Environmental and social impacts of oil palm cultivation on tropical peat – a scientific review

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Abstract

This report provides an independent review of available scientific information and published literature on impacts of the use of tropical peat for oil palm cultivation in Southeast Asia. It describes the carbon flows and greenhouse gas emissions from degraded and native 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 also presents conclusions on the various aspects, gaps in knowledge, uncertainties and confusion in existing datasets.

The palm oil sector has created in the past few decades millions of jobs, and is still expanding. Over the next decade for example, 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 creates new income opportunities to many farmers in the short term; the longer term economic implications remain uncertain. Transformation of tropical peat forest into plantations will lead to loss of ecosystem services and biodiversity and will affect the social and cultural basis of forest dependant communities. Human health is also affected negatively in Southeast Asia by the haze resulting from large forest and peat fires related to drainage of the peat. There may also be other negative ecological consequences such as soil subsidence and greenhouse gas (GHG) emissions. Soil subsidence can be a major problem in the near future because it may lead to flooding and to salt water intrusion. It is wise to think about a certain ‘cut-off point’ before an undrainable level (the drainage base) is reached.

Oil palm plantation development on peat also leads to the release of carbon and greenhouse gases to the atmosphere. When peat is developed for agriculture, carbon is lost because of 1) oxidation of the peat, 2) an increase in fire frequency and 3) carbon loss from biomass if this exceeds the gain due to growth of the oil palms, as is the case when forest is converted. The most obvious measure to limit GHG emissions, based on this review, is to limit development of oil palm plantations on peat. If development of plantations is on mineral, low carbon soils, the impacts are far less significant in terms of GHG emissions. For existing plantations on
peat, effective water management (keeping water tables as high as practical) helps to reduce GHG emissions and reduces soil subsidence and fire risk. However, it has to be noted that these measures will not turn the system into a carbon and/or GHG sink.

*Keywords: tropical peat, oil palm cultivation, forest, carbon, greenhouse gases, biodiversity, socio-economic aspects, Southeast Asia.*
1 Introduction

1.1 Context

On November 4th 2009, a resolution was adopted at the 6th General Assembly of the RSPO on the ‘Establishment of a working group to provide recommendations on how to deal with existing plantations on peat’ (Box 1).

Box 1
Background and objective 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 oil palm products through credible global standards and engagement of stakeholders. The Peat Land Working Group (PLWG) is part of the RSPO and functions as a work stream of its 2nd Working Group on Greenhouse Gases (GHG Working Group). It is envisaged to be 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 and additionally on biodiversity, social and livelihood implications and to advise the Executive Board in order to develop a process that will lead to meaningful and verifiable reductions in greenhouse gas emissions from the palm oil supply chain. Part of this process is to review scientific literature on the influence of oil palm plantation development and to provide recommendations for reducing greenhouse gas emissions from palm oil production on peat and the associated management.

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 soil carbon oxidation. The resolution also referred to the fact that the first RSPO Greenhouse Gas (GHG) Working Group, which had been established to investigate and develop principles and criteria for 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 noted that even when assuming minimum estimates of CO₂ emissions from existing oil palm plantations on peat, these plantations were not sustainable in terms of emissions. In addition it mentioned that besides GHG issues, in many cases oil palm plantations on peat in the long-term may also result in significant on- and off-site hydrological impacts as a result of soil subsidence and reduced water retention capacity. The resolution therefore called for the RSPO General Assembly to agree to establish a Committee to explore and develop business models for optimising sustainability of existing oil palm plantations on peat, including options for restoration and development of alternative economic uses, and exploring water management regimes appropriate to reduce emissions, mechanisms that facilitate restoration of peat and
recommendations on after-use of plantation areas on peat. The resolution was adopted by an overwhelming majority of RSPO members.

This report (commissioned by the Peatland Working Group (PLWG) of the RSPO) provides an independent review of available scientific information on impacts of the use of tropical peat for oil palm cultivation in Southeast Asia. It assesses sources of uncertainty, gaps in knowledge and structures the findings of relevant publications on topics related to the cultivation of oil palm on tropical peat. Implications of this transformation have been reviewed in a broader context. In summary, the objectives of the review are to:

- To clarify issues related to cultivation of oil palm plantations on tropical peatlands in terms of carbon and GHG, as well as in terms of other ecological, social, economic and livelihood implications.
- To define spatial boundaries of the system and major categories of carbon and GHG sources and sinks.
- To highlight uncertainties and gaps in knowledge.
- To provide recommendations for reducing GHG emissions.

1.2 Tropical peatlands

USDA defined peat as organic soils (Histosols) if more than half of the upper 100 cm is organic. 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 (Driessen, 1978; Wösten and Ritzema, 2001). The existence of peat depends on plant cover and hydrological conditions. Peat lands have their greatest extent in the boreal and temperate zones, but tropical peats, located in Southeast Asia, Africa, the Caribbean, and Central and South America, are also important components of the global resource and 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 climate zones (Box 2). The most extended tropical peat lands occur in Southeast Asia (representing 77% of global tropical peat carbon stores (Page et al., 2011)), most of which are located in Indonesia (22.5 million ha or 65%) followed by Malaysia (10%) (Hooijer et al. 2010). Global awareness of the significant role that tropical peats and their forests play in the global carbon cycle has increased, 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.

Tropical peats in Southeast Asia occupy mostly 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 peatslands are located at elevations less than 50 m above mean sea level. Most Southeast Asian peats are ombrotrophic (receiving precipitation only), while a few basin peats are minerotrophic (receiving ground water 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 Guine, 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 has 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, 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 (Page et al., 2011). Carbon content of tropical peat usually ranges between 40% and 60% depending on the nature, mineral content and location of the peat.

**Box 2**

**Tropical peat versus temperate and sub-arctic peat**

Tropical peats differ from temperate peats. Temperate and sub-arctic peats are mainly derived from the remains of low growing plants \((\text{Sphagnum spp. Gramineae and Cyperaceae})\). Tropical lowland peats are formed from forest species and hence tend to have large amounts of undecomposed and partially decomposed logs, branches and other plant remains and are formed at a much faster rate. Ombrogenous moss peat in cold and temperate regions consists largely of cellulose whereas peat from deep lowland peat formations in Indonesia and Malaysia consist two-thirds of lignin, with cellulose/hemicellulose accounting for only 1-10 percent of the dry sample weight. Tropical peat soils decompose rapidly when exposed to aerobic conditions. Drained peat 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 is essentially undecomposed woody material.
A recent 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 e.g. 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. The destruction of the organic matter can be performed chemically (which was often used in the past) or via heat (which is currently used). In the studies where chemical methods were used, carbon contents were underestimated with reported carbon contents of 20-30% in tropical peat. Currently, the method with elevated temperatures is recommended.

### 1.3 The peat ecosystem

The carbon and GHG balance of tropical peat ecosystems is determined by 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 plants and roots) (Page et al., 2011a). Besides the function of tropical peat lands as carbon sinks, tropical peat forest areas are unique ecosystems with a very high biodiversity value. Species diversity is regarded as one of the fundamental prerequisites of ecosystem stability. Until a few decades ago, tropical peat forests remained relatively uninhabited and unexploited and they acted as sinks for carbon. However, as a result of economic development during the past two decades, peat swamp forests have been subject to intensive logging, drainage and conversion to plantations (Rieley and Page, 2002), and have thus been transformed into C sources.

Posa et al. (2011) state that the current precise 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 that a maximum of 36.8% of the historical peat swamp forest area remains (Table 1).
Table 1. Estimates of major peat swamp forest area (in ha) in SE Asia (Posa et al., 2011).

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

*excluding Papua New Guinea

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, 7.45% 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 (4.76%) (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 million ha, Kalimantan 5.8 million ha, Papua 7.9 million ha and other islands around 0.5 million ha. Page et al (2010) have also published their best estimates of peat area, thickness and volume as shown in Table 3.

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).

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

*Bappenas estimated 14,000,000 ha of 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).

<table>
<thead>
<tr>
<th>Country</th>
<th>Peat area (ha)</th>
<th>Peat thickness (m) (average)</th>
<th>Volume ( \times 10^6 ) m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>20,695,000</td>
<td>5.5</td>
<td>1138225</td>
</tr>
<tr>
<td>Brunei</td>
<td>90,900</td>
<td>7</td>
<td>6363</td>
</tr>
<tr>
<td>Malaysia</td>
<td>2,588,900</td>
<td>7</td>
<td>181223</td>
</tr>
<tr>
<td>Myanmar (Burma)</td>
<td>122,800</td>
<td>1.5</td>
<td>1842</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>1,098,600</td>
<td>2.5</td>
<td>27465</td>
</tr>
<tr>
<td>Philippines</td>
<td>64,500</td>
<td>5.3</td>
<td>3418.5</td>
</tr>
<tr>
<td>Thailand</td>
<td>63,800</td>
<td>1</td>
<td>638</td>
</tr>
<tr>
<td>Vietnam</td>
<td>53,300</td>
<td>0.5</td>
<td>266.5</td>
</tr>
</tbody>
</table>

1.4 Land use change

1.4.1 Deforestation

In Indonesia, peat development is most extensive in Sumatra, and less so in Kalimantan, while much of the peat in Papua remains undeveloped. In Malaysia, deforestation rates in the past 6 years based on satellite data with a 50 m spatial resolution, were highest in Sarawak with a yearly deforestation rate around 8% on average for peat land (SarVision, 2011; table 4a), and an overall deforestation rate of around 2% in the last 5 years (SarVision, 2011; table 4b) for all soil types.

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Forest area (ha)</th>
<th>Forest area change (ha)</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>1,055,896.7</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>2006</td>
<td>990,437.6</td>
<td>-65,459.1</td>
<td>-6.20</td>
</tr>
<tr>
<td>2007</td>
<td>924,978.5</td>
<td>-65,459.1</td>
<td>-6.61</td>
</tr>
<tr>
<td>2008</td>
<td>847,256.4</td>
<td>-77,722.1</td>
<td>-8.40</td>
</tr>
<tr>
<td>2009</td>
<td>769,534.3</td>
<td>-77,722.1</td>
<td>-9.17</td>
</tr>
<tr>
<td>2010</td>
<td>702,966.7</td>
<td>-66,567.5</td>
<td>-8.65</td>
</tr>
</tbody>
</table>
Table 4b. Yearly total deforestation in Sarawak, Malaysia in the period 2005-2010 (SarVision, 2011).

<table>
<thead>
<tr>
<th>Year</th>
<th>Forest area (ha)</th>
<th>Forest area change (ha)</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>8,984,450.7</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>2006</td>
<td>8,814,801.7</td>
<td>-169,648.9</td>
<td>-1.89</td>
</tr>
<tr>
<td>2007</td>
<td>8,645,152.8</td>
<td>-169,648.0</td>
<td>-1.92</td>
</tr>
<tr>
<td>2008</td>
<td>8,470,649.8</td>
<td>-174,503.0</td>
<td>-2.02</td>
</tr>
<tr>
<td>2009</td>
<td>8,296,146.8</td>
<td>-174,503.0</td>
<td>-2.06</td>
</tr>
<tr>
<td>2010</td>
<td>8,118,614.4</td>
<td>-177,532.4</td>
<td>-2.14</td>
</tr>
</tbody>
</table>

Table 5 shows a list of studies on peat swamp forest losses for different areas in Southeast Asia. Overall deforestation rates in Sarawak, Malaysia are the highest and SarVision (2011) reported that of 41% all peat soil in Sarawak is covered by oil palm plantations. 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 with land cover maps with regional methodologies and 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 (10°S-7°N latitude and 95°E-140°E longitude), 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 in peat swamp forest were higher than deforestation rates in forests on mineral soils.

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

<table>
<thead>
<tr>
<th>Area</th>
<th>Period</th>
<th>Reference</th>
<th>Peat swamp forest converted to other LU</th>
<th>% of peat forest (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insular SE Asia</td>
<td>2000-2005</td>
<td>WI Malaysia 2010</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>Sarawak</td>
<td>2005-2007</td>
<td>SarVision 2011</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>Sarawak</td>
<td>2009-2010</td>
<td>SarVision 2011</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>Malaysia and Indonesia</td>
<td>2000-2010</td>
<td>Miettinen et al 2011</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Borneo</td>
<td>1997-2002</td>
<td>Fuller et al 2004</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>1990-2000</td>
<td>Hansen et al 2009</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>
When excluding Papua and the Moluccas from the analysis, the yearly rate of forest loss for Indonesia would rise 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 the areas deforestation was concentrated in peat lands. Riau and Jambi provinces together had lost 40% of their year 2000 peat swamp forest cover by 2010, while in Sarawak the extent of peat swamp forests decreased by 55% (Miettinen et al., 2011). Earlier studies 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 km² 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 not stable, but are merely intermediate stages towards further change, such as that towards plantation establishment.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>North Sumatra</th>
<th>Riau</th>
<th>Jambi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearly pristine forest</td>
<td>190.8</td>
<td>0</td>
<td>202.4</td>
</tr>
<tr>
<td>Mod. Degr. forest</td>
<td>14.6</td>
<td>2.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Heav. Degr. forest</td>
<td>0.6</td>
<td>11.1</td>
<td>0</td>
</tr>
<tr>
<td>Secondary forest</td>
<td>4.6</td>
<td>5.1</td>
<td>0</td>
</tr>
<tr>
<td>Clearance/burnt</td>
<td>0</td>
<td>10.8</td>
<td>0</td>
</tr>
<tr>
<td>Smallholder mosaic</td>
<td>10.7</td>
<td>69.1</td>
<td>7</td>
</tr>
<tr>
<td>Industrial plantation</td>
<td>1.9</td>
<td>87.9</td>
<td>0</td>
</tr>
</tbody>
</table>

Areas are given in ha x 10^3

1.4.2 Plantation development

Oil palm (*Elaeis guineensis*) has become one of the most rapidly expanding equatorial 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 (Fig. 1).

![Fig. 1. World palm oil production 2010 (United States Dep. of Agric., 2011, www.indexmundi.com/agriculture).](image)

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 come 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, foest
Cover has been affected most by conversion to agriculture and more specifically to oil palm plantations (Wicke et al., 2010). The largest change in Indonesia has occurred in forest land, which decreased from 130 million ha in 1975 to 91 million ha in 2005, while agricultural land increased from 38 million ha in 1975 to 48 million ha in 2005. Approximately half of this agricultural expansion was due to an expansion in palm oil production (Wicke et al., 2010).

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

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

<table>
<thead>
<tr>
<th>Region</th>
<th>Oil Palm (ha)</th>
<th>Oil Palm on peat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ha)</td>
<td>(ha) (%)</td>
</tr>
<tr>
<td>Peninsula Malaysia</td>
<td>2.503.682</td>
<td>207.458 8.29</td>
</tr>
<tr>
<td>Sabah</td>
<td>1.340.317</td>
<td>21.406 1.60</td>
</tr>
<tr>
<td>Sarawak</td>
<td>1.167.173</td>
<td>437.174 37.45</td>
</tr>
<tr>
<td>Total</td>
<td>5.011.172</td>
<td>666.038 13.29</td>
</tr>
</tbody>
</table>

**Table 9. Oil palm concessions (projections 2020) on peat in 2006 in Indonesia (Peat-CO₂ report WI, 2006, by SarVision).**

<table>
<thead>
<tr>
<th>Region</th>
<th>Peat Area (ha)</th>
<th>Oil Palm plantation concessions on peat (ha)</th>
<th>Percentage of peat with oil palm plantation concessions %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sumatra</td>
<td>6.931.700</td>
<td>1.249.400</td>
<td>18</td>
</tr>
<tr>
<td>Kalimantan</td>
<td>5.837.900</td>
<td>1.472.500</td>
<td>25</td>
</tr>
<tr>
<td>Papua</td>
<td>7.554.300</td>
<td>79.000</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>20.323.900</td>
<td>2.800.900</td>
<td>14</td>
</tr>
</tbody>
</table>

In order to be able to produce sustainable palm oil, several life cycle assessment studies have been performed which were based on past trends, land availability and projected demand for palm oil. They calculated the possible expansion of oil palm, 1) according to past land use change trends (business as usual), 2) using all available land (maximum) and 3) following
sustainability criteria (*sustainable*) (Kaper et al., 2008). The most sustainable case avoids the use of 1) forest land, 2) steep terrain, and 3) vulnerable peat soils for oil palm plantation establishment. Wicke *et al.* (2008) and Germer and Sauerborn (2006) concluded in their studies that in order for products to be sustainably produced from palm oil and its derivates, 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 and Wilcove 2007) and will put further pressure on peat swamp forests (Rijenders and Huijbregts, 2006; Fargione *et al.*, 2008). However, while biofuels such as palm oil have been identified as potential low-carbon energy sources, with advanced understanding it has turned out that when oil palms are grown on peat they instead create a ‘carbon debt’ and increase overall global carbon emissions (Fargione *et al.*, 2008; Gibbs *et al.*, 2008).

1.5 **Implications of land use (change)**

1.5.1 **Carbon and greenhouse gas implications**

Tropical peat swamp forest ecosystems are one of the most important carbon stores on earth. Indonesian peat lands store at least 55 ± 10 Gt of carbon and 10-30% of the global peat carbon stock (Jaenicke *et al.*, 2008; Page *et al.*, 2002) and Malaysian peats store around 9 Gt of carbon (Page *et al.*, 2011). An important factor that controls the peatland C-balance is hydrology (e.g. Jauhiainen *et al.*, 2005; Couwenberg *et al.*, 2010). Drainage of peat will lead to peat oxidation and a higher frequency of forest and peat fires, resulting in an increase in GHG emissions and carbon losses (Gomeiro *et al.*, 2010). Conversion of forest for agricultural development is a one-point emission in time, while emissions resulting from peat drainage are continues processes. Emissions from peat drainage are not mainly caused by *land use change*, but rather by the *land use* itself. This is different in the case of mineral soils, where the main emissions result from land use change.
1.5.2 Other ecological implications

The rapid and massive expansion of oil palm has led to concerns about impacts on natural habitats and biodiversity as well as the climate (Fargione et al., 2008; James, 2008; Koh and Ghazoul, 2008). Locally, the development of oil palm plantations in forested areas will have several consequences, such as increased erosion, loss of biodiversity, chemical run off (pollution) and increased fire risk (Naidoo et al., 2009). Impacts also include soil subsidence (because of drainage and fires) and therefore increased flooding risk and salt water intrusion, causing problems in the future. Oil palm monocultures require use of insecticides, herbicides and fertilizers that enter water bodies as runoff or groundwater seepage and can seriously impact aquatic biodiversity (Koh and Wilcove, 2008). Another problem are the haze conditions following peat and forest. People exposed to high levels of air pollution, suffer increases in asthma, bronchitis and other respiratory illnesses (e.g. Brown 1998; Sastry 2000). Hazy skies can result in a 92% reduction in photosynthetic active radiation (PAR) levels compared to clear days, and this greatly affects C-fixation (Yule 2010).

1.5.3 Social, economic and livelihood implications

The broader economic, social and livelihood implications of oil palm cultivation on peat swamps remains poorly understood (Rist et al., 2009; Rist et al., 2010). Although many households profit from the palm oil business, large-scale oil palm expansion will lead to loss of ecosystem services. In addition, some studies published on livelihood and economic implications warn of instability in food prices because smallholders may be over dependent on the price of palm oil. In Indonesia, another point of concern is that transnational corporations and large landowners establish larger and larger landholdings at the expense of small farmers (Rist et al., 2010). However, findings are contradictory and differ per country and region and are also depending on the time frame on which the studies focused. Short term economic consequences can be positive, while the longer term implications can be negative. Fig. 2 shows the linkages between the loss of peat swamp forests and global market forces, mediated by national export policies and international investment (adapted). The increasing demand for a product in one part of the world may affect a wetland system on another continent. In this process, the sustainability of the tropical peats in Southeast Asia are threatened. In contrast, oil palm appears to be an attractive new income opportunity to Indonesian farmers, as attested by its widespread uptake by many smallholder communities.
(Rist et al., 2010). Oil palm is widely considered by communities as the best option for meeting their financial needs.

Fig. 2. Transformation of wetlands in perspective: schematic overview of drivers, pressures, states and impacts (FAO, 2008). It has to be noted that the increased demand for palm oil as ‘food’ is not included in this scheme.
2 Carbon balances and greenhouse gas emissions in tropical peatlands

2.1 Introduction
Intact peat swamp forest stores 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 forest areas on peat 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.

2.2 Data availability and restrictions
Although a lot of research has been performed in the past, using different approaches (box 4), some of the earlier studies on GHG fluxes suffered from several methodological problems. General pitfalls were/are:

- Short-term nature of the studies (usually < 1 y) with a limited number of point measurements in 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.
- Focus of most studies on CO₂. (Relatively few studies have included N₂O from e.g. fertiliser application and CH₄ from drainage ditches in the total GHG balance).

Comparison studies for CO₂ emissions based on chamber measurements have generally only included forest floor respiration (or ‘field’ fluxes), and autotrophic and heterotrophic respiration have seldom been separated (Melling et al., 2005ab; Melling et al., 2007; Furukawa et al., 2005; Reijnders and Huijbregts, 2006; Hadi et al., 2005).

Flux estimates can be seriously biased by failure to detect ‘event’ emissions such as those due to sudden climatic changes or discontinuous management activities (e.g. changes in temperature or rainfall, fertilizer application, dredging etc.; Kroon et al., 2010; Veenendaal et
Outliers may be caused by pressure changes during chamber installation, resulting in very high fluxes that can dominate the balance. Spatial biases exist when sample locations are not representative of the total area.

Current studies have been undertaken that avoid these deficiencies, and by doing so scientific knowledge has increased greatly in the last couple of years. One approach used is to collect data from several studies and attempt to infer emissions based on drainage depth (e.g. Couwenberg et al., 2010). Others have tried to avoid all major deficiencies related to chamber measurements (e.g. Jauhiainen et al., 2012). Some studies base their carbon and CO$_2$ emission estimates on soil subsidence rates (Draudjad et al., 2003; Couwenberg et al., 2010; Hooijer et al., 2012), assuming bulk density (BD) and the percentage subsidence due to oxidation. The latest methods for calculating CO$_2$ emissions from soil subsidence avoid the use of an oxidative component by using the BD of the peat below the water table as a proxy for the original BD of the peat above the water table. This method thus integrates the effect of initial consolidation. Compaction continues to work on consolidated peat once it reaches the aerated zone above the water table (Hooijer and Couwenberg, accepted).
Ecosystem flux values differ in relation to the system boundaries. Some studies address the entire oil palm biofuel production chain, others include management-related fluxes or e.g., solely soil respiration within a single plantation (see Fig. 3 for system boundaries and possible carbon and GHG sources and sinks in oil palm plantations). The amount of release or uptake of GHGs in an ecosystem is dependent on a variety of interrelated processes and climatic and other variables such as temperature, moisture, water table depth, microbial activity, drainage, logging, compaction, peat type, vegetation type etc. To completely understand the fluxes from a peat ecosystem (their temporal and spatial variation) and to upscale fluxes from a small (m²) to a large scale (e.g. landscape scale), these processes and variables and their inter-relationships have to be studied.

**Box 4**

**Greenhouse gas and carbon measurement techniques**

**Chamber based methods:** These cover up to 1 m² spatially and measurements are discontinuous. Chamber methods are best suited for capturing spatial variability of CO₂, CH₄ and N₂O, but if appropriate spatial and temporal upscaling methods are used (appropriate spatial stratification, regression analyses instead of linear interpolation), they can also be used to determine average GHG fluxes at a landscape scale (e.g. Schrier-Uijl et al., 2010a,b).

**Eddy covariance (EC) based methods:** These cover a spatial scale of 100 – 1000 m², depending on the height of the tower. Eddy covariance towers are equipped with instruments for measuring incoming and outgoing radiation, GHG fluxes, and energy exchanges, and measure continuously over time. The EC technique is best suited for determining average GHG fluxes at the landscape scale and capturing temporal variability. EC techniques for CO₂ have been established for decades; however, EC techniques for CH₄ and N₂O are currently under development. The EC technique integrates emission over large areas, and footprint analysis (back calculation of where the fluxes originate) is currently insufficient to capture small scale variability.

**Soil subsidence based methods:** In principle, land subsidence can be studied using several measurement techniques, e.g. leveling surveys, subsidence poles, extensometer measurements, and Global Positioning System (GPS) surveys. Wösten et al. (1997) report an oxidation component of subsidence of 60% from a limited field study in Johor, Malaysia, while Stephens et al. (1984) and Hooijer et al. (2012) found an oxidative component of around 90% as derived from large-scale studies in subtropical and tropical regions. The most recently applied soil subsidence method avoids the use of an oxidative component by using the BD of the peat below the water table as a proxy for the original BD of the peat above the water table (Hooijer and Couwenberg, accepted).

**Satellite based approaches:** These usually focus on loss of carbon through loss of above ground biomass on large scales. Changes in soil carbon stocks through drainage and increased soil respiration are usually not included in the quantifications. Satellites can be used for determination of loss of carbon through large scale fires, and for estimating CO₂ respiration from peat if the oxidative component is known.
2.3 Carbon dioxide and carbon

2.3.1 Direct loss of carbon

Agricultural development of tropical peat requires a change in vegetation cover and in most 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., 2008), ranging from 111-432 t C ha\(^{-1}\) in natural or primary peat swamp forest to 73-245 t C ha\(^{-1}\) in logged forest, while the carbon stock in oil palms ranges from 25-84.6 t C ha\(^{-1}\) (Agus et al., 2009; Lasco 2002; Gibbs et al 2008; Verwer and 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 into secondary vegetation by intensive logging, 2) conversion of forest areas into large scale plantations, 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 t C ha\(^{-1}\) (Verwer and van der Meer, 2010).
2.3.2 CO₂ emissions from Land use (change)

**Deforestation**

Forests absorb CO₂ by photosynthesis and release CO₂ by plant respiration (autotrophic respiration of roots and AGB) and by soil respiration (heterotrophic respiration). Suzuki *et al* (1999) demonstrated in their micrometeorological studies in tropical peat areas in Thailand that 5.32 t C ha⁻¹ yr⁻¹ was absorbed by the primary peat swamp forest canopy (photosynthesis) while a secondary forest absorbed 5.22 t C ha⁻¹ yr⁻¹ (because of greater plant growth compared to primary forest). During deforestation (e.g. for development of an oil palm plantation), living biomass will be harvested, the GPP will decrease and the net ecosystem exchange (NEE) will increase (Hirano *et al*., 2007). The carbon loss from forest conversion clearly exceeds the potential carbon fixation of oil palm plantings and in addition, artificial drainage that is needed for cultivation of oil palm on peat will cause an increase in microbial respiration (which will be ongoing) compared to the situation with no drainage (e.g. Jauhiainen *et al*., 2005; de Vries *et al*., 2010; Henson 2009; Jeanicke *et al*., 2008; Danielsen *et al*., 2008; de Vries 2008; Fargione *et al*., 2008; Rieley *et al*., 2008; Gibbs *et al*., 2008; Wösten and Ritzema, 2001; Hooijer *et al*., 2006). The total carbon that is stored in palm trees will be lost after the trees are cut at the end of the plantation cycle, although they will be replaced by young palms and a time-averaged biomass will be established that will be similar over successive plantings.

**Drainage**

Artificial drainage causes an increase in peat oxidation, an increase in the release of CO₂ and an increased fire risk (Furukawa *et al* 2005; Wösten *et al*., 1997; Inubushi *et al*., 2003; Hooijer *et al*., 2006; Veenendaal *et al*., 2007). Page *et al* (2011a) conclude that a value of 86 t CO₂-eq ha⁻¹ yr⁻¹ represents the most robust, currently available, empirical estimate of peat CO₂ emissions from oil palm plantations on deep, fibric peat with uncertainties ranging between 54 and 115 t CO₂-eq ha⁻¹ yr⁻¹ for a typical drainage depth of 60 – 85 cm, annualized over 50 years, including the initial emission peak just after drainage. Hooijer and Couwenberg (submitted) suggest a CO₂ emission value of 55-73 t CO₂-eq ha⁻¹ yr⁻¹ for continuous peat emissions under best to common practice, excluding initial emissions just after drainage. Couwenberg *et al* (2010) and Hooijer *et al* (2010) calculated emissions of at least 9 t CO₂ ha⁻¹ yr⁻¹ and 9.1 t CO₂ 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 emissions by about 55-72
t CO₂ ha⁻¹ yr⁻¹ (Fig. 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, so. correcting for compaction and consolidation, and from CO₂ gas flux measurements that exclude root respiration. A summary of the relation between carbon loss (in CO₂-eq ha⁻¹ yr⁻¹) and the average water table depth is shown in Fig 4.

![Figure 4](image)

**Fig 4.** Comparison of the relation between carbon loss (in CO₂-eq ha⁻¹ yr⁻¹) and water table depth in tropical peatlands more than 5 years after drainage, as determined in the studies of Hooijer et al. (2012, 2010 and 2006), Wöstten and Ritzema (2001), Jauhiainen et al. (2012), and Couwenberg et al. (2010). The relations by Hooijer (2006, 2010) and Couwenberg et al. (2010) were based on partly overlapping sets of literature sources. The relation by Jauhiainen et al. (2012) is based on daytime CO₂ flux measurements in the same (Acacia) plantation as Hooijer et al. (2012), excluding root respiration and corrected for diurnal temperature fluctuations. The figure is taken from Hooijer et al. (2012).

Recent studies showed that plantation emissions in both Acacia and oil palm plantations beyond 5 years after drainage (i.e. after the initial peak period following drainage), was consistently around 73 t CO₂ ha⁻¹ yr⁻¹ at a water depth of 0.7 m. Note that the initial peak may be as high as 178 t CO₂-eq ha⁻¹ yr⁻¹ in the first 5 years after drainage (Hooijer et al., 2012). Page et al (2011a) has summarized available literature and they concluded that around 73 t CO₂ ha⁻¹ yr⁻¹ is being released from drained peat in oil palm plantations and 86 t CO₂ ha⁻¹ yr⁻¹ if the initial peak directly after drainage upon land development is being considered as well. Lower estimates have been found by e.g. Melling et al., 2005a who report a value of 55 t CO₂ ha⁻¹ yr⁻¹. It should be noted that studies in Sarawak, such as those by Melling et al. (2005a), reflect a very different rainfall regime than those in most of Indonesia, where dry season
rainfall is far lower, soil moisture deficits are common, and rates of peat oxidation and carbon loss are therefore expected to be substantially higher. The most recent research is that of Hooijer and Couwenberg, where a CO₂ emission range of 55–73 t CO₂ ha⁻¹ yr⁻¹ (average 64 t CO₂ ha⁻¹ yr⁻¹) is proposed for continuous peat emission, excluding the initial peak. This is in line with the Hooijer and Couwenberg equations of ~ 9 t CO₂-eq ha⁻¹ yr⁻¹ per each 10 cm of drainage depth. One of the few studies in Indonesia and Malaysia that used the eddy covariance methodology to measure fluxes (continuously measured on a half hour basis) is the study by Hirano et al. (2007) in a degraded and drained tropical peat swamp forest. Taking into account the total CO₂ balance (NEE), the drained forest appeared to be a CO₂ source of 16 t CO₂ ha⁻¹ yr⁻¹ with an uptake by living biomass (GPP) of 126 t CO₂ ha⁻¹ yr⁻¹ averaged over three years, and an ecosystem respiration (Reco) of 142 t CO₂ ha⁻¹ yr⁻¹ (in comparison to 85 t CO₂ ha⁻¹ yr⁻¹ for the drained peat swamp forest measured by Furukawa et al. (2005)).

In tropical regions, CO₂ respiration 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**

As an indirect result of drainage and management activities, fire frequency increases (Hope et al., 2005). Although land clearance by fire has been banned for some years, it is still in widespread use, particularly by smallholders lacking access to heavy machinery (Page et al., 2011). Couwenberg (2010) estimated a release of 260 t 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 t C ha⁻¹ for the drought years 2002 and 1997, respectively. Based on available measurement data, the mean burn depth and rate of fire related peat loss amounts to 34 cm per fire event and 261 t 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 and Bakar, 1996).
Other CO₂ 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 Fig 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. Fig. 5 shows the wastes from fresh fruit bunches (FFB) as studied by Chavalparitk (2006) and the application of the wastes. 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 have been estimated at 0.39 t C-eq ha⁻¹ yr⁻¹ (1.43 t CO₂ ha⁻¹ yr⁻¹) and losses through initial biomass loss (e.g. FFB waste) have been estimated at 3.47 t C-eq ha⁻¹ yr⁻¹ (12.7 t CO₂ ha⁻¹ yr⁻¹). Carbon gains through fertilizer inputs are estimated at 1.5 – 2 t CO₂ ha⁻¹ yr⁻¹.

The drainage needed for agricultural use of peat, such as the cultivation of oil palm, implies also that dissolved organic matter (DOM) leached to drainage ditches and rivers will be enhanced (Rixen et al., 2008; Miyamoto et al., 2009; Yule and Gomez, 2009), especially in the transitions from dry to wet periods. Increases of 15% in dissolved organic carbon (DOC) have been recorded (Rixen et al., 2008) during this transition. The carbon is exported and rapidly decomposes, which may cause high fluxes of CO₂ from water bodies (Couwenberg et al., 2010; Holden et al., 2004). The most recent study of Moore et al (2013) concluded that the fluvial organic carbon flux from disturbed, drained peat swamp forest is about 50% larger than that of undisturbed peat swamp forest. They also concluded that adding these fluvial carbon losses (estimated at 0.97 t C ha⁻¹ yr⁻¹) to the total peatland carbon budget of disturbed and drained peatlands increases the total ecosystem carbon loss by upto 22%. Jauhiainen and Silvennoinen (2012) used floating closed chambers to measure greenhouse gas 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 t CO₂-C ha⁻¹ yr⁻¹ from drainage ditches in disturbed peat areas (ditch area 2% of the total), which is in the same order as the fluxes found by Moore et al (2013).
2.4 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 effect compared to the emissions of CO$_2$, and play only a minor role in the carbon balance. However, the extent of emissions from open water, management practices and fires are likely to contribute considerably, since the warming potential is 25 times that of CO$_2$. Net CH$_4$ fluxes from tropical peats are low compared to fluxes from temperate peat soils and they usually show a clear relationship to water level, which is positive (indicating emission of CH$_4$) for water levels above -20 cm, as is also the case for temperate wetlands (e.g. Watanabe et al., 2009). An overview of the available scientific literature on methane emissions in tropical peat is given in Table I1 and Appendix A.

2.4.1 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) conclude 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 which should not be considered negligible (Jauhiainen et al., 2010). In some cases in 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 the depth of the water (Schrier-Uijl et al., 2010c). Typical drainage parameters (spacing and width of canals) in oil palm plantations in Indonesia are given in Table 10; the water surface from drainage canals may account for up to 5% of the total plantation area. Guerin and Abril (2007) measured a methane emission rate of 350 ± 412 kg ha$^{-1}$ yr$^{-1}$ (or 8.4 ± 9.9 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$) from a tropical lake in a peat area in French Guiana, suggesting that in the tropics fluxes from open water bodies also have to be considered.

Melling et al (2005b) estimated CH$_4$ from peat soils under different management regimes: oil palm, sago and (degraded) forest. They performed monthly measurements over one year with closed chambers and determined parameters that control CH$_4$ emission: groundwater table, precipitation, nutrients, bulk densities, and moisture conditions. The results indicated that the sago plantation and degraded forest were sources for CH$_4$ and that the oil palm plantation was a sink for CH$_4$. They attributed the switch from emissions from forest (2.27 ug C m$^{-2}$ hr$^{-1}$) to uptake in oil palm plantations (-3.58 ug C m$^{-2}$ hr$^{-1}$) to a lowering of the water table and soil compaction through machinery and concluded that the cultivation of tropical peat primary forest to oil palm promoted CH$_4$ oxidation due to an increased thickness of aerobic soil after drainage. However it should be noted that the increased fire frequency following drainage and management activities will also increase CH$_4$ emissions. Scholes et al (1996) suggests that when vegetation is burned, for each ton of CO$_2$ emitted, 1.5 kg CH$_4$ is produced.

*Table 10. Drainage canal dimensions and spacing in oil palm plantations on peat areas.*

<table>
<thead>
<tr>
<th></th>
<th>Spacing</th>
<th>Top width</th>
<th>Depth (m)</th>
<th>Bottom width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main drain</td>
<td>2000</td>
<td>4</td>
<td>1.2</td>
<td>0.75</td>
</tr>
<tr>
<td>Collection drain</td>
<td>300</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Boundary drain (canal)</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Field drain</td>
<td>1:4 palm rows or 30</td>
<td>1.5</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 11. 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.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Land use</th>
<th>Chamber measurements frequency</th>
<th>Mean CH₄ emissions (g CH₄ m⁻² yr⁻¹)</th>
<th>Min CH₄ emissions (g CH₄ m⁻² yr⁻¹)</th>
<th>Max CH₄ emissions (g CH₄ m⁻² yr⁻¹)</th>
<th>Mean CO₂-equ (t CO₂ ha⁻¹ yr⁻¹)</th>
<th>Min CO₂-equ (t CO₂ ha⁻¹ yr⁻¹)</th>
<th>Max CO₂-equ (t CO₂ ha⁻¹ yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ueda et al., 2000</td>
<td>Fresh water swamp</td>
<td></td>
<td>4.38</td>
<td>109.5</td>
<td>1.05</td>
<td>26.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadi et al., 2005</td>
<td>Rice</td>
<td>1 year, monthly</td>
<td>3.5</td>
<td>14.0</td>
<td>0.3</td>
<td>1.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sec. forest</td>
<td>1 year, monthly</td>
<td>5.87</td>
<td></td>
<td>1.41</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paddy field</td>
<td>1 year, monthly</td>
<td>26.13</td>
<td></td>
<td>6.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rice-soybean</td>
<td>1 year, monthly</td>
<td>3.47</td>
<td></td>
<td>0.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Couwenberg et al., 2010*</td>
<td>Swamp forest</td>
<td>1 year, monthly on average</td>
<td>-0.37</td>
<td>5.87</td>
<td>-0.9</td>
<td>1.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Agriculture</td>
<td>1 year, monthly on average</td>
<td>0.025</td>
<td>3.4</td>
<td>0.006</td>
<td>0.816</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melling et al., 2005</td>
<td>Sec. forest</td>
<td>1 year, monthly</td>
<td>0.02</td>
<td></td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sago</td>
<td>1 year, monthly</td>
<td>0.24</td>
<td></td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oil palm</td>
<td>1 year, monthly</td>
<td>-0.02</td>
<td></td>
<td>-0.006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Furukawa et al., 2005</td>
<td>Drained forest</td>
<td>1-2 years, monthly</td>
<td>1.17</td>
<td></td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cassava</td>
<td>1-2 years, monthly</td>
<td>3.39</td>
<td></td>
<td>0.81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paddy field</td>
<td>1-2 years, monthly</td>
<td>3.62</td>
<td></td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paddy field</td>
<td>1-2 years, monthly</td>
<td>49.52</td>
<td></td>
<td>11.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Swamp forests</td>
<td>2 months</td>
<td>6.15</td>
<td>2.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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.

2.4.2 Other CH₄ emission sources

Transformation of forest into an agricultural area often leads to increased management intensity (e.g. traffic, inputs of fertilizer, mill activities) and therefore CH₄ emissions (e.g.
emissions to the hydrosphere through mill effluents, gaseous losses through anaerobic fermentation, and biomass burning in mill boilers) increase. Reijnders and Huijbregts (2006) estimated CH$_4$ emissions of about 32 – 48 kg CH$_4$ ha$^{-1}$ yr$^{-1}$ (0.8 – 1.2 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$ or 24 – 36 kg C ha$^{-1}$ yr$^{-1}$) from palm oil mill effluents.

2.5 Nitrous oxide

Nitrous oxide is primarily emitted from agricultural landscapes and natural ecosystems as a by-product of nitrification and denitrification. Emission of N$_2$O mainly depends 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$_2$O (Nykanen et al., 2002) but may consume small amounts in denitrification, when atmospheric N$_2$O is reduced to N$_2$. However, this might be different in tropical peat soils and as soon as fertilizer and/or manure is applied, emissions of N$_2$O may count for a considerable part of the total GHG gas balance.

N$_2$O fluxes have a high temporal variability. In a study by Kroon et al. (2010) in a temperate peat area in the Netherlands, three years of half-hourly measurements of N$_2$O were performed using Eddy Covariance. Because of the large number of measurements, it was possible to split the N$_2$O emissions into background emissions and event-emissions (fluxes following fertilizer application and/or climatic events such as rainfall). In these temperate agricultural peat areas, N$_2$O contributed up to 45% of the total GHG balance (expressed in warming potential) (including CO$_2$ and CH$_4$). Event emissions accounted for a considerable part of the N$_2$O emissions and therefore it is of great importance to conduct high frequency measurements, especially at times of climatic events and fertilizer application.

In oil palm plantations it seems likely that application of nitrogen fertilizers will accelerate release of N$_2$O. The extent of N$_2$O release from the system and the processes that cause N$_2$O emissions in these types of ecosystems are poorly understood. Hadi et al (2005) compared the N$_2$O emissions from a paddy field, a rice-soya bean rotation field and a peat forest (Table 12). They integrated monthly measurements and scaled these up to give an annual value. They upscaled fluxes spatially to cover the entire tropical peat land. However, scaling up monthly fluxes (covering only one year of measurements) to the entire tropical peat area in SE Asia causes major complications because of large spatial and temporal variability. Takakai et al.
(2005) estimated an emission of 3.6 – 4.4 t CO₂-eq m⁻² d⁻¹ from one year's data by using linear interpolation for temporal upscaling. Melling et al (2007) performed a one year study (monthly measurements with closed chambers) of N₂O emissions from tropical peat soils under different management regimes: oil palm, sago and forest. They estimated the N₂O source strength in a Malaysian oil palm plantation at 1.2 kg N ha⁻¹ yr⁻¹ (0.48 t CO₂-eq ha⁻¹ yr⁻¹). However, uncertainties were large and data were too limited to distinguish background emissions from event emissions due to fertilizer application, nor to do regression analyses. The default value in the IPCC guidelines for synthetic nitrogen fertilizer-induced emissions for Histosols in tropical regions is 10 kg N₂O-N ha⁻¹ yr⁻¹ (IPCC 1997). Based on the IPCC default value, the N₂O emissions correspond to a total emission of 4.8 t CO₂-eq ha⁻¹ yr⁻¹. Nitrous oxide emission values for tropical peatlands found in the scientific literature are given in Table 12.

Table 12. Nitrous oxide emission values for tropical peat areas as found in the scientific literature, measured by chamber-methodology at different temporal scales.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Land use on peat</th>
<th>Chamber measurement frequency</th>
<th>Emission (kg CO₂-eq ha⁻¹ yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadi et al (2005)</td>
<td>Rice paddy field</td>
<td>3 measurement days</td>
<td>0.5781</td>
</tr>
<tr>
<td>Furukawa et al (2005)</td>
<td>Rice paddy field</td>
<td>1 year, monthly</td>
<td>0.016</td>
</tr>
<tr>
<td>Hadi et al (2005)</td>
<td>Cultivated upland field</td>
<td>3 measurement days</td>
<td>6600-36754</td>
</tr>
<tr>
<td>Furukawa et al (2005)</td>
<td>Upland cassava field</td>
<td>1 year, monthly</td>
<td>0.257</td>
</tr>
<tr>
<td>Melling et al (2005)</td>
<td>Sago</td>
<td>10 months, monthly</td>
<td>1556</td>
</tr>
<tr>
<td>Hadi et al (2005)</td>
<td>Soya</td>
<td>3 measurement days</td>
<td>4543</td>
</tr>
<tr>
<td>Hadi et al (2005)</td>
<td>Forest, not primary</td>
<td>3 measurement days</td>
<td>6600</td>
</tr>
<tr>
<td>Melling et al (2005)</td>
<td>Forest, not primary</td>
<td>10 months, monthly</td>
<td>330</td>
</tr>
<tr>
<td>Furukawa et al (2005)</td>
<td>Forest, not primary</td>
<td>1 year, monthly</td>
<td>0.101</td>
</tr>
<tr>
<td>Inubushi et al (2003)</td>
<td>Forest, not primary Abandoned upland field Rice</td>
<td>1 year, monthly</td>
<td>range -664 - 4498</td>
</tr>
<tr>
<td>Melling et al (2005)</td>
<td>Oil palm</td>
<td>10 months, monthly</td>
<td>566</td>
</tr>
<tr>
<td>Furukawa et al (2005)</td>
<td>Pineapple</td>
<td>1-2 months</td>
<td>132-1017</td>
</tr>
</tbody>
</table>

2.6  Discussion, gaps in knowledge and uncertainties

This section has aimed to summarize the impacts of conversion of tropical peat into oil palm plantations in terms of carbon and GHG emissions. Therefore, available studies have been
reviewed and compared. Studies use different approaches to assess GHG emissions and in many cases it remains uncertain how accurate the published values are.

There has long been a lack of data and knowledge on long-term (multiple year) rates of carbon emissions (CO₂ and CH₄) and N₂O emissions and uptake, and their explanatory variables (e.g. temperature, moisture, chemistry, water table, management, fertilizer inputs) in tropical peats. Although studies in the last couple of years have successfully filled knowledge gaps, it is still of great importance to develop empirical evidence for the relationships between emissions (CO₂, CH₄ and N₂O) and their driving variables, to investigate the carbon and nitrogen cycling in peat and the relation to climate change and so help apply appropriate adaptation and mitigation measures.

Data availability on biomass and carbon content in the remaining peat swamp forests is scarce and broad ranges of AGB and emissions rates in peat swamp forests are 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 natural swamp forest into an oil palm plantation will cause a direct release of carbon, ranging between 153 – 359 t C ha⁻¹. Development of a logged forest into an oil palm plantation will cause a direct release of carbon, ranging between 47 – 214 t C ha⁻¹, depending on the degree of forest degradation. Oil palms store around 24-40 t C ha⁻¹ in their AGB but after every crop cycle of 20 -30 years this stock will be released.

A common finding is that the transformation of an intact peat swamp area to oil palm plantations leads to a release of carbon and GHG to the atmosphere. The drainage that is needed for development of oil palm plantations leads to a release of carbon from peat oxidation. Emissions from oil palm plantations on peat are about 86 t CO₂ ha⁻¹ yr⁻¹ (Page et al., 2011a) with values in the literature ranging from 26- 146 t CO₂ ha⁻¹ yr⁻¹ (or 7-40 t C ha⁻¹ yr⁻¹) and are mainly dependent on drainage depth. Oxidation of drained peat and fires are the largest emission sources related to the drainage needed for oil palm plantation development. The processing of the fresh fruit bunches and the related production of wastes also adds to GHG emissions.

The increased fire frequency due to drainage of peat results in the release of high amounts of CO₂ and CH₄ from biomass and from the peat. Based on available measurement data in an
abandoned, degraded tropical peat area, the mean burn depth and fire-related peat loss in Indonesia amounted to as much as 34 cm per fire event and 261 t C ha$^{-1}$ yr$^{-1}$ emission for the years 1997, 2001 and 2002 (which were dry years in which many large fires occurred). Peat with a high water table usually does not burn. There are indications that for each ton of CO$_2$ emission as a result of fire, 1.5 kg CH$_4$ is produced. CH$_4$ fluxes from mill effluents are in the order of 0.8 – 1.2 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$.

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 t 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, but unpublished studies indicate that they might be high.

N$_2$O measurements in tropical peat systems are likewise scarce and emission estimates are uncertain. N$_2$O source strength 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$_2$O emissions from fertilized, tropical Histosols is 4.1 t CO$_2$-eq ha$^{-1}$yr$^{-1}$.

While N$_2$O 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 are not fully captured yet and recent conclusions on GHG emissions from tropical peatlands have been largely based on (very) short term studies that have high uncertainties in terms of emission estimates and rely on weak methodologies and poor upscaling techniques. Recent studies have started to overcome these problems, but further field inventories using similarly rigorous methodologies and experimental design and modelling are needed. Because both carbon pools and carbon emissions may vary considerably over time, the research focus should be on quantification of carbon pools and emissions related to land use and land use change.
Carbon release can also take place via waterways (streams, rivers and drainage canals) in the form of dissolved organic carbon (DOC), particulate organic carbon (POC), dissolved inorganic carbon (DIC) and dissolved CO$_2$. Studies of these potential carbon release pathways from tropical peat are very limited but the most recent study by Moore et al (2013) suggest that Indonesian rivers, particularly those draining peatland areas, transfer large amounts of DOC into the sea and they concluded that the fluvial organic carbon flux from disturbed, drained peat swamp forest is about 50% larger than that of undisturbed peat swamp forest. Ongoing studies by Moore and co-workers indicate that land use change and fire both increase the loss of fluvial carbon from tropical peat.

**2.7 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. In fact, recent findings suggest that emissions cannot be reduced very much under any management regime, relative to those occurring 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 sinks.

The most obvious measure to limit GHG emissions based on this review, is to limit or stop development of oil palm plantations on peat. Peat drainage (and thus peat oxidation) and the related (off-site) fires, often in combination with forest clearance, are the largest sources of GHG emissions in oil palm plantations. If development of plantations is on mineral soil, the impacts are less significant in terms of GHG emissions. If oil palm plantations are developed on peat, oxidation due to drainage will continue until 1) undrainable levels are reached, resulting in increased or permanent flooding, 2) all 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 fields at 40-60 cm. However, if palms are immature, water levels of 35-45 cm should be sufficient to obtain high yields (Mohammed et al., 2009). This will reduce GHG emissions by more than 50% compared to water levels at -70 - -100 cm. Flooding has to be avoided because this
enhances the formation and emission of methane and reduces yields. A certain (high) spacing of drains is needed and most drainage systems need to be optimized. The RSPO Manual on Best Management Practices for Oil Palm Cultivation on existing peat (RSPO, 2012) gives guidance on this.

Burning of biomass for clearance and burning of drained peat in dry years is the second largest source of GHG emissions in peat swamp areas. The implementation of zero burning and fire prevention measures will 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 fertilizing the soil. Different techniques for pulverization and application of the pulverized materials are given in Ooi et al (2004). The risk of fire in oil palm plantations on peat is generally reduced compared to abandoned, degraded peatland. However, peat and forest fires often occur outside the planation related to off-site impacts of drainage. The hydrological system surrounding the plantations can be disrupted and the drained peat is very susceptible to fires. Recommendations for prevention of off-site impacts need to be provided.

The idea that compaction of the peat soil before planting leads to lower CO₂ emissions compared to no compaction before planting of oil palms might or might not be true. 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 with which CO₂ emissions are positively correlated (Jauhianen et al., 2012; Hooijer et al., 2012). Maintenance and rehabilitation of hydrological buffer zones can also minimize peat CO₂ 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 CH₄ capture, maximising energy efficiency and using palm oil mill effluent (POME) and empty fruit bunches (EFB) as fertilizers (studies show that a 40-tonne capacity mill can provide 20-30% of an estate’s fertilizer needs), are possible ways to reduce emissions. The use of ‘coated’ nitrogen fertilizer, composting and careful fertilizer application during rainy seasons will help to reduce N₂O emissions.
2.8 Recommendations for further research

- Long term (several years) measurements are needed of CO₂, CH₄ and N₂O fluxes using a combination of chamber-based measurements to capture spatial variation at the small scale, eddy covariance measurements to capture temporal variation at the landscape scale, and soil subsidence measurements to tackle the very high uncertainties in emissions studies.
- Simultaneous recording of variables that control the fluxes (soil temperature, moisture, water table, soil and water chemistry, incoming and outgoing radiation, etc.) are required to establish robust predictive relationships that explain the fluxes.
- Comparisons should be made of carbon fluxes and GHG emissions between ecosystems that differ in management intensity and land use (e.g. primary forest, secondary forest, oil palm plantations; low and high water tables).
- GHG fluxes of the total ecosystem should be captured, including, e.g., fluxes from water bodies, using robust, well established, sampling designs.
- After establishment of regression models or predictive relationships based on emission data, it is of great importance to develop methodologies that enable local communities and stakeholders to monitor variables that drive the emissions.
- New allometric models should be developed for estimating biomass (above and below ground) of peat swamp forests (Verwer and van der Meer, 2010).
3 Other environmental impacts of oil palm plantation development on tropical peat swamps

3.1 Changes in land use and their implications

With oil palm being the most rapidly expanding crop in Southeast Asia, the main questions are where the development of oil palm plantations has the least impact and how to make oil palm that has already been planted a more environmentally-friendly crop (Fitzherbert et al., 2008; Koh et al., 2009). The consequences of the transformation of peat swamp forests into oil palm plantations in terms of sustainability are:

1. Subsidence of soils and possible increased flooding risk and salt water intrusion which have effects on the prospects of agriculture and fisheries in coastal zones (Wösten et al., 2007).

2. Loss of biodiversity and ecosystem services.

3. Emissions into the hydrosphere through erosion and effluents from palm oil mills and consequences for water quality.

4. Increased (off-site) fire risk through drainage, increased air pollution through clearance of forest by fire, and adverse implications for human health.

3.2 Subsidence, salt water intrusion and flooding risk

Indo-Malaysian 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 of the peat as usually needed for cultivation of the peat, will have many consequences for hydrological regulation. For example, oil palm on drained peat is very sensitive to drought. Because of the low capillary rise in peat soils, dry periods will often result in significant yield reductions (Mantel et al., 2007).

Drainage of peat leads to soil subsidence resulting from peat oxidation, consolidation and compaction (Polak, 1933; Andriesse, 1988; Dradjad, 2003; Schothorst, 1977; Couwenberg, 2010; Hooijer et al., 2012). The initial or primary subsidence depends on the type and depth of peat and the drainage level, and subsidence rates can be more than 50 cm yr\(^{-1}\) in drained tropical peat mainly due to compaction and consolidation (Hooijer et al., 2012; Wösten et al.,
After a few years of drainage, the balance between these processes will change and oxidation will become the main factor responsible for subsidence. Hooijer et al. (2012) indicated that consolidation contributes only 7% to the total subsidence in the first year after drainage, and that in fibric peat with low mineral content the role of compaction is also reduced 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, close to the 85-90% reported for subtropical peat by Stephens et al. (1984) based on over 76 years of measurements. Stephens et al. (1984) report that peat surface subsidence continues at a constant rate for many decades, which is explained by the dominance of oxidation and the limited role of compaction. Wösten et al., 1997, report similar average subsidence rates of 4.6 cm y⁻¹ for oil palm plantations in Johor, 14 to 28 years after drainage (Fig 7). The most recent, extended research of Hooijer et al. (2012) shows that constant long-term subsidence rates are 5 cm y⁻¹, on the basis of literature reviews and subsidence monitoring for water tables between 60 and 80 cm at 218 locations in Acacia and oil palm plantations in Indonesia (Fig 6). No studies have been published on the relationship between soil subsidence and CH₄ or N₂O emissions.

Fig. 6. Subsidence rates for individual monitoring locations in relation to water table measured in Acacia plantations 6 years after drainage, oil palm plantations 18 years after drainage, and adjacent forest, in Sumatra, Indonesia (Hooijer et al., 2012).
In the study by Mohammed et al (2009) in Sessang, Sarawak, soil subsidence rates were almost stable after 15 years of drainage, ranging from 2.48 cm yr\(^{-1}\) in shallow peat (100 – 150 cm), to 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 after drainage 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 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 decrease, resulting in a decreased freshwater buffer against salt water intrusion in the dry
seasons (Silvius et al., 2000). Subsidence also enhances the risk and frequency of sea water floods. Examples of the consequences of increased salt water intrusion are, 1) the decline in fish larvae abundance and large scale fish habitat (Cruz et al., 2007; Loukos et al., 2003), 2) negative impacts on Indonesia’s turtle populations (WWF, 2007), 3) changes in species distribution, reproduction timings, and phenology of 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 the 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 °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 liable to be nutrient deficient, or, in the case of acid sulphate soils, to contain pyrite (FeS\(_2\)) and be detrimental to growth (Wösten and Ritzeman, 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 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 sustainable 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 (Fig. 8), while soil subsidence is low and emissions are reduced by 50% compared to deeply drained soils.
3.3 Biodiversity

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

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

<table>
<thead>
<tr>
<th>Total number of species</th>
<th>Plants</th>
<th>Mammals</th>
<th>Birds</th>
<th>Reptiles</th>
<th>Amphibians</th>
<th>Freshwater fish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recorded from PSF</td>
<td>1524</td>
<td>123</td>
<td>268</td>
<td>75</td>
<td>27</td>
<td>219</td>
</tr>
<tr>
<td>Restricted to PSF</td>
<td>172</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Strongly associated with PSF</td>
<td>6</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PSF, Peat Swamp Forest
Source: Data compiled from various sources available from authors by request
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 carbon storing ecosystems. 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*), the sap of which 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 speciosa*), and Nyatoh (*Palaquium spp*) (Giesen 2004). Past logging has not adversely affected the fish fauna significantly, but recent extensions, deepening of drains, increased salt water intrusion and flooding risks may have significant impacts (Yule, 2010).

Other than plants, peat swamp forests are the habitat of a number of 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 and 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 javanensis*)] and 14 different reptiles and amphibians. Peat water areas are also habitats of various endemic fishes, such as arowana (*Scleropages spp.*) in Sumatra, Kalimantan and Papua (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).

Several authors have promoted strategies that reduce emissions and that also enhance biodiversity within oil palm landscapes, such as production of oil palm beneath shade trees, diverse agro-forestry on plantation boundaries, and maintenance of forest patches within plantations (Koh 2008 and Koh *et al.*, 2009). 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 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* (2005) 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 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*., 2006).

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 its abundance and biodiversity of species. There is no single best approach for dealing with oil palm plantation development and its impact in Southeast Asia. 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 and 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 of great importance to include local experiences and thoughts of communities and stakeholders about possible solutions to the problems. Another important aspect is creating awareness and willingness to cooperate.

### 3.4 Emissions to the hydrosphere

Studies have indicated rising concentrations of dissolved organic carbon (DOC) in the 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, which may cause high fluxes of CO₂ 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 only represents 10% of the global riverine DOC input to the ocean. Rixen et al. (2008) suggest that peat soils in the area they studies (Siak river catchment, central Sumatra) are destabilized by deforestation, drainage and conversion of peat swamp forests into oil palm and rubber estates. Anthropogenic enhanced leaching as seen in other studies (Holden 2005; Holden et al. 2004) is very difficult to quantify as often no data are available prior to the main deforestation. However, oil palm monocultures are associated with erosion as forest clearance leaves soils bare and exposed to heavy tropical rainstorms. Erosion in turn, causes contamination and sedimentation in water courses. Water quality is also influenced by the runoff of fertilizers into the surrounding drainage ditches, causing eutrophic conditions (Rixen et al., 2008; Alkhatib et al., 2007; Miyamoto et al., 2009; Yule and 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.

In addition, palm oil processing companies also have an impact on water quality because of the large quantities of effluents which they release into rivers. The effluent from palm oil mills is subjected to anaerobic treatment at the mill site. In factories that try to achieve a sustainable system of palm oil extraction, this is predominantly done in open ponds, but in almost all cases CH₄ is released to the atmosphere. Despite treatment, significant quantities of nutrients are often still discharged into the rivers and pollute the ecosystems there.

3.5 Increased fire risk
Fires are dependent on four conditions: presence of fuel (organic material), oxygen, dryness and an ignition factor, that are usually linked to human intervention and activities such as forest clearance, road development, careless camping, and poor management of the ecosystem. Primary undisturbed rainforests usually do not burn, due to high moisture levels in the atmosphere, vegetation and soil. However, drainage and forest clearance in particular disturb the hydrological stability (Langner et al., 2007; Page and Rieley 1998) and make both the forests and the 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 CO₂ 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 ha of forest burnt in Kalimantan and Sabah (Brown 1998). In Malaysia, where burning is not allowed, the fire risk in oil palm plantations on peat is generally reduced compared to that for abandoned, degraded peat land, because of 1) artificial soil compaction during land preparation to provide strong anchorage for the palm trees, and 2) intensive monitoring and control of fires by state agencies and estates (Paramananthan, unpublished in 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 and to prevent salt water intrusion), a loss of biodiversity and wildlife habitat, elimination of seeds and seedlings so preventing re-establishment (Yule, 2010); emission of a large amount of CO₂ and other GHGs due to the loss of soil carbon from forest and peat fires (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. Satellite-derived atmospheric concentrations of carbon monoxide (CO) suggest that peat fires in Southeast Asia emitted 0.12 ± 0.06 Pg C yr⁻¹ over the period 1997-2006.

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 CO, ozone (O₃) and nitrogen dioxide (NO₂) (Ostermann and Brauer, 2001). At least 20 million people were exposed to dangerously high levels of air pollution during the 1997 fires, with an increase in asthma, bronchitis and other respiratory illnesses (Yule, 2010). In addition, many communities are rely on forest goods and services such as timber and non-timber forest products and use of clean water whose quantity and quality is dependent on the presence of the forest. Forest fires thus destroy the income sources of these communities.
3.6 Discussion and gaps in knowledge

Drainage of tropical peat for cultivation leads to soil subsidence (range 2.5 - > 50 cm per year in the initial stage). Subsidence rate is mainly dependent on peat type, soil structure, drainage depth and number of years after drainage. Soil subsidence comprises three processes: compaction, consolidation, and oxidation, of the peat. Oxidation becomes the dominant process that drives soil subsidence after the first years of drainage. Soil subsidence can in the long term lead to flooding and to salt water intrusion in coastal areas. Good water management (water table as high as possible, e.g. 35-60 cm) is the most obvious measure to reduce soil subsidence and good practice would be to define a ‘cut-off’ point for cultivation of a plantation on peat, long before undrainable levels (the drainage base) are reached. This could be defined in terms of a minimum distance between the water table and the ‘drainage base’.

Tropical peat swamp forests are ecosystems with a rich variety of unique plant and animal species. Transformation of these peat swamp forests, for example 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 protection of 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 and inputs of fertilizer. These result in contamination and sedimentation of water courses if no measures are taken. Effluents from production mills add to the release of wastes in the drainage canals which leads to further GHG emissions, loss of carbon and adverse effects on fisheries.

Fires in forest and peat are the second largest GHG sources after emissions resulting from drainage of peats. Undisturbed peat swamp forests do not usually burn, but if they are drained they can become susceptible to fires. Forest fires can cause, 1) destruction of the hydrological functioning of peat swamps, 2) loss of biodiversity, 3) loss of wild life habitat, 4) elimination of seeds and seedlings, 5) release of large amounts of CO₂ and CH₄ to the atmosphere, 6) smoke, resulting in lower ecosystem production, and 7) air pollution and effect on human’s health.
Peat fires affect ecosystems worldwide by contributing significantly to climate change through increased GHG emissions. Information on air pollution associated with the increased fire frequency after drainage and from forest burning is scarce. It could reduce photosynthesis and carbon fixation (Davies and Unam 1999ab), affect coral reefs as a potential long term carbon sink and affect human health. However, more research on these aspects is needed.
4 Socio-economics and palm oil production in South Asia’s tropical peat lands.

4.1 Introduction

4.1.1 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 as fresh fruit bunch (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 part of an economic network ranging from oil plant growers to downstream industries (Fig. 9). Relations between the different stakeholders are predominantly of an economic and financial nature.

![Economic network diagram](image)

*Fig. 9. Economic networks relevant to the palm oil industry (adapted from Chavalparit, 2006).*

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).
4.1.2 Indonesia

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

4.1.3 Malaysia

Plantation development commenced in Peninsular Malaysia at the end of the 19th century (Colchester, 2007b). Already in 1925, nearly one million ha of land had been cleared of forest and planted with rubber (Jomo et al., 2004). In Malaysia the area of oil palm plantations is still growing quickly, especially in the states of Sabah and Sarawak. Large-scale production of palm oil in Malaysia started in Peninsular Malaysia, where plantations covered over 2.36 million ha in 2007 (Kamphuis et al., 2011). In Malaysia, as in Indonesia, there are different sectors involved in the production of palm oil. Colchester (2007b) described the example of Sarawak where successive governments since independence in 1963, have supported plantation schemes to promote ‘development’ and 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 (e.g. Colchester et al., 2007ab).
4.1.4 Socio economics

Large scale conversion of crops, grasslands, natural and semi-natural ecosystems, (such as the conversion of forests to oil palm plantations), may 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 (eg. Schrevel 2008) have indicated that changes may be irreversible and socio-economic impacts largely negative for the local populations. 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 (e.g. 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.

4.2 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 ecological, social and economic costs of increased fire frequency (Sodhi et al., 2010). Also, the large number of people that depend on forest products for their livelihood, will be affected by such on-going development.

4.3 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 indigenous populations. When forests are replaced by oil palm monocultures, communities lose, for example, 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 from areas with a stronger tradition of sedentary agriculture. This can lead to ethnic conflict between newcomers and indigenous groups.

Colchester (2007b) interviewed indigenous people in Sarawak about their situation 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, promised benefits not delivered and measures to secure their consent to proposed schemes, overlooked.

4.4 Health

Human health is affected by the haze resulting from ongoing burning of AGB and peat in Southeast Asia. Transboundary haze mainly from burning peat fires has been identified as the most important regional environmental problem in the ASEAN region. Smoke from tropical fires causes respiratory problems (Kamphuis et al., 2011) as well as 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 years. After the 1997 fires in Southeast Asia, patient visits in Kuching, Sarawak, increased between two and three times during the peak period of smoke haze, 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, constituents and length of exposure to smoke but include respiratory and cardiovascular difficulties among other illnesses. The complex mix of particles, liquids and gaseous compounds released depend upon the type and efficiency of burning. Fire emissions have been studied and quantified for deforestation and 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 (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 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.
4.5 Employment

4.5.1 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 (the first years of repayment, before production is reached and fertilizer costs are high) to the company and are paid compensation for loss of land use opportunities. Deals differ significantly; e.g. variation 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, as well as 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 million ha, with a share of 35% of the total crude palm oil produced and of 41% of the productive area (Sheil et al., 2009; Vermeulen and Goad, 2006). Because of the required machinery and the need for palm oil mills, most smallholder plantations occur in cooperation with larger, company owned plantations termed nucleus estates (Sheil et al., 2009; Kamphuis et al., 2011). Wakker (2006) argue 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 import workers from outside the area of operation, fostering social conflicts (Casson 2000, Wakker 2005, 2006; Schrevel, 2008; Wilcove and Koh, 2010; McCarthy and Cramb 2009). However, the large-scale development of oil palm plantations also leads to a multiplier effect such as construction of infrastructure and provision of houses, health and educational services (Bertule and Twiggs, 2009). As a result, rural communities have easier access, for example, to local markets, schools, hospitals, and villages.
4.5.2 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 is now accounting for 71% of the national agricultural land bank. Malaysia has some of the highest FFB yields at about 21 tonnes per ha per year. Malaysia’s palm oil industry is regulated by the Malaysian Palm Oil Board (MPOB), which develops policies, guidelines and practices. 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 share of palm oil plantation area under the ownership of organised and independent smallholders, who still account for 28 percent and 12 percent of the total area respectively (Government of Malaysia, 2011).

Malaysia's oil palm industry is labour intensive especially in the plantations. MPOB estimated the total size of the workforce in Malaysian oil palm plantations in 2010 to be 446,368. This number consists of mainly foreigners (69%) with locals comprising only 31% (Ramli, 2011).

4.6 Income

In Indonesia, the plantation, 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 in their study that at a regional level there was a rise in GDP in both the expanding and established regions. At the farm level, the government’s nucleus estates and support to individual smallholdings has resulted in an increase in the income of more than half a million farmers (Zen et al, 2005). 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 their questionnaire study that most of the 200 farmers they interviewed in Sungai Panjang, Malaysia, worked 1.1 - 1.5 ha of land for an annual average income of RM 5,001 - RM 10,000. One of the main constraints on 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 do choose oil palm because it provides a
slightly better income than fruit and vegetables. Rist *et al* (2010) examined the economic implications (positive and negative) of oil palm as an alternative land use for smallholder income (using research sites in Central Sumatra, West Kalimantan, East Kalimantan and Central Kalimantan) (see box 6 for a smallholder case). 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 results published by Wilcove and Koh (2010)), but district authorities (which are not always very effective) and smallholder cooperatives and the terms under which smallholders engage with palm oil companies play key roles in the realization of benefits (e.g. McCarthy, 2010). Susila (2004) concluded that there is a positive effect on farmers’ income generated by palm oil production which reduces inequality in income and poverty in the palm oil communities. However, income is just one aspect of a sustainable livelihood. The conclusion of the research of Rist *et al* (2010) is that in Indonesia rural smallholders are not impoverished by oil palm development but they can be 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 also admit that 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) their vulnerability to crop failure and dependency on 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). In addition, smallholders are sometimes unaware of their rights and the nature of agreements made with the company (Rist *et al*., 2010). New insight into more sustainable oil palm production includes 1) the need for clarification of smallholder land rights to avoid 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 rate do not fluctuate substantially.
4.7 Discussion, gaps in knowledge and recommendations

4.7.1 Summary of main conclusions

The palm oil sector has created millions of jobs, 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 a 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 to dependency 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 will affect the social and cultural basis of forest dependant communities. Also health has been affected negatively in tropical Southeast Asia 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.

### 4.7.2 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.
5 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 livelihood for 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 carbon and GHGs to the atmosphere (De Vries et al., 2010; Henson, 2009; Jeanicke et al., 2008; Danielson et al., 2008; Fragioni et al., 2008; Rieley et al., 2008; Gibbs et al., 2008; Wösten and Ritzema, 2001; Hooijer et al., 2006). When oil palm plantations are developed on peat, oxidation due to drainage, (off-site) increased fire frequency and carbon losses when vegetation is cleared, are major sources of GHG emissions.

The most important means of minimizing GHG emissions is the selection of non-peat, low-carbon stock sites for oil palm plantation development. Once a plantation is developed on peat, this can lead to serious land degradation and in the long term, it can lead to floods because of high soil subsidence rates and to increased salt water intrusion which will adversely affect palm oil production.

Effective water management in order to maintain the water table as high as practical can reduce soil subsidence and GHG emissions considerably and can also reduce fire risk. Because in all cases peat loss and soil subsidence will continue due to drainage, it is wise to determine a ‘cut-off-point’ before an undrainable level (drainage base) is reached and flooding becomes inevitable.

Methane emissions from open water bodies such as drainage canals and ponds are likely to affect the methane 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. 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 the 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.
**Appendix A: Greenhouse gases in oil palm plantations and tropical forest**

This table shows terrestrial fluxes and management related fluxes of CO₂, CH₄, and N₂O as found in the literature. Sources are given in the first column, the GHG is given in the second column, emissions from oil palm plantations and (drained) forests are given in the next columns together with their references.

<table>
<thead>
<tr>
<th>Terrestrial Source</th>
<th>Plantation</th>
<th>Reference</th>
<th>Drained forest (groundwater table &lt; -25 cm)</th>
<th>Reference</th>
<th>Forest (groundwater table &gt; -25 cm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field fluxes</strong></td>
<td>CO₂ Ecosystem respiration</td>
<td>86</td>
<td>1.2, 3, 27, 28, 29, 30</td>
<td>26-74 and 85-142 and 54-72</td>
<td>6.4 / 5.7</td>
<td>34-39</td>
</tr>
<tr>
<td>CO₂ Photosynthesis (GPP)</td>
<td>unknown</td>
<td>126</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ Net Ecosystem Exchange</td>
<td>3.8</td>
<td>26</td>
<td>-16</td>
<td>5</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>CH₄</td>
<td>negligible - minus 0.0007</td>
<td>11</td>
<td>0.0-0.0007</td>
<td>10, 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td>0.48 and 4.1</td>
<td>8, 9</td>
<td>not applicable</td>
<td>not applicable</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Water fluxes | Considerable but unknown | unknown | unknown |

| Management | CH₄ | 0.8-1.2 | 16 |
| CO₂ | unknown |
| CO₂ | unknown |
| C-leaching hydrosphere | unknown |

| Traffic and fuel | CO₂ | 1.43 and 1.0 | 14 and 16 |
| CO₂ | 12.7 | 14 |

| C losses through initial biomass loss converted to CO₂ | CO₂ | considerable through burning |

| Gains through import of fertilisers | CO₂ | 1.5-2 | 14 |

| Inevitable management consequence | CO₂ | 957 and 685 | 10, 20, 21, 22 and 16 | 957 and 685 | 10, 20, 21, 22 and 16 | not applicable |
| CH₄ | ~ 1.5 kg per t CO₂ | 19 | not applicable |

| Leaching | DOC/DIC/POC | considerable but unknown | 17, 18 |

1. Agus et al., 2009
2. Melling et al., 2002
3. Lamade and Bouillet, 2005
4. Furukawa et al., 2005
5. Hirano et al., 2007
6. Jauhainen et al., 2008
7. Wösten et al., 1997
8. Melling et al., 2005a
9. IPCC, 2006
10. Couwenberg et al., 2010
11. Melling et al., 2005b
12. Guerin et al., 2007
13. Schrier-Uijl et al., 2010c
14. Henson et al., 2005
15. Cramer Commission 2007
16. Reijnders and Huijbregts, 2007
17. Myamoto et al., 2009
18. Yule and Gomez, 2009
19. Scholes et al. 1996
20. Heil et al., 2007
21. Vd Werf et al., 2008
22. Page et al., 2002
23. Jauhainen et al., 2005
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