spread around 30 different sites. Within these sampling sites, 600 sample plots were selected using stratified random sampling. Half of the plots were selected from outside industrial plantations to estimate the level of omission errors of the mapping. Half of the sample plots were selected within areas classified as industrial plantations to evaluate the accuracy of the plantation species identification and the level of commission errors in the mapping. The 300 sample plots selected within plantation areas were distributed between different plantation species based on their proportions on the 2007 map.

Projections of future expansion

The projections of the potential expansion of industrial plantations by 2020 were based on recent expansion trends. The simplest (steady increase) projection assumed that plantation extent in coming years would expand at the same rate as it did in the most recent period of analysis, 2007–2010. This is a conservative approach, as the expansion rate has accelerated continuously over the last 20 years. A second model was derived by using the degree to which the increase from 2000 to 2010 had been greater than that over the 1990s. This takes into account the longer-term acceleration although still not the sharp acceleration since 2007.

It is important to understand that both of the future projection methods used in this study are purely based on historical trends of plantation expansion over the past 20 years and do not take into account any economical, political or other factors that may affect future plantation expansion rates. Therefore, the projections approximate the rate of future plantation development in 'business-as-usual' scenarios assuming that no significant changes in the circumstances affecting plantation expansion rates and distribution in the region would take place. The projections for 2020 plantation extent were, however, tested against the total area of available peatland that was not yet converted to plantation by 2010. For Indonesia, the projection was also tested against land allocation maps for 2011. For Malaysia, such maps were not available to us.

Calculation of carbon emission from industrial plantations on peatland

Recent extensive field analyses on heterotrophic carbon emission from plantations on tropical peatland (Jauhiainen *et al.*, 2012) and of carbon loss as measured through subsidence (Hooijer *et al.*, 2012) conclude that unit emissions at five or more years after drainage can be considered to be 75 t ha^{-1} yr^{-1} CO_{2e} at water table depths around 0.75 m that are representative for actual conditions in most relatively well-managed plantations. Although the majority of the measurements in the above-mentioned papers were conducted in *Acacia* plantations, the similarity of the environmental factors regulating peat decomposition and a smaller amount of measurements conducted in oil palm plantations indicate that the emission estimate is generally applicable for all large-scale industrial plantations in Southeast Asia (Hooijer *et al.*, 2012). This estimate agrees well with earlier findings on carbon emissions from peat decomposition in the region (Couwenberg *et al.*, 2010; Hooijer *et al.*, 2010). If 'best practice' water management is introduced and water levels could be kept at 0.6 m, these emissions could potentially be lowered to around 63 t ha^{-1} yr^{-1} CO_{2e} following the relations reported by Hooijer *et al.* (2012) and Jauhiainen *et al.* (2012). If, however, the initial high carbon emission peak occurring within the first 4 years after the establishment of the plantation highlighted by Hooijer *et al.* (2012) is included, and water levels remain at 0.75 m depth, plantations can be expected to emit 100 t ha^{-1} yr^{-1} CO_{2e}, calculated as an average over a 25 year period after drainage.

In this study, these emission estimate numbers were multiplied with the number of hectares of plantation to quantify total carbon emissions from peat decomposition in industrial plantations in the region. The resulting total emission numbers are considered low estimates since the loss of preplantation above ground vegetation biomass and fire induced emissions during plantation development were excluded. It is also important to understand that the emission estimates presented in this study are based on the actual plantation area coverage alone and do not take into account impacts beyond the plantation limits, which can be substantial (see, e.g. Hooijer *et al.*, 2012).

Preplantation vegetation cover

Taking advantage of two recently published land cover maps (Miettinen & Liew, 2010; Miettinen *et al.*, 2012a), we were able to analyse the preplantation vegetation cover of new plantation areas. In this analysis, the plantation maps were overlaid on maps describing the land cover distribution in a given area a decade before a plantation was detected. Those areas that were first detected as plantations in 2000 were compared with 1990 land cover. Similarly, the plantation areas that had been established between 2000 and 2010 were compared with 2000 land cover. It has to be acknowledged that the plantations have most likely not directly replaced the land cover type that was detected in the given location a decade earlier. Plantation establishment often is a gradual process which typically goes through several phases. Nevertheless, we believe that the land cover on a given area, a decade before a new plantation is detected, describes adequately the type of vegetation that was present in the future plantation areas when the plantation development process was set in motion.

Results

Accuracy assessment results

Overall accuracy of the industrial plantation mapping including species identification reached 94% with a kappa value of 0.91. Both oil palm and pulp wood plantations had user's and producer's accuracies of 90% or better (Table 1). The accuracy assessment also revealed that around half of the plantations classified as 'other/unknown' were in fact shown to be oil palm plantations. In theory, this could lead to an underestimation of the extent of oil palm plantations. Owing to the very small proportion of 'other/unknown' plantations (~3%),

Table 1 Error matrix for mapping of industrial plantations

	Reference					
	Oil palm	Pulp	Other/unknown	Other mapped	Total	User's accuracy
LC map						
Oil palm	185	0	4	6	195	94.9
Pulp	4	89	0	6	99	89.9
Other/unknown	4	0	1	1	6	16.7
Other mapped	6	0	4	290	300	96.7
Total	199	89	9	303	600	
Producer's accuracy	93.0	100.0	11.1	95.7		

however, any potential underestimation due to this cause can be expected to be in the order of only 1–2%. On the whole, these statistics indicate that the maps used in this study enable reliable analysis on the current extent and historical expansion of industrial plantations in the study area.

Extent of industrial plantations in 2010

Our results show that over 3.1 Mha of peatland had been converted to industrial plantations by 2010 (Table 2), equal to 20% of peatlands in the study area. Industrial plantations were, however, not evenly distributed in the region. Over 60% were found in Sumatra Island which contains less than half (47%) of peatlands in the study area (Fig. 1). Overall, industrial plantations covered 26% of the peatland areas in Sumatra and 13% of peatlands in Borneo. Furthermore, there was a clear difference between the Malaysian part of Borneo (i.e. Sarawak and Sabah states) and the Indonesian part of the island (i.e. Kalimantan). In Sarawak and Sabah, 36% and 27% of peatlands had been converted to plantations, respectively, whereas none of the provinces in Kalimantan had more than 10% plantation cover in 2010. Overall, Riau and South Sumatra provinces in Sumatra and Sarawak state in Borneo contained 62% of all industrial plantations in the region (Fig. 2).

Over two-thirds (69%) of all industrial plantations in 2010 were used for oil palm cultivation, with the remainder being mainly pulp wood (27%) and a small extent of other (4%) plantations (Table 2). While oil palm plantations occurred in all parts of the study area, pulp wood plantations were very unevenly distributed, with 98% being found in three Sumatran provinces: Riau, Jambi and South Sumatra. The distribution of pulp wood plantations is dependent on the location of pulp mills, which require far larger investments than the relatively small-scale infrastructure necessary for palm oil processing. They are, therefore, limited in number (there are two pulp mills in Riau) and slow to be developed in new areas.

Historical expansion of industrial plantations with future projections

Analysis of the overlapping areas of the plantation maps of 1990, 2000, 2007 and 2010 (81% of total study area) allowed us to investigate the expansion of industrial plantation areas in the region since 1990. Apart from Peninsular Malaysia, where plantation agriculture on peatlands was already well established by 1990, nearly all peatland plantations have been created over the past 20 years (Fig. 3). Furthermore, plantation development has accelerated fast with 70% of plantations established over the decade 2000–2010 and 27% within the 3 years of 2007–2010 alone. The acceleration of plantation development since 2000 has been particularly fast in South Sumatra, Riau and Sarawak which together accounted for 75% of all new plantations established since 2000 (Table 3). The recent increase in plantation development in West Kalimantan must also be highlighted, with 48% of the plantations existing in 2010 being established since 2007. Nevertheless, throughout the study period, Riau province experienced the main concentration of new plantation development (Table 3). With this widespread and rapid rate of plantation development and large extent of peatland (26% of the peatland in the study area), Riau Province dominated all Provincial (Indonesian) and State (Malaysian) level peatland plantation statistics in the region.

Based on the historical expansion of plantation areas presented above, using two different projection models (steady increase and decadal acceleration), we estimated that in 2020 industrial plantations would cover between 6.0 and 9.2 Mha of peatland in the study area (Fig. 3). Further analysis on potential limitations for future expansion (see more details in Miettinen *et al*., 2012b) revealed that in no Province in Indonesia, nor in the Malaysian States in Borneo, would the total peatland area limit further plantation expansion by 2020. For Indonesia, the projection was also tested against land allocation maps for 2011, and it was found that the area allocated for plantation expansion would easily accommodate the projections. This may not, however, be the case in some parts of Malaysia where available land resources are scarcer. Limited availability of land for agricultural development on mineral soils, e.g. in Sarawak, may increase the pressure on conversion of peatlands leading to shortage of area available for further plantation development. This shortage of peatland in Malaysia may become effective even sooner if land allocation laws begin to limit availability of the remaining peatlands; however, the status of such laws currently remains unknown to us.

Preplantation vegetation cover

The analysis of the preplantation vegetation cover revealed that in the 1990s plantation development took place almost entirely in forested areas. Eighty-five percent of all new plantations detected in 2000 were covered by peat swamp forest in 1990 (Table 4). Between 2000 and 2010, the proportion of forest conversion to plantation dropped to 56%. However, this was mainly due to the seemingly low peat swamp forest conversion rates for new plantations in South Sumatra and Central, South and East Kalimantan provinces where vast areas of forest had already burnt in the late 1990s (Miettinen

Table 2 Distribution of industrial plantations (IP) in Peninsular Malaysia, Sumatra and Borneo in 2010* (in 1000 ha)

	Oil palm IP			Pulp IP			Other/unknown IP			Total IP			
	Area	% Within island	% Within study area	Area	% Within island	% Within study area	Area	% Within island	% Within study area	Area	% Within island	% Within study area	IP% of total peatland
Peninsular Malaysia	238	NA	11	0	NA	0	23	NA	20	262	NA	8	29
Aceh	46	4	2	0	0	0	0	0	0	46	2	1	17
North Sumatra	198	19	9	0	0	0	1	5	1	200	10	6	57
Riau	487	46	23	464	55	54	18	55	15	968	51	31	24
West Sumatra	89	8	4	0	0	0	0	0	0	89	5	3	42
Jambi	84	8	4	63	8	7	0	0	0	146	8	5	20
Bengkulu	2	0	0	0	0	0	4	14	4	7	0	0	13
South Sumatra	131	12	6	309	37	36	9	27	7	449	23	14	31
Lampung	10	1	0	0	0	0	0	0	0	10	1	0	11
Total Sumatra	1047	100	49	836	100	98	32	100	28	1915	100	62	26
Sarawak	494	58	23	0	0	0	31	50	26	525	56	17	36
Sabah	50	6	2	0	0	0	2	4	2	52	6	2	27
West Kalimantan	133	16	6	10	63	1	13	22	11	157	17	5	9
Central Kalimantan	114	13	5	0	0	0	4	6	3	118	13	4	4
South Kalimantan	28	3	1	0	0	0	4	6	3	31	3	1	10
East Kalimantan	39	5	2	6	37	1	8	13	7	53	6	2	8
Total Borneo	858	100	40	16	100	2	62	100	53	936	100	30	13
Total study area	2143		100	852		100	118		100	3113		100	20

*Note that the 2010 mapping covers 100% of peatland areas.

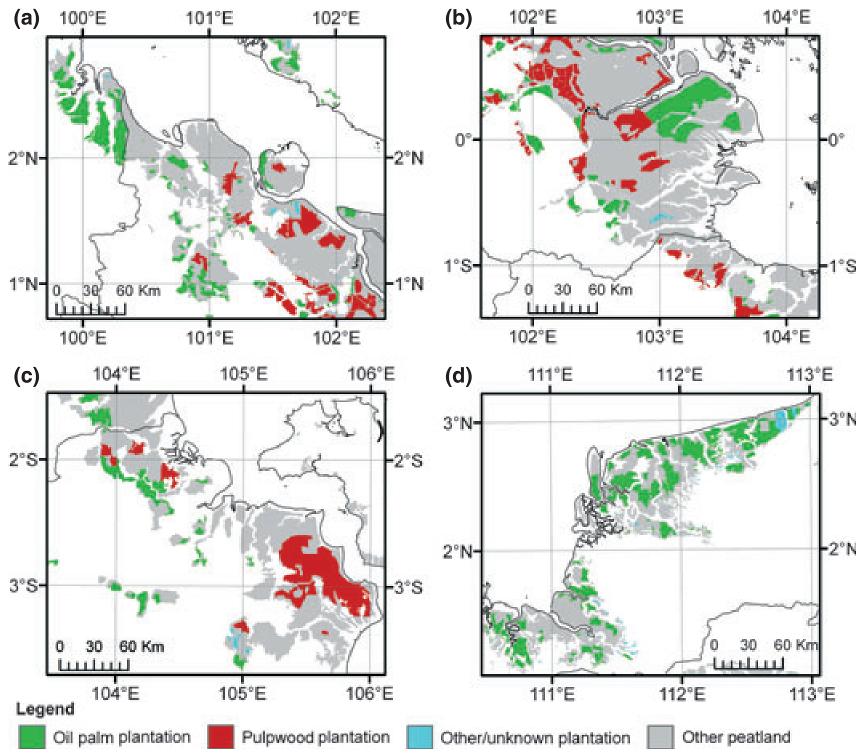

Fig. 2 Extent of plantations on the peatlands of Riau, South Sumatra and Sarawak in 2010. Locations of the insets within the region are outlined in Fig. 1.

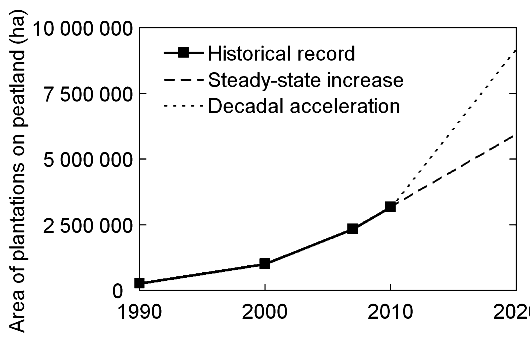

Fig. 3 Expansion of industrial plantations on peatland in Sumatra, Borneo and Peninsular Malaysia since 1990 and projection of future expansion until 2020.

et al., 2011a). The three high intensity plantation development areas of Riau, Sarawak and West Kalimantan, on the other hand, continued to show around 80% conversion rates from peat swamp forest to industrial plantations since 2000 (Table 4).

Carbon emissions from peat decomposition in industrial plantation area

Assuming average water table depths of 0.75 m, the industrial plantation area of 2010 is estimated to produce a carbon emission from peat decomposition of at least 233 Mt yr^{-1} CO_2 equivalents, up from 79 Mt yr^{-1} CO_{2e} in 2000 and 20 Mt yr^{-1} CO_{2e} in 1990. Of the total emission in 2010, 161 Mt yr^{-1} CO_{2e} (69%) is caused by oil palm plantations. If the initial peak in emissions within the first 5 years after drainage is included, and the total emissions are averaged over a 25 year period, the yearly emissions from the industrial plantation area in 2010 would reach up to 311 Mt yr^{-1} CO_{2e}. Depending on the plantation expansion projection method, the 2020 emission from industrial plantations on peatlands in this part of Southeast Asia would be somewhere between 447 and 688 Mt yr^{-1} CO_{2e} (including emissions of 308–465 Mt yr^{-1} CO_{2e} from oil palm plantations alone) based on the assumption of 0.75 m water table depth or up to 596–917 Mt yr^{-1} CO_{2e} (of which 410–620 Mt yr^{-1} CO_{2e} is from oil palm) if the initial peak in emissions is included. If, however, we assumed that 'best practice' water management could be achieved in all plantations in future, and if we exclude the initial emission peak, total emissions from industrial plantations in 2020 would be between 376 and 578 Mt yr^{-1} CO_{2e} (including emissions of 258–391 Mt yr^{-1} CO_{2e} from oil palm plantations).

Discussion

In this paper, we have presented the extent and spatial distribution of industrial plantations in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2010, with

Table 3 Distribution of new plantation establishment in the 1990s and in the 2000s (in %)

	1990–2000		2000–2010		
	Within island	Total	Within island	Total	Proportion of peatland mapped
Peninsular Malaysia	NA	4	NA	1	52
Aceh	3	3	2	1	78
North Sumatra	21	16	5	3	83
Riau	59	46	49	33	97
West Sumatra	7	5	3	2	84
Jambi	3	3	7	5	81
Bengkulu	1	1	0	0	93
South Sumatra	3	3	34	23	97
Lampung	2	1	0	0	97
Total Sumatra	100	77	100	68	93
Sarawak	72	13	62	19	78
Sabah	18	3	2	1	80
West Kalimantan	7	1	22	7	79
Central Kalimantan	2	0	4	1	75
South Kalimantan	0	0	5	2	80
East Kalimantan	0	0	5	1	36
Total Borneo	100	18	100	31	73
Total study area		100		100	81

Table 4 Preplantation vegetation (in %)

	1990 vegetation of plantations detected in 2000				2000 vegetation of plantations detected in 2010			
	PSF	Regrowth	Mosaic	Open	PSF	Regrowth	Mosaic	Open
Peninsular Malaysia	56	8	9	27	33	39	12	16
Aceh	97	0	1	2	46	40	7	7
North Sumatra	76	4	1	19	55	24	9	11
Riau	93	1	0	6	83	10	3	5
West Sumatra	88	2	0	10	54	22	11	13
Jambi	83	14	0	3	41	36	19	4
Bengkulu	47	28	3	22	0	72	26	2
South Sumatra	75	18	2	5	11	72	9	8
Lampung	13	15	0	72	0	0	0	0
Total Sumatra	86	3	1	10	52	34	6	7
Sarawak	92	4	3	1	74	17	4	5
Sabah	78	6	2	14	33	24	26	17
West Kalimantan	92	2	1	5	86	9	4	1
Central Kalimantan	23	2	2	73	19	30	36	15
South Kalimantan	0	0	0	0	0	31	37	32
East Kalimantan	100	0	0	0	15	23	30	32
Total Borneo	88	4	2	6	67	16	9	8
Total	85	4	1	10	56	29	7	7

Class descriptions: PSF stands for peat swamp forest. The regrowth-class includes all natural and planted secondary vegetation excluding industrial plantations. The mosaic-class includes areas with a mixture of woody vegetation and open land. Typically, this land cover class occurs in either sparsely vegetated newly cleared areas or small-holder farming areas. The open-class includes agricultural fields and areas that are either bare or covered by ferns typically less than 2 m in height.

analysis of expansion since 1990 and projections for future development. In general, our results agree well with previous studies. Hooijer *et al.* (2006) estimated that in 2010 around 3 Mha of Southeast Asian peatlands would be covered by industrial plantations. In this study, we revealed that 3.1 Mha, or 20% of peatlands in the study area, had been converted to industrial plantations by 2010. Based on a newly published 250 m

Table 5 Land cover distribution on the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2010

	Peat swamp forest 1000 ha	%	Regrowth 1000 ha	%	Mosaic 1000 ha	%	Open 1000 ha	%	Industrial plantation 1000 ha	%	Other nonforest 1000 ha	%	Total 1000 ha
Peninsular Malaysia	230	26	182	20	128	14	76	9	262	29	13	1	890
Aceh	108	39	94	34	18	6	10	4	46	17	0	0	277
North Sumatra	25	7	69	20	33	9	21	6	200	57	0	0	348
Riau	1382	34	1051	26	326	8	263	7	968	24	24	1	4014
West Sumatra	20	9	62	29	34	16	17	8	78	37	1	0	211
Jambi	181	25	255	36	75	10	60	8	146	20	1	0	717
Bengkulu	0	0	24	46	14	26	7	14	7	13	1	1	52
South Sumatra	107	7	537	37	134	9	220	15	449	31	2	0	1450
Lampung	3	3	24	26	6	7	45	49	10	11	3	3	92
Other provinces	24	32	33	45	4	6	11	15	0	0	1	1	74
Total Sumatra	1850	26	2150	30	643	9	655	9	1904	26	32	0	7234
Sarawak	380	26	403	28	47	3	82	6	525	36	6	0	1443
Sabah	39	20	49	26	15	8	33	17	52	27	3	2	191
West Kalimantan	1042	60	318	18	94	5	101	6	157	9	31	2	1743
Central Kalimantan	1454	48	780	26	291	10	357	12	118	4	8	0	3009
South Kalimantan	4	1	96	29	46	14	149	45	31	10	3	1	329
East Kalimantan	250	36	207	30	62	9	110	16	53	8	7	1	688
Total Borneo	3169	43	1853	25	555	7	832	11	936	13	57	1	7403
Total	5249	34	4186	27	1326	9	1563	10	3102	20	102	1	15528

Please refer to Table 4 for land cover class descriptions.

resolution regional land cover map, large-scale oil palm plantations covered 0.88 Mha in the peatlands of the study area around the year 2000 (Miettinen *et al.*, 2012a), compared with our high-resolution (10–30 m) assessment resulting in 0.93 Mha.

In a recent study performed with high-resolution satellite data, Wahid *et al.* (2010) estimated that less than 0.7 Mha of peatland was covered by oil palm plantations in Malaysia in 2009. This is significantly less than the over 0.8 Mha estimated in this study for 2010. It must be remembered, however, that oil palm expansion is currently very fast in some parts of Malaysia as documented by both Sarvision (2011) and our study. In their analysis, Wahid *et al.* (2010) used satellite data acquired in 2008–2009, as opposed to some images in our study which were acquired as late as March 2011. This indicates that in some areas, the difference in acquisition dates of satellite data may have been nearly 3 years.

Overall, it is important to remember that this study concentrated on the western part of insular Southeast Asia. Plantations in the Indonesian provinces of Papua and West Papua, as well as the countries of Papua New Guinea, Brunei and Thailand, were excluded from the analysis. The total extent of industrial plantations on peatland in the entire Southeast Asian region will be higher than presented in this paper, although none of the areas missed in this study are known to have had extensive plantation agriculture established on peatlands by 2010.

The projection methods used in this study simply assume continuation of recent plantation development trends in 'business-as-usual' scenarios, assuming that various aspects regulating the rate and distribution of the expansion of industrial plantations in this region would not change significantly. We acknowledge that this approach has several limitations. First, it does not take into account the demand drivers, under different scenarios for economic development, and potential biofuel market regulation. Second, as the longer term risks and costs of draining peatlands, namely land subsidence and reduced drainability in time, become clearer to companies, they may potentially choose to focus on plantation development on mineral dryland soils, where tens of millions of hectares of deforested land (particularly in Indonesia) are currently unproductive.

Moreover, it is not known what the response of local Governments will be to the international and national pressures to reduce greenhouse gas emissions from peatlands and to conserve remaining wetland forests. Enforcement of existing and potential future rules banning drainage and deforestation of peatlands is still possible. One example of a recent political development is the 2 year moratorium on allocation of new concession areas on forested peatlands as part of a bilateral cooperation between Indonesia and Norway (Murdiyarso *et al.*, 2011). However, the final forms of implementation of the moratorium at a practical level are still taking shape and the developments beyond the 2 year period are uncertain. Therefore, it is unclear how and to what extent the moratorium and future political decisions will affect the expansion of industrial plantations on the peatlands of Southeast Asia during this decade. In the absence of information on the abovementioned issues, we believe that our projection estimates represent a valid indication of the future direction of plantation expansion in this region under 'business-as-usual' scenarios that continue the practices that have prevailed over the past 20 years.

We estimate that in 2010 industrial plantations produced carbon emission to the atmosphere of at least 233 Mt yr^{-1} CO_2 equivalents, or up to 311 Mt yr^{-1} CO_{2e} if the initial peak in carbon emissions after plantation development (Hooijer *et al.*, 2012) is included. These figures exceed the total annual carbon emission from fossil fuel burning of a country like Malaysia (208 Mt yr^{-1} CO_{2e} in 2008; Boden *et al.*, 2010). Note also that the values presented in this paper, based on updated knowledge on carbon emissions from peat decomposition and on extensive new high-resolution plantation mapping, are substantially higher than some earlier estimates; e.g. a recent paper (Koh *et al.*, 2011) suggested 17 Mt yr^{-1} CO_{2e} emissions for 0.88 Mha of oil palm plantations around the year 2000 as opposed to our estimate of 70 Mt yr^{-1} CO_{2e} for 0.93 Mha in 2000. Furthermore, it is important to understand that the 233 Mt yr^{-1} CO_{2e} emission estimate presented in this study excludes emissions from drained peatlands under other land covers in the region, including adjoining areas that are affected by plantation drainage, as well as emissions from peatlands outside the study area (e.g. Papua). In comparison, biomass burning carbon emissions from the entire equatorial Southeast Asia, largely attributed to peatland fires in this region, averaged around 700 Mt yr^{-1} CO_{2e} between 1997 and 2009 (van der Werf *et al.*, 2010). However, this estimate was heavily affected by an extreme fire episode in 1997–1998. Since 1999, fire induced carbon emissions have ranged between 80 and 1300 Mt yr^{-1} CO_{2e}, averaging at 400 Mt yr^{-1} CO_{2e}.

Amid the intense debate related to industrial plantation development on Southeast Asian peatlands, it is important to remember that plantation development is not the only threat that tropical peatlands are currently facing. A combination of the industrial plantation mapping performed for this study and a recently published regional land cover map (Miettinen *et al.*, 2012a) allowed us to analyse the proportion of industrial plantations on all deforested peatlands (Table 5). In addition to an overall 20% coverage of industrial plantations, secondary regrowth and small-holder plantations were estimated to cover 27% of peatlands in the study area. Furthermore, a mosaic of vegetated and nonvegetated areas (including both natural and managed land use types) covered 9% and open clearances or extremely degraded areas 10%. Only 34% of the peatlands in the study area remained forested in 2010 (Miettinen *et al.*, 2012a), down from around 75% in 1990 (Miettinen & Liew, 2010). This deforestation rate of nearly 4% yr^{-1} substantially exceeds earlier analyses of historical and projected forest losses (e.g. Hooijer *et al.*, 2006) and is indeed dramatically higher than deforestation levels generally around the world (Hansen *et al.*, 2010) and in other parts of this region (Miettinen *et al.*, 2011b), especially when it is considered that much of the remaining peat swamp forest is also degraded to some extent (Miettinen & Liew, 2010).

The results reported in this paper highlight the accelerating nature of industrial plantation expansion on peatland since 1990. Projections indicate that half of the peatland area on the islands of Sumatra and Borneo and in Peninsular Malaysia may be covered by plantations by 2020 if current expansion trends persist. Furthermore, under current policies, there is no indication that expansion will stop in 2020. This expansion is also likely to result in degradation well beyond the plantation limits as peatland drainage and access roads have an impact over at least 2 km (Hooijer *et al.*, 2012). Bearing in mind that other causes of peatland deforestation, including small-holder agriculture and logging, are also still expanding, it would appear that very little peatland forest is likely to remain in Southeast Asia by the end of the current decade unless land use planning policies are changed or markets for palm oil and pulp products from these areas are reduced.

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