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Current and future CO_2 emissions from drained peatlands in Southeast Asia

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Abstract. Forested tropical peatlands in Southeast Asia store at least 42 000 Million metric tonnes (Mt) of soil carbon. Human activity and climate change threatens the stability of this large pool, which has been decreasing rapidly over the last few decades owing to deforestation, drainage and fire. In this paper we estimate the carbon dioxide (CO_2) emissions resulting from drainage of lowland tropical peatland for agricultural and forestry development which dominates the perturbation of the carbon balance in the region. Present and future emissions from drained peatlands are quantified using data on peatland extent and peat thickness, present and projected land use, water management practices and decomposition rates. Of the 27.1 Million hectares (Mha) of peatland in Southeast Asia, 12.9 Mha had been deforested and mostly drained by 2006. This latter area is increasing rapidly because of increasing land development pressures. Carbon dioxide (CO_2) emission caused by decomposition of drained peatlands was between $355\,\mathrm{Mt\,y^{-1}}$ and $855\,\mathrm{Mt\,y^{-1}}$ in 2006 of which 82% came from Indonesia, largely Sumatra and Kalimantan. At a global scale, CO_2 emission from peatland drainage in Southeast Asia is contributing the equivalent of 1.3% to 3.1% of current global CO_2 emissions from the combustion of fossil fuel. If current peatland development and management practices continue, these emissions are predicted to continue for decades. This warrants inclusion of tropical peatland CO_2 emissions in global greenhouse gas emission calculations and climate mitigation policies. Uncertainties in emission calculations are discussed and research needs for improved estimates are identified.

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1 Introduction

Undrained peat deposits consist of plant remains (about 10% by weight of peat) and water (90%), accumulated in waterlogged and usually acidic conditions over thousands of years. The tropical peatlands of Southeast Asia are the result of a fine balance between hydrology, ecology and landscape morphology (Page et al., 1999). A change in any of these three components will lead inevitably to a change in the rate of peat accumulation. Human intervention has major impacts on peatland hydrology through rapid transformation of landscape structure and function unless appropriate water management is implemented (Hooijer, 2005a; Wösten et al., 2006).

Lowland peatlands in Southeast Asia cover 27.1 Million hectares (Mha) (Wetlands International, 2003, 2004; FAO, 2004) of which over 22.5 Mha are in Indonesia where they make up 12% of the land area and over 50% of the lowland area. Peat thicknesses range from 0.5 to 20 m (Page et al., 2002), with at least 17% over 4 m deep in Indonesia (calculated from Wetlands International 2003, 2004). This yields an estimated conservative carbon store in Southeast

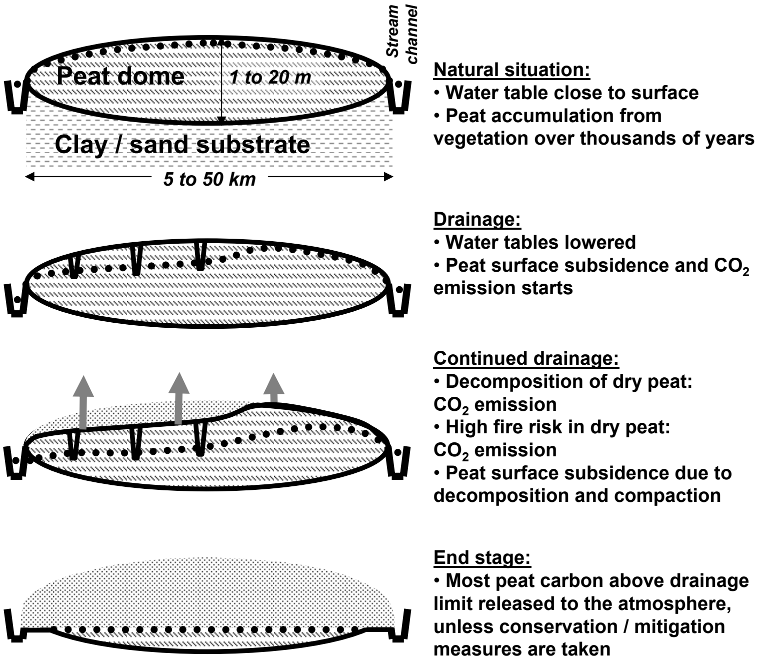

Fig. 1. Schematic illustration of progressive subsidence of the peat surface in drained peatland, due to peat decomposition resulting in CO_2 emission, as well as compaction.

Asian peatlands of at least 42 000 Million metric tonnes (Mt) assuming a carbon content of 60 kg m^{-3} (Kanapathy, 1976; Neuzil, 1997; Shimada et al., 2001).

Forested peatlands in Southeast Asia are being deforested, drained and often burned for agricultural development (mainly oil palm and pulpwood plantations). Widespread concession-based and illegal logging, particularly in Indonesia, has also resulted in peat drainage through construction of logging canals which leads to increased risk of fire (Page et al., 2002; Aldhous, 2004; Langner and Siegert, 2009). Recently domestic and international interest in using palm oil as a source of biofuel has contributed to further deforestation and drainage of peat swamp forest, particularly in Indonesia and Malaysia (Hooijer et al., 2006; Stone, 2007).

All these land use activities have impacts on the net greenhouse gas (ghg) balance of peatlands which are dominated by five flux components: (i) net CO_2 uptake by vegetation, (ii) CO_2 emissions from drainage-related peat decomposition, (iii) CO_2 and other emissions from fires, (iv) exports of dissolved and particulate organic carbon, and (v) smaller role of emissions of methane (CH_4) and possibly nitrous oxides (N_2O). For pristine swamp forests the two main fluxes determining the net carbon balance are the net carbon uptake by plants and emissions from heterotrophic respiration of the peat.

This paper focuses on one of the dominant components, namely CO_2 emissions from drainage-related peat decomposition. Development of agriculture and other human activities on peatland requires drainage. This leads to aerobic conditions and higher redox potentials that favour microbial activity and nitrogen mineralization in the peat profile above the water table (Ueda et al., 2000; Jali, 2004) resulting in enhanced CO_2 loss by peat decomposition (Fig. 1).

Carbon emissions from drained tropical peatlands (other than from fires) have received limited attention in analyses of emissions from land use, land use change and forestry (LULUCF) (Canadell et al., 2007; Gullison et al., 2007), and are overlooked in ghg emission budgets as considered by the UN Framework Convention on Climate Change (UNFCCC) (IPCC, 2007). While the links between peatland utilization and CO_2 emission are relatively well established for temperate and boreal peatlands (Minkkinen et al., 2008; Oleszczuk et al., 2008) there is relatively little information on CO_2 emission from drained peatlands in the tropics.

In this paper we present the first geographically comprehensive analysis of CO_2 emission from the decomposition of organic matter from drained peatlands in Southeast Asia with particular reference to lowland peatlands in Indonesia, Malaysia, Papua New Guinea and Brunei. The analysis is based on data for peatland area, thickness and carbon content, and on rates of deforestation and drainage. In addition, we establish a relationship between water table depth and peat decomposition in order to estimate present and future CO_2 emissions in Southeast Asia. Finally, we discuss key uncertainties and future research needs for improved emission estimates.

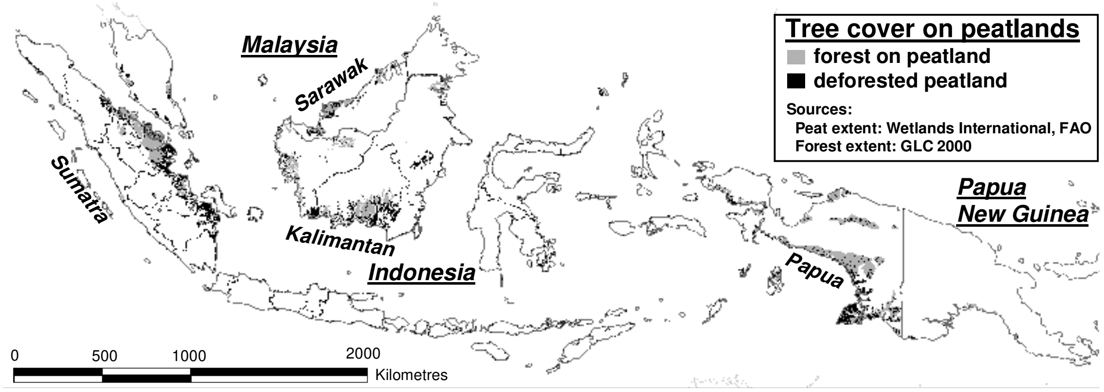

Fig. 2. Forest cover on peatland in the year 2000 (GLC 2000 land cover data; Bartholomé and Belward 2000), in Indonesia, Malaysia and Brunei.

2 Methods

2.1 Data

To estimate current and future CO_2emissions from drained peatlands, the following information was obtained: (i) where and how thick the peatlands are, (ii) where they are drained, (iii) to what depth, (iv) what further deforestation and drainage developments can be expected, (v) how much CO_2 emission is caused by drainage, and (vi) how much peat carbon is available for oxidation. The required information is addressed step-by-step below (additional details on methodologies and data sources see Hooijer et al., 2006).

2.1.1 Peatland location, area and thickness

A peatland distribution map (Fig. 2) was obtained for the Indonesian areas of Sumatra and Kalimantan (Wetlands International, 2003, 2004). For the remaining areas, the Digital Soil Map of the World from the Food and Agriculture Organization (FAO, 2004) was used to determine peat area percentage in soil association classes. Peat thickness data for Sumatra, Kalimantan and Papua (Indonesia) were obtained from Wetlands International (2003, 2004) which provides maps of peat area in 6 thickness ranges (<0.5 m, 0.5–1 m, 1–2 m, 2–4 m, 4–8 m and 8–12 m) based on available field surveys in Indonesia. The <0.5 m thickness range covers a relatively small area and was excluded from the analysis. Average thicknesses were calculated from these ranges. Average peat thicknesses for Malaysia, Brunei and Papua New Guinea were estimated conservatively at 3 m, on the basis of thicknesses in Indonesia. For the purpose of this study, we excluded smaller peatland areas found in other Southeast Asian countries (Philippines, Thailand and Vietnam) which are less studied and represent only a small fraction of the total area and carbon stock in SE Asia. Peatlands over 300 m above sea level were also excluded for the same reasons.

2.1.2 Location and area of drained peatlands in the year 2000

was derived from the Global Land Cover 2000 map (Bartholomé and Belward, 2005) that is based on a classification of "SPOT-VEGETATION" satellite images that have 1 km^2 grid cell resolution. Of the sixteen land cover categories, those that occurred on peat were divided into four drainage classes on the basis of the drainage characteristics commonly observed in these categories: "certainly drained if peatland" (large croplands, which includes plantations and other large agricultural areas), "probably drained if peatland" (mixed cropland and shrubland; small scale agriculture), "possibly drained if peatland" (shrubland; recently cleared and burnt areas) and "probably not drained" (natural peat swamp forest). Grid cells were assigned accordingly to drainage classes (Table 1) by fraction of area. The fraction of area drained within drainage classes was estimated based on field studies (Hooijer, 2005b; Hooijer et al., 2008a), in which the area that is effectively drained is observed to be a function of the type and intensity of land use. Highly productive croplands including plantations will always be 100% drained. Mixed croplands will be mostly drained (a range of 75–100% drained area is assumed) as drainage impacts extend far enough (1 to 3 km) to also affect most or all unproductive areas in such mosaic landscapes. The degree of drainage in unproductive shrublands is most variable, therefore a wide range of 25–75% drained area is assumed for this drainage class. Areas of peatland within each drainage class are presented in Table 2, by Province (in Indonesia), State (in Malaysia) and Country (outside Indonesia and Malaysia).

2.1.3 Groundwater depths for the drainage classes

Average groundwater depths in drained areas as presented in Table 1, were estimated from scarce published data (Murayama and Bakar, 1996; Wösten and Ritzema, 2001; Jauhiainen et al., 2004; Hooijer, 2005a, b; Melling et al., 2005; Ali

Table 1.

			minimum	*likely*	*maximum*
1. Drained area	Large croplands, including plantations	%	100	100	100
(within land use class)	Mixed cropland / shrubland: small-scale agriculture	%	75	88	100
	Shrubland; recently cleared & burnt areas	%	25	50	75
2. Groundwater depth	Large croplands, including plantations	*m*	0.80	0.95	1.10
(within land use class)	Mixed cropland / shrubland; small-scale agriculture	*m*	0.40	0.60	0.80
	Shrubland; recently cleared & burnt areas	*m*	0.25	0.33	0.40
3. Apply relation between groundwater depth and CO_2 emission: 91 t/ha/y CO_2 emission per m depth					
4. Result: unit CO_2 emission	Large croplands, including plantations	$t\ ha^{-1}\ y^{-1}$	73	86	100
(calculated from 1, 2 and 3)	Mixed cropland / shrubland: small-scale agriculture	$t\ ha^{-1}\ y^{-1}$	27	48	73
	Shrubland; recently cleared & burnt areas	$t\ ha^{-1}\ y^{-1}$	6	15	27

Table 2.

Drainage class:		Shrubland + burnt			Mixed: crop+shrub			Cropland	Forest cover 2000				Forest change	
Original GLC 2000 class:		6	8	**total**	2	9	**total**	12	1	4	5	**total**	1985	85-'00
	Lowland peatland area (km^2)	*Mosaics & Shrub Cover, shrub component dominant, mainly evergreen*	*Shrub cover, mainly deciduous, (Dry or burnt)*	***Total shrubland + burnt***	*Mosaic: Tree cover and Cropland (incl.very degraded and open tree cover)*	*Mosaics of Cropland / Other natural veg. (shifting cultivation in mountains)*	***Total mix cropland + shrub (small-scale agr.)***	***Cultivated and managed, non irrigated (mixed)***	*Tree cover, broadleaved, evergreen, closed and closed to open*	*Tree cover, regularly flooded, Mangrove*	*Tree cover, regularly flooded, Swamp*	***Total forest (including logged)***	Global Forest Watch / World Res. Inst.	Annual change over the period 1985 - 2000
		% area	% area	%area	% area	% area	%area	% area	% area	% area	% area	% area	% area	%/y
Total Indonesia	**225234**	**4**	**2**	**6**	**3**	**24**	**27**	**5**	**27**	**4**	**30**	**61**	**81**	**-1.3**
Kalimantan	**58379**	**15**	**4**	**19**	**2**	**17**	**19**	**3**	**30**	**2**	**27**	**58**	**87**	**-1.9**
Central Kalimantan	30951	19	2	21	2	15	18	3	33	1	24	57	90	-2.2
East Kalimantan	6655	22	19	40	0	9	9	5	29	4	11	44	85	-2.8
West Kalimantan	17569	5	1	6	2	17	19	1	28	3	43	74	92	-1.2
South Kalimantan	3204	15	3	18	6	45	51	14	14	0	4	18	41	-1.6
Sumatra	**69317**	**0**	**1**	**1**	**3**	**34**	**37**	**10**	**14**	**2**	**35**	**52**	**78**	**-1.8**
D.I. Aceh	2613	0	0	0	4	28	32	8	37	0	22	59	87	-1.8
North Sumatera	3467	0	2	2	3	39	42	20	20	1	16	36	76	-2.6
Riau	38365	0	1	1	2	24	26	7	14	3	49	66	87	-1.4
Jambi	7076	0	1	1	3	38	40	17	9	0	33	42	67	-1.7
South Sumatera	14015	0	1	1	4	57	61	12	11	1	14	26	66	-2.6
West Sumatera	2096	0	5	5	4	42	46	11	24	0	13	38	69	-2.1
Papua	**75543**	**0**	**1**	**1**	**4**	**20**	**25**	**1**	**36**	**9**	**27**	**72**	**80**	**-0.5**
Other Indonesia~	**21995**	**4**	**2**	**6**	**3**	**24**	**27**	**5**	**27**	**4**	**30**	**61**	**81**	**-1.3**
Malaysia	**20431**	**2**	**1**	**2**	**7**	**32**	**39**	**7**	**36**	**4**	**15**	**54**	**78***	**-1.8***
Peninsular	5990	0	1	1	4	47	50	13	37	0	0	37	78*	-2.8*
Sabah	1718	8	2	10	3	28	31	17	21	21	2	43	86*	-2.9*
Sarawak	12723	2	1	2	9	26	35	4	38	3	23	64	76*	-1.1*
Brunei	**646**	**3**	**1**	**4**	**1**	**9**	**10**	**2**	**39**	**6**	**39**	**85**	**85***	**-0.2***
Papua N. Guinea	**25680**	**0**	**1**	**1**	**4**	**32**	**36**	**3**	**38**	**5**	**19**	**62**	**80***	**-1.3***
SE ASIA	**271991**	**4**	**2**	**5**	**4**	**26**	**29**	**5**	**29**	**4**	**28**	**61**	**81***	**-1.3***

~ Land use distribution for 'Other Indonesia' assumed equal to Total Indonesia.

** 1985 forest cover outside Indonesia is visually estimated from map.*

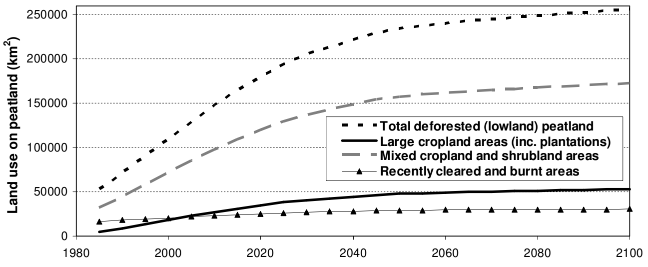

Fig. 3. Trends and projections of land use change in lowland peatland in SE Asia.

et al., 2006), and unpublished data collected by the authors in water management projects in Central Kalimantan (Hooijer et al., 2008a), Jambi and Riau (Hooijer et al., 2008b). Water depths in densely drained palm oil and pulp wood plantations on peatland, which are the most abundant plantation types, are best known; common practice is to keep average water tables always below 0.7 m, but they are often as deep as 1.2 m on average (Hooijer et al., 2008b). A likely groundwater depth of 0.95 m was therefore assumed for this class (Table 1). Water depths in small-scale agriculture are generally between 0.4 and 0.8 m. Water depths in recently cleared and burnt peatlands, that usually have some drainage canals used for logging but not a dense network, are often not much greater than in a natural situation, and were estimated at 0.25 to 0.4 m.

2.1.4 History and future trends in peatland drainage

Historical information on peatland cover, and therefore of drained area, was obtained from changes in forest cover between 1985 (Global Forest Watch, 2002) and 2000 (Bartholomé and Belward, 2005) (Table 2). The deforestation rate in peatlands over this period was 1.3% y^{-1} for Indonesia, varying from 0.5% y^{-1} in Papua Province to 2.8% y^{-1} in East Kalimantan Province. Similar rates apply to the other countries in Southeast Asia included in this analysis (Hooijer et al., 2006). These historical peatland deforestation rates per Province were projected to future years, applying the annual percentage rate of deforestation, i.e. assuming a "business as usual" continuation of current developments. Changes in relative areas within deforested peatland of the drainage classes "large cropland areas", "mixed cropland + shrubland" and "recently burnt and cleared areas", as the total deforested area increases, were projected using relationships derived from distribution of drainage classes in Indonesian Provinces in 2000, as a function of the deforested area (Hooijer et al., 2006) (Fig. 3).

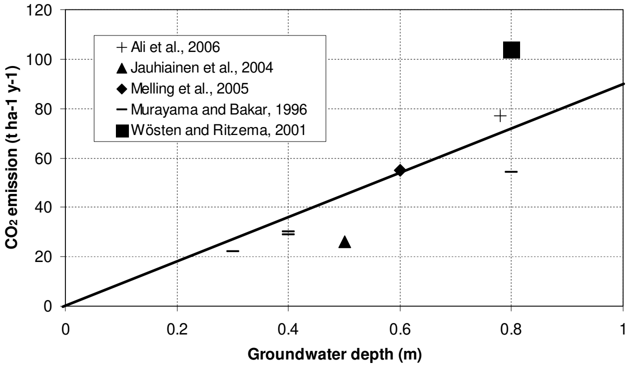

Fig. 4. Linear relation between groundwater depth in peatland and CO_2 emission caused by peat decomposition. The line has been fitted through published measurements in agricultural areas in peatland, including oil palm plantations. Measurements in forest and unproductive degraded peatlands are excluded because these are not representative for agricultural areas. Measurements in sites where average water depth is reported to be within 0.3 m are also excluded, because such sites are not effectively drained and often subject to frequent inundation. Most measurements are gas flux measurements at the peat surface; the Wösten and Ritzema 2001 data point is based on analysis of subsidence records.

2.1.5 Relationship between groundwater depth and CO_2 emission

A relation was derived from the results of two types of emission studies. The first type of study is CO_2 gas emission monitoring in relation to water depth (Murayama and Bakar, 1996; Jauhiainen et al., 2004; Melling et al., 2005; Ali et al., 2006). The second is long term monitoring of peat subsidence in drained peatlands, combined with peat carbon content and bulk density measurements to separate the contribution of compaction from the total subsidence rate; the remainder is attributed to CO_2 emission (as reviewed by Wösten et al., 1997; Wösten and Ritzema, 2001). The analysis yields the following regression relationship (Fig. 4):

$$CO_2 \text{ emission} = 91 \cdot \text{Groundwater depth } [R^2{=}0.71,\ n=8]$$

Where CO_2 emission is expressed in t ha^{-1} y^{-1} and groundwater depth is the average depth of the water table below the peat surface, expressed in metres. This linear relation implies that every 10 cm water table drawdown will result in an increase in CO_2 emission rate of 9.1 t CO_2 ha^{-1} y^{-1}.

2.1.6 Carbon content

Carbon content of Southeast Asian peat was taken to be 60 kg m^{-3} (Kanapathy, 1976; Neuzil, 1997; Shimada et al. 2001) and this value was applied to all areas.

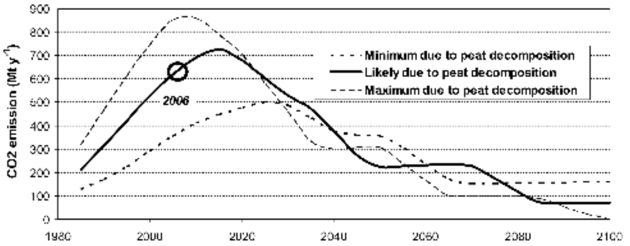

Fig. 5. Historical, current and projected CO_2 emissions from peatlands, as a result of drainage (fires excluded). The increase in emissions is caused by progressive drainage of an increased peatland area. The following decrease is caused by peat deposits being depleted, starting with the shallowest peat deposits that represent the largest peatland area. The stepwise pattern of this decrease is explained by the discrete peat thickness data available (0.75 m, 1.5 m, 3 m, 6 m, 10 m). The "minimum", "likely" and "maximum" lines correspond with possible drainage intensities as presented in Table 1.

2.2 Calculations

Using the data and relationships described above, the CO_2 emission from all geographical units was calculated as follows:

$$CO_2 \text{ emission} = \text{LU\_Area} \cdot \text{D\_Area} \cdot \text{D\_Depth} \cdot CO_2\text{\_1 m [t/y]}$$

Where:

LU_Area = peatland area with specific land use [ha]

D_Area = drained area within peatland area with specific land use [fraction]

D_Depth = average groundwater depth in drained peatland area with specific land use [m]

CO_2_1 m = CO_2 emission at an average groundwater depth of 1 m = 91 [t CO_2 ha^{-1} y^{-1}]

Different groundwater depths were applied to the three land use classes as presented in Table 1 ("large cropland areas", "mixed cropland and shrubland", and "recently burnt and cleared shrubland"), and emission calculated for the total area of each class within each country and region. Peatland drained to 0.95 m on average (considered "most likely" in plantations and other large-scale 'cropland' areas; Table 1) emits 86 t CO_2 ha^{-1} y^{-1}. Peatland drained to 0.6 m depth on average (typical in small-scale agricultural areas, i.e. "mixed cropland and shrubland") for 88% of the area emits 48 t CO_2 ha^{-1} y^{-1}. Peatland drained to 0.33 m over half of the area (considered likely for "shrubland", i.e., recently deforested areas, and burnt and degraded agricultural areas) emits 15 t CO_2 ha^{-1} y^{-1}. Subsequently, "minimum", "likely" and "maximum" emission rates for the land use classes were calculated by varying drained area and groundwater depth in each class as presented in Table 1. Total annual emissions were estimated by multiplying CO_2 emissions per hectare of each land use class by the total area of that class (Fig. 5).

3 Results and discussion

3.1 Carbon fluxes and climate mitigation

Land cover trends from 1985–2000 (Table 2), extended to 2000–2006, indicate that 12.9 Mha, or about 47% of peatlands in Southeast Asia, were deforested by 2006 (Fig. 3). Projected rates of land use change within deforested areas in Southeast Asia over the same period suggest that by 2006, 2.3 Mha (17% of deforested peatlands) of this land had been drained intensively for large-scale agriculture (drainage class "cropland"), 8.5 Mha (67%) was affected by moderately intensive drainage for small-scale agriculture ("mixed cropland and shrubland"), and 2.2 Mha (16%) had been recently cleared or burnt. Applying the drainage percentages for land cover areas as provided in Table 1, this results in an estimated total drained peatland area for 2006 of 11.1 Mha (9.5 Mha–12.7 Mha).

The earlier described method for calculating carbon dioxide emissions was applied to these drained areas, and to the specific groundwater depths per land cover type as provided in Table 1. The range of calculated unit area emissions is between 6 and 100 t CO_2 ha^{-1} y^{-1} as demonstrated in Table 1. The resulting total estimated CO_2 emission from peat decomposition in drained peatland in 2006 is estimated to be 632 Mt y^{-1} (with a possible range of 355 Mt y^{-1} and 855 Mt y^{-1}; Fig. 5). At present, Indonesia is the single largest emitter of CO_2 from ongoing peat decomposition (excluding fires), being responsible for 82% of Southeast Asian emissions in 2006. Within Indonesia, Sumatra is the largest emitter closely followed by Kalimantan.

If current rates and practices of peatland development and degradation continue, CO_2 emission is expected to peak at 745 Mt y^{-1} in 2015, followed by a steady decline over subsequent decades as the remaining peat deposits become increasingly depleted (Fig. 5). By 2030, emission is projected to decline to a likely value of 514 Mt y^{-1} if peatland drainage continues without mitigation, and decline further to 236 Mt y^{-1} by 2070. Total cumulative CO_2 emission, up to 2006 from all peatlands in Southeast Asia included in this analysis, was estimated at 9700 Mt (5300 Mt–13 700 Mt). Total cumulative emission by 2030 is projected to be 25 900 Mt (17 200 Mt–31 000 Mt), and by 2070 it is projected to be 37 300 Mt (28 900 Mt–39 900 Mt).

These emissions, on a unit area basis and for the same groundwater depth, are higher in the tropics than in temperate and boreal areas, because the rate of aerobic decomposition is strongly influenced by temperature. A review of emissions from European peatlands gives median values of 8.6 and 15.1 t CO_2 ha^{-1} y^{-1} for grassland

and 16.1 and 15.0 t CO_2 ha^{-1} y^{-1} for arable cultivation on drained bog (ombrotrophic) and fen (minerotrophic) peats, respectively (Byrne et al., 2004). These fluxes are at the lower end of the emission range reported for drained tropical peatlands in our study. As a further comparison, the IPCC annual emission factors for cultivated organic soils are 5.0 ± 90% t Cha^{-1} y^{-1} (=18.3 t CO_{2e} ha^{-1} y^{-1}) for boreal/cool temperate, 10.0 ± 90% t Cha^{-1} y^{-1} (=36.7 t CO_{2e} ha^{-1} y^{-1}) for warm temperate and 20.0 ± 90% t Cha^{-1} y^{-1} (=73.3 t CO_{2e} ha^{-1} y^{-1}) tropical/sub-tropical climatic regimes (IPCC, 2006). The latter value is towards the upper end of our range of most likely emissions from tropical peatland under cultivation (48 to 86 t CO_2 ha^{-1} y^{-1}).

Carbon dioxide emissions from decomposition of drained peatlands in Southeast Asia, of 355 Mt y^{-1} to 855 Mt y^{-1} in 2006, are equivalent to 1.3% to 3.1% of the 28 000 Mt y^{-1} of global fossil fuel emissions during the same year (Canadell et al., 2007).

In addition to continuous emissions caused by peat decomposition, infrequent emissions caused by peatland fires are of similar magnitude and much higher during El Niño-years. Average annual fire emissions is estimated to be at least 1400 Mt y^{-1} CO_2 for 1997–2006 (Hooijer et al., 2006) and 469 ± 187 Mt y^{-1} CO_2 for 2000–2006 (van Werf et al., 2008). For the 1997–1998 El Niño alone, estimates of fire emissions range from 6197 Mt CO_2 for Indonesia (2970 Mt–9423 Mt CO_2; Page et al., 2002) to 2662 ± 836 Mt CO_2 for Indonesia, Malaysia and Papua New Guinea (van der Werf et al., 2008).

If the various numbers for CO_2 emissions for peat decomposition and peatland fires are added up, the minimum total emission would be 637 Mt y^{-1} CO_2 (355+469–187; over 2000–2006, excluding the 1997–98 El Niño) and the maximum 2255 Mt y^{-1} CO_2 (855+1400; over 1997–2006). Even though these estimates cover quite a range they consistently show that emissions from both peat decomposition and peatland fires in SE Asia make large contributions to global carbon dioxide emissions.

The large magnitude of the emissions makes conservation of remaining pristine forested tropical peatlands, and rehabilitation of degraded ones, a significant opportunity for carbon emission reductions. The concentrated nature of these emissions that are produced on less than 0.1% of the global land area makes them potentially easier to manage than many other emissions caused by multiple sources and types of land conversion. Improved water management planning for complete hydrological units (peat domes), reducing or avoiding effects of drainage on water depths, is the basis for conservation of peat resources.

Conservation and rehabilitation become even more critical when we place carbon dynamics from tropical peatlands in a long-term context that includes climate change (in addition to land use change). An analysis of climate projections to 2100 shows that 7 of 11 models agree on decreased rainfall during the dry seasons in a number of peatland regions of Southeast Asia (Li et al., 2007), and 9 of the models agree on greater interannual variability in dry season rainfall. These changes are strongest and most consistent for southern Sumatra and Borneo, where most peatland in Indonesia occurs. Decreased rainfall during the dry season will result in lower water tables exposing larger carbon stocks to aerobic conditions and so enhancing decomposition and CO_2 emissions. Already multiple El Niño events since 1997 have shown the characteristics of predicted future climate for the region and the effects of those changes interacting with intense land use change on CO_2 emissions.

Management and conservation of tropical peatlands clearly expose the connectivity and complexities between local development agendas, and global agendas on climate change and conservation of wetlands and biodiversity. Synergistic opportunities exist for sustainable regional development and climate change mitigation through supporting peatland management practices that result in reduced carbon emissions and enhanced forest conservation.

4 Uncertainties and research needs

In this section, we highlight the main data uncertainties and research needs for improving estimates of CO_2 emissions from drainage of tropical peatland.

Peatland area: The area of peatland in the various countries in Southeast Asia is reasonably well documented and is listed in national soil and land use inventories. The accuracy of these can be improved by adopting standardized methods for survey and evaluation of peatland and peat. Peat soils are Histosols but their definition varies from country to country and also according to land use. Some classifications adopt a minimum organic matter of 65% in a minimum accumulated organic layer of 30 cm, others specify an organic content of only 35% while some require an accumulation of at least 40 or even 50 cm to qualify.

Peat thickness: This is subject to the largest degree of uncertainty owing to a lack of field data. Information from some areas where intensive research has been carried out is quite detailed, e.g. the Ex Mega Rice Project area and Sabangau River catchment in Central Kalimantan, and the Kampar Peninsula in Riau Province in Sumatra. Elsewhere, data are limited, usually from the edges of these vast peatland landscapes where peat is shallow with the internal "domes" on deeper peat remaining under sampled.

Carbon content: Peat carbon content is obtained by combining the area of peatland with the bulk density of and carbon concentration in peat. The carbon "density" of Southeast Asian peat used in this paper is based on a mean peat dry bulk density of 100 kg m^{-3} and average carbon concentration of 60% (Wösten et al., 2001; Rieley et al., 2008) both of which vary greatly across the surface of tropical peatland and in peat profiles (Page et al., 2004). Carbon densities between 24 kg C m^{-3} and up to 95 kg C m^{-3} have been reported

(Shimada et al., 2001; Page et al., 2004; Wetlands International, 2003, 2004; Wösten and Ritzema, 2001). This reflects a significant spatial variation in carbon density, which can only be understood with additional measurements of peat bulk density and peat carbon content.

Drainage depth classification: For this study, it was derived from the GLC 2000 global land cover classification (Bartholomé and Belward, 2005) and needs to be improved with the addition of more drainage classes to encompass the diversity of land use classes and drainage depths. For example, areas in Papua (Indonesia) are classified as "mixed cropland + shrubland" while they are known to actually be savannah-like swamps created as a result of traditional land management that involves regular burning (Silvius and Taufik, 1990). These areas are generally not "drained" in the normal sense because agriculture is often carried out on elevated islands of organic mud dug up from the submerged swamp soil.

The *percentages of peatland drained* within the drainage classes are conservative estimates derived from surveys carried out in Indonesia and focused on deforested peatland. It is assumed that the situation in other countries in Southeast Asia is similar but it is not certain whether this is indeed the case. The percentage of drained peatland may be considerably larger than expressed in this paper, as several activities affecting the hydrology of tropical peatland were not taken into account. These include construction of canals in forested areas for transport of logged timber, and roadside drainage, the effects of which often extend over distances of kilometres into adjacent forested areas. Detailed mapping of these small canals would improve estimates of total drained peatland.

G*roundwater depths* (i.e. drainage depths): The water table depths used in this assessment (Table 1) are greater than those recommended in existing management practices (e.g. Wösten et al, 1997), but in the case of croplands and plantations they are shallower than depths observed frequently by the authors in the field. It is common to find water tables well below one metre from the surface in oil palm and pulp wood plantations. There is a need for an extensive system of groundwater depth monitoring in the range of tropical peatland types under different forms of management.

Land cover trends and the rate of peatland deforestation in 2006: These were derived from peatland cover in 2000 (GLC, 2000) and the rate of deforestation from 1985 to 2000 (Global Forest Watch, 2002) as described by Barthtolomé and Belward (2005). These data are still the most up-to-date and validated information available for all of Southeast Asia. In addition, inaccuracies were found when field-checking the GLC-2000 data, mostly to the effect that intact forest cover was overestimated with heavily degraded forest and some plantations included in this class. Continued improvement and updating of land use data based on recent satellite data are required.

Projections have not taken into account *peatland drainability and future management responses*. When subsidence brings the peat surface close to the drainage base, resulting in increased flooding and reduced agricultural productivity, they may be abandoned and drainage intensity would decline. In such cases, CO_2 emissions may be reduced. Part of the carbon stock in peatlands is below the drainage base and may never be oxidized. However, a common observation is that drainage systems in abandoned peatlands continue to draw down water levels for decades, because no funding is available for canal blocking.

CO_2 emission rate and water table depth: This relationship is difficult to determine precisely. Data are obtained from two sources of information: gas flux measurements and peat subsidence monitoring. The former can be difficult to interpret because CO_2 emissions resulting from peat oxidation (decomposition) must be separated from that originating from plant root respiration. There are very few datasets of CO_2 emissions and even fewer of annual fluxes over multiple years that allow determination of the likely high interannual variation. Monitoring of peat subsidence and peat carbon content provides a more direct and accurate measurement of net carbon loss provided the effects of peat oxidation are separated from those of compaction and shrinkage of the peat. Subsidence measurements have the additional advantage that they account for lateral export of particulate and dissolved organic matter into rivers and canals, a component that is not included in CO_2 emissions measurements.

Our assessment is based on a linear relationship between water table depth and CO_2 emissions, fitted through data points derived from 6 different studies (Fig. 4). This needs further refinement as more field data, particularly under different land uses and at different times since the start of drainage, become available. The linear relationship is considered the best estimate currently available for determining CO_2 emissions at water table depths between 0.5 and 1 m, which covers the range of the most common groundwater depths in the study region. As additional information is incorporated it may be that the relationship proves to be curved. If this is the case it will make little difference to estimates of CO_2 emissions at water tables around one metre below the surface.

Emissions other than CO_2: Methane (CH_4) emissions from both undrained and drained peatlands are found to be modest in comparison with CO_2 (Jauhiainen et al., 2005, 2008; Rieley et al., 2008; Couwenberg et al. 2009), but may still be significant from a climate perspective given that CH_4 is a much stronger greenhouse gas (25 times stronger in "CO_2 equivalents", Forster et al., 2007). New continued CH_4 flux measurements over multiple years will confirm to what extent this gas plays a significant role in the net ghg-balance of tropical peatlands. Likewise, very limited information on nitrous oxide (N_2O) emissions in peatlands requires new continued measurements, particularly in agricultural areas with nitrogen inputs (Couwenberg et al., 2009).

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