Environmental and Social Impacts of Oil Palm Cultivation on Tropical Peat – A Scientific Review

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ENVIRONMENTAL AND SOCIAL IMPACTS OF OIL PALM CULTIVATION ON TROPICAL PEAT
A SCIENTIFIC REVIEW

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ABSTRACT

This report provides a review of available scientific information and published literature on impacts of using tropical peat for oil palm cultivation in Southeast Asia. It describes carbon flows and greenhouse gas (GHG) emissions from native and degraded forest and oil palm plantations on peat, as well as other environmental impacts and social and economic aspects of the cultivation of oil palm on peat. Based on the available literature, the report presents conclusions on the gaps in knowledge, uncertainties and confusion in existing datasets.

The palm oil sector has created in the past few decades millions of jobs. Over the next decade, the Indonesian government plans to double the annual production of palm oil, creating new jobs for an estimated 1.3 million households. Although the cultivation of oil palm on peatlands creates new income opportunities for many farmers in the short term, longer term economic implications remain uncertain. Transformation of tropical peat forest into plantations will lead to the loss of ecosystem services and biodiversity and will affect the social and cultural basis of forest dependant communities. Human health is affected negatively by haze resulting from forest and peat fires related to land preparation and drainage of the peat. There may be other negative ecological consequences linked to soil subsidence, which can lead to flooding and salt water intrusion when water tables reach levels and the land becomes undrainable.

When peat is developed for agriculture, carbon is lost as CO2 because: 1) oxidation of the peat; 2) fire; and 3) loss from biomass due to land use change. The simplest way to limit CO2 and other GHG emissions is to avoid the development of oil palm plantations on peat. Development of plantations on mineral, low carbon, soils has fewer impacts in terms of GHG emissions. For existing plantations on peat, effective water management (keeping water tables as high as practical) reduces GHG emissions, soil subsidence and fire risk. Nonetheless, even these measures will not turn the system into a carbon or GHG sink.

Keywords: *tropical peat, oil palm cultivation, forests, carbon, greenhouse gases, biodiversity, socio-economic impacts, Southeast Asia.*

INTRODUCTION

Context

On November 4th 2009, a resolution was adopted at the 6th General Assembly of the Roundtable on Sustainable Palm Oil (RSPO) on the 'Establishment of a working group to provide recommendations on how to deal with existing plantations on peat' (Box 1). In the justification for the resolution, it was noted that peat lands are the most efficient and the largest terrestrial carbon store. Accounting for less than 3% of the global land surface, they store more carbon than all terrestrial biomass, and twice as much as all forest biomass. It was mentioned that peat land ecosystems and their natural resources are under great threat as a result of large scale reclamation, deforestation and drainage, causing degradation and the loss of soil carbon by oxidation.

The resolution also referred to the first RSPO greenhouse gas (GHG) working group, which had been established to investigate and develop principles and criteria for reducing GHG emissions from land use change, had not been able to reach a consensus on the issue of how to deal with existing oil palm plantations on peat. It was noted that even when assuming minimum estimates of CO_2 emissions from existing oil palm plantations on peat, these plantations were not sustainable because of such emissions. In addition it mentioned that besides GHG issues, oil palm plantations on peat also result in significant on- and off-site hydrological impacts such as soil subsidence and reduced water retention capacity. The resolution therefore called for the RSPO General Assembly to agree to establish a Committee, later known as the Peatland Working Group (PLWG) to explore and develop business models for optimising sustainability of existing oil palm plantations on peat, including options for restoration and after-use of peat, development of alternative economic uses, and application of water management regimes that lead to reduce emissions. The resolution was adopted by an overwhelming majority of RSPO members.

Box 1

Background and objectives of the RSPO Peatland Working Group (PLWG)

The objective of the Roundtable on Sustainable Palm Oil (RSPO) is to promote the growth and use of sustainable palm oil products through credible standards and the engagement of stakeholders. The Peat Land Working Group (PLWG) as part of the RSPO is a short-term, multi-stakeholder expert panel established to review the impacts of plantation development and palm oil production in terms of carbon and greenhouse gas emissions, as well as any additional effects on biodiversity, livelihoods. The panel seeks to advise the Executive Board regarding actions and processes that will lead to meaningful and verifiable reductions in greenhouse gas emissions in the palm oil supply chain. This review of the scientific literature on the impacts of oil palm plantation development is meant to provide a baseline for recommendations for reducing greenhouse gas emissions for palm oil production on peat and its associated management.

This report was commissioned by the RSPO PLWG and provides a review of available scientific information on the impacts of the use of tropical peat soils for oil palm cultivation in Southeast Asia. It assesses sources of uncertainty and gaps in knowledge, and structures the findings of available publications related to the cultivation of oil palm on tropical peat. In summary, the objectives of the review are:

- Examine the effects of establishing oil palm plantations on tropical peatlands on fluxes of CO_2 and other GHGs, and on other ecological, social, economic and livelihood issues.
- Define the spatial boundaries of the system and the major categories of GHG sources and sinks.
- Highlight uncertainties and gaps in knowledge.
- Provide recommendations for reducing GHG emissions and other adverse impacts.

Tropical peatlands

The United States Department of Agriculture (USDA) defines peat as soils as histosols where more than half of the upper 100 cm consisting of organic matter. Peat is often also defined as a soil that contains at least 65% organic material, is at least 50 cm in depth, covers an area of at least 1 ha and is acidic in nature (Driessen, 1978; Wösten & Ritzema, 2001). The formation of peat depends on plant cover and hydrological conditions. Peat lands have their greatest extent in the boreal and temperate zones. Tropical peats are located in Southeast Asia, Africa, the Caribbean, and Central and South America and are also important components of the global terrestrial carbon (C) store in terms of both their above ground biomass (AGB) and their large underlying peat mass (Rieley *et al*., 1996; Page *et al.,* 1999, 2004, 2011). Differences exist between peats in different climatic zones (Box 2). The most extensive tropical peat lands occur in Southeast Asia, representing 77% of the global tropical peat carbon store (Page *et al*., 2011b), most of which are located in Indonesia with 22.5 Mha (65% of global total of tropical peat) and Malaysia with about 2.4 Mha (10%) (Hooijer *et al.,* 2010). Awareness of the significant role that tropical peats and their forests play in the global carbon cycle has improved , and. while the full magnitude of this role is still uncertain (Malhi, 2010), recent studies have greatly increased our understanding of carbon emissions arising from peat land disturbance, especially for peat in Southeast Asia.

Box 2

Tropical lowland peat versus temperate and sub-arctic peat

Tropical lowland peat differs from temperate and sub-arctic peats. The latter are mainly derived from the remains of herbaceous plants (mainly species of *Sphagnum, Gramineae and Cyperaceae*) while tropical lowland peats are formed from the remains of woody forest species and, consequently, tend to have large amounts of undecomposed and partially decomposed trunks branches and woody roots that cause tropical peats to be formed at a much faster rates when compared to temperate peat bogs. Peats in cold and temperate regions are composed of humus-like compounds derived from decomposed cellulose, but peats in lowland swamp formations in tropical countries are composed largely of lignin, the compound that distinguishes wood from straw. Tropical peat soils decompose rapidly when exposed to aerobic conditions and drained peats usually consists of three horizons differentiated by their level of humification. The top or sapric horizon is most humified, followed by the hemic horizon (partially humified), while the bottom fibric horizon consists essentially of un-decomposed woody material.

Tropical peats in Southeast Asia occupy mostly in low altitude coastal and sub-coastal environments and extend inland for distances of hundreds of kilometres along river valleys and across watersheds. Most of these peatlands are located at elevations less than 50 m above mean sea level. Southeast Asian peats are largely ombrotrophic (receiving water by precipitation only), while a few basin peats are minerotrophic (receiving ground water and/or run off water) (Page *et al*., 2010). Peats occur along the coasts of East Sumatra, Kalimantan (Central, East, South and West), West Papua, Papua New Guinea, Brunei, Peninsular Malaysia, Sabah, Sarawak, Southeast Thailand and the Philippines, and can be subdivided into three main categories: 1) coastal, 2) sub-coastal or valley, and 3) high, interior or watershed (Rieley *et al*., 1996; Page *et al*., 1999, 2006). A combination of low topographic relief, waterlogged conditions, high effective rainfall and impermeable substrates provided conditions suitable for the accumulation of thick deposits of peat in these areas (Page *et al.,* 2010).

Information on peat structure, age, development and rates of peat accumulation is scarce. However, the study by Page *et al*. (2010) shows peat depth and carbon accumulation rates for four sites (in Peninsular Malaysia, in Kalimantan and in two areas in Sumatra), with depths ranging from 5.5 – 13.5 meters and accumulation rates ranging from 0 – 40 mm yr^{-1}. Peat accumulation occurs when the average rate of carbon sequestration exceeds the losses due to decomposition or runoff (Page *et al*., 2011b). Carbon content of tropical peat usually ranges between 40% and 60% depending on the nature, mineral content and location of the peat.

A study by Dommain *et al.* (2011) reported a mean Holocene carbon sequestration rate of 31.3 g C m^{-2} yr^{-1} for Central Kalimantan and 77.0 g C m^{-2} yr^{-1} for coastal sites in Indonesia, with the C content of the peat being 50-60% of its dry weight; a C content in line with results of studies by Neuzil (1997) and Page *et al.* (2004) in Central Kalimantan. The basic principle for the quantification of total organic carbon relies on the destruction of organic matter present in the soil. This can be performed chemically (the method often used in the past) or by using heat (the current method). In the studies where chemical methods were used, carbon contents were underestimated, giving values of 20-30% in tropical peat. Currently, the method using elevated temperatures is recommended.

The peat ecosystem

The carbon balance of tropical peat ecosystems is a result of CO_2 uptake by photosynthesis and release by respiration. The respiration component consists of heterotrophic respiration (decomposition of the peat by microbes) and autotrophic respiration (respiration from plant roots) (Page *et al.*, 2011a). Besides their function as carbon sinks, tropical peat lands are unique ecosystems with a high biodiversity . Species diversity is regarded as one of the fundamental prerequisites of ecosystem stability. Until a few decades ago, tropical peat forests remained relatively undisturbed and acted as sinks for carbon. However, as a result of economic exploitation during the past two decades, peat swamp forests have been subject to intensive logging, drainage and conversion to plantations (Rieley & Page, 2002), and have thus been transformed into C sources.

Posa *et al.* (2011) state that the current extent and condition of tropical peatlands in Southeast Asia is still unclear, as accurate delineation of peat soil is difficult and many areas have already been lost or degraded. Using published estimates from various sources, they calculated the maximum remaining area of historical peat swamp forest to be 36.8% (*Table 1*).

The distribution of peat in Malaysia, Indonesia and Brunei in 2000 was determined by Wetlands International Malaysia (2010) using literature and satellite data (*Table 2*). In Malaysia, 7.5% of the total land area encompasses peat soils, of which Sarawak supports the largest area (69.1% of the total peat area in Malaysia), followed by Peninsular Malaysia (26.1%) and Sabah (4.8%) (Wetlands International, 2010). Wahyunto *et al.* (2005) reported that 10.8% of Indonesia's land area is comprised of peat lands, with Sumatra having 7.2 Mha, Kalimantan 5.8 Mha, Papua 7.9 Mha and other regions around 0.5 Mha. Page *et al.* (2010) have also published their best estimates of peat area, thickness and volume in Southeast Asia as shown in *Table 3*.

Table 1. Estimates of major peat swamp forest area (in ha) in SE Asia (Posa et al., 2011).

Region	Initial Area (ha)	Remaining (ha)	% remaining	Protected (ha)	% Protected
Indonesia					
Sumatra	8,252,500	2,562,200	31.1	721,200	8.7
Kalimantan	6,787,600	3,160,600	46.6	763,200	11.2
Sulawesi	311,500	1,800	0.6	30,000	9.6
Malaysia					
Peninsular	984,500	249,200	25.3	44,400	4.5
Sabah and Sarawak	1,746,000	632,800	36.2	98,400	5.6
Brunei	104,000	87,300	83.9	21,800	21.0
Thailand	68,000	30,400	44.7	20,600	30.3
SE Asia Total*	**18,254,100**	**6,724,300**	**36.8**	**1,699,500**	**9.3**

*excluding Papua New Guinea

Table 2. The lowland peat extent in Southeast Asia and the estimated peat carbon stock, forest cover in 2000 and total area of degraded peatland using satellite data (WI Malaysia, 2010).

Country	Peat area (ha)	Peat carbon stock (Mton C)	Forested peatland in 2000 (ha)	Total degraded peatland area (ha)
Indonesia	26,550,000	54,016	14,000,000*	12,500,000
Brunei	99,100	98	85,000	14,000
Malaysia	2,668,500	5,431	140,000	1,200,000

**Bappenas estimated 14.000.000* ha *peat for Indonesia in 2009.*

Table 3. Best estimates of peat area, mean thickness and volume of peat in tropical Southeast Asia (Page et al., 2010).

Country	Peat area (ha)	Average peat thickness (m)	Volume ($m^3 * 10^6$)
Indonesia	20,695,000	5.5	1,138,225
Brunei	90,900	7	6,363
Malaysia	2,588,900	7	181,223
Myanmar (Burma)	122,800	1.5	1,842
Papua New Guinea	1,098,600	2.5	27,465
Philippines	64,500	5.3	3,418.5
Thailand	63,800	1	638
Vietnam	53,300	0.5	266.5

Land use change

Deforestation

In Indonesia, peat development is most extensive in Sumatra, followed by Kalimantan; most of the peat formations in Papua remain undeveloped. In Malaysia, deforestation rates in the past 6 years were highest in Sarawak with a yearly deforestation rate of around 8% on average for peat land (SarVision, 2011; *Table 4a*), and an overall deforestation rate of around 2% in the last 5 years for all soil types (SarVision, 2011; *Table 4b*).

Table 4a. Yearly deforestation of peatland in Sarawak,Malaysia in the period 2005-2010 (SarVision, 2011)

Year	Forest area (ha)	Forest area change (ha)	% change
2005	1,055,896.7	No data	No data
2006	990,437.6	-65,459.1	-6.20
2007	924,978.5	-65,459.1	-6.61
2008	847,256.4	-77,722.1	-8.40
2009	769,534.3	-77,722.1	-9.17
2010	702,966.7	-66,567.5	-8.65

Table 4b. Yearly total deforestation in Sarawak, Malaysia in the period 2005-2010 (SarVision, 2011).

Year	Forest area (ha)	Forest area change (ha)	% change
2005	8,984,450.7	No data	No data
2006	8.814,801.7	-169,648.9	-1.89
2007	8,645,152.8	-169,648.0	-1.92
2008	8,470,649.8	-174,503.0	-2.02
2009	8,296,146.8	-174,503.0	-2.06
2010	8,118,614.4	-177,532.4	-2.14

Table 5 lists studies on peat swamp forest loss for different areas in Southeast Asia. Overall, deforestation rates in Sarawak, Malaysia are the highest and SarVision (2011) reported that 41% of the peat soil in Sarawak was covered by oil palm plantations by 2010. In a study by Miettinen *et al.* (2011), deforestation rates in insular Southeast Asia were determined by comparing satellite imagery between 2000 and 2010 using a spatial resolution of 250 m to produce land cover maps using regional classification schemes (*Table 6*). The results revealed an overall 1.0% yearly decline in forest cover when considering Brunei, Indonesia, Malaysia, Singapore and Timor Leste, of which 68%-80% of the total study area was turned into plantations or underwent regrowth (shrub land to young secondary forest). In the past years, deforestation rates for peat swamp forest were higher than deforestation rates for forests on mineral soils.

By excluding Papua and the Moluccas from the analysis, the yearly rate of forest loss for Indonesia rises to 1.5% (3.3% for peat swamp forest). The highest deforestation rates were found for the eastern lowlands of Sumatra (mainly Riau and Jambi provinces) and for the peat lands of Sarawak. In both of these areas deforestation was concentrated in peat lands. Riau and Jambi provinces together had lost 40% by the peat swamp forest cover by 2010, while in Sarawak the extent of peat swamp forests decreased by 55% (Miettinen *et al*., 2011). Earlier studies of these areas reported average yearly deforestation rates of 1.7% between 1990-2000 (FAO, 2006), 2.0% between 1997-2002 for Borneo (Fuller *et al*., 2004) and 1.5% between 1990-2000 for Indonesia (Hansen *et al*., 2009).

Miettinen *et al.* (2012) did an extensive study using high-resolution satellite imagery to analyse sequences and interrelations in the progression of peat degradation and conversion processes in Sumatra, Indonesia (*Table 7*). Changes were monitored in three study areas of 2,500–3,500 km^2 since the 1970's and examined in conjunction with satellite-based active fire data sets. They concluded that forests disturbed by intensive logging and/or drainage are merely intermediate stages leading to further change, such as plantation establishment.

Table 5. Peat swamp forest loss (%) for different areas in Southeast Asia, for different periods in time.

Area	Period	Reference	Peat swamp forest converted to other LU % of peat forest (average)
Insular SE Asia	2000-2005	WI Malaysia 2010	1.47
Sarawak	2005-2007	SarVision 2011	7.1
Sarawak	2009-2010	SarVision 2011	8.9
Malaysia and Indonesia	2000-2010	Miettinen *et al* 2011	2.2
Borneo	1997-2002	Fuller *et al* 2004	2
Indonesia	1990-2000	Hansen *et al* 2009	1.5

Table 6. Forest cover change from 2000-2010. Peat swamp forest numbers are given in Italics (Miettinen et al., 2011)

Area	2000		2010	
	x 1000 ha	%	x 1000 ha	%
Peninsular Malaysia	5,388 ***287***	41.1 ***2.2***	4,947 ***235***	37.7 ***1.8***
Sumatra	14,555 ***3,131***	33.5 ***7.2***	11,104 ***1,839***	25.5 ***4.2***
Borneo	41,688 ***4,182***	56.6 ***5.7***	36,688 ***3,144***	49.8 ***4.3***
Java	866 ***0.0***	6.8 ***0.0***	902 ***0.0***	7.1 ***0.0***
Sulawesi	8,959 ***0.0***	53.0 ***0.0***	7,993 ***0.0***	47.1 ***0.0***
New Guinea	31,625 ***6,336***	84.4 ***17.0***	30,859 ***5,970***	82.7 ***16.0***
Indonesia	94,867 ***12,740***	51.3 ***6.9***	86,039 ***10,541***	46.5 ***5.7***
Malaysia	17,242 ***1,230***	52.4 ***3.7***	14,962 ***673***	45.4 ***2.0***
Total study area	112,536 ***13,970***	51.2 ***6.4***	101,434 ***11,214***	46.1 ***5.1***

Table 7. Land cover changes in the study areas (1970's – 2009/2010) in Sumatra (Miettinen et al., 2012).

Land Cover	North Sumatra		Riau		Jambi			
					Outside Berbak nat. park		Inside Berbak nat. park	
	1977	2009	1979	2010	1970's	2009	1970's	2009
Nearly pristine forest	190.8	0	202.4	5.56	183	53.1	120.1	92.2
Mod. Degr. forest	14.6	2.9	0.6	2.23	8.2	14.9	5.3	5.5
Heav. Degr. forest	0.6	11.1	0	7.5	2.4	29.3	0	1.8
Secondary forest	4.6	5.1	0	1.8	0.1	18.0	0	5.2
Clearance/burnt	0	10.8	0	12.6	0	4.3	0	1.1
Smallholder mosaic	10.7	69.1	7	11.9	7.3	17.6	0.1	0.7
Industrial plantation	1.9	87.9	0	6.07	0	27.9	0	0

Areas are given in ha x 10^3

Plantation development

Oil palm (*Elaeis guineensis*) has become one of the most rapidly expanding food and biofuel crops in the world. The two main palm oil producing countries are Malaysia and Indonesia, with Malaysia currently responsible for up to 38% and Indonesia for up to 49 %, of the world's palm oil production (Figure 1).

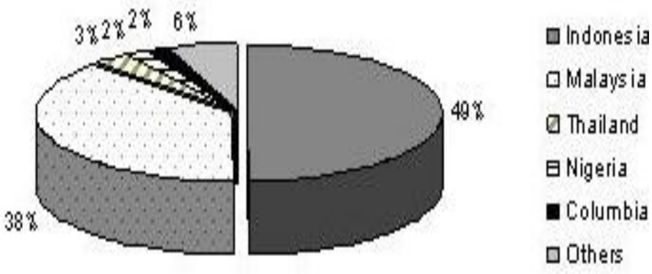

Figure 1. World palm oil production in 2010. (see www.indexmundi.com/agriculture).

A large part of the area needed for the expansion of the palm oil industry has involved the conversion of forest. A study by Wicke *et al*. (2008) shows that in Indonesia the largest land use change was from forest to oil palm and other agricultural crops, while in Malaysia oil palm development has been mainly at the expense of other permanent crops, rather than directly from deforestation. The causes of forest cover loss in Malaysia vary with region. In Sabah and Sarawak, the most important causes have been timber extraction and shifting cultivation, while in Peninsular Malaysia, and in recent years increasingly in Sabah, forest cover has been affected most by direct conversion to agriculture and more specifically to oil palm plantations (Wicke *et al*., 2010). The largest change in Indonesia has occurred in forested land, which decreased from 130 Mha in 1975 to 91 Mha in 2005, while agricultural land increased from 38 Mha in 1975 to 48 Mha in 2005. Approximately half of this agricultural expansion was due to an expansion in palm oil production (Wicke *et al*., 2010).

A recent study documented oil palm land use in Malaysia (Peninsular Malaysia, Sabah and Sarawak) using 2008-2009 satellite images (Omar *et al*., 2010). The total area of oil palm detected was 5.01 Mha, of which 0.67 Mha was on peat (*Table 8*). According to this study, the largest proportion (>37%) of oil palm plantations on peat in Malaysia, some 0.44 Mha, occurred in Sarawak. In Indonesia, oil palm plantations on peat are currently estimated to cover 1.3 Mha, with around 1.0 Mha in Sumatra and 0.3 Mha in Kalimantan (Page *et al*., 2011a,b). *Table 9* shows the area of oil palm concessions on peat (which represent future development) to increase to a total of 2.5 Mha in Sumatra and Kalimantan by 2020 (Hooijer *et al*., 2006; Page *et al.,* 2011a,b).

Table 8. Oil palm on peat in 2009 Malaysia (Omar et al., 2010).

Region	Oil Palm (ha)	Oil Palm on peat	
		(ha)	(%)
Peninsula Malaysia	2.503.682	207.458	8.29
Sabah	1.340.317	21.406	1.60
Sarawak	1.167.173	437.174	37.45
Total	**5.011.172**	**666.038**	**13.29**

Table 9. Oil palm concessions (projections 2020) on peat in 2006 in Indonesia (Peat-CO_2 report WI, 2006, by SarVision).

Region	Peat Area (ha)	Oil Palm plantation concessions on peat (ha)	Percentage of peat with oil palm plantation concessions (%)
Sumatra	6.931.700	1.249.400	18
Kalimantan	5.837.900	1.472.500	25
Papua	7.554.300	79.000	1
Total	**20.323.900**	**2.800.900**	**14**

Several studies have been performed based on past trends, land availability and projected demand for palm oil. These calculated the possible expansion of oil palm, 1) according to past land use change trends (*business as usual*), 2) using all available land to grow oil palm (a *maximum* production scenario), and 3) a scenario emphasising sustainability criteria (*sustainable* case). The most sustainable scenario avoids the use of forest land, steep terrain, and vulnerable peat soils for oil palm plantation establishment (Kaper *et al.*, 2008). Wicke *et al.* (2008) and Germer & Sauerborn (2006) concluded in their studies that in order for oil palm products to be sustainably produced, only non-peat, low-carbon, degraded land should be used for palm oil production and plantation management should be improved. With growing demand for both food and fuel for export, as well as for domestic biodiesel production, it is likely that significant further land use conversions to oil palm will occur (Koh & Wilcove 2007) and this will put further pressure on peat swamp forest ecosystems (Rijenders & Huijbregts, 2008; Fargione *et al.*, 2008). While biofuels such as palm oil were identified initially as potential low-carbon energy sources, further research has shown that oil palms grown on peat create a 'carbon debt' and so increase overall global carbon emissions (Fargione *et al.*, 2008; Gibbs *et al.*, 2008).

Implications of land use change

Carbon and greenhouse gas implications

Tropical peat swamp forest ecosystems are one of the most important terrestrial carbon stores on earth. Indonesian peat lands store at least 55 ± 10 Pg (gigaton) of carbon, equal to 10-30% of the global peat carbon stock (Jaenicke *et al.*, 2008; Page *et al.*, 2002) and Malaysian peats store around 9 Pg of carbon (Page *et al.*, 2011b). The most important factor that controls the peatland C-balance is hydrology (Jauhiainen *et al.*, 2005; Couwenberg *et al.*, 2010). Drainage of peat leads to peat oxidation and a higher frequency of fires, resulting in an increase in GHG emissions and carbon loss (Gomeiro *et al.*, 2010). Conversion of forest for agricultural development is a one-point emission in time, while emissions resulting from peat drainage are continuous processes. Emissions due to peat drainage are not caused just by *land use change*, which generally involves a loss of biomass, but rather to its long-term effects on the carbon store in the soil. This is different in the case of deforestation on mineral soils, where the largest proportion of emissions results from the loss of biomass at the time of land use change.

Other ecological implications

The rapid and massive expansion of oil palm has also led to concerns about its impact on natural habitats and biodiversity (Fargione *et al.*, 2008; James, 2008; Koh & Ghazoul, 2008). Locally, the development of oil palm plantations in forested areas will have several consequences, such as increased erosion, loss of biodiversity, pollution by chemical runoff, and increased fire risk (Naidoo *et al.*, 2009). Other impacts include soil subsidence due to drainage and fires, which can lead to an increased risk of flooding, salt water intrusion, and, in some cases, eventual loss of the entire peat formation. Oil palm monocultures require use of insecticides, herbicides and fertilizers, which may enter water bodies as runoff or groundwater seepage and can seriously impact aquatic biodiversity (Koh & Wilcove, 2008). Another problem is haze following peat and forest fires. Exposure to high levels of air pollution increases risk of asthma, bronchitis and other respiratory illnesses (e.g. Brown 1998; Sastry 2000).

Haze can also result in the reduction, by as much as 92%, in photosynthetically active radiation (PAR) which can affect rates of carbon fixation (Yule, 2010).

Social, economic and livelihood implications

The broader economic, social and livelihood implications of oil palm cultivation on peat remain poorly understood (Rist *et al*., 2009; Rist *et al*., 2010). Although many households profit from the palm oil business, the expansion of large-scale oil palm plantations will lead to loss of ecosystem services. Some studies warn of instability in food prices because smallholders may become over dependent on the price of palm oil. In Indonesia, one point of concern is from transnational corporations and other large landowners who establish extensive landholdings at the expense of small farmers (Rist *et al*., 2010). However, many findings are contradictory and differ among regions and may be affected by the time frame of the studies, while short term economic consequences are often positive, the longer term implications can be the reverse. Figure 2 shows the linkages that exist between the loss of peat swamp forests and global market forces, as mediated by national export policies and international investments. The increasing demand for a product in one part of the world may negatively impact wetland ecosystems elsewhere. In the process, the conservation and sustainable management of tropical peats in Southeast Asia is threatened. Nonetheless, oil palm appears to be an attractive new income opportunity for Indonesian farmers, as attested by its widespread uptake by many smallholder communities (Rist *et al*., 2010). Oil palm is widely considered by these communities as the best option for reducing rural poverty.

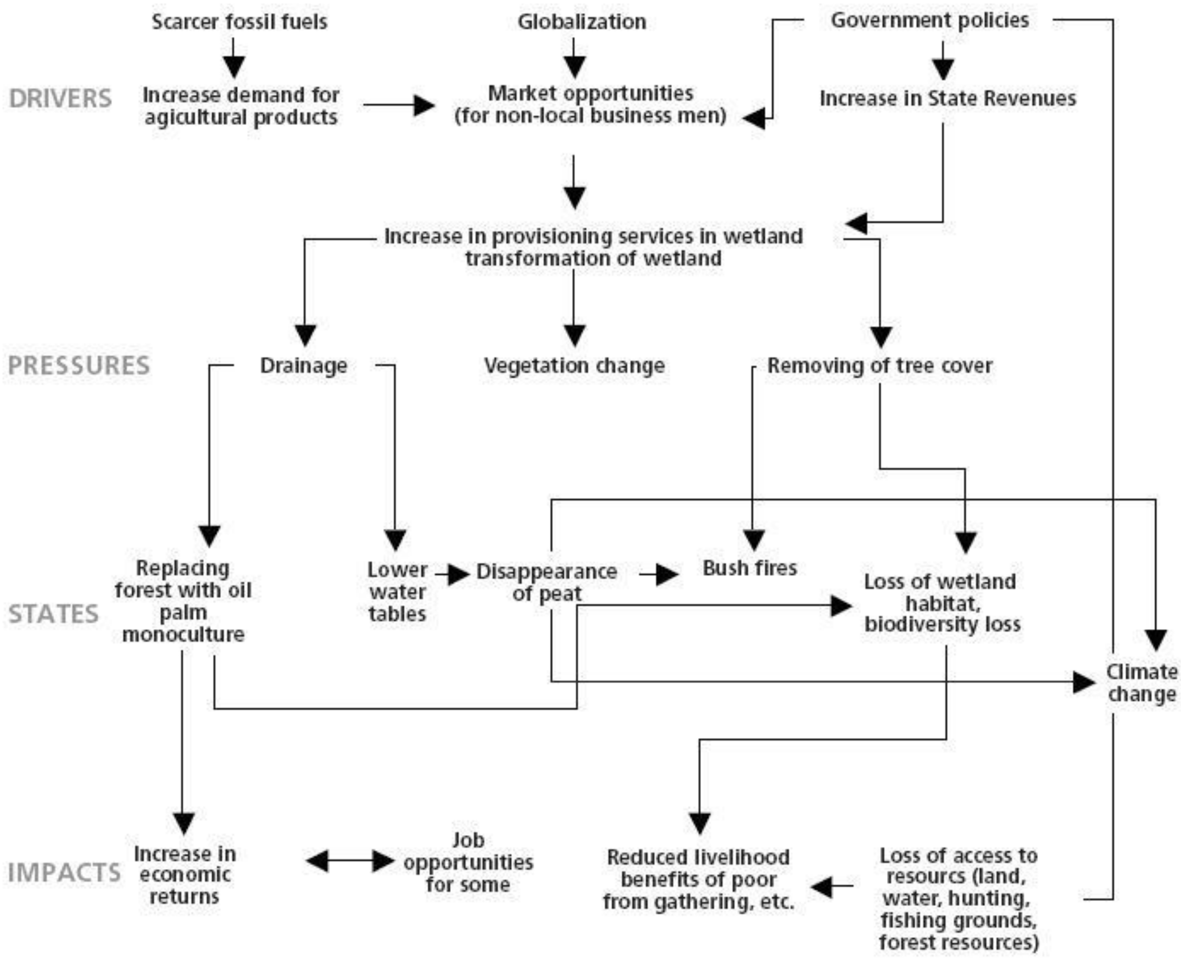

Figure 2. Transformation of wetlands in perspective: schematic overview of drivers, pressures, states and impacts (FAO, 2008). Note that the increased demand for palm oil as food is not included in this scheme.

CARBON BALANCES AND GREENHOUSE GAS EMISSIONS IN TROPICAL PEATLANDS

Introduction

Intact peat swamp forests store large amounts of carbon in the peat and in the vegetation. Since the 1980s large areas of tropical peat swamp forest in Southeast Asia have been converted for urban development, forestry and agriculture, including for palm oil production. Conversion of tropical peat forest areas into agricultural land has various consequences for the carbon and GHG balance in the years following disturbance. These consequences are mainly dependent on the extent of deforestation, drainage depth and water management.

Data availability and restrictions

Although a lot of research has been performed in the past, using different approaches (Box 3), some of the earlier studies on GHG fluxes suffered from several methodological limitations. General pitfalls were:

- The short-term nature of the studies (usually < 1 y), with a limited number of point measurements over time. In the tropics, large differences in annual balances can be expected between dry and wet years.
- Failure to address temporal and spatial variability in a systematic way.
- Use of linear interpolation to perform temporal upscaling of fluxes instead of using a regression based approach.
- The focus of most studies on CO_2 with relatively few studies on other major GHGs such as N_2O (which arises from fertilizer applications) and CH_4 (a potential emission source fom drainage ditches).

Comparison studies of CO_2 emissions have largely been based on chamber measurements of total soil respiration and have failed to distinguish between autotrophic and heterotrophic respiration (Melling *et al*., 2005b; Melling *et al*., 2007; Furukawa *et al*., 2005; Reijnders & Huijbregts, 2008; Hadi *et al*., 2005).

Flux estimates can also be seriously biased by the failure to detect and allow for 'event' emissions such as those due to sudden climatic changes or discontinuous management activities, such as changes in temperature or rainfall, fertilizer application, and dredging (Kroon *et al*., 2010; Veenendaal *et al*., 2007; Hirano *et al*., 2007). Atypical results, or outliers, may be caused by pressure changes during chamber installation, which results in very high fluxes that can dominate the overall balance estimate. A complex micro-topography may be present consisting of hummocks and hollows than can cause a spatial bias, which may not be representative of the total area.

Studies have been undertaken in the last few years that avoid or minimise these potential problems. One approach is to collect data from several studies and attempt to infer emissions based on drainage depth (Couwenberg *et al*., 2010). Others have tried to avoid all major deficiencies related to chamber measurements (Jauhiainen *et al.*, 2012). Some studies base their carbon and CO_2 emission estimates on soil subsidence rates (Dradjad *et al*., 2003; Couwenberg *et al*., 2010; Hooijer *et al*., 2012), using an assumed bulk density and allocating a percentage of subsidence to peat oxidation. The latest methods for calculating CO_2 emissions from soil subsidence avoid the use of an assumed oxidative component by using the bulk density of peat below the water table as a proxy for the original bulk density of the peat above the water table, which integrates the impact of initial consolidation. Compaction continues to work on consolidated peat, however, once it reaches the aerated zone above the water table (Couwenberg & Hooijer, 2013).

Ecosystem flux values differ depending on the system boundaries. Some studies address the entire oil palm biofuel production chain; others include management-related fluxes or only soil respiration within a single plantation (Figure 3). The amount of release or uptake of GHGs in an ecosystem is dependent on a variety of interrelated processes, including climate and variables such as temperature, moisture, water table depth, microbial activity, drainage, logging, compaction, peat type, and vegetation type. To completely understand the temporal and spatial variation of fluxes from a peat ecosystem and to upscale fluxes from a small (m^2) to the landscape scale, these processes and variables and their inter-relationships need to be documented.

Box 3

Greenhouse gas and carbon measurement techniques

Chamber based methods: Sample areas are usually smaller than one square meter (1 m^2) and are discontinuous in both space and time. They are best suited for capturing spatial variability and can be used to measure fluxes of the three major GHG: CO_2, CH_4 and N_2O. If appropriate, spatial and temporal upscaling methods can be used to determine average GHG fluxes at the landscape scale (note: correct spatial stratification requires regression analyses rather than a simple linear interpolation).

Eddy covariance (EC) based methods: These cover areas of 100 – 1000 m^2 depending on the height of the measurement instruments, which are located mainly on towers that extend above the vegetation canopy. An array of instruments on these towers continuously measure both incoming and outgoing radiation, GHG fluxes, and energy exchanges. The EC technique is best suited for determining average GHG fluxes at the landscape scale and for capturing temporal variability at multiple temporal scales ranging from a single day to several months or even years. EC techniques for CO_2 have been used for more than a deade, while EC techniques for CH_4 and N_2O are still under development. The EC technique integrates emissions over large areas, and footprint analysis (models used to estimate where the fluxes originate) is currently insufficient to capture small scale variability.

Soil subsidence based methods: In principle, land subsidence can be determined using several straight forward measurement techniques, such as leveling surveys, subsidence poles and Global Positioning System (GPS) systems. A field study in Johor, Malaysia determined the oxidation component of subsidence to be about 60% (Wösten *et al* (1997), but other studies based on several large-scale studies in subtropical and tropical regions have estimated the oxidative component of subsidence to be around 90% (Stephens *et al*. 1984; Hooijer *et al*.(2012). Recently, soil subsidence methods avoids the errors in estimating the oxidative component by using the bulk density of the peat below the water table as a proxy for the original bulk density of the peat above the water table (Couwenberg & Hooijer , *2013*).

Satellite based approaches: These usually focus on loss of carbon by documenting land use change and deforestation at relatively large scales. Changes in soil carbon stocks, in both mineral and peat soils, are usually not included in these studies, except by the use of models based on assumptions derived from ground-based studies. Satellites are extremely useful, however, for monitoring the distribution and frequency of fires, which can be used for estimating carbon loss from peat fires.

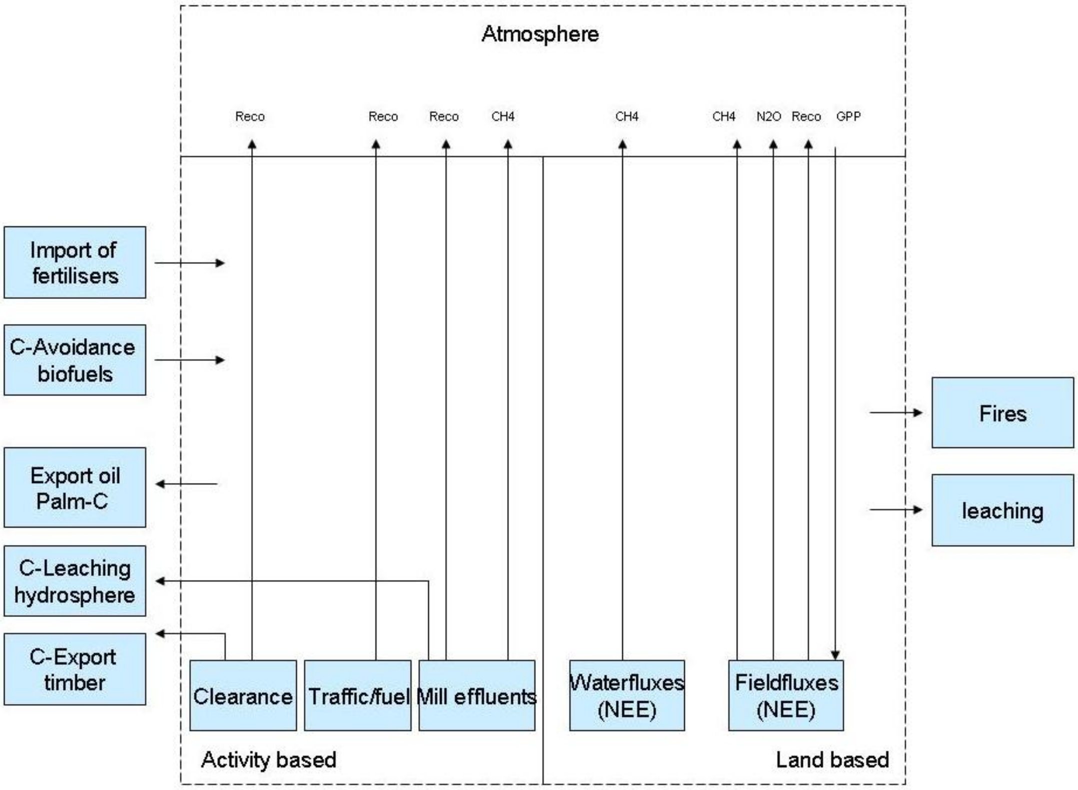

Figure3. System boundaries of an oil palm plantation (dotted line) with the carbon (C) and GHG sources and sinks: NEE = Net Ecosystem Exchange, GPP = gross primary production or photosynthesis, Reco = ecosystem respiration, CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide.

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Carbon dioxide and carbon

Direct loss of carbon

Agricultural development of tropical peat involves a change in vegetation cover and, in almost all cases, permanent drainage. The land use change from forest to oil palm plantation (clearing and/or burning of AGB), causes a direct loss of carbon (Danielsen *et al*., 2009) ranging from 111-432 Mg C ha^{-1} in natural or primary peat swamp forest to 73-245 Mg C ha^{-1} in logged forest, while the carbon stock in oil palms ranges from only 25-84.6 Mg C ha^{-1} (Agus *et al*., 2009; Lasco, 2002; Gibbs *et al.,* 2008; Verwer & van der Meer, 2010; Murdiyarso *et al*., 2010). Loss of forest cover in Southeast Asia can be grouped into three main categories: 1) forest degradation caused by logging, 2) conversion of forest areas into large scale plantations by clear felling, and 3) expansion of small-holder dominated farming areas (Miettinen *et al*., 2011). The effects of logging may be highly variable depending on logging intensities, rotation cycles and damage to the residual stand. Root biomass in relatively undisturbed peat swamp forests is estimated at 29-45 Mg C ha^{-1} (Verwer & van der Meer, 2010) and can be a further source of carbon loss following conversion.

CO_2 emissions from land use change

Deforestation

Forests absorb CO_2 by photosynthesis and release it by respiration; autotrophic respiration refers to the respiration from roots and above ground plant organs. Soil respiration is the CO_2 release at the soil surface due to microbial activity, referred to as heterotrophic respiration, and the autotrophic respiration of plant roots. Suzuki *et al.* (1999) demonstrated in their micrometeorological studies in tropical peat forest in Thailand that 5.32 Mg C ha^{-1} yr^{-1} was absorbed by the primary peat swamp forest canopy in photosynthesis while secondary forest absorbed 5.22 Mg C ha^{-1} yr^{-1} because of greater plant growth compared to primary forest. During deforestation for development of an oil palm plantation, living biomass is harvested; at the same time, gross primary production (GPP) decreases and the net ecosystem exchange (NEE) increases (Hirano *et al*., 2007). The carbon loss from forest conversion exceeds the potential carbon fixation of oil palm plantings and, in addition, artificial drainage needed for cultivation of oil palm on peat will increase microbial respiration compared to the situation without drainage (e.g. Jauhiainen *et al.,* 2005; de Vries *et al.,* 2010; Henson, 2009; Jeanicke *et al.,* 2008; Danielsen *et al.,* 2009; Fargione *et al.,* 2008; Rieley *et al*., 2008; Gibbs *et al*., 2008; Wösten & Ritzema, 2001; Hooijer *et al.,* 2006).

Drainage

Drainage causes peat carbon to be oxidised and released as CO_2. It also increases the risk of peat fire (Furukawa *et al.,* 2005; Wösten *et al*., 1997; Inubushi *et al*., 2003; Hooijer *et al*., 2006; Veenendaal *et al*., 2007). Page *et al.* (2011a) concluded that a value of 86 Mg CO_2-

$_{eq}$ ha^{-1} yr^{-1} represents the most robust, empirical estimate of peat CO_2 emissions currently available for oil palm plantations on deep, fibric peat with uncertainties ranging from 54 to 115 Mg CO_{2-eq} ha^{-1} yr^{-1} for typical drainage depths of 60 – 85 cm, when annualized over 50 years and including the initial emission peak just after drainage. Couwenberg & Hooijer (2013) suggest a CO_2 emission value of 55-73 Mg CO_{2-eq} ha^{-1} yr^{-1} for continuous peat emissions under best to common practice, management, excluding initial emissions just after drainage. Couwenberg *et al.* (2010) and Hooijer *et al.* (2010) calculated emissions of at least 9 Mg CO_2 ha^{-1} yr^{-1} and 9.1 Mg CO_2 ha^{-1} yr^{-1}, respectively, for each 10 cm of additional drainage depth. Transforming an undrained peat with the water table at the soil surface into a drained peat area with a drainage depth of 60-80 cm would thus increase the peat

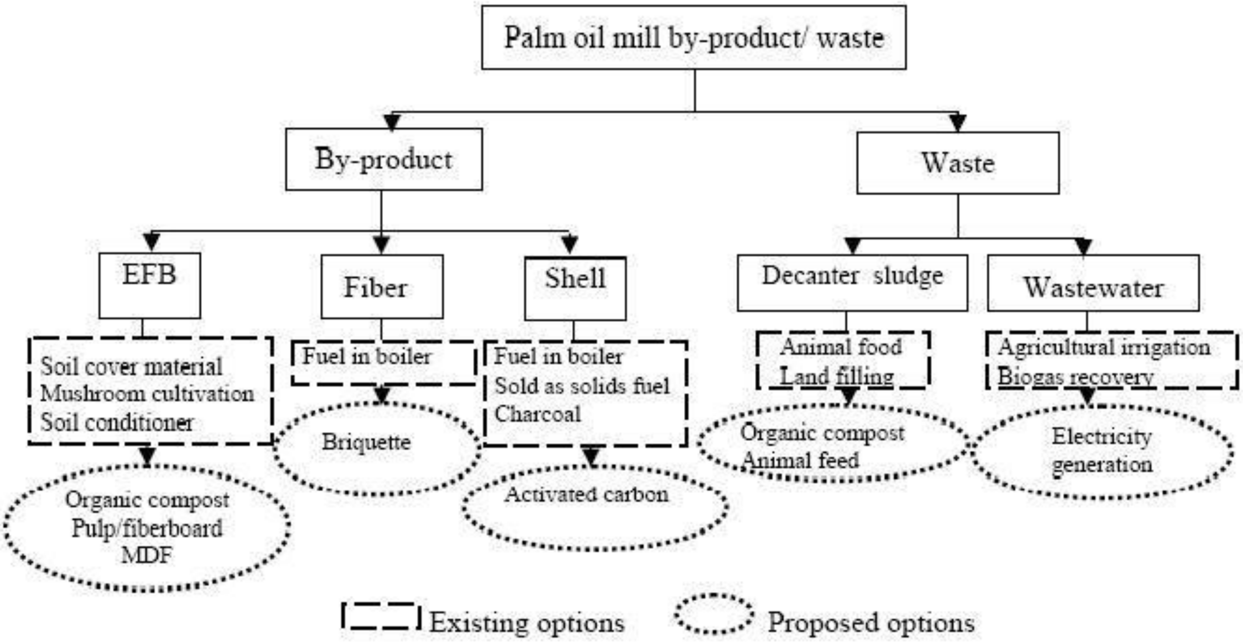

Figure 4. By-products and wastes from oil fresh fruit bunch (FFB) processing (Chavalparit, 2006).

emissions by about 55-72 Mg CO_2 ha^{-1} yr^{-1} (Figure 4). These relations have been refined recently as more field data have become available (Hooijer *et al.*, 2012; Jauhiainen *et al.*, 2012) both from subsidence studies that account for changes in bulk density (thus correcting for compaction and consolidation), and from CO_2 gas flux measurements that exclude root respiration.

Recent studies showed that emissions in both *Acacia* and oil palm plantations after more than 5 years following initial drainage (i.e. excluding the initial peak) was consistently around 73 Mg CO_2 ha^{-1} yr^{-1} with a water table depth of 0.7 m. Note that the initial peak may be as high as 178 Mg CO_2-eq ha^{-1} yr^{-1} in the first 5 years after drainage (Hooijer *et al.*, 2012). Page *et al.* (2011a) after reviewing available literature concluded that around 73 Mg CO_2 ha^{-1} yr^{-1} is released from drained peat in oil palm plantations, but increases to 86 Mg CO_2 ha^{-1} yr^{-1} if the initial peak directly after drainage is taken into account. Lower estimates were found by Melling *et al.* (2005a) who reported a value of 55 Mg CO_2 ha^{-1} yr^{-1}. It should be noted that studies in Sarawak, such as those by Melling *et al.* (2005a), reflect a different rainfall regime than those in most of Indonesia, where dry season rainfall is lower, soil moisture deficits are common; consequently, the rate of peat oxidation and carbon loss are expected to be substantially higher. The most recent research proposes a mean CO_2 emission rate of 64 Mg CO_2 ha^{-1} yr^{-}1, with a range between 55-73 Mg CO_2 ha^{-1} yr^{-} for continuous peat emission, excluding the initial peak (Couwenberg & Hooijer, 2013). This is in line with the previous equations by the same authors of ~ 9 Mg CO_2-eq ha^{-1} yr^{-}1 per 10 cm of drainage depth.

One of the few studies in Indonesia and Malaysia that used the eddy covariance methodology to measure fluxes in a degraded and drained tropical peat swamp forest using the total CO_2 balance approach (Hirano *et* *al.* 2007) showed that the drained forest appeared to be a CO_2 source of 16 Mg CO_2 ha^{-1} yr^{-1}, which was the difference between the uptake by living biomass (GPP) of 126 Mg CO_2 ha^{-1} yr^{-1} and an ecosystem respiration (Reco) of 142 Mg CO_2 ha^{-1} yr^{-1}.

In tropical regions, peat oxidation is dependent on factors such as time of year (dry-wet season), quantity and quality of organic matter, and environmental factors such as soil temperature and moisture (e.g. Hirano *et al*., 2007). Even in the small range of temperatures typical for tropical areas, particularly in the early stages of plantation establishment when the canopy is not closed, emissions are positively related to temperature (Hooijer *et al*., 2012; Jauhiainen *et al*., 2012; Murdiyarso *et al*., 2010; Hirano *et al*., 2007).

Fires

An indirect result of drainage and inappropriate management activities is an increase in fire frequency (Hope *et al*., 2005). Although land clearance by fire has been banned for several years, it is still a widespread practice, particularly by smallholders who lack access to heavy machinery (Page *et al*., 2011a). Couwenberg (2010) estimated a release of 260 Mg C ha^{-1} yr^{-1} during the 1997 peat fires in Southeast Asia, which corresponded well with the estimates of van der Werf *et al*. (2008) and Page *et al.* (2002). Limin *et al.* (2004) estimated a carbon emission of 186 and 475 Mg ha^{-1} respectively for the drought years 2002 and 1997. Based on available measurement data, the mean burn depth and rate of fire related peat loss amounted to 34 cm per fire event and 261 Mg C ha^{-1} yr^{-1} averaged for the years 1997, 2001 and 2002 in an abandoned, degraded peat area (Heil, 2007). Additionally, the ash produced during a fire enhances peat decomposition (Murayama & Bakar, 1996).

Other CO_2 emission sources

The focus of this chapter is on emissions from peat; however, to create a complete and clear picture of the system as shown in Figure 3, management related fluxes also have to be taken into account. Oil processing leads to losses of carbon and GHGs because mills produce large amounts of organic waste. These losses add to the emissions for oil palm plantations on peat soils, as well as those on mineral soils. Figure 4 shows the wastes from fresh fruit bunches (FFB) as studied by Chavalparitk (2006). Data from Thai production for 1993 suggests that on a weight basis such wastes amount to nearly 80% of the inputs (Prasertsan *et al*., 1996). Based on the OPCABSIM model of Henson (2009) (RSPO, 2009), C losses through fossil fuel use were estimated to be 0.39 Mg C-eq ha^{-1} yr^{-1} (1.43 Mg CO_2 ha^{-1} yr^{-1}), losses through initial biomass loss (e.g. FFB waste) were 3.47 Mg C-eq ha^{-1} yr^{-1} (12.7 Mg CO_2 ha^{-1} yr^{-1}) and carbon gains through fertilizer inputs were 1.5 – 2 Mg CO_2 ha^{-1} yr^{-1}.

The drainage needed for the cultivation of oil palm means that dissolved organic matter leached to drainage ditches and rivers will also be enhanced (Rixen *et al*., 2008; Miyamoto *et al*., 2009; Yule & Gomez, 2009), especially in the transitions from dry to wet periods. Increases of 15% in dissolved organic carbon have been recorded during this transition (Rixen *et al*., 2008). The carbon exported rapidly decomposes, causing high fluxes of CO_2 from water bodies (Couwenberg *et al*., 2010; Holden *et al*., 2004). A recent study concluded that the fluvial organic carbon flux from disturbed, drained peat swamp forest is about 50% larger than that of undisturbed peat swamp forest (Moore *et al*., 2013). These workers concluded that adding these fluvial carbon losses (estimated at 0.97 Mg C ha^{-1} yr^{-1}) to the total carbon budget of disturbed and drained peatlands increased the total ecosystem carbon loss by up to 22%. Jauhiainen & Silvennoinen (2012) used floating closed chambers to measure GHG fluxes from drainage ditches in tropical peatlands, including plantations, and found that total GHG fluxes from canals are generally higher than from the neighbouring fields. They found fluxes of 15.2 Mg CO_2-C ha^{-1} yr^{-1} from drainage ditches in disturbed peat areas (with a ditch area 2% of the total), which is in the same order as the fluxes found by Moore *et al*. (2013).

Methane

Methane is formed from organic or gaseous carbon compounds by methanogenic bacteria living in the anaerobic, water saturated peat layers. In the upper, more oxic peat layers methanotrophic bacteria oxidize part of the CH_4, diffusing it upwards as CO_2. Currently it is believed that the emissions of CH_4 from tropical peat areas only make a minor contribution to the GHG flux compared to the emissions of CO_2, and thus play only a minor role in the carbon balance. However, the extent of emissions from open water and those promoted by management practices and fires, are likely to contribute considerably, particularly because the warming potential of CH_4 is 25 times that of CO_2. However, net CH_4 fluxes from tropical peats are low compared to fluxes from temperate peat soils and they usually show a clear positive relationship to water level for water levels above 20 cm, as is also the case for temperate wetlands (Watanabe *et al.*, 2009). An overview of the available scientific literature on methane emissions in tropical peat is given in *Table 10* and Appendix A.

Table 10. Annual terrestrial (land based) methane emissions from peat in tropical Southeast Asia from available scientific literature calculated in different ways. Fluxes related to open water and to management activities are excluded.

Reference	Land use	Chamber measurements frequency	Mean CH_4 emissions (g CH_4 m^{-2} yr^{-1})	Min CH_4 emissions (g CH_4 m^{-2} yr^{-1})	Max CH_4 emissions (g CH_4 m^{-2} yr^{-1})	Mean CO_2-eq (t CO_2 ha^{-1} yr^{-1})	Min CO_2-eq (t CO_2 ha^{-1} yr^{-1})	Max CO_2-eq (t CO_2 ha^{-1} yr^{-1})
Ueda *et al*, 2000	Fresh water swamp			4.38	109.5		1.05	26.28
Hadi *et al*, 2005	Rice	1 year, monthly		3.5	14.0		0.3	1.22
	Sec. forest	1 year, monthly	5.87			1.41		
	Paddy field	1 year, monthly	26.13			6.28		
	Rice-soybean	1 year, monthly	3.47			0.83		
Couwenberg *et al*, 2010*	Swamp forest	1 year, monthly on average		-0.37	5.87		-0.9	1.41
	Agriculture	1 year, monthly on average		0.025	3.4		0.006	0.816
	Rice	1 year, monthly on average		3.26	49.5		0.87	11.88
Melling *et al*, 2005	Sec. forest	1 year, monthly	0.02			0.006		
	Sago	1 year, monthly	0.24			0.06		
	Oil palm	1 year, monthly	-0.02			-0.006		
Furukawa *et al*, 2005	Drained forest	1-2 years, monthly	1.17			0.28		
	Cassava	1-2 years, monthly	3.39			0.81		
	Paddy field upland	1-2 years, monthly	3.62			0.87		
	Paddy field lowland	1-2 years, monthly	49.52			11.89		
	3 Swamp forests	2 months	6.15			2.02		

* Combined research adapted from Couwenberg *et al.*, 2010: Inubushi *et al.*, 2003; Furukawa *et al.*, 2005; Hadi *et al.*, 2005; Jauhainen *et al.*, 2005; Melling *et al.*, 2005; Takakai *et al.*, 2005; Hirano *et al.*, 2009.

CH_4 emissions from land use change

Only a few studies have focused on CH_4 fluxes from tropical peat land. Couwenberg *et al.* (2010) concluded that CH_4 emissions in tropical peat are negligible at low water levels and amount to up to 3 Mg CH_4 m^{-2} hr^{-1} (6.3 kg CO_2-eq ha^{-1} yr^{-1}) at high water levels. Raised soil temperature following land use change may stimulate the process of methanogenesis, and the abundance of drainage canals, ponds or flooded areas may promote CH_4 emissions to non-negligible levels (Jauhiainen *et al*., 2012). In some temperate regions, these emissions from water bodies may account for 60% of the total annual CH_4 flux of a drained peat ecosystem, depending on the amount of nutrients in the water and its depth (Schrier-Uijl *et al*., 2011). Typical drainage parameters , such as the spacing and width of canals, in oil palm plantations in Indonesia (Table 10) show that water surface from drainage canals may account for up to 5% of the total plantation area. Guerin & Abril (2007) measured a methane emission rate of 350 ± 412 kg ha^{-1} yr^{-1} (8.4 ± 9.9 Mg CO_2-eq ha^{-1} yr^{-1}) from a tropical lake in a peat area in French Guiana, suggesting that in the tropics GHG fluxes from open water bodies also have to be considered.

Melling *et al.* (2005b) estimated CH_4 flux from peat soils supporting oil palm, sago and degraded forest, performing monthly measurements over one year using closed chambers. They examined parameters likely to control CH_4 emission: groundwater table, precipitation, nutrients, bulk density, and moisture conditions. The results indicated that the sago plantation and degraded forest were sources for CH_4 while the oil palm plantation was a CH_4 sink. They attributed the switch from the forest as a source (2.27 ug C m^{-2} hr^{-1}) to the oil palm as a sink (-3.58 ug C m^{-2} hr^{-1}) to a lowering of the water table and soil compaction due to use of machinery and concluded that the conversion of tropical peat primary forest to oil palm promoted CH_4 oxidation due to an increased thickness of aerobic soil after drainage. However, increased fire frequency following drainage and management will also increase CH_4 emissions and when vegetation is burned, for each ton of CO_2 emitted, an addional 1.5 kg CH_4 is produced (Scholes *et al.* 1996).

Other CH_4 emission sources

Transformation of forest to agricultural use involves increased management activities such as use of machinery, inputs of fertilizer and mill operations, many of which may promote CH_4 emissions such as those from mill effluent and biomass burning in mill boilers. POME is a major source of methane emission during palm oil production and methods to reduce this are being actively pursued by the industry (RSPO, 2009), which have been estimated estimated at about 32 – 48 kg CH_4 ha^{-1} yr^{-1} (0.8 – 1.2 Mg CO_2-eq ha^{-1} yr^{-1} or 24 – 36 kg C ha^{-1} yr^{-1}) from palm oil mill effluent (Reijnders & Huijbregts (2008).

Nitrous oxide

Nitrous oxide (N_2O) is primarily emitted as a by-product of nitrification and denitrification in both agricultural landscapes and natural ecosystems. Nitrogen fertilizer use, both inorganic and organic, are a major factor in determining levels of N_2O emission, which vary depending on soil moisture conditions and land use (e.g. Mosier *et al*., 1991; Kroeze *et al*., 1999; Hadi *et al*., 2001; Takadi *et al*., 2006). Natural boreal wetlands with high water tables do not necessarily produce N_2O (Nykanen *et al*., 2002), but may consume small amounts via denitrification when atmospheric N_2O is reduced to N_2. However, tropical peat soils have different biophysical attributes emissions of N_2O from fertilizers and manure may represent addional GHG emissions.

N_2O fluxes have a high temporal variability as shown in a temperate peat in the Netherlands, where three years of half-hourly measurements of N_2O were collected using the eddy covariance methodology (Kroon *et al*., 2010). The large number of measurements allowed the source of N_2O emissions to be differentiated between background emissions and emissions linked to fertilizer application and abrupt climatic events such as rainfall. In this temperate agricultural peat area, N_2O contributed up to 45% to the total GHG balance, when expressed in terms of global warming potential and including CO_2 and CH_4 in the total GHG balance. Event emissions accounted for a considerable part of these N_2O emissions and, therefore, demonstrate the importance to conduct measurements frequently, especially during weather events and fertilizer application.

In oil palm plantations, it seems likely that the application of nitrogen fertilizers will accelerate release of N_2O; however, the extent of those emissions in these types of ecosystems remain poorly documented. Hadi *et al.* (2005) compared the N_2O emissions from a paddy field, a field with a rice-soya bean rotation, and a peat forest (*Table 11*). They integrated monthly measurements and scaled these up to provide annual estimates of N_2O emissions. Takakai *et al.* (2006) estimated an emission of 3.6 – 4.4 Mg CO_2-eq m^{-2} d^{-1} from one year of data by using linear interpolation for temporal upscaling. Melling *et al.* (2007) made monthly measurements of N_2O emissions over one year using closed chambers on tropical peat soils under different vegetation cover: oil palm, sago and forest. In the last study, the N_2O source in the Malaysian oil palm plantations were 1.2 kg N_2O ha^{-1} yr^{-1} (0.48 Mg CO_2-eq ha^{-1} yr^{-1}). However, uncertainties were large and data were too limited either to distinguish background emissions from event emissions due to fertilizer applications and there was too much variability for a robust regression analyses. The default value in the IPCC guidelines for synthetic nitrogen fertilizer-induced emissions for Histosols in tropical regions is 10 kg N_2O-N ha^{-1} yr^{-1} (IPCC, 2006). Based on this value, the N_2O emissions correspond to a total emission of 4.8 Mg CO_2-eq ha^{-1} yr^{-1}. Nitrous oxide emission values for tropical peatlands found in the scientific literature are given in *Table 11*.

Table 11. Nitrous oxide emission values for tropical peat areas as found in the scientific literature, measured by chamber-methodology at different temporal scales.

Reference	Land use on peat	Chamber measurement frequency	Emission (kg CO_2-eq ha^{-1} yr^{-1})
Hadi *et al* (2005)	Rice paddy field	3 measurement days	0-5781
Furukawa *et al* (2005)	Rice paddy field	1 year, monthly	0.016
Hadi *et al* (2005)	Cultivated upland field	3 measurement days	6608-36754
Furukawa *et al* (2005)	Upland cassava field	1 year, monthly	0.257
Melling *et al* (2005)	Sago	10 months, monthly	1556
Hadi *et al* (2005)	Soya	3 measurement days	4543
Hadi *et al* (2005)	Forest, not primary	3 measurement days	6600
Melling *et al* (2005)	Forest, not primary	10 months, monthly	330
Furukawa *et al* (2005)	Forest, not primary	1 year, monthly	0.101
Inubushi *et al* (2003)	Forest, not primary Abandoned upland field Rice	1 year, monthly	range -664 - +498
Melling *et al* (2005)	Oil palm	10 months, monthly	566
Furukawa *et al* (2005)	Pineapple	1-2 months	132-1017

Discussion, gaps in knowledge and uncertainties

In this review, we have attempted to summarize the impacts from the conversion of tropical peatlands into oil palm plantations in terms of both carbon and GHG emissions. All recent pertinent studies have been reviewed and compared; studies differ in the approaches used to assess GHG emissions and there is an element of uncertainty linked to their accuracy and precision.

There has long been a lack of studies that focus on on long-term rates of GHG emissions measured over several years and the uptake of carbon in tropical peats, as well as examining the explanatory variables that mediate the process (e.g. temperature, moisture, chemistry, water table, management, fertilizer inputs). Although recent studies have successfully filled some knowledge gaps, empirical evidence is required to adequately document the relationships between emissions of CO_2, CH_4 and N_2O and their driving variables.

Data on biomass and carbon content in the remnant peat swamp forests are rare and only broad ranges of AGB and emissions rates in peat swamp forests have been documented. On deep peat (>3m) most of the carbon is stored in the peat soil and therefore the relative contribution of the forest carbon stock is less than on shallow peats. Development of a primary (undisturbed) swamp forest into an oil palm plantation will result in a direct release of carbon, ranging between 153 – 200Mg C ha^{-1} due to changes in AGB and peat fire, while development of a logged forest into an oil palm plantation will cause a direct release of carbon, ranging between 47 – 160 C ha^{-1} depending on the degree of forest degradation. The time-avetraged AGB carbon stock of an oil palm plantation is between 24 and 40 t C ha^{-1}, which at the end of each crop cycle is likewise released, or maintained at that amount if a second replanting is pursued.

The conversion of an intact peat swamp to an oil palm plantations releases carbon and GHG to the atmosphere from its AGB and upper peat profiles due to fire. However, these emissions are considered as 'one - time" emission event. In contrast, the emission linked to drainage and oxidation of peat soils are addional to those initial emissions, and will occur for as long as the soil is drained. Drainage-induced emissions from oil palm plantations on peat have been estimated at about 86 Mg CO_2 ha^{-1} yr^{-1} including the initial emissions peak (Page *et al.*, 2011a), with values in the literature ranging from 26 - 146 Mg CO_2 ha^{-1} yr^{-1} (or 7 - 40 Mg C ha^{-1} yr^{-1}) and the most recent estimation is 64 Mg CO_2 ha^{-1} yr^{-}1, with a range between 55-73 Mg CO_2 ha^{-1} yr^{-} for continuous peat emission, excluding the initial peak (Couwenberg & Hooijer , 2013) . Oxidation of drained peat and peat fires are the largest emission sources incurred during oil palm plantation development on peat soils. The processing of FFB and the related production of mill wastes add further to GHG emissions.

The increased fire frequency during clearance and drainage of peat leads to addional in the release of high amounts of CO_2 and CH_4 from both biomass and peat. Based on available measurement data in an abandoned, degraded tropical peat area, the mean burn depth in Indonesia during drought years was estimated at 34 cm per fire event, which translates into approximately 261 Mg C ha^{-1} emission for the years 1997, 2001 and 2002.

Knowledge on CH_4 emissions from tropical peatland is insufficient and only a limited number of short term CH_4 measurements are available. Results are variable and outcomes differ significantly between studies. Based on this very limited number of measurements, terrestrial CH_4 fluxes are estimated to range from 0 - 2 Mg CO_2-eq $ha^{-1}yr^{-1}$ in swamp forests. CH_4 fluxes from open water bodies (drainage ditches and small ponds) have not yet been extensively quantified. Measurment of N_2O emissions in tropical peat systems are likewise scarce and uncertain. The potential N_2O source in an oil palm plantation has been estimated at 566 kg CO_2-eq ha^{-1} yr^{-1} (Melling *et al.*, 2007), which is likely to prove conservative. The IPCC (2006) default value for N_2O emissions from fertilized for tropical Histosols is 4.1 Mg CO_2-eq $ha^{-1}yr^{-1}$.

While N_2O and CH_4 should not be ignored, the available data indicates that it is CO_2 that dominates the GHG balance. A point of concern is that in most GHG studies only the 'field' component is taken into account, while emissions from drainage canals, ponds and shallow lakes on subsided or burned land might also be considerable.

Spatial and temporal variations have yet been not fully captured and recent estimates of GHG emissions from tropical peatlands have been based largely on short term studies with high levels of uncertainties due to the reliance on inherently weak methodologies and poor upscaling techniques. Recent studies have started to address these problems, but further field inventories using more technologically sophisticated methods and rigorous experimental design and objective modelling approaches are needed. Because both carbon pools and carbon emissions vary considerably over space and time, the research focus should be on quantification of carbon pools and emissions related to long term land use and land use change at the landscape level.

Carbon release can also take place via waterways (streams, rivers and drainage canals) in the form of dissolved and particulate organic carbon, as well as via dissolved inorganic carbon and CO_2. Studies of these potential carbon flux pathways from tropical peat have been limited, but a recent study suggests that Indonesian rivers, particularly those draining peatland areas, transfer large amounts of DOC into the sea (Moore *et al.* (2013). In that study, it was concluded that the fluvial organic carbon flux from disturbed, drained peat swamp forest is about 50% larger than that of undisturbed peat swamp forest due to land use change and fire.

Recommendations for reducing greenhouse gas emissions

Current sustainability measures in oil palm plantations on peat will decrease the emission source strengths, but will not turn these systems into carbon or GHG sinks. Recent findings suggest that emissions cannot be reduced very much under any management regime when water table depths are around 0.7 m; a common feature of many plantations. Only rehabilitation and restoration of drained peat can turn these systems back into long term carbon sinks.

The simplest measure to limit GHG emissions is to limit or stop development of oil palm plantations on peat. Peat drainage, and thus peat oxidation, and clearance related fires are the largest sources of GHG emissions when establishing oil palm plantations on peat soils. Development of plantations on mineral soil has fewer impacts and impacts are less significant in terms of GHG emissions. If oil palm plantations are developed on peat, oxidation due to drainage will continue either until undrainable levels have been reached, resulting in increased or permanent flooding, or all the peat has disappeared, resulting in exposure of the underlying mineral layers, often potential acid sulphate soils or infertile sands.

The most practical way to reduce GHG emissions in existing plantations is to increase the level of the water table. The RSPO Manual on Best Management Practices for Oil Palm Cultivation on Existing Peat (RSPO, 2012) recommends maintaining water levels in the field at between 40 and 60 cm. If palms are immature, water levels can be as high as 35 to 45 cm below the surface without affecting FFB yield (Mohammed *et al*., 2009). At this level of drainage, GHG emissions can be reduced by more than 50% compared to those with water levels at 70 to 100 cm of depth below the surface. However, flooding should be avoided, because this might enhance methane emissions and reduce FFB yields. To facilitate control of water table depth, correct spacing of drains are required and many exisiting drainage systems need to be modified (RSPO, 2012).

The use of fire for clearing of biomass and the associated burning of drained peat in dry years is the next largest source of GHG emissions in peat swamp areas. The implementation of zero burning and provision of fire prevention measures can help to minimize emissions. Shredding of old palms is a technique that is commonly used to clear old plantations for replanting. The pulverized material can be applied in the field for protection of the soil from drying and erosion and for maintaining soil fertility. Different techniques for pulverization and application of the pulverized materials are examined by Ooi *et al.* (2004). The risk of fire in oil palm plantations on peat is generally reduced when compared to similar peat soil types located in abandoned peatland. Peat and forest fires often occur outside the plantation because of off-site impacts of drainage within the plantations, because the hydrological system surrounding the plantations has been disrupted, which makes these degraded but remnant peat ecosystems susceptible to wildfire.

It is uncertain whether compaction of the peat soil before planting oil palms leads to lower CO_2 emissions compared to no compaction. The oxidation of the peat might be reduced due to the decreased porosity of the soil. Maintenance of a natural vegetation cover of grasses, ferns and mosses and a planted legume cover will reduce decomposition of the peat by reducing soil temperature (Jauhianen *et al*., 2012; Hooijer *et al*., 2012). Maintenance and rehabilitation of hydrological buffer zones can also minimize peat CO_2 emissions from forested areas surrounding plantations (Page *et al*., 2011b).

Recycling of wastes, use of renewable fuels, maximizing fuel savings by using water and rail transport systems, and implementation of mill practices that include CH_4 capture, maximising energy efficiency are possible ways to reduce emissions. The use POME and empty fruit bunches as compost brings addional benefits, as studies show that a40-ton CPO per day capacity mill can provide 20-30% of an estate's fertilizer needs. The use of 'coated' nitrogen fertilizer, composting and careful fertilizer application during rainy seasons will help to reduce N_2O emissions.

Recommendations for further research

- Long term measurements are needed of CO_2, CH_4 and N_2O fluxes using a combination of chamber-based measurements to capture small scale spatial variation and eddy covariance measurements to capture temporal variation at the landscape scale. These should be combined with soil subsidence measurements to tackle the very high uncertainties in GHG emission studies.
- Simultaneous recording of variables that may affect the fluxes (e.g. soil temperature, moisture, water table depth, soil and water chemistry, incoming and outgoing radiation) are required to establish robust predictive relationships for GHG models.
- Comparisons should be made of carbon and GHG emissions between ecosystems differing in land use and management intensity (e.g.

primary forest, secondary forest, oil palm plantations, and sites varying in depth of water table).

- GHG fluxes of the total ecosystem should be captured, including fluxes from water bodies, using robust, well established, sampling designs.
- In addition to establishing regression models and predictive relationships based on emission data, it is of important to develop methodologies that enable local communities and stakeholders monitor the variables on their holdings that drive the emissions.
- New allometric models should be developed for estimating both above- and below-ground biomass of peat swamp forests and other land cover types prior to establishing plantations (e.g. Verwer & van der Meer, 2010).

OTHER ENVIRONMENTAL IMPACTS OF DEVELOPING OIL PALM PLANTATIONS ON TROPICAL PEAT SWAMPS

Changes in land use and their implications

With oil palm being the most rapidly expanding crop in Southeast Asia, there is a need to identify sites where the development of oil palm plantations has the least impact, as well as ensure that oil palm that has already been planted enjoys improved management (Wösten *et al*., 2007; Fitzherbert *et al*., 2008). The negative impacts in terms of sustainability of transforming peat swamp forests into oil palm plantations include:

1. Soil subsidence leading to increased flooding risk and salt water intrusion.
2. Loss of biodiversity and ecosystem services.
3. Carbon emissions into the hydrosphere through runoff and erosion.
4. Methane emissions from POME ponds.
5. Discharge of other effluents from palm oil mills into waterways with adverse consequences for water quality.
6. Increased fire risk through peat drainage, leading to adverse implications for human health.

Subsidence, salt water intrusion and flooding risk

Tropical peat swamps affect the hydrology of surrounding ecosystems due to their large water storage capacity which slows the passage of flood waters in wet seasons and maintains stream base flows during dry seasons (Yule, 2010). Disruption of this hydrological system, for example by clear cutting and drainage will have consequences for hydrological regulation. For example, because of the low capillary rise in peat soils, oil palm on drained peat is very sensitive to drought and dry periods often result in significant yield reductions (Mantel *et al*., 2007).

Drainage of peat leads to soil subsidence (Polak, 1933; Andriesse, 1988; Dradjad, 2003; Schothorst, 1977; Couwenberg *et al.* 2010; Hooijer *et al*., 2012). Soil subsidence is caused by several processes: consolidation, compaction, oxidation, fires, and water and wind erosion. Consolidation refers to surface height loss caused by tighter packing of the peat soil below the water table. Consolidation of tropical peat drained for plantation development may result in considerable height losses, but usually ends within one year (Den Haan et al., 2012). Like compaction (and shrinkage) of peat above the water table it does not result in carbon losses.

The initial or primary subsidence depends on the type and depth of peat and the drainage level; subsidence rates can be more than 50 cm yr^{-1} in drained tropical peat (Hooijer *et al*., 2012; Wösten *et al*., 1997; Mohammed *et al*., 2009). After a few years of drainage, the balance between the processes contributing to subsidence will change and oxidation becomes the main factor responsible for subsidence. Hooijer *et al.* (2012) indicated that consolidation contributes only about 7% to the total subsidence after the first year after drainage; in fibric peat with low mineral content the role of compaction is reduced rather quickly and becomes negligible after 5 years. Over 18 years of drainage, 92% of the cumulative subsidence was found to be caused by peat oxidation, which is close to the 85-90% reported for subtropical peat by based on more than 76 years of measurements in the Florida Everglades (Stephens *et al.* 1984). Those studies also report that peat surface subsidence continues at a constant rate for many decades, which can explained by the dominance of oxidation and the limited role of compaction (Stephens *et al.* 1984). Wösten *et al*. (1997) report average subsidence rates of 4.6 cm yr^{-1} for oil palm plantations in Johor at 14 to 28 years after drainage (Figure 5). The most recent, extended research of Hooijer *et al*. (2012) shows that constant long-term subsidence rates are 4.5 - 5 cm y^{-1}, on the basis of both literature reviews and subsidence monitoring for water tables between 60 and 80 cm at 218 locations in *Acacia* and oil palm plantations in Indonesia. No studies have been published on the relationship between soil subsidence and CH_4 or N_2O emissions.

In the study in Sessang, Sarawak, soil subsidence rates stabilized after 15 years of drainage, ranging from 2.48 cm yr^{-1} in shallow peat (100 – 150 cm), 2.97 cm yr^{-1} in moderately deep peat (150 – 300 cm), and 4.28 cm yr^{-1} in deep peat (> 300 cm). With increasing insight it is more appropriate to split 'first year soil subsidence' from soil subsidence in subsequent years because compaction and consolidation have a greater contribution to soil subsidence in the earlier, than in later years after drainage. In later years subsidence is mainly driven by oxidation.

Soil subsidence can cause the peat surface to drop to levels that enable the water table to reach and rise above the new surface level in periods of high rainfall. This may lead to flooding of adjacent land and downstream areas (Page *et al*., 2009). In addition, because of the soil subsidence and reduced water retention, the freshwater buffer function of the peat swamps decreases, resulting in a decreased buffer against salt water intrusion in the dry seasons (Silvius *et al*., 2000). Examples of the consequences of increased salt water intrusion are, 1) a decline in fish larvae abundance and large scale fish habitats (Cruz *et al*., 2007; Loukos *et al*., 2003), 2) a negative impacts on turtle populations (WWF, 2007), 3) changes in species distribution, reproductive timings, and phenology of ground cover plants (Cruz *et al*., 2007), and 4) impacts on coastal agriculture (Silvius *et al*., 2000). The current sea water rise of about 1-3 mm yr^{-1} in coastal areas of Asia and its projected acceleration to a rate of about 5 mm yr^{-1} over the next century (based on projected climate change with a warming of 0.2 – 0.3 ^{o}C per decade in Indonesia) will amplify the flooding risk (Cruz *et al*., 2007).

With on-going drainage in oil palm plantations the peat will eventually disappear, exposing underlying mineral substrates that will hold far less water and are likely to be nutrient deficient, or, in the case of acid sulphate soils, to contain pyrite (FeS_2) that is detrimental to plant growth (Wösten and Ritzema, 2001). As soon as these soils are drained, pyrite is oxidized and severe acidification results. A number of chemical, biological and physical problems arise from this acidification: aluminium and iron toxicity, decreased availability of phosphate, other nutrient deficiencies, hampered root growth, blockage of drains by ochre, and corrosion of metal and concrete structures. As a result, habitats located downstream of acid sulphate soils may also be threatened (Wösten *et al*., 1997). Exposing these soils will lead to new and difficult problems for local people and land managers (Silvius *et al*., 2000).

To reduce the negative impacts of drainage, such as soil subsidence, high CO_2 emissions, irreversible drying of soils, and eventually drying of oil palm leaves due to moisture stress, the water table has to be managed properly. Mohammed *et al.* (2009) studied soil subsidence in a 1,000 ha peat area in Sarawak, with a peat depth ranging from 100 – 400 cm, and bulk densities ranging from 0.09 g cm^{-3} in deep peat to 0.14g cm^{-3} in shallow peat. The study suggests that sustainably high oil palm yields can be attained by maintaining the water table between -35 and -45 cm from the peat surface after the first two years of planting, with soil subsidence remaining low and CO_2 emissions reduced by 50% compared to more deeply drained soils (Figure 6).

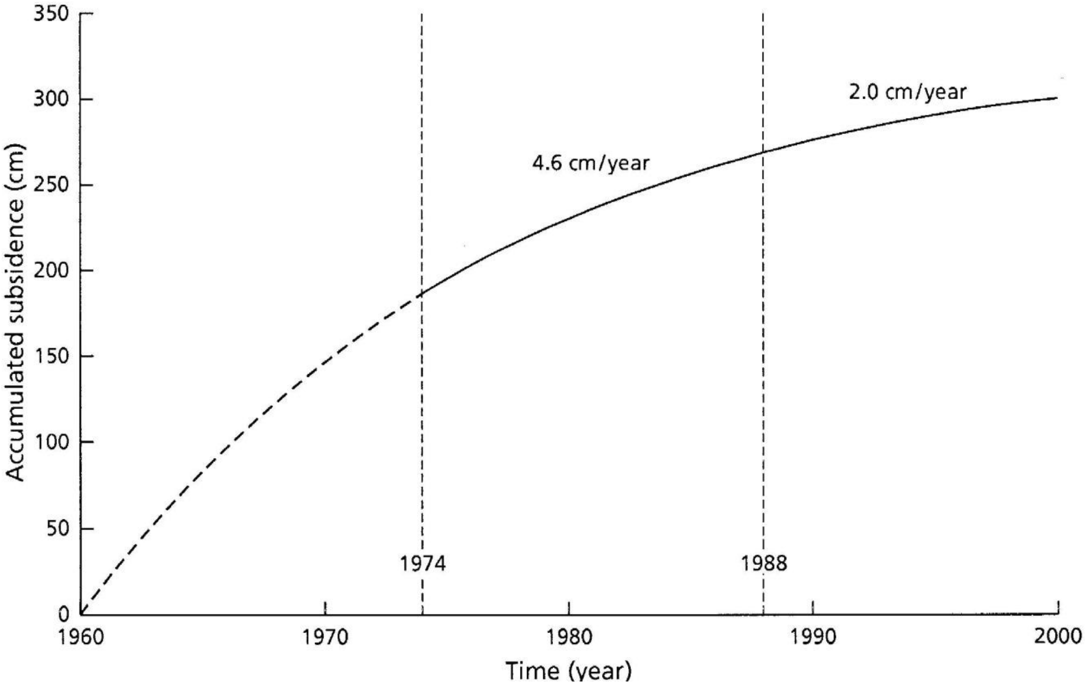

Figure 5. Subsidence rates for individual monitoring locations in relation to depth of water table as measured in *Acacia* plantations six years after drainage, in oil palm plantations 18 years after drainage, and in adjacent forest in Sumatra, Indonesia (Hooijer *et al.,* 2012).

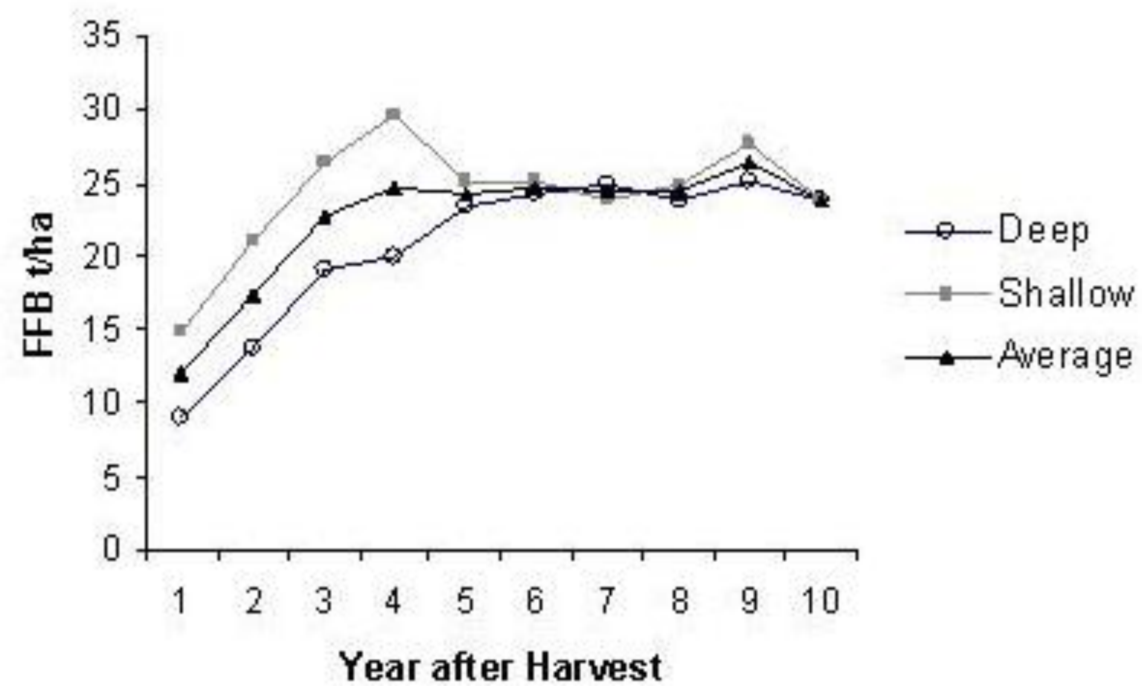

Figure 6. Fresh fruit bunch (FFB) yields of oil palm planted on peat with water table maintained at 35 to 45 cm below field level in the MPOB Research Station in Sessang, Sarawak (Mohammed *et al.*, 2009).

Biodiversity

Myers *et al.* (2000) included Malaysia and Indonesia in a list of the top three global biodiversity hotspots. Simbolon & Mirmanto (2000) reported 310 vegetation species in the peat swamp forests of Central Kalimantan. Deforestation and the transformation to oil palm plantations in the tropics has therefore led to a high rate of species decline (e.g. Clements *et al*., 2010; Edwards *et al*., 2010; Wilcove & Koh, 2010; Sodhi *et al*., 2010; Berry *et al*., 2010; Brühl *et al*., 2003; Danielsen *et al*., 2009; Fitzherbert *et al*., 2008; Koh & Wilcove, 2007, 2008, 2009; Hamer *et al.*, 2003). This loss is significant because reductions in species diversity are considered to be irreversible and therefore the need to conserve peat swamp forests in the Indo-Malayan region is clearly urgent (Yule, 2010). Posa *et al.* (2011) have estimated the numbers of species in Southeast Asian peat swamp forests, including those restricted to or strongly associated with this ecosystem (see *Table 13*).

The various types of vegetation on peat all sequester carbon through photosynthesis. Based on the amount of C stored, peat swamp forests are one of the world's most important terrestrial carbon reserves. In terms of usefulness for humans, the diversity of species in the tropical forests is of value for breeding useful animals and plants, as well as for the development of medicines. Among the various types of vegetation in peat swamp forests, some species have high economic value such as Jelutung (*Dyera polyphylla),* whose sap can be used in the production of chewing gum and many other products, and timber species such as Ramin (*Gonystylus bancanus*), Meranti (*Shorea spp.*), Kempas (*Koompassia malaccensis*), Punak (*Tetramerista glabra*), Perepat (*Combretocarpus rotundatus*), Pulai rawa (*Alstonia pneumatophora*), Terentang (*Campnosperma spp.*), Bungur (*Lagastroemia spesiosa*), and Nyatoh (*Palaquium spp.*) (Giesen, 2004). Logging has not adversely affected the fish fauna significantly, but recent incursions such as deepening of drains have increased risks of salt water intrusion (Yule, 2010).

Other than plants, peat swamp forests are the habitat of a number of rare animal species. Tanjung Puting and Sebangau National Parks in Central Kalimantan, both peatland forest ecosystems, are major habitats for the endangered orangutan (*Pongo*) (Gaveau *et al.*, 2009). A number of peat swamp forest areas in Sumatra are habitats for the Sumatran Tiger (*Panthera tigris sumatrana)* and tapir (*Tapirus indicus*). A study by van Eijk & Leeman (2004) in Berbak National Park showed the presence of 107 bird species, 13 mammal species [e.g. wild boar (*Sus scrofa)*, tapir, Sumatran tiger, Malayan sun bear (*Helarctos malayanus*), silvery leaf monkey (*Presbytis cristata*), and Malay stink badger (*Mydaus javenensis*)] and 14 different reptiles and amphibians. Peat swamps in Sumatra, Kalimantan and Papua are also habitats of various endemic fishes, such as arowana (*Scleropages* spp.) (Simbolon, 2011). Sebastian (2002) recorded 57 mammal species and 237 bird species for Malaysian peat swamp forests. Of these, 51% of the mammals and 27% of the bird species were on the IUCN red list of globally threatened species. Regional peat swamp forests are the last refuge for many endangered species from other lowland forests, which are under even greater pressures from logging, hunting and development (e.g. Sodhi *et al*., 2010; Wich *et al*., 2008).

Table 13. Estimated numbers of plant and animal species in peat swamp forests in Southeast Asia (Posa et al., 2011).

Total number of species	Plants	Mammals	Birds	Reptiles	Amphibians	Freshwater fish
Recorded from PSF	1524	123	268	75	27	219
Restricted to PSF	172	0	0	0	0	80
Strongly associated with PSF		6	5	1	3	

PSF, Peat Swamp Forest
Source: Data compiled from various sources available from authors by request

Several authors have proposed strategies that both reduce emissions and enhance biodiversity within oil palm landscapes, such as production of oil palm beneath shade trees, establishment of diverse agro-forestry on plantation boundaries, and maintenance of forest patches within plantations (Koh & Wilcove 2008). A regulation to restrict oil palm expansion to only degraded lands and existing agricultural lands would partly solve the problem. But if logged forests are classified as degraded lands, then biodiversity will continue to decline. Many of the largest palm oil producers have expressed a desire to implement environmentally friendly management. Maintenance of forest patches within oil palm plantations has been suggested as a means to increase biodiversity. However, Edwards *et al.* (2010) have shown that forest patches, if not inter-connected, did not increase bird abundances in adjacent oil palm, had lower species richness than contiguous forest, and had an avifaunal composition that was more similar to oil palm than to contiguous forest. Another study by Benedick *et al.* (2007) shows that in Borneo, species richness and diversity of butterflies and ants declined significantly with declining forest area and endemic species were not recorded within small forest remnants (<4000 ha). Many studies highlight the importance of retaining areas of contiguous forest for biodiversity protection and they suggest that from a conservation perspective any investment in the retention of forest patches would be better directed toward the protection of contiguous forest (e.g. Berry *et al*., 2010; Edwards *et al*., 2010; Sodhi, 2010; Benedick *et al*., 2007).

The conclusion of Myers *et al.* (2000) is that what we do (or do not do) within the next few decades in terms of biodiversity protection will determine the long-term future of a vital feature of the biosphere, namely the abundance and biodiversity of species. A mixture of regulations, incentives and disincentives targeted at all sectors of the palm oil industry is necessary to protect the region's rapidly disappearing forest (Koh & Wilcove, 2008; 2009). In addition to protecting relatively undisturbed forests, conservation biologists also have to develop strategies to make human-dominated areas more hospitable for forest biodiversity (Gardner *et al*., 2009; Sodhi *et al.*, 2010). No conservation strategy can be successful without the cooperation and involvement of local communities. It is, therefore, of great importance to involve local communities and stakeholders in conservation projects, and to create awareness and willingness to cooperate in such schemes.

Emissions to the hydrosphere

Studies have indicated rising concentrations of dissolved organic caribon (DOC) in past decades in rivers and streams in tropical peat swamp areas. Increases of 15% DOC have been recorded during the transition from dry to wet periods around plantations (Rixen *et al*., 2008). The carbon is transported and rapidly decomposes, causing high fluxes of CO_2 from water bodies (Couwenberg *et al*., 2010; Holden *et al*., 2004). Baum *et al.* (2007) extrapolated DOC losses to the whole of Indonesia and suggested that Indonesia represents some 10% of the global riverine DOC input to the ocean. Rixen *et al.* (2008) suggest that peat soils in the area they studied (the Siak river catchment in central Sumatra) were being destabilized by deforestation, drainage and conversion into oil palm and rubber estates. Anthropogenically enhanced leaching as seen in other studies (Holden, 2005; Holden *et al*., 2004) is very difficult to quantify as base data are usually unavailable prior to deforestation. However, oil palm monocultures are frequently associated with erosion as forest clearance leaves soils bare and exposed to heavy tropical rainstorms before ground cover is re-established. Erosion in turn, causes contamination and sedimentation in water courses. Water quality is also influenced by the runoff of fertilizers into surrounding drainage ditches, causing eutrophic conditions (Rixen *et al*., 2008; Miyamoto *et al*., 2009; Yule & Gomez, 2009). Moore *et al,* (unpublished data) have also shown that deforestation and fire on tropical peat in Central Kalimantan has led to significant increases in fluvial carbon fluxes.

Palm oil processing also has an impact on water quality because palm oil mill effluent (POME) is released into rivers. While the impacts of this are minimised by anaerobic treatment prior to discharge such treatment is predominantly done using open ponds, resulting in large amounts of CH_4 being released into the atmosphere.

Increased fire risk

Fires are dependent on four conditions: the presence of fuel (organic material), oxygen, dryness and an ignition factor, and are usually caused by human intervention and linked to activities such as forest clearance, road development, and poor land use management. Undisturbed rainforests usually do not burn, due to high moisture levels in the atmosphere, vegetation and soil. However, drainage, excessive logging and forest clearance disturb the hydrological balance (Langner *et al*., 2007; Page & Rieley, 1998) and make both forests and peat highly susceptible to fires, especially in times of periodically occurring droughts typically coinciding with *El Niño* events (Page *et al*., 2002). Taylor (2010) shows that fire has increasingly affected forests in Indonesia over the last few decades, leading to severe consequences for biodiversity and air quality. Global climate change, coupled with land use changes, could lead to more frequent fires, which in turn could result in positive feedbacks with climate change (Page *et al*., 2002; Hooijer *et al*., 2006; Taylor, 2010). Research suggests that fires were the cause of the largest recorded increase in global CO_2 levels since records began in the 1950s (Aldhous, 2004). The *El Niño* event of 1982-1983 resulted in one of the largest forest fires ever recorded, where four million hectares of forest burnt in Kalimantan and Sabah (Brown, 1998). The fire risk in oil palm plantations on peat is generally reduced compared to that for abandoned, degraded peat land, because of intensive monitoring and control of fires by state agencies and estates (Paramananthan, quoted by Verwer *et al*., 2008).

The consequences of forest and peat fires are numerous and include destruction of the hydrological functioning of peat swamps (e.g. their ability to reduce flood peaks and maintain base flow in periods of drought), a loss of biodiversity and wildlife habitat, the death of seeds and seedlings so preventing re-establishment of vegetation (Yule, 2010), emission of CO_2 and other GHGs (Malhi, 2010), a reduction in photosynthesis due to dense smoke emitted from large fires and thus lower ecosystem production (Hirano *et al*., 2007), and soil erosion.

Another major impact of peat fires with far reaching effects on other ecosystems is air pollution. Adverse effects on human health in the region have been well documented (Brown, 1998). Forest fires release toxic gases such as carbon monoxide (CO), ozone (O_3) and nitrogen dioxide (NO_2) (Ostermann & Brauer, 2001). At least 20 million people were exposed to dangerously high levels of air pollution during the 1997 fires, with increases in asthma, bronchitis and other respiratory illnesses (Yule, 2010). In addition, many communities rely on forest goods and services such as timber and other forest products as well as water supplies, the quantity and quality of which is dependent on the presence of intact forest.

Discussion and gaps in knowledge

Drainage of tropical peat for cultivation leads to soil subsidence that ranges from 2.5 to > 50 cm per year. The subsidence rate is affected by peat type, soil structure, drainage depth and the number of years of drainage. Soil subsidence comprises three processes: compaction, consolidation, and oxidation. Oxidation is the dominant process that drives soil subsidence after the first years of drainage. Soil subsidence can, in the long term, lead to flooding and, in coastal areas to salt water intrusion. Maintaining the water table as high as possible (e.g. 35-60 cm) is the most effective means of reducing soil subsidence. A good practice is to define a 'cut-off' point for cultivation of a plantation before an undrainable level (the drainage base) is reached. This can be defined in terms of a minimum distance between the actual water table and the drainage base.

Tropical peat swamp forests support a rich variety of unique plant and animal species. Transformation of these forests to oil palm plantations always leads to a loss of biodiversity. Many studies highlight the importance of retaining areas of forest and they suggest that the focus should be on protecting existing contiguous forest rather than retention of forest patches within plantations. However, both measures should be encouraged.

Palm oil production on peat is associated with erosion of the drained peat resulting in sedimentation of the waterways and with inputs of fertilizer and crop protection chemicals that act as pollutants. Effluents from palm oil production mills add further to the production and release of wastes leading to further GHG emissions, loss of carbon and adverse effects on aquatic ecosystems.

Peat and forest fires are the second largest GHG sources after emissions due to drainage of peat. Undisturbed peat swamp forests do not usually burn, but can do so if drained and subject to seasonal droughts. Such fires can cause, 1) destruction of the hydrological functioning of the peat swamps, 2) loss of biodiversity and wild life habitats, 3) elimination of seeds and seedlings, 4) release of large amounts of CO_2 and CH_4 to the atmosphere, 5) smoke, resulting in lower ecosystem production, 6) air pollution and adverse effects on human's health, and 7) reduced photosynthesis due in reductions in photosynthetically active radiation (Davies & Unam, 1999a, b)..

Peat fires affect ecosystems worldwide by contributing significantly to climate change through increased GHG emissions. However, information on air pollution associated with the increased fire frequency after peat and forest burning is scarce and more research on these aspects is needed.

SOCIO-ECONOMICS AND PALM OIL PRODUCTION IN SOUTHEAST ASIA'S TROPICAL PEAT LANDS.

Introduction

Networks involved

In the past few decades, palm oil has become a major agricultural product which is used for various purposes such as cooking oil, medicines, pharmaceuticals, animal feed and biodiesel. In general, the raw product, harvested in the form of FFB, passes through various stages before it reaches the consumer. It provides income for many people along this production chain (Kamphuis *et al*., 2011). The oil palm industry is thus part of an economic network ranging from oil palm growers to downstream processing industries (Figure 7). Relations between the different stakeholders are predominantly of an economic and financial nature. The major increase in palm oil production in Indonesia and Malaysia is mainly driven by the global demand for crude palm oil (Kamphuis *et al*., 2011).

Indonesia

The development of oil palm plantations in Indonesia has increased from less than 1 Mha around 1990 to more than 8.1 Mha in recent years (IPOC, 2013). According to Sheil *et al.* (2009) the total planted area in 2009 was 7.3 Mha, of which 5.06 Mha was mature and producing fruit. Indonesian Ministry of Forestry statistics indicate that 70% of the current oil palm estates are located in areas formerly designated as forest for conversion, including over-logged forest (IPOC, 2013; Sheil *et al*., 2009). The large-scale development of plantations in Indonesia is facilitated by different levels of government. An important development in this respect has been the decentralisation of power, which has given local level authorities the right to decide on the use of state land. Large areas of peat forests have been awarded as concessions to private companies and this has resulted in the felling of valuable tree species even in the absence of actual oil palm plantation establishment (Schrevel, 2008). In 2007 the total planted area accounted for over 6.8 Mha of which around 3.4 Mha was controlled by private companies, around 2.8 Mha by smallholders and around 0.7 Mha by public companies.

Malaysia

Plantation development commenced in Peninsular Malaysia at the end of the 19th century (Colchester, 2007a). By 1925, nearly one Mha of land had been cleared of forest and planted with rubber (Jomo *et al*., 2004). Oil palm planting followed and the area of oil palm plantations is still growing, especially in the states of Sabah and Sarawak. In Peninsular Malaysia plantations covered over 2.36 Mha in 2007 (Kamphuis *et al*., 2011). In Malaysia as in Indonesia, there are different sectors involved in the production of palm oil. (2007a) described the example of Sarawak where successive governments since independence in 1963, have supported plantation schemes to promote 'development' and the more productive use of land. Many of the early schemes were with rubber and cocoa. The first pilot scheme with oil palm was implemented in 1966. The crops and techniques may differ but the underlying policy has remained essentially the same while the State has experimented with a series of initiatives to acquire land and capitalize estates in various different ways. None of the schemes have been without problems. Plans continue to promote development of oil palm plantations in so called 'unproductive forest' and in peat swamp forest (Colchester *et al*., 2007a).

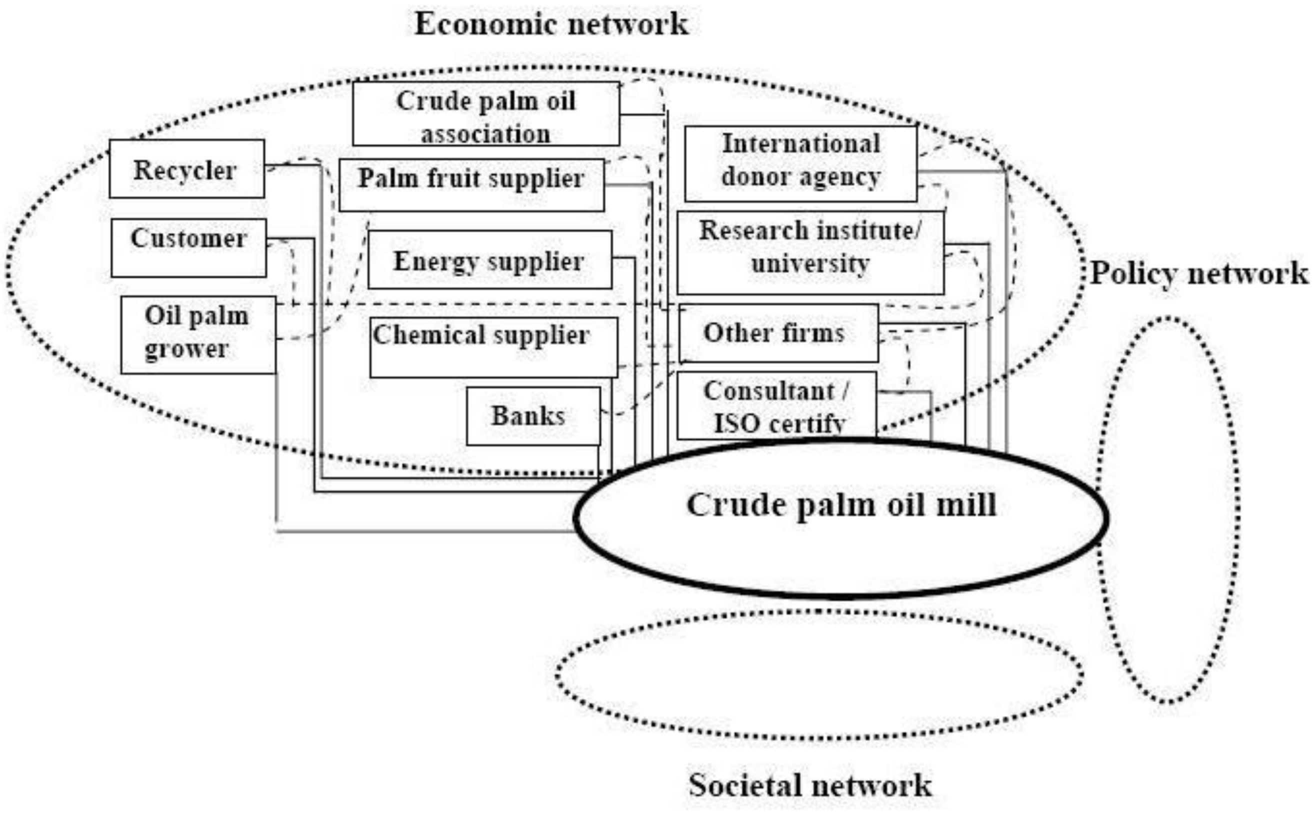

Figure 7. Economic networks relevant to the palm oil industry (adapted from Chavalparit, 2006).

Socio economics

Large scale conversion of crops, grasslands, natural and semi-natural ecosystems have social and ecological consequences. Development of estates has often led to negative impacts on ecosystem services and pressure on the remaining natural environment. Some authors have indicated that changes may be irreversible and socio-economic impacts largely negative for the local populations(Schrevel, 2008). The overall economic implications of oil palm as an alternative land use for smallholder income are not yet clear. They differ between regions and type of plantation (Kamphuis *et al*., 2009). Few studies have been published on the economic and social consequences of the transformation of forest to oil palm plantations. Often, studies provide contradictory results and the broader social and livelihood implications of oil palm cultivation remain poorly understood (Rist *et al*., 2009). Some of the reasons that research on this topic is complicated include the large number of stakeholders involved, the interrelationships between actors with different interests, and geographical differences.

Ecosystem services

Ecosystem Services are the economic benefits that ecosystems provide to humanity (Naidoo *et al*., 2009; Sodhi *et al*., 2010). Tropical forests provide a large number of ecosystem services both at the global level (e.g. climate control) and at the local level, including cultural, provisioning, and regulating services (e.g. erosion control, hydrological control, delivery of natural forest products, fisheries and tourism) (Sodhi *et al*., 2010). Their loss has consequences such as increased erosion, reduced biodiversity, decreases in crop pollination and increased chemical run off, as well as the ecological, social and economic costs of increased fire frequency (Sodhi *et al*., 2010). Also, the large number of people who depend on forest products for their livelihood will be affected by such on-going development.

Forest dependant communities

There are serious concerns about the impacts of oil palm expansion on forest dependant communities. Many people who live in rural areas depend on forests for a wide range of goods and services (Wakker, 2005). Conversion of forest has an impact on the livelihoods and culture of these indigenous populations. When forests are replaced by oil palm monocultures, communities lose their access to timber for construction, to rattan and to jungle rubber gardens (Sheil *et al*., 2009), and if they plant oil palm they may become affected by fluctuations in oil palm prices. Many of Indonesia's indigenous people practice shifting cultivation and companies generally prefer hiring workers with backgrounds in sedentary agriculture. For this reason there is a tendency for companies to hire migrant workers, which can lead to ethnic conflict between newcomers and indigenous groups.

Colchester (2007b) interviewed indigenous people in Sarawak and most of them were outspoken in their opposition to the way oil palm plantations are being developed on their lands. They feel their customary rights are being ignored and were promised benefits that were not delivered and measures to secure their consent to proposed schemes to be insincere.

Health

Human health in Southeast Asia has been affected by the haze resulting from ongoing forest and peat fires. Transboundary haze mainly from peat fires has been identified as the most important environmental problem in the ASEAN region. Smoke from tropical fires causes respiratory problems (Kamphuis *et al*., 2011) ,as well as other long-term health problems. Thousands of people died from smoke-related illnesses resulting from forest fires in Indonesia and Brazil (Cochrane, 2003). Components of smoke haze include known carcinogens whose effects may not be apparent for some time. During the 1997 fires, patient visits in Kuching, Sarawak, increased between two and three times and respiratory disease outpatient visits to Kuala Lumpur General Hospital increased from 250 to 800 per day. Effects were found to be greatest for children, the elderly, and people with pre-existing respiratory problems (Sastry, 2000). In Indonesia up to 500,000 people sought hospital treatment for smoke-related illnesses. Health effects depend on the concentration, composition and length of exposure to smoke. The complex mix of particles, liquids and gaseous compounds released depend upon the type and efficiency of burning. These emissions have been studied and quantified for savannah fires but not for tropical forest fires. In addition to respiratory illnesses, blockage of sunlight may promote the spread of harmful bacteria and viruses that would otherwise be killed by ultra-violet B radiation (Beardsley, 1997). Although not all fires leading to smoke haze are set by oil palm plantations and many plantations have adopted zero-burning strategies, there are still well documented cases of large-scale burning by plantation companies and recent analyses by the RSPO GHG Working Group 2 have determined that fires were used in land clearing prior to establishment of many oil palm plantations on peat in recent years.

Employment

Indonesia

The Indonesian oil palm sector has created around three million jobs, the numbers of which are still increasing. Over the next 10 years the Indonesian government plans to double the annual production of palm oil, creating new jobs for an estimated 1.3 million households and reducing poverty for around five million people (Bahroeny, 2009). This has been achieved largely through Nucleus Estate and Smallholders schemes (NES). In these schemes farmers transfer a proportion of their land to an oil palm company for establishment of an estate plantation; the remaining land also being planted by the company but retained as individual smallholdings by the farmers (Rist *et al*., 2010). In some cases smallholders sell their land directly or after one or two years to the company and are paid compensation for loss of land use opportunities. Deals differ significantly in detail, such as in the amount of land given up to the company in relation to that received back as an oil palm smallholding, the amount of debt that the farmer must pay back for the planting of oil palm on the area of land retained, and in the time period over which this must be done (Chong *et al*., 2008; Rist *et al*., 2010).

In 2010 smallholders had a land area of 3.08 Mha, with a share of 35% of the total crude palm oil produced and of 41% of the productive area (Sheil *et al*., 2009; Vermeulen & Goad, 2006). Because of the required machinery and the need for palm oil mills, most smallholder plantations are part of larger, company owned plantations termed nucleus estates (Sheil *et al*., 2009; Kamphuis *et al*., 2011). Wakker (2006) argued that the majority of the economic benefits of oil palm plantations accrue nationally or regionally to a few large palm oil plantation owners and the Indonesian government rather than to smallholders. In addition, because companies prefer experienced labour, large-scale oil palm projects in Indonesia have tended to employ workers from outside the area of operation, fostering social conflicts (Wakker, 2005, 2006; Schrevel, 2008; Wilcove & Koh, 2010; McCarthy & Cramb, 2009). However, these effects are mitigated by the construction of infrastructure and provision of houses, health and educational services that usually accompany the large-scale development of oil palm plantations (Bertule & Twiggs, 2009). As a result, rural communities have easier access to local markets, schools and hospitals.

Malaysia

Oil palm is one of the main drivers of the Malaysian agricultural industry. Malaysia's palm oil industry is the fourth largest contributor to the national economy. Oil palm plantation development started about 100 years ago and production now accounts for 71% of the national agricultural land bank. Malaysia has some of the highest FFB yields at about 21 tonnes ha^{-1} $year^{-1}$. Malaysia's palm oil industry is regulated by the Malaysian Palm Oil Board (MPOB), which develops policies, guidelines and practices for the industry. As of 2009, Malaysia had 4.7 million hectares of oil palm plantations. The industry is dominated by large plantation companies (both private and government-linked) which hold 60 percent of total plantation land. However, there is a significant proportion of palm oil plantations under the ownership of both organized and independent smallholders who account for 28 and 12% of the total area respectively (Government of Malaysia, 2011). Malaysia's oil palm industry employs a large labour force; MPOB estimated its total size in 2010 in the plantations to be 446 368. This number consists mainly of foreign workers (69%) with locals comprising only 31% (Ramli, 2011).

Income

In Indonesia plantations, particularly oil palm and forestry sectors, contributed 3% to the national economy in 2007 (BAPPENAS, 2009), while the oil palm plantation sector was estimated to contribute 0.85% to GDP. Kessler *et al.* (2007) showed that at a regional level there was a rise in GDP in both the expanding and established regions. At the farm level, the support of the government's nucleus estates that is provided to individual smallholdings has resulted in an increase in income of more than half a million farmers (Zen *et al.*, 2006). The average income for these farmers is seven times higher than the average income of subsistence farmers (Sheil *et al*., 2009). Noormahayu *et al.* (2009) concluded from a questionnaire study that most of the 200 farmers they interviewed in Sungai Panjang, Malaysia, worked 1.1 - 1.5 ha of land giving an annual average income of RM 5,001 - RM 10,000.

One of the main constraints to such farming was found to be the limited area of land that individual farmers own, which means that most of them plant just one crop, which has no yield during the first 3 years after planting. This renders them vulnerable to exploitation by buyers and other outsiders. Nonetheless, many choose oil palm because it provides a better income than fruit and vegetables. Rist *et al.* (2010) examined the economic implications of oil palm as an alternative land use for smallholders using research sites in Central Sumatra, West Kalimantan, East Kalimantan and Central Kalimantan (see Box 4). They concluded that many smallholders have benefited substantially from the higher returns on land and labour afforded by oil palm, which is in line with published results of Wilcove & Koh (2010), but district authorities, smallholder cooperatives, and the terms under which smallholders engage with palm oil companies, play key roles in the realization of benefits (McCarthy, 2010).

Susila (2004) concluded that there is a positive effect on farmers' income generated by palm oil production which reduces income inequality and poverty in palm oil communities. However, income is just one aspect of a sustainable livelihood. The conclusion of Rist *et al.* (2010) is that in Indonesia smallholders are not impoverished by oil palm development but they can suffer by the sale of their land during development. Although Rist *et al.* (2010) show that the cultivation of oil palm may afford new income opportunities to many Indonesian farmers in the short term, they note that the longer term economic implications remain uncertain.

Box 4

Profile of Smallholders in Siak district, Riau Province, Indonesia.

A group of smallholders coordinated are seeking to improve the management of plantations on peat. These smallholders are located in Siak district in two sub districts, Bunga Raya and Pusako, and are organized into seven separate cooperatives coordinated by the *Kelompok Tani* farmers cooperative. With a total membership is about 1,140 families, about 850 families with a total of about 2,200 hectares have elected to pursue RSPO certification with the assistance of the local NGO, Yayasan ELANG.

The total land area is about 3,500 hecatres, all of which is located in shallow peat soils located close by the Siak River. According to PTPN5, a state owned plantation company that collaborates with the smallholders, about 30% of the area has mineral soils and 70% is classifies as shallow peat. The plantation was developed under the auspices of the local government with the objective of reducing poverty in the Siak area and to provide opportunities to smallholders for participating in the oil palm supply chain. The project was initiated in 2003 when smallholders were provided assistance to establish oil palm plantations. The establishment was contracted by the local government via PTPN5, which built the drainage ditches and obtained seeds sourced from a reliable seed supplier. The transfer of the plantation from PTPN5 to the smallholders was done in 2009, when the palms first started producing fruitAssessments of the communities by the RSPO PLWG in 2011 revealed that although many Best Management Practices (BMPs) have been followed, most smallholders were using fertilizer regimes that were better suited for mineral soils and had not yet installed adequate control structures in the drainage ditches in order to maintain appropriate water levels throughout the year. The visit revealed that significant improvements in yield could be made if assistance on implementing BMPs was provided to communities, which would likewise reduce GHG emissions.

Concerns have been raised on topics such as, 1) the adoption of oil palm by smallholders at the expense of more diverse agro-forestry and swidden systems, 2) their vulnerability to crop failure and over dependence on support by companies, and 3) exposure to future economic risk because of price fluctuations or negative ecological impacts (e.g. soil subsidence, exposure of toxic sediments, etc.; Butler *et al.*, 2009; Syafriel, 2009; Rist *et al.*, 2010; Sheil *et al.*, 2009; Schott, 2009).

Smallholders are sometimes unaware of their rights and the nature of agreements made with companies (Rist *et al.*, 2010). Newer, more equitable practices recommended include: 1) the need to clarify smallholder land rights to avoid land tenure conflicts (Chong, 2008), 2) the reformation and standardization of contracts for agreements between farmers and oil palm companies at districts level (Rist *et al.*, 2010), 3) the need to improve management capacity of smallholders' cooperatives (in particular, that of the head of the district who plays a key role in raising awareness of rights), and 4) promotion by governments at the national and district level of further oil palm development via individual smallholdings rather than by large businesses (Rist *et al.*, 2010). Noormahayu *et al*, (2009) conclude that oil palm cultivation on peat can be a profitable investment so long as growth conditions, costs, selling price and interest rates do not fluctuate substantially.

Discussion, gaps in knowledge and recommendations

Summary of main conclusions

The palm oil sector has created millions of jobs and the number of which are still increasing. Oil palm is one of the main drivers of the Malaysian and Indonesian agricultural industry. Oil palm plantation development started about 100 years ago and production now accounts for 71% of the Malaysian agricultural land bank. The Indonesian oil palm sector has created around three million jobs, which are still increasing. Over the next 10 years the Indonesian government plans to double the annual production of palm oil, creating new jobs for an estimated 1.3 million households and reducing poverty for around five million people.

Many smallholders have benefited substantially from the higher returns on land and labour afforded by oil palm. However, in Indonesia, a large part of the economic benefits of oil palm accrue nationally or regionally to relatively few large palm oil companies as well through taxes and fees to the government.

Smallholder cooperatives and the terms under which smallholders engage with oil palm companies play key roles in the realization of benefits to local communities. Although the cultivation of oil palm may afford new income opportunities to many local farmers in the short term; the longer term economic implications remain uncertain. Concerns have been raised on topics such as: 1) the adoption of oil palm by smallholders at the expense of, for example, diverse agro-forestry and swidden systems, 2) the vulnerability of smallholders to crop failure and their dependence on companies, and 3) the exposure to future economic risk because of price fluctuations and negative ecological consequences.

Transformation of tropical peat forests to plantations will lead to loss of ecosystem services and affect the social and cultural basis of forest dependant communities. Also health in Southeast Asia has been affected negatively by haze resulting from ongoing burning of above-ground biomass and peat. Health effects depend on the concentration, composition and length of exposure to smoke and include respiratory and cardiovascular complaints among other illnesses.

Gaps in knowledge and uncertainties

- Information on the social and economic effects of oil palm development is scarce and contradictory.
- There is a major need for alternative production scenarios that allow ecologically and socially sustainable oil palm development and give the highest yields with the lowest social and environmental impacts.
- There is a major need for social studies at all levels, including plantation owners, people depending on forest products or other crops, smallholder cooperatives, and indigenous communities.

MAIN CONCLUSIONS

About 60% of the world's tropical peats are located in Southeast Asia. The original tropical peat swamp forests are important for carbon storage, biodiversity conservation, climate regulation and as a source of for the livelihoods of local communities. The large-scale conversion and drainage of peat swamp forests in Indonesia and Malaysia, in a large part for oil palm plantation development, has significant impacts on the environment.

Currently, most studies indicate that the transformation of an intact peat swamp area to oil palm plantations leads to a release of GHGs to the atmosphere (de Vries *et al.*, 2010; Henson, 2009; Jeanicke *et al.*, 2008; Danielson *et al.*, 2008; Fargioni *et al*., 2008; Rieley *et al.*, 2008; Gibbs *et al.*, 2008; Wösten & Ritzema, 2001; Hooijer *et al.*, 2006). When oil palm plantations are developed on peat, oxidation due to drainage, fires and carbon losses when vegetation is cleared, are major sources of GHG emissions.

Once a plantation is developed on peat, this can lead to serious land degradation over the long term, increased flooding and salt water intrusion into coastal watertables. These conditions also will adversely affect palm oil production eventually.

Effective water management directed at maintaining the water table as high as possible while still maintaining oil palm yield can reduce soil subsidence, GHG emissions and fire risk. Because in all cases peat loss and soil subsidence will continue as long as these landscapes are subject to drainage, a 'cut-off-point' for growing oil palm is recommended before an undrainable level is reached and flooding becomes inevitable.

Methane emission from open water bodies such as drainage canals and ponds is likely to affect the GHG balance. This may be significant as the water surface of drainage canals may account for 2-5% of the total area of a plantation on peat. Better quantification of this emission is required.

Nitrous oxide is primarily emitted from agricultural landscapes as a by-product of nitrification and denitrification. In oil palm plantations the application of N fertilizers and N-containing organic mulches accelerates its release.

The Indonesian and Malaysian oil palm sectors have created millions of jobs and average incomes have risen since oil palm cultivation started. However, although many smallholders have benefited substantially, the majority of the economic benefits accrue to relatively few palm oil companies and to governments. Cooperatives and the terms under which smallholders operate play key roles in the realization of benefits at the local level.

Good implementation of Best Management Practices (RSPO, 2012) in the cultivation of oil palm on peat is necessary to enhance sustainability. However, it is important to note that current sustainability measures in oil palm plantations on peat may decrease emission source strengths, but will not turn these systems into carbon or GHG sinks.

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