Current and future CO$_2$ emissions from drained peatlands in Southeast Asia

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Abstract (250 words max)
Forested tropical peatlands in Southeast Asia store at least 42,000 Million metric tonnes of soil carbon. Human activity and climate change threatens the stability of this large pool which has been rapidly decreasing over the last few decades due to deforestation, drainage and fire. In this paper we investigate the emission due to drainage for agricultural and silvicultural development which has dominated, and is expected to dominate, the perturbation of the carbon balance in this part of the world. Present and future emissions from drained peatlands were quantified using data on peat extent and depth, present and projected land use, water management practice and decomposition rates. Of the 27.1 million hectares of peatland in Southeast Asia, 12.9 million hectares are currently deforested and mostly drained; this area is rapidly increasing. Current carbon dioxide (CO$_2$) emissions caused by decomposition of drained peatlands alone, not including the effect of peatland fires, are 632 Mt y$^{-1}$ (range: 355-855 Mt y$^{-1}$). Based on a ‘business as usual’ scenario of land use change, the magnitude of emissions may peak at 745 Mt y$^{-1}$ in coming decades unless land management practices and peatland development plans are significantly changed, and will continue throughout the 21st century. Peatland drainage in Southeast Asia is a globally significant source of CO$_2$ emissions and a major obstacle to meeting the aim of stabilizing global greenhouse gas emissions. It is therefore recommended that international action is taken to help Southeast Asian countries to better conserve their peat resources through both forest conservation and water management improvements aiming to restore high water tables.

**Key words**

peatlands, peat decomposition, water management, drainage, subsidence, CO$_2$ emission, climate change

**INTRODUCTION**

Peat deposits consist of plant remains (some 10% by weight) and water, accumulated in permanently waterlogged and acidic conditions. Peatlands are, more than any other ecosystem, the result of a fine balance between hydrology, ecology and landscape morphology (Page and others 1999). A change in one of these three system components will inevitably lead to a change in the other components and in peat accumulation rate. It follows that human intervention will have a major impact on the peatland hydrological system, and that water management must be carefully adapted to minimize this impact (Hooijer 2005a; Wösten and others 2006a).
Peatlands cover 27.1 Million hectares in Southeast Asia according to the data used in this study (Wetlands International 2003, 2004; FAO 2004). Over 22.5 Million hectares (83%) of this are in Indonesia, where peatlands make up 12% of the land area, with a further 2 Million hectares in Malaysia and 2.6 Million hectares in Papua New Guinea. Peat thicknesses range from less than 1 to up to 20 metres (Page and others 2002); a substantial fraction of peatlands is over 4 metres thick (at least 17% in Indonesia). These numbers yield a total carbon store in Southeast Asian peatlands of at least 42,000 Million tonnes (assuming a carbon content of 60 kg m$^{-3}$).

Peatlands in Southeast Asia are now rapidly being deforested, drained and burnt for development of agriculture (including oil palm and timber plantations) and for logging. These developments cause major changes in the peatland hydrology, and as a result the carbon stored is now being released to the Earth’s atmosphere through two mechanisms:

- Drainage of peatlands leads to aeration of the peat soil and hence to aerobic decomposition of peat material that results in a sustained release of CO$_2$ as illustrated in Figure 1.
- Fires in degraded and often drained peatlands result in further and abrupt release of CO$_2$.

We analyzed present and ‘business as usual’ future CO$_2$ emissions in Southeast Asia caused by peatland drainage, not including the effects of peatland fires. Although the link between peatland development and CO$_2$ emissions is well-known from a vast body of work in Northern Hemisphere peatlands, and research has been published into CO$_2$ emissions due to deforestation in tropical areas (Santilli and others 2005) and from fires in Southeast Asian peatlands specifically (Page and others 2002), little is known on the significance of sustained atmospheric C sources due to drainage in the deep tropical peatlands.

From national and regional perspectives, policy makers are insufficiently aware of the global implications of peatland drainage. This makes it difficult to establish fundamental connections between...
the agendas of development and climate change that would support actions consistent with long term sustainable development (Gullison and others 2007).

In this paper we provide a comprehensive regional analysis of CO\textsubscript{2} emissions from drained peatlands in Southeast Asia pertaining to lowland peatlands in Indonesia, Malaysia, Papua New Guinea and Brunei. The goal of the study is twofold: to improve understanding of the global spatial attribution of sources of atmospheric carbon by providing estimates of carbon emissions from Southeast Asia’s peatlands, and to provide information to national and regional policy makers and local peatland managers working towards a better integration of the development and climate change agendas.

**DATA AND CALCULATION METHODS**

In order to estimate current and future CO\textsubscript{2} emissions from drained peatlands, the following information was obtained: (A) where and how thick the peatlands are, (B) where and how they are drained, (C) what further drainage developments can be expected, (D) how much CO\textsubscript{2} emission is caused by drainage to a certain depth, and (E) how much peat carbon is available for oxidation i.e. how long emission will continue before the peat carbon stock is depleted. The required information is addressed in the following steps (for further details on methodologies and data sources see Hooijer and others 2006).

(A) **Peatland distribution and thickness.** A peatland distribution map (Figure 2) was derived from data provided by Wetlands International 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 (2004) was used to determine peat percentage in soil classes. Peat thickness data for Sumatra, Kalimantan and Papua (Indonesia) were obtained from Wetlands International. Average peat thicknesses for Malaysia, Brunei and Papua New Guinea were conservatively estimated on the basis of thicknesses in Indonesia (Figure 3). For the purpose of this study, we excluded smaller peatland areas found in other Southeast Asian countries which are less studied and represent only a small fraction of the total area and carbon volume. Peatlands over 300m above sea level were also excluded for the same reasons.
(B) **Distribution of drained peatlands in the year 2000.** A drained area map for the year 2000 was derived from a global land cover map, GLC 2000 (Bartholomé and Belward 2005). This dataset has a 1km resolution and is based on a classification of SPOT VEGETATION satellite images for the year 2000. The 16 land cover categories of GLC 2000 were divided into four drainage classes: ‘certainly drained if peatland’ (cropland), ‘probably drained’ (mosaics of cropland and other land uses), ‘possibly drained’ (shrubland and burnt areas) and ‘probably not drained’ (natural vegetation). Cells were accordingly assigned to drained area classes (by fraction of area) as shown in Table 2. Drainage depths for different land uses were estimated from field measurements (Table 2).

Areas of peatland within each drainage class were determined by the following geographic analysis units using the Arc-GIS package: Provinces (in Indonesia), States and Countries (outside Indonesia). The results were then organized by these geographic units and further calculations were performed using this information (Table 1 provides a summary).

(C) **Historical and future trends in peatland drainage.** Historical trends of land use, and therefore of drained area, were derived from changes in forest area between 1985 (FWI/GFW 2002) and 2000 (GLC 2000 data), as shown in Table 1. Overall deforestation rate in peatlands over this period was found to be 1.3%/yr. An independent analysis of forest cover change between 2000 and 2006 for most of Southeast Asia (reported in Hooijer and others 2006) shows that deforestation in peatlands continues at an unchanged rate since 2000. In a ‘business as usual’ scenario, estimates of drained peatland area in 2006 and in future decades are therefore based on unchanged projection of trends over 1985-2000, by Province (in Indonesia), State and Country (outside Indonesia). Rates of land use change within the deforested area, as the deforested area increases, were determined using relations derived from relative areas on peatland of ‘cropland’, ‘mosaic cropland + shrubland’ and ‘shrubland’ within deforested areas in Indonesian Provinces in the year 2000 (Figure 4).
(D) **Relation between drainage depth and CO$_2$ emissions.** The relation between drainage depth and CO$_2$ emissions was based on findings by Wösten and Ritzema (2001), who propose that drainage in agricultural peatlands in Malaysia results in a subsidence rate of 1 cm y$^{-1}$ and CO$_2$ emissions of 13 tonnes ha y$^{-1}$ for every 10 cm of water table drawdown, on the basis of data on subsidence and soil characteristics in drained peatlands. After comparison with findings of a number of gas flux studies in drained peatlands in Southeast Asia (e.g., Ali and others 2006; Hadi and others 2006; Jauhiainen and others 2005), it was estimated that every 10 cm water table drawdown results in 9.1 t CO$_2$ ha y$^{-1}$ (Hooijer and others 2006). This relation needs further development, as in reality it is non-linear and dependent on land cover as well as drainage depth, but it is considered the best estimate now available for drainage depths between 0.5 m and 1m, which is the most common drainage depth range in the study region. It should be noted that CO$_2$ emissions from drained peatlands, on a unit area basis and at the same drainage depth, are far higher in the tropics than in temperate and boreal areas, because the rate of aerobic decomposition is strongly influenced by temperature (Wösten and others 1997).

(E) **Carbon content.** Carbon content of Southeast Asian peat was assumed to be 60 kg m$^{-3}$ (Wösten and Ritzema 2001). This figure was applied to all areas.

**RESULTS**

Using the data and relations described above, the CO$_2$ emission from all geographic units was calculated as follows:

\[
CO_2 \text{ emission} = LU\_Area \times D\_Area \times D\_Depth \times CO_2\_1m \quad \text{[t/yr]}
\]

Where:

- $LU\_Area = $ peatland area with specific land use [ha]
- $D\_Area = $ drained area within peatland area with specific land use [fraction]
- $D\_Depth = $ drainage depth in peatland area with specific land use [m]
It follows that a peatland area drained fully to 0.95 m on average (considered ‘most likely’ in plantations and other large-scale ‘cropland’ areas; Table 2) will emit 86 t CO$_2$ ha$^{-1}$ y$^{-1}$. A peatland area drained to 0.6 m depth (typical in small-scale agricultural areas, i.e. ‘mosaic cropland and shrubland’) for most of its area (88%, Table 2) will emit 48 t CO$_2$ ha$^{-1}$ y$^{-1}$. An area drained to 0.33 m for half its area (considered likely for ‘shrubland’, i.e., recently deforested areas, and burnt and degraded agricultural areas; see Table 2) will emit 15 t CO$_2$ ha$^{-1}$ y$^{-1}$. Following this calculation method, ‘minimum’, ‘most likely’ and ‘maximum’ emission rates for 3 land use types (‘cropland’, ‘mosaic cropland and shrubland’, and ‘shrubland’) were calculated by varying drained area and drainage depth in each land use type (Table 2). The overall range of emissions calculated was between 6 and 100 t CO$_2$ ha$^{-1}$ y$^{-1}$. Values in this range are also reported for several gas flux studies in experimental plots (Ali and others 2006; Furukawa and others 2006; Hadi and others 2006; Jauhiainen and others 2006).

Projections based on land cover data for 1985 and 2000 indicate that about 47% of peatlands in Southeast Asia, or 12.9 Million hectares, 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 affected by intensive drainage for large-scale agriculture (GLC 2000 class ‘cropland’), 67% is affected by moderately intensive drainage for small-scale agriculture (‘mosaic cropland and shrubland’), and 16% is affected by unmanaged drainage in degraded non-agricultural areas (‘shrubland’). This results in an estimated total drained peatland area of 11.1 Million hectares (range: 9.5 - 12.7).

By multiplying CO$_2$ emissions per hectare of each land use type with the total area in that land use class, we estimated that present CO$_2$ emissions from drained peatlands are 632 Mt y$^{-1}$ (range: 355 - 855). If current rates and practices of peatland development and degradation continue, CO$_2$ emissions will peak at 745 Mt y$^{-1}$ in 2015, followed by a steady decline over many decades when increasingly thicker peat deposits become depleted (Figure 5). In the maximum drainage scenario, projected emissions peak at 936 Mt y$^{-1}$ by 2010. After reaching a maximum, CO$_2$ emissions will steadily decline while ever deeper peat deposits are depleted, but they will be significant throughout this century. By
In 2030, total projected emissions are 514 Mt y\(^{-1}\) if peatland drainage continues unmitigated; by 2070 they would still be 236 Mt y\(^{-1}\).

Cumulative CO\(_2\) emissions from all peatlands in Southeast Asia were calculated at 9,700 Mt (range: 5,300-13,700) by 2006, 25,900 Mt (range: 17,200-31,000) by 2030 and 37,300 Mt (range: 28,900-39,900) by 2070. Indonesia with its vast peat resources is the single largest CO\(_2\) emitter from drained peatlands, responsible for 82% of Southeast Asian emissions in 2006, with Sumatra being the largest emitter closely followed by Kalimantan.

(Figure 5 near here)

**DISCUSSION**

Current CO\(_2\) emissions from drained peatlands in Southeast Asia (excluding emissions from fires) are estimated to be 632 Mt y\(^{-1}\) year (range: 355 – 855). This is equivalent to 2.4% of the 26.4 Billion metric tonnes of CO\(_2\) y\(^{-1}\) of global emissions from fossil fuel combustion during the period 2000-2005 (IPCC 2007). In a ‘business as usual’ scenario that extends current drainage trends into the future, emissions from drainage will further increase in coming decades before starting to decrease due to depletion of shallower peat resources. Emissions from the deeper peatlands will continue throughout this century.

Further CO\(_2\) emissions from degraded and drained peatlands are associated with peatland fires, which during non-ENSO (El Niño-Southern Oscillation) years can be of similar magnitude to those from decomposition and several times larger during ENSO years. Page and others (2002) estimated that emissions from peatland fires in Indonesia during the 1997 ENSO were 3000 Mt CO\(_2\) (range: 1800 – 8800), equivalent to 14% of global emissions from fossil fuel combustion. An assessment on the basis of this figure and of annual ‘fire hotspot’ counts in Borneo over the period 1997-2006 estimated an average emission of 1400 Mt CO\(_2\) y\(^{-1}\) from peatland fires in Southeast Asia (Hooijer and others 2006). This brings the total CO\(_2\) emissions to about 2000 Mt y\(^{-1}\) or equivalent to 7.6% of current global CO\(_2\) emissions from the combustion of fossil fuel.
One final component needs to be computed to understand the full impact of drainage and loss of forest in peatlands on the net carbon balance of tropical swamp forests: the loss of carbon sink capacity. Peatlands in their natural state store carbon at an average rate in the order of 84 g C m\(^{-2}\) y\(^{-1}\) (Page and others 2004; Rieley and others 1996). Loss of all peatland forest in Southeast Asia means a loss of CO\(_2\) uptake capacity of 84 Mt y\(^{-1}\). The present loss of peatland forest in SE Asia has already reduced global CO\(_2\) uptake capacity by at least 40 Mt y\(^{-1}\).

The emissions from drained peatlands in Southeast Asia, even without including the effect of fires, contribute more to atmospheric greenhouse gas emissions than industrialized nations like Germany or the United Kingdom produce by the combustion of fossil fuels (804 and 558 Mt y\(^{-1}\) respectively, CO\(_2\) emission in 2003, CDIAC 2007). Emissions from drained peatlands are produced on what is effectively only less than 0.1% of the global land area. Deforested and drained peatlands in Southeast Asia are major Earth system hotspots for carbon emissions rivalled by few, if any, CO\(_2\) emission sources in terms of emission per unit area.

Although deforestation and drainage are the current dominant factors driving carbon emissions from peatlands, future climate change will add further pressure to peat ecosystems and most likely enhance carbon emissions. An analysis of climate projections contributing to the IPCC Fourth Assessment show that 7 out of 11 models predicted that by the end of this century there will be a decrease of rainfall during the dry seasons in a number of regions of Southeast Asia (Li and others 2007). Moreover, 9 out of 11 models predict greater interannual variation in dry season rainfall. These changes are strongest and most consistent across the 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 suitable aerobic conditions for decomposition, and hence larger CO\(_2\) emissions. A further potential effect of climate change on CO\(_2\) emissions from peatlands is supported by field studies in southern Sumatra which shows strong positive influence of increased soil temperature on CO\(_2\) emission (Ali and others 2006).

The carbon consequences of recent El Niño years are a good window into the future to understand the likely positive feedbacks of climate change (lower rainfall and higher air temperatures) and continued
land use change (deforestation and drainage). Particularly vulnerable are degraded areas where the natural self-regulating hydrological systems have been lost and no artificial water level control system has been implemented.

**Sustainability of peatland drainage and environmental consequences**

Drainage of peatlands in Southeast Asia often does not bring sustainable agricultural or economic development. Most peatlands are located at or close to the Sea coast, with surface elevations only a few metres above Sea level and the mineral subsoil often below the gravity drainage base, so continued subsidence of the drained peat surface (caused by compaction, aerobic decomposition and fires) will ultimately cause the peat area to become undrainable, often within decades of the initial excavation of canals (Hooijer 2005b). Inundation frequency will increase and areas below the high-water level will be affected by salt water intrusion. As the cost involved in non-gravity drainage (i.e. water pumping) is usually too high to be economical in this region, agricultural productivity will decline. Another cause of reduced productivity and sometimes abandonment of coastal drained peatland areas is when the mineral subsoil is aerated and acid sulphate problems develop, as are common along many coastlines in Southeast Asia.

Furthermore, an array of environmental and socio-economic impacts occurs as a result of deforestation and drainage. Peat fires cause haze (smoke) problems which affect public health and economy (e.g. transport, tourism) in much of the Southeast Asian region. Loss and degradation of conservation forest affects biodiversity and natural timber production in the longer term. Flooding problems are reported, but not quantified, downstream of drained and burnt peatland areas such as the former Mega Rice Project in Indonesia (Wösten and others 2006b).

**Perspectives for sustainable peatland management**

Given the high CO₂ emissions, per unit area and in absolute terms, and the relatively small area involved from a global perspective, it seems that emissions from peatland deforestation and mismanagement in Southeast Asia are both important enough to require international action and ‘compact’ enough for mitigation policies to be effective. Carbon emissions and other negative effects resulting from unsustainable peatland management can be reduced, particularly in Indonesia, if
international support is provided to adopt and implement a land development policy based on the following three principles:

1. Forest conservation and drainage avoidance in remaining peat swamp forests.
2. Where possible, rehabilitation of degraded peatlands through restoration of natural hydrological systems and of forest cover.
3. Raised water levels through improved water management in existing plantations in peatlands, embedded in water management master plans for peatland areas.

Improved water management is the basis of conservation of peat resources in Southeast Asia. Current management priority in most agricultural areas in peatlands is to prevent high water levels in the wet season, and in many cases to maintain boat access along canals during the dry season. However the excessive drainage capacity maintained in such a system, without further mitigative measures, also leads to a drop in water table depth below the peat surface by more than 1 or often even more than 2 metres during the dry season in many drained peatland areas. Such low water levels can often be prevented through improved water management which stabilizes water levels by adjusting drainage capacity to meet seasonal requirements (Wösten and Ritzema 2001, Hooijer 2005b). However such management is more costly and requires specific technical knowledge that is often not available locally.

One important issue that was not addressed in the analysis, but which should be taken into account in peatland water management, is the fact that drainage affects peatlands over large distances, well beyond the 1km cell resolution used in the analysis. This means that a single road or small plantation in peatland will cause peat surface subsidence, CO2 emission and enhanced fire risk over much larger areas. It also implies that exclusion from development of peat deposits over 3 metres thick as is now the law in Indonesia (although rarely enforced), is of limited practical relevance as in time most peat deposits will be less than 3 metres thick through progressive subsidence following drainage, and would become available for development. It seems more practical and realistic to recognize that peat ‘domes’ are self-contained hydrological units that may be kilometres or tens of kilometres across; interventions in part of the unit will in the long term affect the entire unit. Single peat domes are therefore best managed under a single water management regime or at least a water management regime that aims to
maintain the hydrological integrity of most of the unit. A decision may be made to develop a peat dome for agriculture/silviculture, or to conserve it as an undrained forest area, but combining development and conservation can often not be sustainable unless major and costly water management measures are taken and maintained in buffer zones that are a minimum width of several kilometres.

Finally, an issue which deserves further attention is the fact that development of oil palm (and pulp wood, for paper production) plantations is a major cause of peatland deforestation and drainage in Southeast Asia. The global demand for palm oil is growing fast, and according to research by the Indonesian Ministry of Forestry and the European Union (Sargeant 2001) much of the 300,000 ha additional oil palm plantation development required annually will take place in Indonesia’s peatlands. Some 25% of palm oil is already produced on peatlands and this percentage is expected to rise (Hooijer and others 2006). A major driver of the increasing demand for palm oil is its use as a biofuel in the European and other markets, with the aim of reducing global CO$_2$ emissions to meet targets under the Kyoto Protocol. We suggest that the CO$_2$ emission from drained peatlands should be taken into account when considering use of palm oil as a biofuel.

**Future research for reduced uncertainties**

In this section we discuss the main uncertainties of this analysis and identify knowledge gaps with the aim to guide future research priorities.

- **The thickness** of many peatlands in Indonesia is not very well known. Peat thicknesses tend to be greatest in the central parts of the inaccessible and often vast dome-shaped peat bodies, often tens of kilometres across. Many of the measurements on peat thicknesses are nearer to the fringes. For this study no data was available on thickness of peatlands in Malaysia and Papua New Guinea; conservative estimates were used. Overall, this is likely to result in underestimation of peat thickness and the size of the carbon stock. With the data used, the original carbon stock in Southeast Asia is calculated at 42,000 Mt; this is at the low end of published estimates.

- **Data on extent and distribution** of peatlands can be improved, especially for areas outside of Kalimantan and Sumatra.

- **Carbon content** of Southeast Asian peat was assumed to be 60 kg m$^{-3}$ (Wösten and Ritzema, 2001), while carbon contents up to 90 kg C m$^{-3}$ have been reported for various peat deposits (e.g.
Wetlands International 2003, 2004). Assuming higher carbon content would result in higher total carbon stocks and higher CO$_2$ emissions from peatland drainage.

- **Drainage intensity** as derived from the GLC 2000 global land cover classification may not always be accurate, for example in the case of Papua (Indonesia). Here, areas now classified as ‘mosaic cropland + shrubland’ are known to actually be a savannah-like landscape created by traditional land management techniques requiring regular burning (Silvius and Taufik 1990). These areas are generally not ‘drained’ in the normal sense; agriculture often takes place on elevated islands of dug up mud (from the submerged swamp soil). This may have lead to an overestimate of CO$_2$ emissions from Southeast Asian peatlands, with a maximum of 16% in the unlikely case that emissions from Papua would actually be negligible.

- The **percentage of peatland drained** within land use classes was estimated from field work which naturally did not cover all peatland regions. The percentage of drained peatland may be much larger than assessed here, as several interventions in the hydrological system are not taken into account. These are A) log transport canals in forested areas where legal or illegal logging takes place, and B) the impacts of plantation and roadside drainage over distances of kilometres in forested areas. Peatland fires also have a draining effect on the remaining forested peatland as they create depressions in the peat surface. Over 90% of peat swamp forests in Sumatra was already affected by human interventions in the early 1990s (Silvius and Giesen 1992), so probably only few peatlands in Sumatra, Kalimantan and Malaysia are not affected by drainage at present.

- Estimated likely **drainage depths** may be greater than those recommended in existing management guidelines, but are shallower than depths often observed by the authors in practice. Drainage depths between 1 and 2 metres are often observed in oil-palm and pulp wood plantations. In unsuccessful and abandoned plantations such as the ex-Mega Rice Project in Central Kalimantan (with over 1 million hectares of derelict drained peatland), drainage depths of up to 3 metres are reportedly common in the dry season. The ‘likely’ average drainage depth of 0.95m, as assumed for plantations and other cropland areas in this assessment, is considered an underestimate.

- Values for **current (2006) land use** were based on GLC 2000 data from 2000, as this is the most up-to-date published and validated land use dataset available for all of Southeast Asia. More recent land use data would have yielded more accurate results.
• The ‘business as usual’ land use projection used is a continuation of past trends, so assuming there will not be major changes on peatland conservation and management strategies. The projection method for land uses in deforested peatland area limits the area of intensively drained ‘cropland’, including plantations, to 21% of the total peatland area. In reality, the registered area of palm oil and timber plantation concessions alone, which require very intensive drainage, is already 23% of the peatland area in Indonesia (Hooijer and others 2006). In addition, many plantations and other agricultural projects are developed outside this concession system. There are expectations that most of the annual global increase in oil palm plantations, 300,000 ha y

\( -1 \) for the next 15 or 20 years, will be developed in Indonesia’s peatlands (Sargeant 2001). It is therefore conceivable that over 50% of peatlands will be intensively drained in a few decades; this would result in a CO\(_2\) emission of at least 20% higher than calculated.

• Projections have not taken into account peatland drainability and future management responses. If peatlands become less productive because of increased flooding due to subsidence, they may be abandoned and drainage and CO\(_2\) emissions may theoretically be reduced. Part of the carbon stock in peatlands is below the drainage base and may never be oxidized. On the other hand, the current experience is that abandoned peatlands continue to be drained (as drain blocking is labour intensive and reduces access), and frequently experience fires in dry years when drainage is not an issue. The Ex Mega Rice Project area is an example of this.

• Carbon dioxide emission resulting from a specific drainage depth is a very sensitive parameter in the calculations. Few long-term studies of subsidence rates in drained peatlands in Southeast Asia have been published. Short-term studies of CO\(_2\) emissions are difficult to interpret because A) CO\(_2\) emissions from root respiration must be separated from emissions caused by decomposition, B) short-term effects (shortly after drainage) must be separated from long-term effects, C) water table and soil moisture regime are often insufficiently quantified, and D) an unknown part of the carbon will not be emitted to the atmosphere but will leave the drained peatland in dissolved form with the drainage water to end up in the Sea (where much of it will likely be oxidized and add to atmospheric CO\(_2\) concentration after all).

• The only form of carbon emission to the atmosphere considered in this assessment is CO\(_2\) emission. Methane (CH\(_4\)) emissions from both undrained and drained peatlands are found to be modest in comparison with CO\(_2\) (Jauhiainen and others 2005; Takashi and others, this volume), but
may still be significant from a climate perspective given that \( \text{CH}_4 \) is a much stronger greenhouse gas (23 times stronger in ‘\( \text{CO}_2 \) equivalents’). \( \text{CH}_4 \) emissions in drained peatlands may originate especially where peat areas are increasingly flooded for prolonged periods, after fires or after subsidence due to drainage, and reduced conditions are created in the inundated peat soil, but this process has not been investigated to date.

- Several studies confirm that **peatland fires** occur mainly in deforested and degraded areas (Siegert and others 2001; Page and others 2002; Spessa and others, this volume) and are linked to water table drawdown through drainage. Although this relation has not yet been quantified, \( \text{CO}_2 \) emission from Southeast Asia due to peatland fires is highly uncertain as shown in the discussion section but can be as much as double the amount of emissions from peat decomposition. Emissions from peatland fires are not included in the assessment presented here, which results in a significant uncertainty in \( \text{CO}_2 \) emissions related to peatland drainage.

It is concluded that most remaining uncertainties in \( \text{CO}_2 \) emissions from drained peatlands in Southeast Asia are greater to the upside than to the downside. This implies that \( \text{CO}_2 \) emissions caused by drainage in Southeast Asian peatlands are more likely to be above the middle estimate (most likely value, fire emissions excluded) of 632 Mt y\(^{-1}\) than to be below this value.

It should be noted that most uncertainties pertain to the annual estimates of \( \text{CO}_2 \) emission rather than the total \( \text{CO}_2 \) emission over the next 50 or 100 years. That is because in the ‘business as usual’ scenario a lower current emission rate simply means that it will take a few decades longer for the carbon stored in shallower peat layers to be depleted, but eventually it will still be emitted to the atmosphere.

Further work is required to reduce all the uncertainties listed above. In the short term the greatest reduction in the overall uncertainty in \( \text{CO}_2 \) emissions from drained peatlands in Southeast Asia may be achieved through more up-to-date and accurate land use maps. In the longer term the greatest reduction may be achieved through comprehensive field studies of \( \text{CO}_2 \) emissions (and other carbon balance components) and subsidence rates in relation to hydrological (especially water level and soil moisture) and biological (especially vegetation cover) parameters under different water and land management practices.
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## Tables

### Table 1 Lowland peatland distribution land use and rate of forest cover loss.

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

** Table 2 CO₂ emission calculation steps and main parameters. **

| Step A: Drained area (within land use class) | Large croplands, including plantations | % | 100 | 100 | 100 |
| Step B: Drainage depth (within land use class) | Large croplands, including plantations | % | 100 | 100 | 100 |
| Step C: A relation of 0.91 t/ha/y CO₂ emission per cm drainage depth in peatland was used in calculations. |

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| Step C: A relation of 0.91 t/ha/y CO₂ emission per cm drainage depth in peatland was used in calculations. |

** Step D: CO₂ emissions (calculated from A, B, C) | Large croplands, including plantations | t/ha/y | 73 | 86 | 100 |
| Step E: CO₂ emissions (calculated from A, B, C) | Large croplands, including plantations | t/ha/y | 73 | 86 | 100 |
Figures

Figure 1 Schematic illustration of CO$_2$ emission from drained peatlands.

Figure 2 Forest cover on peatland in the year 2000. Note that FAO non-histosol soil classes with 20-40% peat are not shown, hence the peat extent is greater than shown – e.g. Papua New Guinea has significant peatland cover.
Figure 3 Carbon stored in peatlands, by region and by thickness (source: Wetlands International). Average peat thickness in Malaysia and Papua N.G. was estimated from peat thickness in Kalimantan and Papua (Indonesia) respectively.

Figure 4 Trends and projections of land use change in lowland peatland in SE Asia.
Figure 5  Historical, current and projected CO2 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 (see Figure 3). The stepwise pattern of this decrease is explained by the discrete peat thickness data available (0.75m, 1.5m, 3m, 6m, 10m).