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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 as a result of increasing land development pressures. Carbon dioxide (CO_2) emission caused by decomposition of drained peatlands was between 355 and 855 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.

1 Introduction

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. Peatlands 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., 2006a).

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 by most definitions. Peat thicknesses range from 0.5 to 20 m (Page et al., 2002), with at least 17% over 4 m deep in Indonesia. This yields an estimated carbon store in Southeast Asian peatlands of at least 42 000 Mt assuming a carbon content of 60 kg m^{-3} (Page et al., 2002).

Forested peatlands in Southeast Asia are being deforested, drained and often burned for agricultural development (mainly oil palm and pulpwood plantations). Widespread 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) CO_2 uptake by vegetation, ii) CO_2 emissions from 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).

This paper focuses on one of these components, namely CO_2 emissions from 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 development 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.

2 Methods

2.1 Data

In order to estimate current and future CO_2 emissions from drained peatlands, the following information was obtained: i) where and how thick the peatlands are, ii) where they are drained and 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 (for further details on methodologies and data sources see Hooijer et al., 2006).

2.1.1 Peatland distribution and thickness

A peatland distribution map (Fig. 2) was obtained for the Indonesian islands 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 percentage in soil classes. Peat thickness data for Sumatra, Kalimantan and Papua (Indonesia) were obtained from Wetlands International (2003, 2004). Average peat thicknesses for Malaysia, Brunei and Papua New Guinea were estimated conservatively 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. Peatlands over 300 m above sea level were also excluded for the same reasons.

2.1.2 Distribution of drained peatlands in the year 2000

Distribution 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 resolution. Sixteen land cover categories were divided into four drainage classes: "certainly drained if peatland" (cropland, which includes plantations and other large agricultural areas), "probably drained if peatland" (mosaics of cropland and other land uses), "possibly drained if peatland" (shrubland and burnt areas) and "probably not drained" (natural vegetation). Cells were assigned accordingly to drainage classes (Table 1) by fraction of area. 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

Groundwater depths for the drainage classes, i.e. average groundwater depths as presented in Table 1, were estimated from published data (Armentano and Menges, 1986; Murayama and Bakar, 1996; Wösten and Ritzema, 2001; Jauhiainen et al., 2004; Hooijer, 2005b; Melling et al. 2005; Ali et al. 2006) and field observations by the authors.

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, assuming a "business as usual" continuation of current developments. Changes in relative areas within deforested peatland of the drainage classes "cropland", "mosaic cropland+shrubland" and "shrubland", 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).

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 gas emission monitoring in relation to water depth (Armentano and Menges, 1986; Murayama and Bakar, 1996; Jauhiainen et al., 2004; Melling et al., 2005; Ali et al., 2006). The second type of study is long term monitoring of peat subsidence in drained peatlands, combined with peat carbon content and bulk density analysis to factor out 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 relation (Fig. 4):

$$CO_2 \text{ emission } (\text{t ha}^{-1}\,\text{y}^{-1}) = 91 * \text{Groundwater depth (m)} \; [R^2 = 0.71, n = 8]$$

Where CO_2 emission is expressed in $\text{t ha}^{-1}\,\text{y}^{-1}$ 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 value of 9.1 t CO_2 $\text{ha}^{-1}\,\text{y}^{-1}$.

2.1.6 Carbon content

Carbon content of Southeast Asian peat was taken to be 60 kg m^{-3} (Kanapathy, 1976; Neuzil, 1997; Page et al., 2002) and this value was applied to all areas.

2.2 Calculations

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

CO_2 emission = LU_Area ∗ D_Area ∗ D_Depth ∗ CO_2_1m [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_1m = CO_2 emission at an average groundwater depth of 1 m = 91 [t CO_2 $\text{ha}^{-1}\,\text{y}^{-1}$]

Different groundwater depths were applied to land cover types i.e. drainage classes as presented in Table 1 ("cropland", "mosaic cropland and shrubland", and "shrubland"), and emission calculated for the total area of each class within each geographic unit. Peatland drained to 0.95 m on average (considered "most likely" in plantations and other large-scale "cropland" areas; Table 1) will emit 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. "mosaic cropland and shrubland") for 88% of the area will emit 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) will emit 15 t CO_2 ha^{-1} y^{-1}. Subsequently, "minimum", "likely" and "maximum" emission rates for the land cover types were calculated by varying drained area and groundwater depth in each drainage class as presented in Table 1. Overall emissions were estimated by multiplying CO_2 emissions per hectare of each land use type by the total area of the corresponding drainage class,

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 about 47% of peatlands in Southeast Asia, or 12.9 Mha, were deforested by 2006. Projected rates of land use change within deforested areas in Southeast Asia over the same period suggest that 17% of this land is now drained extensively for large-scale agriculture (drainage class "cropland"), 67% is affected by moderately intensive drainage for small-scale agriculture ("mosaic cropland and shrubland"), and 16% is unmanaged, degrading non-agricultural peatland ("shrubland"). This results in an estimated total drained peatland area for 2006 of 11.1 Mha (9.5–12.7 Mh).

Carbon dioxide emission from organic matter decomposition in drained peatlands in 2006 is estimated to be 632 Mt y^{-1} (355–855 Mt y^{-1}). This corresponds to an overall range of emissions between 6 and 100 t CO_2 ha^{-1} y^{-1}. At present, Indonesia is the single largest CO_2 emitter from drained peatlands, responsible for 82% of Southeast Asian emission 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. Cumulative CO_2 emission to 2006 from all peatlands in Southeast Asia was estimated at 9700 Mt (5300–13 700 Mt) and projected to be 25 900 Mt (17 200–31 000 Mt) by 2030 and 37 300 Mt (28 900–39 900 Mt) by 2070.

These emissions, on a unit area basis and for the same groundwater depth, are far higher in the tropics than in temperate and boreal areas, because the rate of aerobic decomposition is strongly influenced by temperature. A recent review of emissions from drained bogs and fens in temperate climates gives a median value of 4.1 t CO_2 ha^{-1} y^{-1} for arable land on drained fen peat Oleszczuk et al. (2008). This flux is one order of magnitude less than the lower end value of the emission range reported for drained tropical peatlands in our study.

Although significant uncertainties remain it is likely that CO_2 emissions from decomposition of drained peatlands in Southeast Asia of 355 to 855 Mt y^{-1} in 2006 are equivalent to 1.3 to 3.1% of the 28 Billion metric tonnes of CO_2 y^{-1} of global fossil fuel emissions during the same period (Canadell et al., 2007).

In addition to the permanent flux of emissions caused by peat decomposition, incidental emissions caused by peatland fires are at least of similar magnitude and much higher during El Niño-years. Average fire emissions have been estimated to be at least 1,400 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 1997–98 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 combined, the minimum total emission would be 637 Mt y^{-1} CO_2 (over 2000–2006, excluding the 1997–1998 El Niño) and the maximum 2255 Mt y^{-1} CO_2 (over 1997–2006). Even though these estimates cover quite a range they consistently show that emissions from both peat decomposition and fires are large contributing fluxes to the net carbon balance of tropical peatlands in Southeast Asia.

The large magnitude of the emissions makes conservation of remaining forested tropical peatlands, and rehabilitation of degraded ones, a significant opportunity for carbon emission reductions. The concentrated nature of these emissions, they 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 types of land conversion. Improved water management planning for whole hydrological units (peat domes) 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 across models 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 ENSO events since 1997 have shown the characteristics of predicted future climates for the region and the positive feedbacks on carbon emissions between low rainfall events and intense land use of peatlands involving deforestation and drainage (Ali et al., 2006).

A post-Kyoto treaty after 2012 which includes carbon credits from Reduced Emissions from Deforestation and Degradation (REDD) is one of the most important opportunities for tropical peatlands to be valued for their environmental importance. This development will largely determine the opportunities for improved management, rehabilitation and conservation, and consequently the magnitude of ghg emissions in the future.

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.

3.1.1 Uncertainties and research needs

In this section we discuss the main uncertainties of this analysis and identify the new research needs to improve future estimates of carbon emissions from peat decomposition.

Peat thickness of many regions in Indonesia is not well known. Peat thicknesses tend to be greatest in the central parts of the inaccessible, dome-shaped peat bodies, which are often tens of kilometres across. Most of the measurements on peat thicknesses are nearer to the fringes. New carbon estimates will improve by acquiring new datasets on peatland thickness particularly for Malaysia and Papua New Guinea for which little data is available.

Data on *extent and distribution* of peatlands need to be improved, especially for regions outside of Kalimantan and Sumatra.

Carbon content of Southeast Asian peat was assumed to be 60 kg m^{-3} in this and several earlier studies (Wösten at al., 2001; Page et al., 2002). Carbon contents between 50 kg C m^{-3} (Rieley et al., 2008) and up to 90 kg C m^{-3} (Wetlands International, 2003; 2004) have been reported. This reflects a significant spatial variation in peat carbon content which can only be improved with additional measurements of peat bulk density.

Drainage depth classification as derived from the GLC 2000 global land cover classification (Bartholomé and Belward, 2005) needs to improve with more drainage classes to encompass the diversity of land uses and drainage depths. For example, areas in Papua (Indonesia) are classified as "mosaic cropland+shrubland" while they are known to actually be savannah-like swamp landscapes created by traditional land management techniques requiring regular burning (Silvius and Taufik, 1990). These areas are generally not "drained" in the normal sense but agriculture often takes place on elevated islands of dug up organic mud (from the submerged swamp soil).

The *percentage of peatland drained* within drainage classes was conservatively estimated from field surveys which did not cover all peatland regions, and focussed on deforested peatland. The percentage of drained peatland may be considerably larger than assessed here, as several interventions in the hydrological system are not taken into account. These include drainage in forested areas for log transport canals where legal or illegal logging takes place, and through the impacts of plantation and roadside drainage which often extend over distances of kilometres into adjacent forested areas.

Estimated likely *groundwater depths* (i.e. drainage depths) used in this analysis (Table 1) are somewhat greater than depths recommended in existing management guidelines. However in the case of intensively drained croplands and plantations they are shallower than depths often observed by the authors in practice; drainage depths over 1 m are common in oil-palm and pulp wood plantations. There is a need for an extended monitor system of groundwater depths in a range of peatland types under different management.

Values for *2006 land use* were projected from GLC 2000 data for the year 2000, corrected for deforestation trends, as this is still the most up-to-date published and validated land use dataset available for all of Southeast Asia. Continued improvement and update of land use 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.

The *relation between* CO_2 *emission and average groundwater depth* as affected by drainage is a very sensitive parameter in the calculations, and has proven difficult to establish. There are two sources of information: gas flux measurements and subsidence monitoring. Gas flux measurements can be difficult to interpret because CO_2 emission resulting from peat oxidation must be separated from plant root respiration. There is also a very limited dataset of gas flux measurements and even more limited dataset on annual fluxes over multiple years to capture the high interannual variability of the system. Determining net carbon loss by monitoring subsidence of the peat surface, as well as changes in peat bulk density and carbon content to distinguish the effects of peat oxidation from those of shrinkage, is a more feasible method for a large scale regional assessment as the one presented here. Subsidence measurements have the additional advantage that they account for lateral export of particulate and dissolved organic matter into rivers and canals, a flux that is missed in gas flux measurements. A much larger network of long-term subsidence measurements will be required to improve regional estimates and links to CO_2 emissions. New relationships need to be explored to best characterize the water table regimes; recent unpublished findings suggest that a relation between minimum water depth (e.g. the 25 percentile) and peat decomposition rate could be more appropriate.

We have used a linear *relationship between groundwater depth and* CO_2 *emission*, fitted through data points derived from 6 different studies (Fig. 4). This relation needs further development as more field data is acquired particularly on land management aspects, peat characteristics and the time since the start of drainage. Additional data will also allow exploring whether this relationship is in fact nonlinear. The linear relation used in this study is considered the best estimate currently available for groundwater depths between 0.5 and 1 m, which covers the range of the most common groundwater depths in the study region.

The only form of carbon emission considered in this assessment is 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), but may still be significant from a climate perspective given that CH_4 is a much stronger greenhouse gas (23 times stronger in "CO_2 equivalents"). 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 peatlands. Likewise, very limited information on nitrous oxides (N_2O) emissions in peatlands requires new continued measurements, particularly in agricultural areas with nitrogen inputs.

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Table 1. CO_2 emission calculation steps and main parameters.

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

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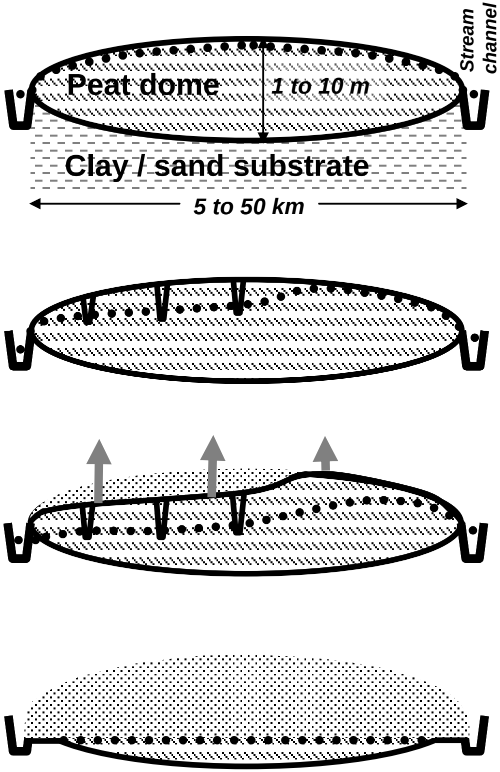
Table 2. Lowland peatland distribution with land use and rate of forest cover loss.

		Shrubland + burnt			**Mosaic: crop+shrub**			**Cropland**	**Forest cover 2000**				**Forest change**	
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**	**7**	**3**	**24**	**27**	**5**	**27**	**4**	**30**	**61**	**81**	**-1.3**
Kalimantan	**58379**	**15**	**4**	**20**	**2**	**17**	**19**	**3**	**30**	**2**	**27**	**58**	**87**	**-1.9**
Central Kalimantan	30951	19	2	22	2	15	18	3	33	1	24	57	90	-2.2
East Kalimantan	6655	22	19	42	0	9	9	5	29	4	11	44	85	-2.8
West Kalimantan	17569	5	1	7	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	2	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**	**2**	**4**	**20**	**25**	**1**	**36**	**9**	**27**	**72**	**80**	**-0.5**
Other Indonesia~	**21995**	**4**	**2**	**7**	**3**	**24**	**27**	**5**	**27**	**4**	**30**	**61**	**81**	**-1.3**
Malaysia	**20431**	**2**	**1**	**1**	**7**	**32**	**38**	**7**	**36**	**4**	**15**	**53**	**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	**59**	76*	-1.1*
Brunei	**646**	**3**	**1**	**4**	**1**	**9**	**10**	**2**	**39**	**6**	**39**	**84**	**85***	**-0.2***
Papua N. Guinea	**25680**	**0**	**1**	**1**	**4**	**32**	**35**	**3**	**38**	**5**	**19**	**61**	**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 estimated.*



Natural situation:
- Water table close to surface
- Peat accumulation from vegetation over thousands of years

Drainage:
- Water tables lowered
- Peat surface subsidence and CO_2 emission starts

Continued drainage:
- Decomposition of dry peat: CO_2 emission
- High fire risk in dry peat: CO_2 emission
- Peat surface subsidence due to decomposition and shrinkage

End stage:
- Most peat carbon above drainage limit released to the atmosphere,
- unless conservation / mitigation measures are taken

Fig. 1. Schematic illustration of CO_2 emission from drained peatlands.

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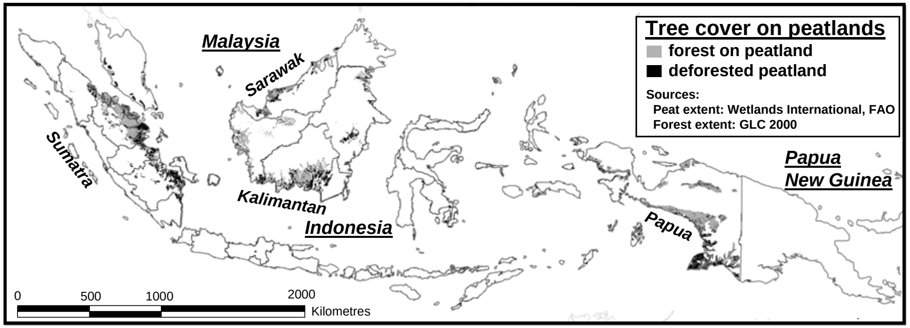

Fig. 2. Forest cover on peatland in the year 2000. Note that FAO non-histosol soil classes with 20–40% peat are not shown, hence peat extent may be greater than shown – e.g. Papua New Guinea has significant peatland cover.

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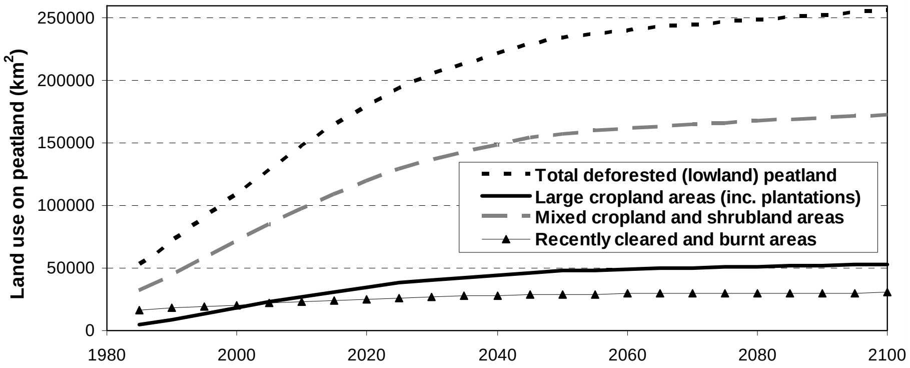

Fig. 3. Trends and projections of land use change in lowland peatland in SE Asia.

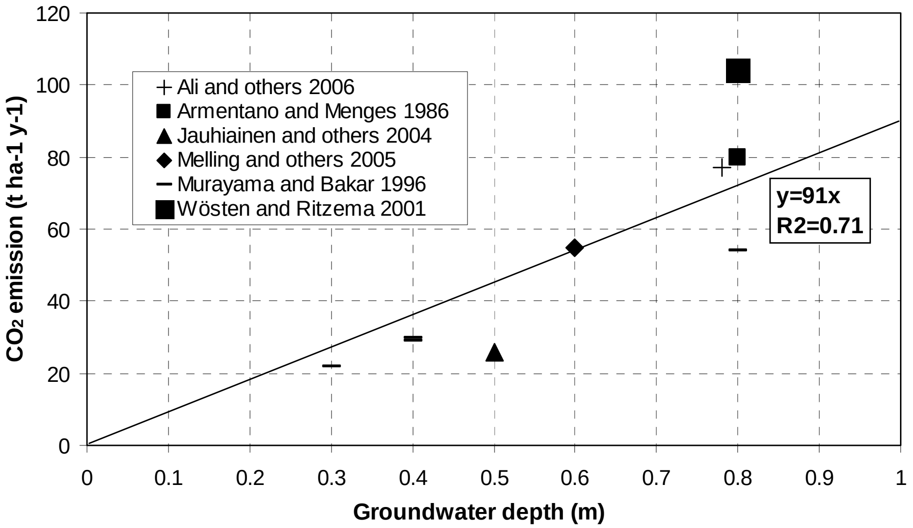

Fig. 4. Linear relation between groundwater depth in peatland and CO_2 emission caused by peat decomposition. The line has been fitted through published measurements in agricultural areas in peatland, including oil palm plantations. Measurements in forest and improductive degraded peatlands are excluded 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 Wosten and Ritzema 2001 data point is based on analysis of subsidence records.

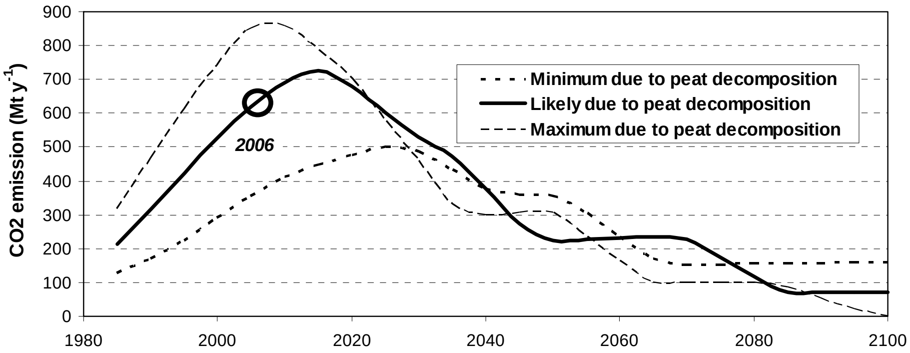

Fig. 5. Historical, current and projected CO_2 emissions from peatlands, as a result of drainage (fires excluded). The increase in emissions is caused by progressive drainage of an increased peatland area. The following decrease is caused by peat deposits being depleted, starting with the shallowest 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).