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Impacts of Oil Palm Plantations on Climate Change: A Review of Peat Swamp Forests' Conversion in Indonesia

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Authors' contributions

This work was carried out in collaboration between the authors. Author SAUR wrote the first draft and collected literature along with author SA. Authors SS and US designed the paper and supervised author SAUR. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Indonesia possesses a rich biodiversity with abundant natural resources such as tropical rain and peat swamp forests, oil and gas deposits, and fertile soils just to name a few. The state policies on natural resource management were decentralized and the power and local autonomy rights were given to provincial and district governments. This resulted in an enormous expansion of oil palm plantations across the country especially over the last three decades. On the one hand it boosted the country's economy by bringing foreign money reserves, but on the other hand has led to severe deforestation, shifting cultivation, peat swamp forests conversion and land degradation. Thus, due to the severity of these environmental consequences and associated climate change implications, oil palm development has received significant attention from all stakeholders and is the subject of global debate. This paper aims to discuss the results of various studies regarding emissions of GHGs from oil palm plantations in Indonesia and highlights the fundamental methodologies

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followed in assessing GHGs emissions. We found throughout contradictions in the reported rates of oil palm encroachment over peatland and GHG emissions. The former because of diverse methodologies followed in each study i.e. different amounts of time spent in the field, scales of study area, analytical techniques in GIS (data sets and supplementary remote sensing); and the later because of both differences in instrumentation and underlying principles; such as indirect GHG assessments from subsurface drainage(level of water table), subsidence, soil and biomass carbon stock differences, autotrophic and heterotrophic respiration, close chamber methods, eddy covariance techniques and utilization of micrometeorological stations. Finally, the review concludes that almost all studies demonstrate a linear increase in oil palm plantations and proclaim a net negative climate change impact due to conversion from peat swamp forests to oil palm plantations. Therefore, it is being suggested that the pre-existing GHG inventories data should be further worked out to developa 'standard carbon sequestration model for peatlands', supported by updated countrywide peatlands mapping and policy reforms which should address both economic development from the oil palm sector and consider mitigation of GHG emissions from peatlands conversion.

Keywords: Climate change; deforestation; GHG emissions; oil palm; Peat Swamp Forests.

1. INTRODUCTION

Tropics cover around 440,000 km^2 or 11% of the global peatland area, of which most are concentrated in insular Southeast Asia; in some areas these peat deposits are up to 20m thick with surface areas about 250,000 km^2 [1]. There are a range of ecosystem functions and societal benefits associated with the tropical peatlands of insular Southeast Asia, most recently including provision of habitat to endangered fauna due to decline in the pre-existing lowland forests above mineral soils [2]. Furthermore, the carbon stocks of these peatlands are as high as 70Gt [1], which is nine times higher than the carbon that was emitted into the atmosphere by fossil fuel combustion in 2006; which was up to 8Gt as estimated by the Intergovernmental Panel on Climate Change (IPCC) [3].

The Southeast Asian peatlands experienced only minor exploitation by indigenous people before the establishment and development of large-scale industrial plantations [4]. However, in the past three decades peat swamp forest has suffered accelerated deforestation and land clearance activities due to the establishment of industrial plantations, compounded by the latest conversion techniques, overwhelming demands for agricultural commodities and shortage of mineral soils for agriculture, leading to increased human pressure on peatland areas. Plantation establishment involves drainage and land preparation works therefore, since the 1980s we see an increase in distorted landscapes and poor smallholder segmentation in the logged peat lands [5]. This conversion of peatlands has caused regional and global debates about oil palm plantations having serious social and environmental consequences [6].

Peat accumulation and storage process in the tropics has been adversely effected by anthropogenic activities which are a cumulative function of peatland hydrology, ecology and landscape morphology [7]. Conversion of peatlands to agriculture requires drainage i.e. avoiding inundation and involves civil works leading to construction of road networks, waterways and railways tracks etc. which ultimately leads to lowering of the water table and creates aerobic conditions thereby accelerating oxidation, nitrogen mineralization and microbial activities [8]. This leads to elevated CO_2loss by peat decomposition and accelerates greenhouse gas (GHG) emissions to the atmosphere [9]. Such logging activities cause the humid tropical forests to be highly prone to forest fires and desiccation because of wood loss and opened canopy [10]. These fires are less frequent but are potentially disastrous causing abrupt changes in the peatland involving carbon stocks burning and sending enormous emissions of GHGs into the atmosphere [11]. Thus at national level, in resource management and policy development regarding peatlands, it is inevitable to explore the social and environmental implication of peatland conversion to oil palm plantations along with understanding of its historical development.

2. HISTORICAL AND CURRENT OIL PALM DEVELOPMENT IN INDONESIA

In Indonesia, the island of Sumatra has the largest absolute extent of oil palm plantations

(Table 1) on peat i.e. 1.4 Mha (29%), followed by Kalimantan with 307,515 ha (11%) and Papua with 1,727 ha [12]. Projections of additional land demand for oil palm production in 2020 range from 1 to 28Mha in Indonesia [13]. An overall majority (62%) of the industrial plantations are located on the island of Sumatra, which contains two-thirds (69%) of oil palm cultivation; 70% of all industrial plantations have been established since 2000 and only 4% of the current plantation area existed in 1990 [14]. Sheil [15] reported FAO statistics and projected that, the annual global demand for biodiesel will be 24 thousand million liters by 2017, up from nearly 11 thousand million at the end of 2007 and less than 1 thousand million in 2000. If this demand was to be met from oil palm alone, the additional area of plantations needed would be 4.6 million hectares by 2017 assuming a yield of 5830 liters of palm oil $ha^{-1}yr^{-1}$.Carlson [16] assessed previous and projected future plantation expansion under five scenarios by using a spatially explicit land change carbon bookkeeping model, parameterized by high-resolution satellite time series and informed by socioeconomic surveys. Fire was the primary proximate cause of 1989–2008 deforestation (93%) and net carbon emissions (69%) from 2007–2008, oil palm directly caused 27% of total and 40% of peatland deforestation, shifting to 69% of peatland deforestation from 2008–2011. This implies that by 2020 nearly 40% of regional and 35% of community lands will be cleared for oil palm, generating 26% of net carbon emissions. The results of Hansen [17] showed a dramatic reduction in forest clearing rate from a 1990s average value of 1.78 $Mhayr^{-1}$ to an average rate of 0.71 $Mhayr^{-1}$ from 2000 to 2005. However, annual forest cover loss indicator maps revealed a near monotonic increase in forest clearing from a low rate in 2000 to higher in 2005. Results illustrated a dramatic downturn in forest clearing at the turn of the century followed by a steady resurgence thereafter to levels estimated to exceed 1Mha yr^{-1} by 2005. The lowlands of Sumatra and Kalimantan were the site of more than 70% of total forest clearing within Indonesia for both epochs; over 40% of the lowland forests of these island groups were cleared from 1990 to 2005.

Carlson [18] reported oil palm development across Kalimantan as 538,346 km^2 from 1990 to 2010, and projected expansion to 2020 within government-allocated leases. Using Land sat satellite analyses to discern multiple land covers, coupled with above and below-ground carbon accounting, the first high resolution carbon flux estimates from Kalimantan plantations were developed. From 1990 to 2010, 90% of lands converted to oil palm were forested (47% intact, 22% logged, 21% agro forests). By 2010, 87% of total oil palm area (31,640km^2) occurred on mineral soils, and these plantations contributed 65–75% of 1990–2010 net oil palm emissions (i.e.0.020–0.024 GtC yr^{-1}). Although oil palm expanded 278% from 2000 to 2010, 79% of allocated leases remained undeveloped. By 2020, full lease development would convert 93,844 km^2 (90% forested lands, including 41% intact forests) to oil palm plantations. Oil palm would then occupy 34% of lowlands outside protected areas. Plantations expansion in Kalimantan alone is projected to contribute 18–22% (0.12–0.15 $GtCyr^{-1}$) of Indonesia's 2020 CO_2-equivalent emissions.

Broich [20] mapped forest cover loss for 2000–2008 using multi-resolution remote sensing data from the Landsat Enhanced Thematic Mapper plus (ETM+) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors and analyzed annual trends per island, province, and official land allocation zone. The total forest cover loss for Sumatera and Kalimantan from 2000 to 2008 was 5.39Mha which is 5.3% of the total area of both islands and 9.2% of the forest cover. Margono [21] quantified 7.54Mha of primary forest loss in Sumatra from 1990 to 2010. Of the 7.54 Mha cleared, 7.25Mha was in a degraded state when cleared, and 0.28Mha was in a primary state. The rate of primary forest cover change for both forest cover loss and forest degradation slowed over the study period, from 7.34Mha from 1990 to 2000, to 2.51Mha from 2000 to 2010. Thus, the dissimilarities in the methodological approaches used to determine current and past oil palm plantation development resulted in different figures and statistics regarding forest loss (Table 2) and oil palm plantations expansion (Table 3).

3. PEAT SWAMP SUITABILITY FOR OIL PALM PLANTATION

As far as agricultural suitability is concerned, peat deposits with greater depths (thickness >3 m) are considered Unsuitable for oil palm (OP) plantations in the long run, thus shallower peats (thickness <3m) are mostly converted to OP plantations and regarded as appropriate for agriculture. Associated issues with this conversion include poor rooting stability, low nutrients availability, reduced temperature conductance, and fire hazards. The most alarming consequence out of all is the subsidence of peat, which causes peat loss up to 2.5 m in the first 25 years and as much as 6 m in the next 100 years due to oxidation and drainage [22].

The drainage leads to subsidence because the peat surface lies 2 to 10 m above the mean sea level. One of the key changes made to peatland landscapes during conversion to agriculture includes semi-permanent flooded conditions which cannot be avoided and has been mostly reported regarding Southeast Asian peatlands [23]. Therefore it has been concluded that Southeast Asian peatlands are not suitable for agriculture except where thickness is less than 2m, and only in those areas selective logging can be allowed. Thus with this standard depth limit in Sarawak Malaysia, the peatland soils with thickness more than 2m have been declared as organic soils in the land capability classification maps and regarded as soils with severe agriculture limitations. On the other hand peatlands which are shallow (thickness <2m) have been presented as marginally suitable for agriculture. The Department of Irrigation and Drainage Sarawak reports these “unsuitable” and “marginally suitable” peatlands converted to OP since 2000 as restorable and they can be “returned to nature” if further drainage is avoided in the future [24].

For the reasons described above, Indonesian Presidential decrees[1] stipulate that peat thicker than 3 m should not be drained or clear-felled. However, implementing this law has proven to be problematic because the Indonesian ban on developing peatlands deeper than 3 m is not strictly enforced, as is clear from the fact that the share of peatland allocated to conversion to OP plantations on peat of 2 to 4 meters deep is as high as 42%, even 19% of the peatland area with thickness more than 4m has already been given on lease for conversion to OP plantations [14]. The distribution of peatlands in Kalimantan Island based on thickness and peat type is given in Table 4.

4. DISTRIBUTION OF PEATLANDS IN INDONESIA WITH THICKNESS <3M

The Wetlands International map for Indonesia presents peat thickness boundaries of 2 and 4 meters (Fig. 1). Miettinen [25] attempted to interpolate the 3 m depth line from this map, but have not produced credible results. In any case, it appears that the 2m and 3m contours are usually very close together as they are located on the relatively steep “slope” part of the peat dome profile. Furthermore, the Wetland International maps tend to underestimate peat depth.

Indonesia can enforce the ban on development of oil palm plantations or other agricultural practices on peat having thickness 3 m or above by encouraging OP expansion on shallow peat or mineral soils. Miettinen [14] projected that, if expansion continued only on peat with thickness less than 3 m, approximately 36% of shallow peats that were not planted with OP in 2010 would be in 2030.Thus only in two provinces having relatively limited peat extent i.e. West and North Sumatra; the available area of shallow peat will exceed if expansion of OP continues with current rates.

Table 1. Comparison of three studies focusing on oil palm plantations on peat

	Omar [19]	Gunarso [12]	Miettinen [14]
Total Peat Area(ha)			
Indonesia (excluding Papua)		13,043,026	13,003,105
Sumatra	6436649	7,212,798	7,234,069
Kalimantan	4778004	5,830,228	5,769,036
Total Peat Area		15,188,056	15,492,164
Oil palm in 2010			
Indonesia (excluding Papua)		1,704,975	1,285,221
Sumatra		1,395,733	1,026,922
Kalimantan		307,515	258,299
Total		2,421,478	2,129,154
		16%	14%

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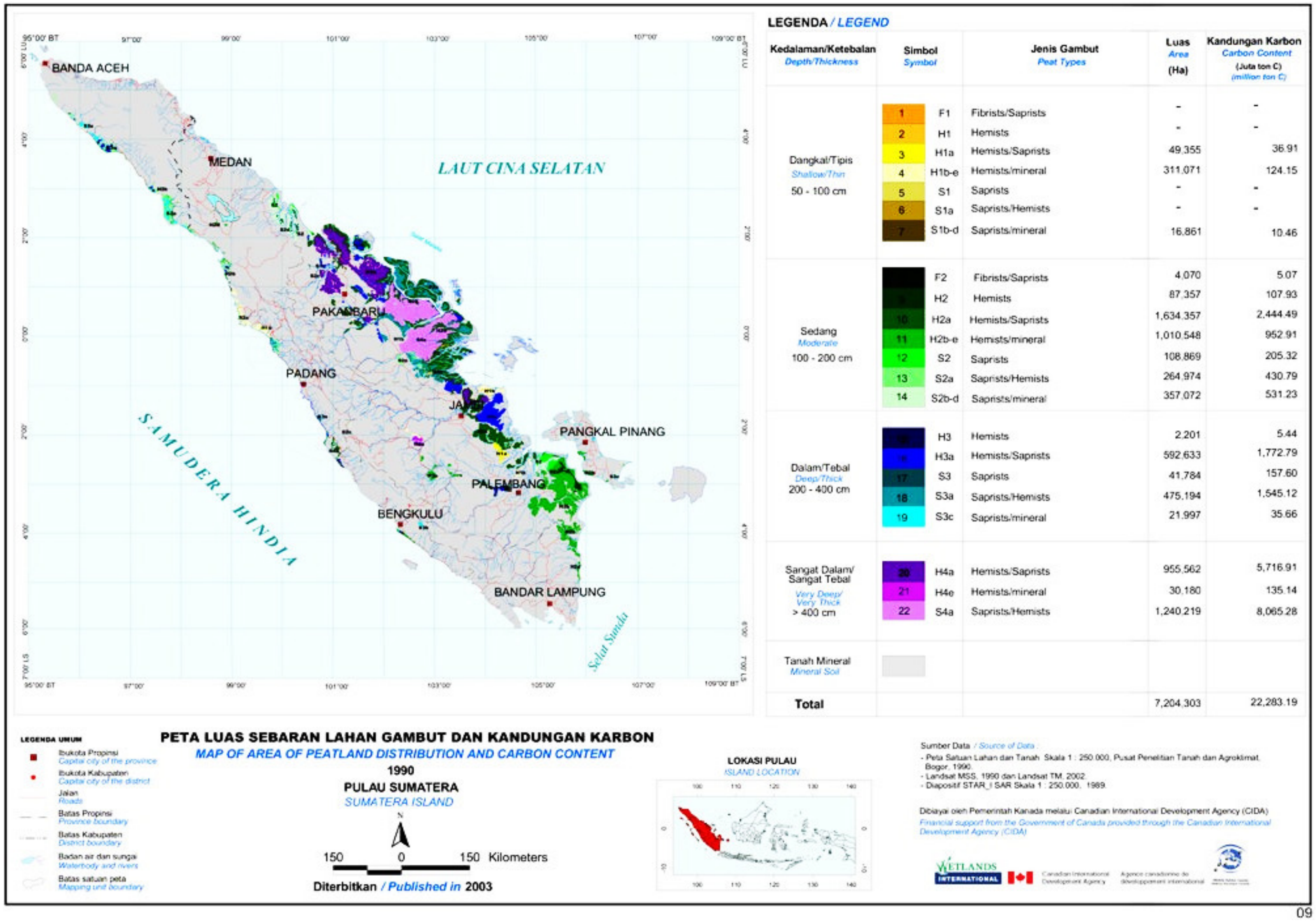
[1] *Presidential decree no 32, 1990 and Presidential decree no 80, 1999*



LEGENDA / *LEGEND*

Kedalaman/Ketebalan *Depth/Thickness*	Simbol *Symbol*		Jenis Gambut *Peat Types*	Luas *Area* (Ha)	Kandungan Karbon *Carbon Content* (Juta ton C) *(million ton C)*
Dangkal/Tipis *Shallow/Thin* 50 - 100 cm	1	F1	Fibrists/Saprists	-	-
	2	H1	Hemists	-	-
	3	H1a	Hemists/Saprists	49,355	36.91
	4	H1b-e	Hemists/mineral	311,071	124.15
	5	S1	Saprists	-	-
	6	S1a	Saprists/Hemists	-	-
	7	S1b-d	Saprists/mineral	16,861	10.46
Sedang *Moderate* 100 - 200 cm		F2	Fibrists/Saprists	4,070	5.07
	9	H2	Hemists	87,357	107.93
	10	H2a	Hemists/Saprists	1,634,357	2,444.49
	11	H2b-e	Hemists/mineral	1,010,548	952.91
	12	S2	Saprists	108,869	205.32
	13	S2a	Saprists/Hemists	264,974	430.79
	14	S2b-d	Saprists/mineral	357,072	531.23
Dalam/Tebal *Deep/Thick* 200 - 400 cm	15	H3	Hemists	2,201	5.44
	16	H3a	Hemists/Saprists	592,633	1,772.79
	17	S3	Saprists	41,784	157.60
	18	S3a	Saprists/Hemists	475,194	1,545.12
	19	S3c	Saprists/mineral	21,997	35.66
Sangat Dalam/ Sangat Tebal *Very Deep/ Very Thick* > 400 cm	20	H4a	Hemists/Saprists	955,562	5,716.91
	21	H4e	Hemists/mineral	30,180	135.14
	22	S4a	Saprists/Hemists	1,240,219	8,065.28
Tanah Mineral *Mineral Soil*	▨				
Total				7,204,303	22,283.19

LEGENDA UMUM

■	Ibukota Propinsi *Capital city of the province*
●	Ibukota Kabupaten *Capital city of the district*
	Jalan *Roads*
— —	Batas Propinsi *Province boundary*
- - -	Batas Kabupaten *District boundary*
	Badan air dan sungai *Waterbody and rivers*
	Batas satuan peta *Mapping unit boundary*

PETA LUAS SEBARAN LAHAN GAMBUT DAN KANDUNGAN KARBON
MAP OF AREA OF PEATLAND DISTRIBUTION AND CARBON CONTENT
1990
PULAU SUMATERA
SUMATERA ISLAND

Diterbitkan ***/ Published in*** **2003**

Sumber Data */ Source of Data :*
- Peta Satuan Lahan dan Tanah Skala 1 : 250.000, Pusat Penelitian Tanah dan Agroklimat, Bogor, 1990.
- Landsat MSS, 1990 dan Landsat TM, 2002.
- Diapositif STAR_I SAR Skala 1 : 250.000, 1989.

Dibiayai oleh Pemerintah Kanada melalui Canadian International Development Agency (CIDA)
Financial support from the Government of Canada provided through the Canadian International Development Agency (CIDA)

Fig. 1. Peatland distribution map of Sumatra Island (reproduced from Wahyunto [27])

Table 2. Comparisons of forest cover loss from four different studies using different satellite imagery, classification methodologies and time periods for Sumatra and Kalimantan

Forest cover	**Land cover (ha x10^6)**					**Annual rates of change (ha x10^3)**				
	1990	**2000**	**2005**	**2008**	**2010**	**1990-2000**	**2001-2005**	**2006-2010**	**2000-2008**	**2000-2010**
Sumatra+Kalimantan (Hansen [17])	68.9	55.7	52.7			1,320	600			
Sumatra+Kalimantan (Broich [20])		57.8		57.8					653	
Sumatra+Kalimantan (Gunarso [12])		50.1	48.2		44.9		377	668*		523
Sumatra (Margono [21])		15.7			13.6					211
Sumatra (Gunarso[12])		15.9	15.1		14.1		152	206		179
Other tree-dominated types (Gunarso [12])										
Sumatra Agro forest		2.9	2.2		2.1		141	13		77
Sumatra Shrub		6.2	6.2		6.3		(5)	(21)		(13)
Kalimantan Agro forest		0.6	0.7		0.4		(14)	65*		25
Kalimantan Shrub		13.3	13.5		13.2		(48)	76*		14

**mosaic images from 2009 and 2010, Values in parenthesis indicate increases in cover for that category (reproduced from Gunarso* [12]*).*

Table 3. Historical trends in OP development across Indonesia and its major islands as reported by Gunarso [12] (cells in grey) and Miettinen [14] (cells in yellow)

Province/Area	**1990 OPP**	**1990 - 2000 mean annual growth rate**		**2000 OPP**	**2000 - 2005 mean annual growth rate**		**2005 OPP** **2007 OPP**	**2005 - 2010 mean annual growth rate**		**2010 OPP**	**2020 OPP**	**2030 OPP**
	(ha)	**(ha yr^{-1})**	**%**	**(ha)**	**(ha yr-^{1})**	**%**	**(ha)**	**(ha yr^{-1})**	**%**	**(ha)**	**(ha)**	**(ha)**
Sumatra	NR	167,000	9.0%†	NR	219,000	9.0%†	NR	151,000	3.8%†	NR	NR	NR
Sumatra	18,955	NR	7%*	528,475	NR	NR	845,904	NR	15%*	1,052,750	1,742,236	2,431,722
Kalimantan	NR	65,000	21.5%†	NR	72,000	9.7%†	NR	360,000	32.9%†	NR	NR	NR
Kalimantan	0	NR	0%*	15,982	NR	NR	111,417	NR	4%*	258,299	747,916	1,237,534
Indonesia (Three Islands)	1,337,000	229,000	10.5%†	3,678,000	295,000	8.0%†	5,155,000	514,000	10.0%†	7,724,000	NR	NR
Indonesia(-Papua)	18,955	NR	4%*	544,457	NR	NR	957,318	NR	10%*	3,669,256	2,490,152	2,431,722
Papua	28,740	1,900	5.1%†	47,560	4,300	9.0%†	68,910	2,900	4.3%†	83,622	NR	NR

** % age of peatland covered by OPP at end of each epoch,† % age annual increment of OPP during each period NR: Not Reported, OPP: oil palm plantations*

Table 4. The distribution of peatlands on Kalimantan Island based on peat nature and thickness (reproduced from Wahyunto [28])

				Area and carbon content in each Province								**Total**	
				West Kalimantan		**Central Kalimantan**		**East Kalimantan**		**South Kalimantan**			
No.	**Depth/ Thickness**	**Peat types**	**Proportion (%)**	**Area** *Ha*	**C Content** *Millionton C*	**Area** *Ha*	**C Content** *Millionton C*	**Area** *Ha*	**C Content** *Millionton C*	**Area** *Ha*	**C Content** *Millionton C*	**Area** *Ha*	**C Content** *Millionton C*
1	*Very Shallow/Very Thin*(< 50 cm)	Hemists/mineral	80 / 20	36,673.00	0.98	75,990.00	2.02	--	--	76,785.00	2.04	189,448	5.04
2	*Shallow /Thin* (50-100cm)	Hemists/Fibrists	60 / 40	125,435.00	77.17	246,316	72.74	49,562	19.20	--	--	421,313	169.11
3		Hemists/Fibrists/mineral	50 / 30 / 20	225,486.00	111.81	45,610	10.57	4,539	1.40	--	--	275,635	123.78
4		Hemists/mineral	80 / 20	44,484.00	24.49	79,055	13.12	24,121	6.97	--	--	147,660	44.58
5		Hemists/Saprists/mineral	40 / 30 / 30	8,793.00	3.82	124,874	43.59	--	--	--	--	133,667	47.41
6		Hemists/mineral	50 / 50	1,078.00	0.37	106,649	11.07	--	--	18,100	2.27	125,827	13.71
7		Hemists/mineral	20 / 80	32,896.00	4.53	353,229	14.66	186,337	13.46	32,340	1.62	604,802	34.27
8		Saprists/mineral	20 / 80	--	--	2,753	0.29	--	--	28,928	1.22	31,681	1.51
9	*Moderate*	Hemists/Fibrists	60 / 40	737,111.00	1,067.09	459,371	301.41	25,528	18.18	--	--	1,222,010	1,386.67
10	(100-200cm)	Hemists/Fibrists/mineral	50 / 30 / 20	--	--	--	--	86,983	53.71	--	--	86,983	53.71
11		Hemists/Fibrists/Saprists	40 / 30 / 30	--	--	3,028	3.00	--	--	--	--	3,028	3.00
12		Hemists/mineral	10 / 90	--	--	--	--	--	--	9,976	3.01	9,976	3.01
13		Saprists/Hemists/mineral	25 / 25 / 50	--	--	--	--	--	--	68,790	15.88	68,790	15.88
14	*Deep/Thick*	Hemists/Fibrists	60 / 40	213,705.00	539.41	574,978	665.98	128,561	350.54	32,669	42.15	949,913	1,598.08
15	(200-400cm)	Hemists/Fibrists/mineral	50 / 30 / 20	--	--	--	--	91,142	201.90	--	--	91,142	201.90
16		Saprists/Hemists/mineral	30 / 30 / 40	--	--	--	--	--	--	64,041	17.74	64,041	17.74
17	*Very Deep/Very Thick* (400 - 800cm)	Hemists/Fibrists	60 / 40	304,319.00	1,795.52	661,093	3,066.36	100,224	546.55	--	--	1,065,636	5,408.42
18	*Extremely Deep/Extremely Thick*(800 - 1200cm)	Hemists/Fibrists	60 / 40	--	--	277,694	2,146.72	--	--	--	--	277,694	2,146.72
Total				1,729,980	3,625.19	3,010,640	6,351.52	696,997	1,211	331,629	85.94	5,769,246	11,273.66
%				29.99	32.15	52.18	56.34	12.08	10.75	5.75	0.76	100.00	100.00

5. PEAT SWAMP FOREST CONVERSION TO OIL PALM PLANTATIONS

Indonesia is considered to have one of the highest rates of deforestation in the world, ranging from 0.7 to 1.7 $Mhayr^{-1}$from 1995 to 2005 [17]. The land use change (LUC) can primarily be characterized by forest cover loss on 40Mha of land, a 30% reduction in forest land [13]. The largest single cause of historical forest loss can be attributed to unsustainable logging followed by the impact of fire, which in combination led to the progressive transition of large areas of forest land [12]. In the last three decades the oil palm industry showed significant growth in Malaysia and Indonesia, from 3.5Mhain1990tomorethan 9.5Mhain2005. Indonesia has the higher proportion of this growth [26], which is being repeatedly associated with deforestation throughout the scientific and popular media.

Initially the impact of deforestation and oil palm development was focused on biodiversity losses and its negative impacts on indigenous people [15], but the emphasis soon included climate change when interest in oil palm for biofuel production commenced [29]. The GHG emissions due to oil palm expansion are because soil organic matter stocks decline when natural forests are replaced by plantations having smaller amounts of residual biomass. Furthermore, the land preparation for oil palm establishment involves drainage and fires which results into two more sources of GH Gemissions [30]: one is forest fires which can release GHGs including CO_2 and N_2O [31] and the second is emissions of GHGs as a result of soil organic matter loss due to drainage [32]. Drainage of the peatlands to prepare them for use as oil palm plantations make the peat soils more vulnerable to catch fire because the upper layer dries out, triggering oxidation and accelerating the decomposition of peat deposits [33].

Some studies have covered deforestation in Indonesia but have not covered the issues of the oil palm plantations in particular [20]and others have reduced scales that make them unsuitable for thorough assessment of the sector [25,16]. These studies in particular do not incorporate all the respective land cover categories that are converted to oil palm plantations, neither have they described the economics of the oil palm sector that drives this conversion [13].

6. GREEN HOUSE GAS (GHG) EMISSIONS FROM OIL PALM PLANTATIONS

By the end of the 1970s Indonesia was relying on its natural forests to support national economic development, and forest concession rights (*Hak Pengusahaan Hutan*- HPH) were the dominant system to utilize natural forests and their resources [34]. Since 1990 industrial plantation development on peatland, especially for oil palm cultivation, has created intense debate due to its potentially adverse social and environmental impacts [14].

The conversion of one hectare of forest on peat releases over 1,300Mg CO_2 equivalents during the first 25-year cycle of oil palm growth. Depending on the peat depth, continuous decomposition augments the emission with each additional cycle at a magnitude of 800 Mg CO_2 equivalents per hectare [35]. Various studies have reported on forest loss, Peat Swamp Forest (PSF) conversion and GHG emission across SEA in general and in Indonesia in particular following a variety of approaches (Table 5).

7. CARBON DIOXIDE (CO_2)

Hooijer [36] estimated CO_2 emission caused by decomposition of drained peat lands, which ranged between $355Mgy^{-1}$ and 855Mg y^{-1} in 2006 of which 82% came from Indonesia, largely Sumatra and Kalimantan. The emission factor for peat oxidation for oil palm plantations operating on peat soils was 43 $MgCO_2ha^{-1}yr^{-1}$, while the GHG emission factors for peat fires for establishing oil palm plantations in swamp forest based on above ground carbon (AGC) estimates was 333Mg CO_2 ha^{-1} and swamp shrub land is 110Mg CO_2 ha^{-1}[37].The emission factor found for drained OP plantations has been different in various studies as given in Table 6.

According to Guerin [45], the rate of methane emission from a tropical lake in a peat area in French Guiana was 350±412kg ha^{-1} yr^{-1} (8.4 ± Mg CO_2-eq ha^{-1} yr^{-1}), signifying that GHG fluxes from open water bodies in the tropics also have to be considered. On the other hand methane emission from drainage canals, ponds or flooded areas in temperate regions may account for 60% of the total annualCH_4 flux of a drained peat ecosystem, depending on depth and the amount of nutrients in the water [46].

Table 5. Results of different studies that estimate GHG emissions from oil palm plantations with negative values denoting a net GHG absorption and positive values an emission

Source	Description	Results
Murdiyarso [38]	Analysis of carbon loss from LUC of tropical peatland to OP and Sago plantations; accounts all ecosystem C fluxes using literature values. Used a physiological model calibrated for mineral soil's root emissions hence estimating peat respiration by subtracting it from root emissions. Estimated carbon lost by land clearance using fire, above and belowground biomass inputs and losses of fluvial carbon. Biomass and emissions data obtained from the literature estimates of fluvial losses of carbon based on losses from northern peatlands; biomass inputs estimated from mineral soils.	Land use conversion of tropical forests results in 59.4 ± 10.2 Mg CO_2eqha^{-1} yr^{-1}of total carbon emissions over a 25-yearproduction cycle. Similarly, 61.6% of CO_2 emissions result from peat and 25% of emissions during land clearance using fire.
Danielsen [39]	Analysis aimed to quantify biodiversity losses and carbon payback times associated with OP plantation for biofuel production. Considered OP plantation development on Impereta grassland, rainforests on mineral soils and peatland. Emissions taken from the literature. Considered CO_2emissions from drained peat soils, replacement of forest biomass, forest clearance (logging and burning). Considered emissions of the OP biofuel chain from non-land use related components also.	Calculated carbon payback times of: 692 years for OP production on peatland;75 to 93 years for OP production on tropical forests (mineral soils); 10 years for Imperata grasslands.
Koh [40]	Aimed to assess biodiversity and C cycle impacts of OP plantation in peninsular Malaysia, Sarawak and Borneo by remote sensing analysis. Estimates of carbon emissions resulting from LUC are based upon results of Murdiyarso [38].	Only closed canopy plantations covering areas greater than 200 hectares were identified; hence extent of OPP was underestimated, 880,000 ha of OPP on peat soils in Peninsular Malaysia, Sarawak and Borneo in 2010 was estimated. An annual loss of ≈140 million Mg AGBC and ≈4.6 million Mg BGBC was estimated from Peat oxidation.
JRC. [41]	Report on iLUC modeling of biofuel feedstock expansion. IFPRI-MIRAGE model applied to assess emissions from OP on tropical peatland.	Reported that the values used to estimate emissions from drained peatlands during production of OP feed-stocks are under estimated because of not considering CO_2 emissions due to deep drainage involved in land preparation. Annualized carbon release from oil palm extension on peat reported as 33 gCO_2eq/MJ
Wicke [42]	GHG emissions from oil palm production in Borneo for electricity generation in the Netherlands was estimated by using degraded grasslands, forests on mineral soils and forests on peatlands; based on criteria of Cramer Commission as 50-70% GHG emission reduction compared to	Results showed that OP plantations on previously rain forest mineral soils or peatlands result in high GHG emissions and are not able to meet 50-70% GHG emissions reduction relative to fossil energy systems. However, OP plantations can be a net carbon sink on degraded and

Source	Description	Results
	fossil energy production systems. IPCC defaults and data from literature review was used.	well managed lands.
Reijnders [43]	The study focused on OP plantations in Southeast Asia and carbon emissions in each cycle replacing tropical forests; reports lack of data regarding peat respiration and fire.	The results show 27.5 Mg $CO_2ha^{-1}yr^{-1}$aboveground biomass carbon losses and 36.7 to 55 Mg CO_2-eq $ha^{-1}yr^{-1}$from peat in 25 year plantation life cycle. CO_2emissions estimated to be 1.5 to 5.8 Mg CO_2-eq per ton of oil palm produced during conversion of forests on mineral soils to OP, and 9 to 17 Mg CO_2-eq on peatland.
Fargione [44]	Quantified the carbon debt of various biofuel production systems i.e. OP production on lowland tropical rainforests on mineral soils in Southeast Asia. Emission estimates based on literature review.	For lowland forest estimated emissions and carbon biofuel debts over a 50-year period= 610 Mg CO_2-eq ha^{-1},for 86 years = 3000 Mg CO_2-eq $ha^{-1}$and carbon debt of 420 years for peatland; the study also estimated emissions over 120 years for peats deeper than 3 m as 6000 Mg CO_2-eq $ha^{-1}$and 840 years of biofuel carbon debt.
Germer [35]	Study aimed to quantify GHG emissions from OP plantations on tropical rain forests (on mineral soils), and peatlands. Considered changes soilin biomass carbon storage, emissions from fire during land clearance.	In degraded grasslands (i.e. net sink)net greenhouse gas balance over 25-year production cycle: -134 ± 36 Mg CO_2-eq ha^{-1};for forest conversion on mineral soils 668 ± 372 Mg CO_2-eq $ha^{-1}$for forest conversion on peatland 1335 ± 690 Mg CO2-eq ha^{-1}.
Agus [37]	The CO_2 emissions from LUC, peat fires and peat oxidation due to OP were estimated for Indonesia, Malaysia and Papua New Guinea. Emission factors calculated from the differences in the mean value of published reports for above-ground carbon (AGC) in undisturbed forest (UDF), disturbed forest (DF), shrub-land (SL), and OP. Emission factor for peat oxidation taken from literature and for fires by assuming fire for land clearing during plantation. CO_2 emission from OP in different time periods was estimated i.e. 1900- 2000, 2001-2005 and 2006-2009/10.	Emission factors based AGC for UDF =189 Mg C ha^{-1} for DF =104 Mg C ha^{-1} for SL =30 Mg C ha^{-1} for OP = 36 Mg C ha^{-1}, for peat oxidation for OP operating on peat soils = 43 Mg CO_2 ha^{-1} yr^{-1}, for fires in swamp forest = 333 Mg CO_2 ha^{-1} and for swamp shrub land = 110 Mg CO_2 ha^{-1}. Estimated CO_2 emission from OP due to peat oxidation and fire in different time periods reported as: for 1900- 2000 = 92 TgCO_2 yr^{-1}, 2001-2005 = 106Tg CO_2 yr^{-1} and 2006-2009/10 = 184Tg CO_2 yr^{-1}. Similarly due to AGC and LUC the CO_2 changed from 55 to 42 to 67Tg CO2 yr^{-1} in each period respectively.

Table 6. GHG emissions from oil palm plantations over peatland estimated in different studies

Reference	Emissions from drained Peat			
	CO_2Mg $CO_2ha^{-1}yr^{-1}$	CH_4Mg $CH_4ha^{-1}yr^{-1}$	N_2O kg N_2O-N $ha^{-1}yr^{-1}$	CO_2-eq Mg CO_2-eq $ha^{-1}yr^{-1}$
Koh [40]	19.2	NR	NR	19.2
JRC. [41]	57	NR	NR	57
Wicke [42]	39	NR	8	42.7
Murdiyarso [38]	19.2	NR	NR	19.2
Germer [35]	31.4±14.1	-0.2	4.1±5.5	33±16
Fargione [44]	55	NR	NR	55
Reijnders [43]	36.7 to 55	NR	NR	36.7 to 55

NR: Not Reported, Negative values denote the system being GHG sink

The process of methanogenesis is stimulated by increased soil temperature and development of drainage canals following land use change which raisesCH_4 emissions to non-negligible quantities [47]. Couwenberg [9] concluded that at low water levels CH_4 emissions in tropical peat are negligible and at high water levels amounts to up to 3Mg CH_4 $m^{-2}hr^{-1}$ (6.3kg CO_2-eq $ha^{-1}yr^{-1}$) may be emitted. In oil palm plantations drainage parameters such as the spacing and width of canals show that water surface from drainage canals may account for up to 5% of the total plantation area and hence become a source of CH_4 emission.

Methane flux from peat soils supporting oil palm, sago and degraded forest was estimated using closed chambers, performing monthly measurements over a year by Melling [48].They examined parameters such as depth to groundwater table, precipitation, nutrients, bulk density, and moisture conditions that were likely to control CH_4 emissions. The results indicated that the sago plantation and degraded forest were sources for CH_4 while the oil palm plantation was a CH_4 sink. They attributed the switch from the forest as a source (2.27 ugC$m^{-2}hr^{-1}$) to the oil palm as a sink (-3.58 ugC$m^{-2}hr^{-1}$) to a lowering of the water table and soil compaction due to use of machinery and concluded that the conversion of tropical peat primary forest to oil palm promoted CH_4 oxidation due to an increased thickness of aerobic soil after drainage. However, it is also evident that increased fire frequency following drainage and management will also increase CH_4 emissions and for each ton of CO_2 emitted, an additional 1.5kg of CH_4 is produced when vegetation is burned [49].

8. METHANE

It is believed that the CH_4 emissions from tropical peat areas only make a minor contribution to the GHG flux compared to the emissions of CO_2, and thus play only a minor role in the carbon balance [50]. The extent of emissions from open water and those promoted by management practices and fires are likely to contribute considerably, particularly because the warming potential of CH_4 is 25 times that of CO_2. However, net CH_4 fluxes from tropical peats are low compared to fluxes from temperate peat soils and they usually show a clear positive relationship to water level for water levels above 20 cm, as is also the case for temperate wetlands [51]. An outline of the scientific literature describing methane emissions in tropical peat under different land uses is given in Table 7.

9. NITROUS OXIDE

A typical oil palm plantation planted on both mineral and peat soils requires around 354 kg N/ha over the first 5 years causing emission of nitrogen oxides and increased eutrophication in neighboring water bodies and wetlands affected by runoff [15]. Nitrous oxide (N_2O) is primarily emitted as a by-product of nitrification and denitrification in both agricultural landscapes and natural ecosystems. The use of nitrogen fertilizer, whether inorganic or organic, is a major factor determining the levels of N_2O emission, which vary depending on soil moisture conditions and land use [51]. Nitrous oxide is not necessarily produced by natural boreal wetlands with high water tables [52], instead they may consume small amounts via denitrification when atmospheric N_2O is reduced to N_2. On the other hand, tropical peat soils may represent additional GHG emissions because of different biophysical attributes leading to emissions of N_2O from fertilizer and manure applications.

It seems likely that in oil palm plantations the application of nitrogen fertilizers will accelerate release of N_2O; however, the extent of those emissions in these types of ecosystems remains poorly documented [51]. Melling [53] made monthly measurements of N_2O emissions over one year using closed chambers on tropical peat soils under oil palm, sago and forest. The N_2O emissions in the oil palm plantations were 1.2kg N_2O $ha^{-1}yr^{-1}$ (0.48Mg $CO_{2\text{-eq}}$ $ha^{-1}yr^{-1}$). However, there was too much variability for a robust regression analyses, uncertainties were large and data were too limited to distinguish background emissions from event emissions due to fertilizer applications. Hadi [54] compared the N_2O emissions from a paddy field, a field with an *Oryza sativa-Glycine max* (rice-soya bean)rotation, and a peat forest. They integrated monthly measurements and scaled these up to provide annual estimates of N_2O emissions. The default value in the IPCC guidelines for synthetic nitrogen fertilizer-induced emissions for histosols in tropical regions is 10 kg N_2O-N ha-$^{1}yr^{-1}$[55], which correspond to a total emission of 4.8Mg CO_2-eq $ha^{-1}yr^{-1}$. Thus N_2O emissions vary according to land use developed over peatland as mentioned in Table 8.

Table 7. Methane emissions estimated from different land uses on peatland in tropical Southeast Asia

Source	Land use	Measurements Frequency	Mean CO_2-eq (tCO_2/ha/yr)	MinCO_2-eq (tCO_2/ha/yr)	MaxCO_2-eq (tCO_2/ha/yr)	Mean CH_4 emissions (gCH_4/m^2/yr)	MinCH_4 emissions (gCH_4/m^2/yr)	MaxCH_4 emissions (gCH_4/m^2/yr)
Furukawa [56]	Drained forest	1-2 years, monthly	0.28			1.17		
	Cassava	1-2 years, monthly	0.81			3.39		
	Paddy field upland	1-2 years, monthly	0.87			3.62		
	Paddy field lowland	1-2 years, monthly	11.89			49.52		
	3 Swamp forests	2 months	2.02			6.15		
Melling [48]	Sec. forest	1 year, monthly	0.006			0.02		
	Sago	1 year, monthly	0.06			0.24		
	Oil palm	1 year, monthly	-0.006			-0.02		
Couwenberg [9]	Swamp forest	1 year, monthly on average		-0.9	1.41		-0.37	5.87
	Agriculture	1 year, monthly on average		0.006	0.816		0.025	3.4
	Rice	1 year, monthly on average		0.87	11.88		3.26	49.5
Hadi[54]	Rice	1 year, monthly		0.3	1.22		3.5	14.0
	Sec. forest	1 year, monthly	1.41			5.87		
	Paddy field	1 year, monthly	6.28			26.13		
	Rice-soybean	1 year, monthly	0.83			3.47		
Ueda[57]	Fresh water swamp			1.05	26.28		4.38	109.5

Table 8. N_2O emissions from various land uses developed over tropical peatlands as reported in the scientific literature

References	Land use	Measurement frequency	Emission (kg CO_2-eq /ha/yr)
Melling [48]	Sago	10 months, monthly	1556
	Forest, not primary	10 months, monthly	330
	Oil palm	10 months, monthly	566
Hadi [54]	Cultivated upland field	3 measurement days	6608-36754
	Rice paddy field	3 measurement days	0-5781
	Soya	3 measurement days	4543
	Forest, not primary	3 measurement days	6600
Inubushi [58]	Forest, not primary Abandoned upland field rice	1 year, monthly	range –664-498
Furukawa [56]	Pineapple	1-2 months	132-1017
	Rice paddy field	1 year, monthly	0.016
	Upland cassava field	1 year, monthly	0.257
	Forest, not primary	1 year, monthly	0.101

10. CONCLUSION AND RECOMMENDATIONS

The oil palm plantations expansion in Indonesia is becoming a great challenge, both for local policy makers and environmental activists worldwide. In this regard, almost all studies conducted in the country shows a linear increase in the oil palm development except where further land is not available for plantations such as in few provinces of Sumatra Island. The policy and economic aspects of oil palm establishment at the national scale requires detailed research; however, to make it easy for decision-makers comparative cost benefit analysis should be carried out by translating the environmental value of conserving peat swamp forests into economic terms that can be compared to fiscal returns from the palm oil sector. Furthermore, the country requires extensive policy reforms regarding forest concession rights and license allotment mechanisms for industrial-scale oil palm plantations. In this regard, Indonesia's 2-year moratorium on new concessions in primary natural forest and peatland areas is an important step towards meeting its voluntary commitment to avoid forest conversion and reducing emissions. However, several issues are unresolved in the moratorium concerning the area such as the amount of carbon stored in the affected forests and peatlands and its biodiversity status. The additional area given protection under the moratorium is at most 22.5Mha. However, about 46.7Mha of secondary forests and logged-over forests have not been included in this moratorium where High Conservation Value Areas (HCVAs) should be identified and be at least considered within the Indonesian framework for Nationally Appropriate Mitigation Actions (NAMAs). Therefore it is recommended that, in order to avoid the degradation of carbon rich ecosystems and associated climate change implications; further development should be meticulously pre-judged at such land scapes; moreover, the current oil palm plantation sites should be intensively managed to maximize its yield potential. Furthermore, the companies involved in industrial plantations should insure their corporate social responsibility by helping the government in alleviating poverty; meanwhile international community should offer maximum price for carbon in order to encourage carbon trading and forest resource conservation in the country.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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