OIL PALM AND LAND USE CHANGE IN INDONESIA, MALAYSIA AND PAPUA NEW GUINEA

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ABSTRACT

Land use change associated with the expansion of industrial scale oil palm plantations in three regions of Indonesia (Sumatra, Kalimantan, and Papua), in Malaysia, and in Papua New Guinea, was documented using Landsat images that were visually interpreted to create a region-wide map of 22 different land cover types spanning three temporal periods (1990 to 2000, 2001 to 2005 and 2006 to 2009/2010). In 1990, there were approximately 3.5 Mha of industrial oil palm plantations in the three countries, which had expanded to 13.1 Mha hectares by 2010. Growth occurred at an approximately constant rate of 7% per year over twenty years; the absolute rate of expansion was greatest in Sumatra in the first and second period (167,000 and 219,000 ha yr^{-1}), which was surpassed in Kalimantan in the last temporal period (360,197 ha yr^{-1}). When averaged over all regions and temporal periods only 4.1% (397,000 ha) of oil palm plantations originated on land derived directly from undisturbed forests (0.2% upland and 4.0% swamp), while 32.4% (3.1 Mha) were established on land previously covered with disturbed forest (25.6% upland and 6.8% swamp). Conversion of low biomass shrub lands and grasslands was documented at 17.8% (1.7 Mha) with 13.5% from upland soils and 4.4% from swamp soils; plantations and agroforest combined contributed 33.9% (3.3 Mha). A category recognized as bare soil, the result of change involving multiple different classes, including the replanting of mature oil palm plantations and the conversion of forest, represented 8.3% (0.8 Mha); miscellaneous categories including annual crops, mines, settlements, mangrove swamps, water bodies, and persistent clouds totaled 3.4% (334,000 ha).

Forest conversion to establish oil palm, including both undisturbed and disturbed forest in both upland and swamp forest habitats summed over all temporal periods was proportionally greatest in Papua (61%: 33,600 ha), Sabah (62%: 714,000 ha) and Papua New Guinea (54%: 41,700 ha), followed by Kalimantan (44%: 1.23 Mha), Sarawak (48%: 471,000 ha), Sumatra (25%: 883,000 ha) and Peninsular Malaysia (28%: 318,000 ha). In Kalimantan, the largest sources of land for new plantations were actually from shrub and grassland (48%: 1.3 Mha), while other types of plantations were more important in Sumatra (59%: 2.1 Mha) and Peninsular Malaysia (44%: 487,000 ha). In Indonesia, 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 landscape into agroforest or shrub land. In Malaysia, the direct conversion of forest to oil palm was more common, particularly in Sabah and Sarawak, but in Peninsular Malaysia the conversion of other types of land use; particularly plantation crops such as rubber, were more important.

A separate analysis using an existing data set for peat soils showed oil palm plantations on peat increased from 418,000 ha (12% of total oil palm area) in 1990 to 2.43 Mha (18%) by 2010 for the total study area. Sumatra has the largest absolute extent of oil palm plantations on peat (1.4 Mha: 29%), followed by Sarawak (476,000 ha: 46%), Kalimantan (307,515 ha: 11%), and Peninsular Malaysia (215,984 ha: 8%), with only 2% of oil palm plantations occurring on peat in Sabah (29,000 ha) and Papua (1,727 ha), while there was no conversion of peat soils in Papua New Guinea.

Key words: *Southeast Asia, land cover, land use change, deforestation, oil palm, peat, forest.*

INTRODUCTION

Land use and land cover change in palm oil producing countries is cited as one of the main drivers of deforestation, particularly in Indonesia and Malaysia which produce approximately 85% of the world's palm oil (USDA-FAS, 2010). The absolute rate of deforestation in Indonesia is considered to be among the highest on the planet, and has been estimated to fluctuate between 0.7 and 1.7 Mha yr^{-1} between 1990 and 2005 (Hansen *et al.,* 2009). Malaysia lost approximately 230,000 ha of forest habitat annually between 2000 and 2010, but since the total forest area is less, the proportional rate is actually higher when compared to Indonesia, averaging almost 1.4% of the total forest area annually in the last decade (Miettinen *et al.,* 2012a). During this period, the palm oil sector grew dramatically in both countries, expanding from less than 3.5 Mha in 1990 to more than 9.5 Mha in 2005 (Teoh, 2009), and numerous reports in both the scientific and popular media have linked the expansion of oil palm plantations with deforestation.

Originally, the issue of deforestation and oil palm focused on the negative impacts on biodiversity and traditional communities (Fitzherbert *et al.,* 2008; Marti 2008; Sheil *et al.,* 2009), but the discussion soon expanded to cover climate change as palm oil was used increasingly as a feedstock for biofuels (Germer & Sauerborn, 2008; Gibbs *et al.,* 2008). The expansion of oil palm is responsible for emissions of greenhouse gases (GHG) when new plantations replace forest habitat because the amount of carbon stored in their stems, leaves and roots is small compared with the carbon stocks of the natural forests they replace (Wicke *et al.,* 2008). In addition, the expansion of the palm oil sector is linked to the drainage and conversion of peat soils, which creates two additional sources of CO_2 emissions: A one-time emission due to soil fire and recurrent annual emissions due to soil drainage. Although currently illegal in both Malaysia and Indonesia, fire has been used historically to clear vegetation at the time of plantation establishment (Someshwar *et al.,* 2011). If the top layers of the peat are dry, these will catch fire and burn down into the soil profile until the peat is sufficiently humid to extinguish the fire. Subsequently, the upper horizons of the peat soil profile are drained to create the conditions necessary for oil palm cultivation; this changes the ecological processes of the soil biota and leads to the gradual oxidation and decomposition of the peat matrix and, as a consequence, the release of CO_2 (Agus *et al.,* 2009; Hoojer *et al.,* 2006, 2010).

Numerous recent studies have addressed deforestation in the region, but either they have not directly addressed the specific issues of oil palm plantations (Stibig & Malingreau, 2003; Miettinen *et al.,* 2012a, Hansen *et al.,* 2009, Broich *et al,.* 2011, Ekadinata & Dewi, 2011; Margono *et al.,* 2012), or have been conducted at a scale that does not allow for a comprehensive evaluation of the oil palm sector as a whole (SarVision, 2011; Carlson *et al.,* 2012a, 2012b; Miettinen *et al.,* 2012b, 2012c). Perhaps more importantly, these studies have not adequately documented the full range of land cover types that are converted to oil palm, nor evaluated land use change linked to the palm oil sector in the context of other economic activities that have similar or larger impacts on deforestation and land use (see discussion in Wicke *et al.,* 2011).

In this study, we document land cover and land use change in three palm oil producing countries (Figure 1): Indonesia, Malaysia, and Papua New Guinea between 1990 and 2010. We seek to identify patterns and trends in the development of oil palm plantations in these countries and to document the effects, extent, distribution, and rate of growth of this globally important commodity on forest landscapes and peat soils, as well as to document the conversion and use of other types of land cover as a source of new oil palm plantations.

Figure 1. Map of the study area, including Indonesia, Malaysia and Papua New Guinea.

MATERIALS AND METHODS

This study focuses on the three principal palm oil producing countries in Southeast Asia and the Pacific Region: Indonesia, Malaysia and Papua New Guinea (Figure 1). In Indonesia, only three main regions were evaluated: Sumatra, Kalimantan (the Indonesian part of the island of Borneo) and Papua (formerly Irian Jaya), which were targeted because the overwhelming majority of palm oil in Indonesia is produced in these provinces. In Malaysia, analysis included the entire country, but was stratified by region: Peninsular Malaysia, Sabah and Sarawak. The study of Papua New Guinea covered the entire country, including the island of New Britain.

This study distinguishes between mineral and peat soils, and within each of these two broad categories, we stratified land cover and land use change for both natural and human altered land cover types, including both productive and so-called degraded land. In Indonesia and Malaysia, landscapes were evaluated over three temporal periods (1990-2000, 2001-2005, and 2006-2009/2010), but in Papua New Guinea land use change was documented for two periods only (1990-2000 and 2001-2009/2010). Mixed data sets were used for 2009 and 2010 due to the scarcity of cloud-free Landsat images for 2010.

The study focused largely on large-scale oil palm plantation complexes that include both corporate and associated (schemed) smallholder plantings; we probably exclude most independent smallholders, whose oil palm plantings are mixed with other crops or trees and which lack obvious spatial patterns necessary for their identification using satellite imagery. In Indonesia, smallholdings are reported to comprise about 40% of the total area dedicated to oil palm (Jelsma *et al.,* 2009), but that value has not been validated by remote sensing studies, nor is it clear what percentage of this area is composed of schemed and independent smallholders. In this study, all oil palm plantations visually identified on the images were aggregated within the polygons.

Landsat 4, 5, and 7 satellite images were viewed using ArcGIS® software and subject to on-screen analysis and differentiation for the land cover types and land uses (Table 1). On screen analysis to directly indentify land cover types relies on the computer mouse as a tracing instrument, which differs from image analysis that classifies individual pixels using mathematical algorithms based on reflectance values of individual pixels (e.g., Hansen *et al.,* 2009; Carlson *et al.,* 2012b). Images covering Indonesia were geometrically corrected using the Forestry Thematic Base system (*Peta Dasar Thematik Kehutanan)* of the Ministry of Forestry of Indonesia (MOFRI, 2008). For Malaysia and Papua New Guinea, images were geo-referenced to previously orthorectfied Landsat images that were downloaded from NASA data distribution web sites.

We distinguished 22 different land cover types adapted from criteria used by MOFRI and the Ministry of Agriculture of Indonesia (MOARI). Land cover classes were delineated based on the classification systems used by MOFRI for Sumatra and Papua and by MOARI for Kalimantan. The MOFRI and MOARI systems use 22 and 21 classes respectively. The two classifications are similar, but MOARI recognizes rubber plantations,

which is included within the crop plantation class of the MOFRI system, while grassland and swamp grassland classes in MOARI are classified as shrub in the MOFRI classification. We harmonized the classification systems to create a slightly modified version composed of 22 classes that reflect differences in above ground carbon stocks and which recognizes a specific oil palm plantation category (Table 1). The land cover classification used by Malaysian authorities is based on a different set of criteria (Rashid *et al.,* 2013 – this publication); consequently, for the purpose of comparability and with the goal of producing a single sector-wide study, we conducted an analysis for Malaysia and Papua New Guinea using the same methodological approach and classification system applied to Indonesia with 22 different land cover types.

We used a multistage visual technique based on an on-screen interpretation to directly digitize land cover units (Figure 2). We displayed the images as false color composites using Landsat bands: 3 (0.63-0.69 µm, red), 4 (0.76-0.90 µm, near infrared) and 5 (1.55-1.75 µm, mid-infrared); the combination of the selected channels was displayed on the screen according to the scheme with bands 5-4-3 displayed as red, green and blue, respectively. To assist in the interpretation and to validate the final product, technicians compared images with high resolution images from Google Earth, when available. In addition, images were overlaid with other layers of information, such as population centers, roads and existing administrative boundaries and a previously conducted study of land cover change in Papua and Riau (Tropenbos, unpublished).

The spatial distribution and extent of peat soils was obtained from Wetlands International for Indonesia (Wahyunto & Suryadiputra, 2008) and from a Harmonized World Soil Map for Malaysia (FAO, 2009), which were used to guide the delineation of swamp forest and other wetland habitats. Nonetheless, the identification and delineation of swamp forest, swamp shrub and swamp grassland were based on multiple criteria, which included the spectral and spatial attributes of the satellite images, as well as the landscape context of the area being evaluated (Table 1). Although there is considerable overlap, swamp categories were not entirely nested within the peat polygon. Consequently, data summaries for the four swamp vegetation classes (undisturbed swamp forest, disturbed swamp forest, swamp shrub land and swamp grassland) include both mineral and peat soils; however, data summaries for peat soils were constrained by the Wetlands International peat soil map polygons.

Figure 2. Flow chart showing the steps in the land cover change analysis.

The primary objective of the study was to document land use for the palm oil sector; however, we also analyzed land cover changes among all 22 land cover classes. The primary output of the data analysis was a 22 x 22 land cover change matrix, which was subsequently used to drive the models that estimate the GHG emissions linked to land use change (see Agus *et al.,* 2013 – this publication). However, to better understand the dynamics of oil palm plantation development and facilitate communication of the results, the output of the land use change analysis was also organized according to aggregate land cover classes based on i) the degree of intervention/disturbance (natural versus productive), ii) hydrology (upland versus wetland), iii) degree of disturbance and iv) type of agriculture or forestry production (Table 2). The results were compared with land cover maps and published statistics from other studies (Hansen *et al.,* 2009; Broich *et al.,* 2011; Miettinen *et al.,* 2012a; SarVision 2011; Ekadinata & Dewi, 201; Rashid *et al.,* 2013 – this publication) as well as with statistics published by the palm oil sector and government agencies.

Table 1. Synchronized land cover classification ranked based on above ground carbon stocks.

Code	Land Cover Type	Description and Landscape Context	Attributes when spectral bands are displayed in false color composite: red (5), green (4), blue (3)
UDF	**Undisturbed Upland Forest**	Natural forest, highly diverse species and high basal area. Well drained soils, often on hilly or mountainous terrain; absence of logging roads or settlements.	Reflectance: Medium in band 4, Medium to low in bands 5 and 3 (strong green). Texture: irregular and conspicuous due to canopy heterogeneity (pixels ranging from light to dark green).
DIF	**Disturbed Upland Forest**	Same as above, but basal area reduced significantly due to logging. Evidence of logging, including roads and small clearings typical of logging platforms.	Reflectance: Similar to UDF, with greater reflectance in all bands (strong green), but brighter in comparison to UDF. Texture: strongly contrasting due to greater reflection in all bands from isolated pixels impacted by logging (yellow to green - speckled appearance).
SCH	**Upland Shrub land**	Open woody vegetation, often as part of a mosaic including forest and grassland. Well drained soils on a variety of landscapes impacted by fire and logging; previous temporal periods reveal forest (UDF) or disturbed forest (DIF).	Reflectance: High to medium in band 4, 5 and 3 (whitish, to light green to yellow). Texture; Rough and irregular with periodic dark patches (disturbed forest remnants) and light patches (grassland).
GRS	**Upland Grassland**	Open vegetation dominated by grasses (most often *Imperata*). Upland, well drained soils often in association with shrub land.	Reflectance: Very high in bands 4, 5 and 3 (light green to tan or grey). Texture: Smooth and uniform.
USF	**Undisturbed Swamp Forest**	Natural forest with temporary or permanent inundation. Associated with peat domes and meandering rivers in coastal areas; absence of logging canals.	Reflectance: Medium in band 4, 5 and medium low in band 3 (dark green). Texture: smooth to irregular dark (green to dark green).
DSF	**Disturbed Swamp Forest**	Same as USF. Evidence of logging, regular network of canals and small-scale clearings.	Reflectance: Similar to USF, but with greater reflectance in all bands (light green color). Texture: smooth due to homogeneous canopy (light green to dark green).
SSH	**Swamp Shrub land**	Open woody vegetation on poorly drained soils; less than 3-6 m in height. On landscapes impacted by fire and logging in areas subject to temporary or permanent inundation; previous temporal periods reveal swamp forest (USF) or disturbed swamp forest (DSF).	Reflectance: High in band 4 and 5, and medium low in band 3 (white, to light green to yellow). Texture: rough and irregular, with periodic dark pixels (water or fire scars) and light patches (grassland).
SGR	**Swamp Grassland**	Extensive cover of herbaceous plants with scattered shrubs or trees. Inundated floodplains or impacted peat domes. Comparison with previous temporal periods revealed forest habitat.	Reflectance: Very high in bands 4, 5 and 3 (tan or grey to dark brownish pink). Texture: Smooth and uniform
TPL	**Timber Plantation**	Large industrial estates planted to timber or pulp species (e.g. *Gmelina* sp., *Paraserianthes falcataria, Acacia mangium*); canopy cover is around 30-50%. Regular geometry, typically in patches greater than 100 hectares; in association with road network and settlements located within forest area.	Reflectance: Medium to high in bands 4, 5 and 3, but with greater variance in reflectance in all bands (purple green color). Texture: smooth due to homogeneous canopy (light green to dark green).

Table 1. Synchronized land cover classification (continued).

Code	Land Cover Type	Description and Landscape Context	Attributes when spectral bands are displayed in false color composite: red (5), green (4), blue (3)
MTC	**Mixed Tree Crops / Agroforest**	Mosaic of cultivated and fallow land, usually located within 0.5-1 km of settlement or road; canopy cover between 5 and 60%; assumed to be small-scale plantings of a range of commercial species. Irregular geometry associated with primary and secondary road networks; comparison with past temporal periods revealed similar pattern on same or nearby landscapes.	Reflectance: Medium to high in bands 4, 5 and 3 (light green to yellow green). Texture: Smooth with periodic dark patches (forest remnants) and light patches (crops/settlements).
RPL	**Rubber Plantation**	Well drained landscapes of variable topography with large to medium sized industrial estates planted to rubber (*Hevea brasiliensis*). Regular geometry, typically in patches greater than 100 hectares; in association with road network.	Reflectance: Moderate to high reflectance in band 4, 5 and 6 (light green to green). Texture: smooth due to very homogeneous canopy of monoculture.
OPL	**Oil Palm Plantation**	Large industrial estates planted to oil palm; canopy cover variable depending on age. Regular geometry characterized by discernible rows and internal plantation road network, typically in patches greater than 1000 hectares.	Reflectance: Medium to high band 4, 5 and 3 (light green to green). Texture: smooth due to homogenous canopy indicating monoculture.
BRL	**Bare Soil**	Bare rock, gravel, sand, silt, clay, or other exposed soil. Often includes recently cleared (deforested) areas, landscapes impacted by fire and portions of estates undergoing replanting procedures.	Reflectance: High in band 4, medium to low in bands 3 and 5 (tan to brown to red). Texture: smooth.
DCL	**Dry Cultivated Land**	Open area characterized by herbaceous vegetation intensively managed for row crops or pasture. Associated with road networks and human settlements.	Reflectance: High in bands 4, 5 and 3 (bright to dark tans and browns, with blue and pink spots). Texture: smooth and uniform, but with dark patches depending on crop cycle.
RCF	**Rice Field**	Open area characterized by herbaceous vegetation (rice paddy), with seasonal or permanent inundation. Reticular patterns of dikes and canals, usually in association with settlements.	Reflectance: Low in band 4, very low in bands 5 and 3 (high absorbance from water – depending on season; (blue to blackish color). Texture: smooth and uniform pattern.
SET	**Settlements**	Villages, urban areas, harbors, airports, industrial areas, open mining; typically associated with road network.	Reflectance: High to very high in bands 4, 5 and 3 (light red to straw colored). Texture: rough due to heterogeneity from buildings, exposed soil, and home gardens.
MIN	**Mining**	Open area with surface mining activities. Irregular, in association with settlements or industrial facilities.	Reflectance: High in bands 3, 4 and 5. (white to light blue). Texture: smooth.
UDM	**Undisturbed Mangrove**	Forest habitat near coast with high density of mangrove tree species in irregular patterns. Featuring temporary or permanent inundation in coastal and estuarine areas.	Reflectance: Low in bands 4, 5 and 3 (dark green). Texture: smooth due to homogenous canopy, but usually in association with water (purple green to dark green).

Table 1. Synchronized land cover classification (continued).

Code	Land Cover Type	Description and Landscape Context	Attributes when spectral bands are displayed in false color composite: red (5), green (4), blue (3)
DIM	**Disturbed Mangrove**	Same as UDM. Evidence of clearing and often in association with coastal fish ponds (CFP, see below).	Reflectance: Similar to UDM, but with greater variance in reflectance in all bands (purple green color). Texture: smooth due to homogeneous canopy (light green to dark green).
CFP	**Coastal Fish Pond**	Permanently flooded open areas. Reticular patterns in coastal areas; comparison with previous temporal periods often showed as DMF or UMF	Reflectance: Very low in all bands (black, dark blue or dark brown). Texture: smooth.
WAB	**Water bodies**	Rivers, streams and lakes. Identified in satellite images by high absorbance in all spectral bands; featuring temporary or permanent inundation, as evidenced in band 4.	Reflectance: Very low in all bands (dark blue to black). Texture: smooth.
NCL	**Not Classified; Cloud**	Not classified due to cloud cover.	Reflectance: Very high in all bands Texture: irregular to smooth.

Table 2. Aggregate land cover classes used to facilitate the communication of results.

Superior Class	Aggregate Class	Land Cover Types Codes
Upland habitats	Undisturbed upland forest	UDF
	Disturbed upland forest	DIF
	Upland shrub and grassland	SCH + GRS
Swamp habitats	Undisturbed swamp forest	USF
	Disturbed swamp forest	DSF
	Swamp shrub and grassland	SSH + SGR
Productive land use types	Agroforest, rubber and timber plantations	MTC + CPL +TPL
	Oil palm	OPL
	Intensive Agriculture	DCL +RCF
	Bare soil	BRL
Others	Others	SET + MIN + NCL +CFP + UDM+DIM+WAB

RESULTS

The multi-temporal analysis spanning from 1990 to 2010 documents the expansion of industrial scale oil palm plantations in Indonesia (Sumatra, Kalimantan and Papua), Malaysia and Papua New Guinea (Figures 3 and 4). Oil palm plantations in these regions grew from 3.5 Mha in 1990 to 13.1 Mha in 2010 (Table 3). The historical trend in oil palm plantation development in the region has stayed remarkably steady at around 7% annual growth rate over twenty years (Table 4).

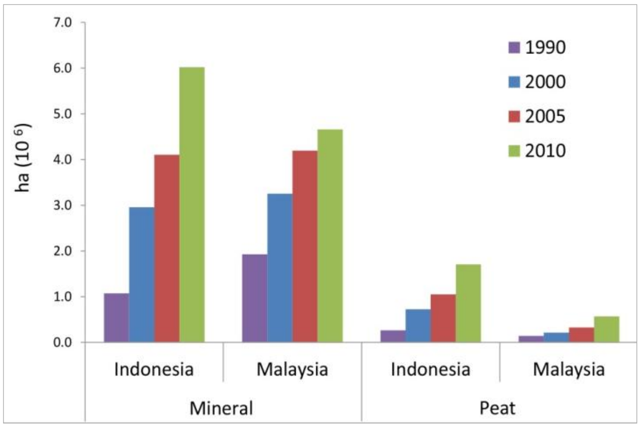

Figure 3. Oil palm plantation development on mineral soil and peat soil between 1990 and 2010 in Indonesia (Sumatra, Kalimantan and Papua), Malaysia and Papua New Guinea.

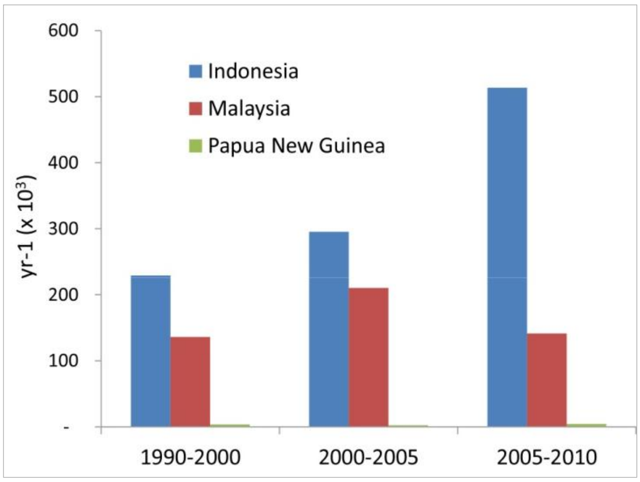

Figure 4. Annual growth in oil palm plantations in the major oil palm regions of Indonesia (Sumatra, Kalimantan and Papua), Malaysia and Papua New Guinea.

Table 3. Area (10^3 ha) of oil palm plantations in Indonesia, Malaysia, and Papua New Guinea 1990-2010.

Country	1990	2000	2005	2010
Indonesia	1,337	3,678	5,155	7,724
Malaysia	2,118	3,467	4,521	5,230
Papua New Guinea	57	91	103	134
Total	3,511	7,236	9,780	13,087

In the Indonesia study areas, the extent of oil palm plantations reached 7.7 Mha by 2010, of which 78% was found on mineral soils and 22% occurred on peat soils. In Malaysia, the total extent of oil palm plantations reached 5.4 Mha by 2010, where 87% occurred on mineral soil and 13% on peat soils (Figure 3). In Papua New Guinea, oil palm plantations reached 134,000 ha, all of which occurred on mineral soils.

Oil palm plantation development in Indonesia is mainly located in two regions: Sumatra and Kalimantan. In 2010, the total palm oil plantation area in Sumatra accounted for 4.7 Mha, while in Kalimantan the total oil palm plantation area accounted for 2.9 Mha. The expansion of oil palm plantations in Indonesia showed robust growth throughout all three temporal periods, while in Malaysia expansion was more moderate and showed a marked reduction in the rate of growth in the last temporal period (Figure 4).

Over the twenty year period between 1990 and 2010, approximately 36.5% of all oil palm plantations came from forest landscapes, including both upland and swamp habitats; nonetheless, only a small fraction of that conversion occurred on undisturbed forest landscapes (Table 5). Only 0.1% of oil palm plantations were sourced from undisturbed upland forest, while undisturbed swamp forest contributed 4.0% between 1990 and 2010. Development in Indonesia tended to follow a period of forest degradation, as evidenced by the large area of shrub land, grassland and agroforest habitats that were converted to oil palm plantations (Table 5). In contrast, conversion tended to be more direct in Malaysia with the conversion of disturbed forest for oil palm plantations, without large areas passing through a transitional stage of shrub land or agroforest that had been created in previous temporal periods via the degradation of forest landscapes.

Table 4. Mean annual growth rates of oil palm plantations for each country and sub-national unit; the values for the first temporal period are based on the mean of ten points generated by simple linear regression models, while the last two epochs are the mathematical average of the total change for the five year period.

	1990 - 2000 mean annual growth rate		2001 - 2005 mean annual growth rate		2006 - 2010 mean annual growth rate	
	10^3 ha yr^{-1}	%	10^3 ha yr^{-1}	%	10^3 ha yr^{-1}	%
Indonesia	229	10.5	295	8.0	514	10.0
Sumatra	*167*	*9.0*	*219*	*9.0*	*151*	*3.8*
Kalimantan	*65*	*21.5*	*72*	*9.7*	*360*	*32.9*
Papua	*1.9*	*5.1*	*4.3*	*9.0*	*2.9*	*4.3*
Malaysia	135	6.4	211	6.1	142	3.1
Peninsular	*44*	*2.6*	*72*	*3.4*	*36*	*1.5*
Sabah	*64*	*9.7*	*73*	*7.4*	*30*	*2.2*
Sarawak	*27*	*16.5*	*66*	*19.9*	*75*	*11.4*
Papua New Guinea	3.4	6.1	2.4	2.7	4.3	4.7
Total	**373**	**7.0**	**509**	**7.0**	**662**	**6.8**

Table 5. Prior land use of all new plantations established between 1990 and 2010.

Aggregate Class	Indonesia 1990 - 2010		Malaysia 1990 - 2010		Papua New Guinea 1990 - 2010		Total 1990 - 2010	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest	13	0.2			4.6	6.0	18	0.2
Disturbed Upland Forest	1,207	18.9	1,239	38.1	37	46.0	2,483	25.6
Upland Shrub & Grasslands	1,268	19.9	15	0.5	28	34.8	1,311	13.5
Undisturbed Swamp Forest	384	6.0	0.5	0.0			384	4.0
Disturbed Swamp Forest	539	8.4	126	3.9	0.2	0.2	665	6.9
Swamp Shrub & Grasslands	411	6.4	4.9	0.2	6.6	8.3	423	4.4
Agroforest & Plantation	2,176	34.1	1,119	34.4			3,295	34.2
Intensive Agriculture	212	3.3	8.5	0.3	3.9	5.2	224	2.3
Bare Soil	74	1.2	731	22.5			806	8.3
Others	102	1.6	7.3	0.3			108	1.1
Total new plantations	**6,387**		**3,252**		**80**		**9,718**	

Indonesia

Land covered with oil palm plantations in the three largest oil palm growing regions in Indonesia (Sumatra, Kalimantan, Papua) reached a total area of 7.7 Mha in 2010 (Figure 5). A relatively small area of oil palm plantations is found on the islands of Java and Sulawesi, but these were not documented by this study. Oil palm plantations have expanded consistently over the last 20 year period, fluctuating from 10.5% of annual growth in the first temporal period, declining slightly to 8% between 2001 and 2010, and then returning to 10% annual growth in the last five year period. In Kalimantan, growth in new plantations reached 33% annually between 2006 and 2010, but this growth was accompanied by a decline in the rate of expansion in Sumatra from 9% to 3.8%. Growth of the sector in Papua was relatively slow throughout the entire study period.

Although land cover change linked to oil palm was documented from 1990 to 2010, changes that involved other land cover types were evaluated only between 2001 and 2010 (Table 6 and 7). Between 2001 and 2005, the conversion of agroforest and plantations was important, which coincided with an era of expansion in Sumatra, a region that is characterized by greater levels of human disturbance and past land use change. Between 2006 and 2010, however, the growing importance of Kalimantan as an expansion zone led to an increase in the conversion of natural habitat types, including mostly disturbed forests, but also large areas of shrub and grassland habitats (Table 7). Low to moderate biomass land cover types, including shrub land in Kalimantan and agroforest in Sumatra, represent important transitional categories between disturbed, albeit intact, forests and productive land use types dedicated to agriculture or plantation estates. Overall, the total area for these transitional land use types do not change greatly between temporal periods, because the increase in area due to forest loss was offset by the conversion of these land cover types to oil palm or other forms of agriculture (see below and in Supplementary Material).

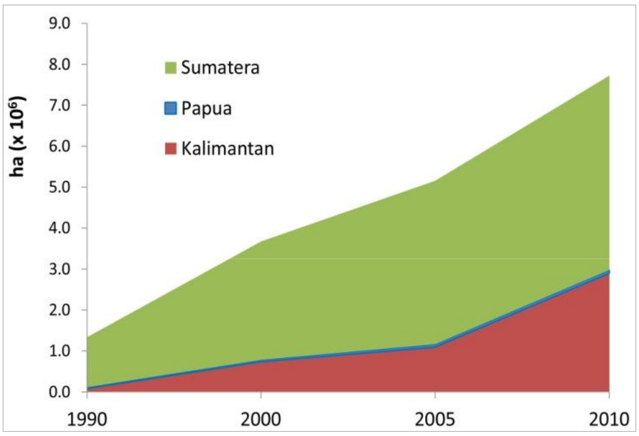

Figure 5. The expansion of oil palm plantations between 1990 and 2010 in the three major oil palm regions of Indonesia (Sumatra, Kalimantan and Papua).

Table 6. Land cover (10^3 hectares) in 2000, 2005, and 2010 in Sumatra, Kalimantan and Papua regions of Indonesia.

Aggregate classes	2000	2005	2010
Undisturbed Upland Forest	42,792	40,485	38,063
Disturbed Upland Forest	23,233	24,336	24,500
Upland Shrub and Grassland	17,399	16,141	15,927
Undisturbed Swamp Forest	10,160	9,791	9,014
Disturbed Swamp Forest	6,267	5,627	5,140
Swamp Shrub and Grassland	7,413	7,372	7,595
Agroforest and Plantation	15,053	14,421	13,762
Oil Palm Plantations	3,678	5,155	7,724
Intensive Agriculture	7,736	9,460	11,316
Bare soil	2,192	2,041	1,996
Others	6,862	7,955	7,749
Total	**142,785**	**142,785**	**142,785**

Table 7. Prior land use of all new oil palm plantations established in the three main oil palm regions of Indonesia (Sumatra, Kalimantan and Papua) between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 -2005		2005 -2010		1990 - 2100	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest	1.3	0.1	2.6	0.2	8.7	0.3	13	0.2
Disturbed Upland Forest	475	20.3	88	6.0	644	25.1	1,207	18.9
Upland Shrub & Grasslands	370	15.8	217	14.7	681	26.5	1,268	19.9
Undisturbed Swamp Forest	374	16.0	0.4	0.0	9.5	0.4	384	6.0
Disturbed Swamp Forest	174	7.4	78	5.3	288	11.2	539	8.4
Swamp Shrub & Grasslands	60	2.6	32	2.2	319	12.4	411	6.4
Agroforest & Plantation	824	35.2	977	66.2	375	14.6	2,176	34.1
Intensive Agriculture	17	0.7	56	3.8	139	5.4	212	3.3
Bare Soil	6.1	0.3	21	1.4	48	1.9	74	1.2
Others	40	1.7	5	0.1	57	2.2	102	1.5
Total New Plantations	**2,341**		**1,477**		**2,569**		**6,387**	

Sumatra

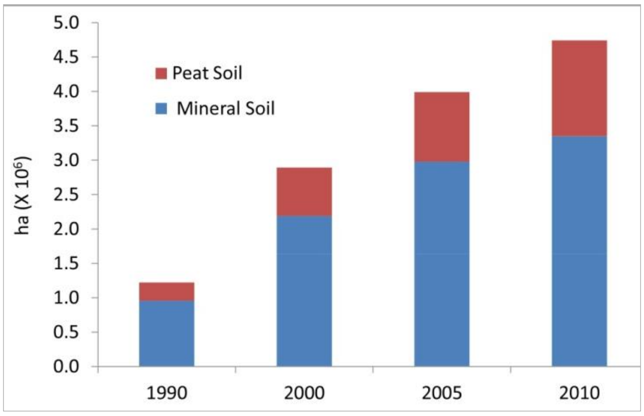

Figure 7. The area planted to oil palm in1990, 2000, 2005 and 2010 on mineral and peat soil in Sumatra.

Sumatra has the oldest and most mature oil palm plantations in Indonesia, which reached a total of 4.7 Mha by 2010, representing 10% of its total land area (Table 8). About 3.4 Mha have been established on mineral soils occupying about 8% of the existing mineral soil land bank, while 1.4 Mha occur on peat soils representing 19.4% of the total peat soil area (Figures 6 and 7). Between 2001 and 2005, oil palm plantation development overwhelmingly occurred due to the conversion of agroforest and rubber plantations, but in the more recent period, the sources of land for development were more diverse. Although the conversion of agroforest and rubber plantations remained the largest source of land for development, more than 866,000 ha of disturbed and undisturbed swamp forest, as well as open swamp habitat (i.e., highly degraded swamp forest) were converted to oil palm plantations (Table 9). In Sumatra, the category bare soil was used largely by GIS technicians for grouping permanently bare soils and did not impact the land use change statistics related to oil palm plantations (see Supplementary Material).

Table 8. Land cover area (10^3 ha) in 2000, 2005, and 2010 in Sumatra.

Aggregate Class	2000	2005	2010
Undisturbed Upland Forest	5,753	5,749	5,321
Disturbed Upland Forest	5,904	5,757	5,686
Upland Shrub and Grassland	4,821	3,403	3,623
Undisturbed Swamp Forest	550	543	467
Disturbed Swamp Forest	3,109	2,519	2,073
Swamp Shrub and Grassland	3,014	2,798	2,681
Agroforest and Plantation	13,432	12,679	12,012
Oil Palm Plantations	2,893	3,990	4,743
Intensive Agriculture	4,554	5,658	6,700
Bare soil	1,364	1,177	1,194
Others	2,396	3,518	3,291
Total	**47,791**	**47,791**	**47,791**

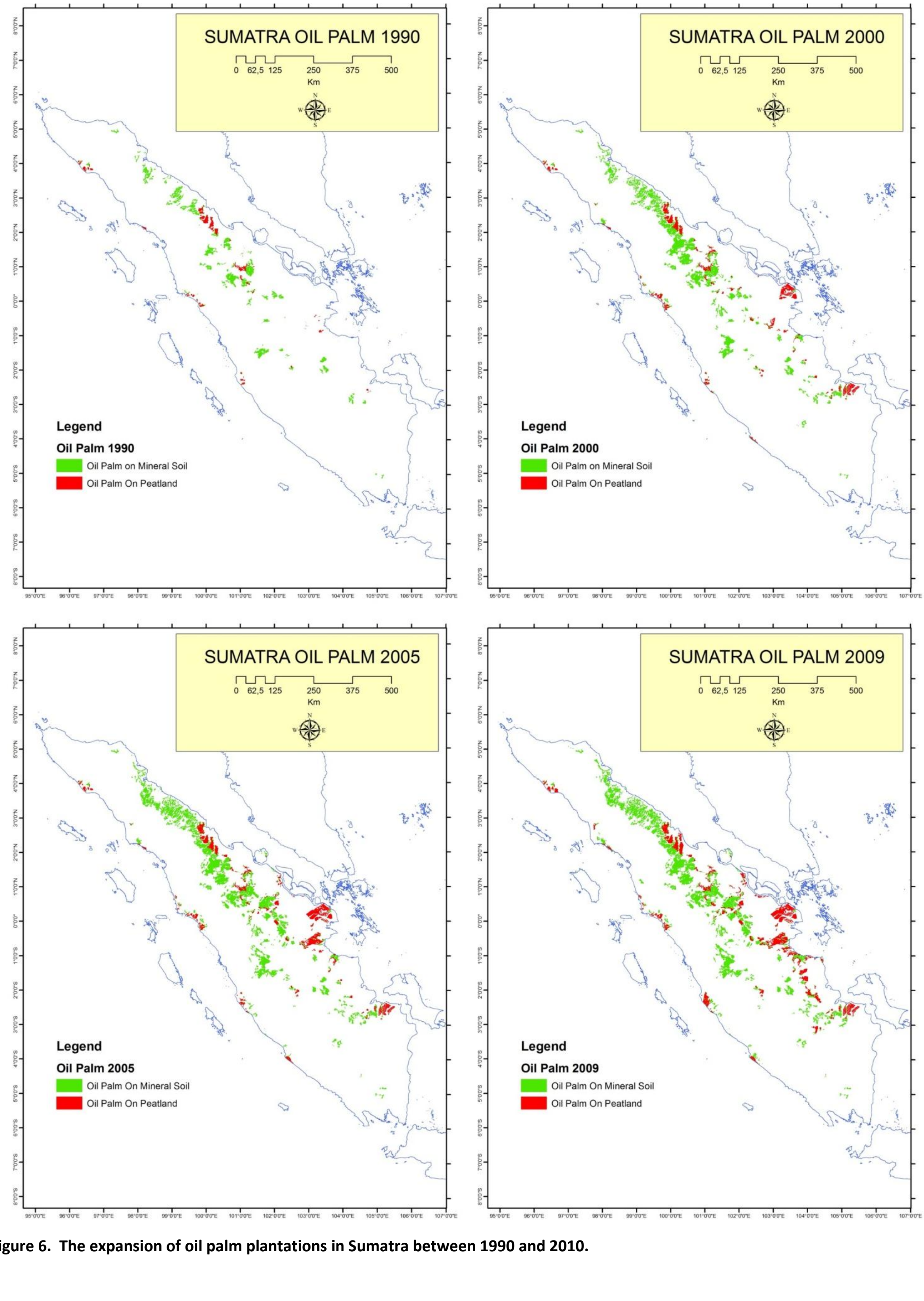

Figure 6. The expansion of oil palm plantations in Sumatra between 1990 and 2010.

Table 9. Prior land use of all new oil palm plantations established in Sumatra between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 -2005		2005 -2010		1990 - 2010	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest								
Disturbed Upland Forest	170	10.2	11	1.0	28	3.7	209	5.9
Upland Shrub & Grasslands	115	6.9	24	2.2	6	0.8	145	4.1
Undisturbed Swamp Forest	364	21.8	0.3	0.0	7	0.9	370	10.5
Disturbed Swamp Forest	142	8.5	53	4.8	108	14.4	303	8.6
Swamp Shrub & Grasslands	56	3.4	11	1.0	126	16.7	192	5.5
Agroforest & Plantation	813	48.7	936	85.3	321	42.6	2,070	58.8
Intensive Agriculture	6.1	0	37	3.3	54	7.1	95	2.7
Bare Soil	4.8	0.3	21	1.9	47	6.2	74	2.1
Others			4.6	0.4	57	8.0	62	1.8
Total New Plantations	**1,671**		**1,097**		**753**		**3,521**	

Kalimantan

Kalimantan has the second largest extent of oil palm plantations in Indonesia, most of which are concentrated in West Kalimantan, followed by Central Kalimantan, East Kalimantan, and South Kalimantan. The total areas dedicated to commercial oil palm plantations reached 2.9 Mha by 2010, or 5.4% of the total area of Kalimantan (Table 10); of these about 2.6 Mha were on mineral soils and 308,000 ha were on peat soils (Figure 8 and Figure 9). Undisturbed forests suffered progressive declines over both temporal periods, which corresponded to an increase in disturbed forest on both upland and swamp forest landscapes. The most notable categories of land cover, when compared to Sumatra and other regions, were shrub lands and grasslands that fluctuated slightly between 2000, 2005 and 2010 (Table 10). This was not a static land cover class, however, as large areas were converted to oil palm and other forms of agriculture, while an approximately equivalent area of forest was degraded by the non sustainable use of forest landscapes (Figure 10).

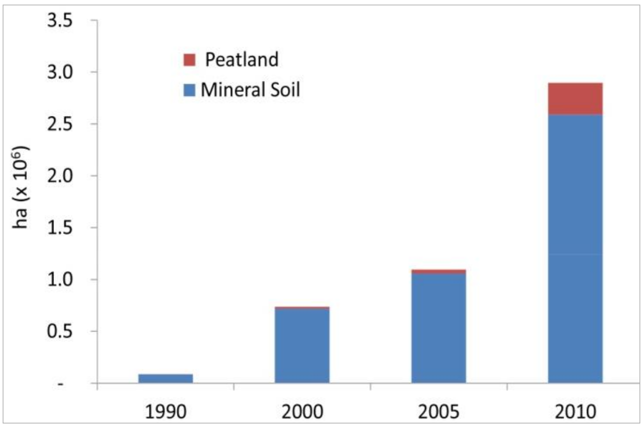

Figure 8. The area planted to oil palm in 1990, 2000, 2005 and 2010 on mineral and peat soil in Kalimantan.

Table 10. Land cover area (10^3 ha) in 2000, 2005, and 2010 in Kalimantan.

Aggregate Class	2000	2005	2010
Undisturbed Upland Forest	13,918	12,885	11,765
Disturbed Upland Forest	14,598	14,817	14,295
Upland Shrub and Grassland	10,967	11,043	10,551
Undisturbed Swamp Forest	2,677	2,690	2,306
Disturbed Swamp Forest	2,734	2,456	2,172
Swamp Shrub and Grassland	3,131	3,173	3,282
Agroforest and Plantation	1,359	1,497	1,492
Oil Palm Plantations	737	1,096	2,897
Intensive Agriculture	2,449	2,878	3,639
Bare soil	-	-	-
Others	1,171	1,208	1,342
Total	53,742	53,742	53,742

Approximately 48% of all oil palm plantations originated from the conversion of shrub or grassland habitats (40% upland and 8% swamp), which were followed closely by the direct conversion of forest habitat, representing about 44% of all new plantations (Table 11). The conversion of peat soils for oil palm increased over time, covering approximately 821 ha in 1990 (1% of all oil palm plantations) to more than 307,500 ha (11%) by 2010 (Figure 8). Similar to the trend observed in upland habitats in Kalimantan, the conversion of peat soils was also the consequence of a trajectory of land use characterized by the sequential degradation of undisturbed forest to disturbed forest to open swamp habitat prior to its conversion to oil palm (Figure 10). The category bare soil was not used by the GIS technicians for Kalimantan and has no impact on the summary calculations for land use.

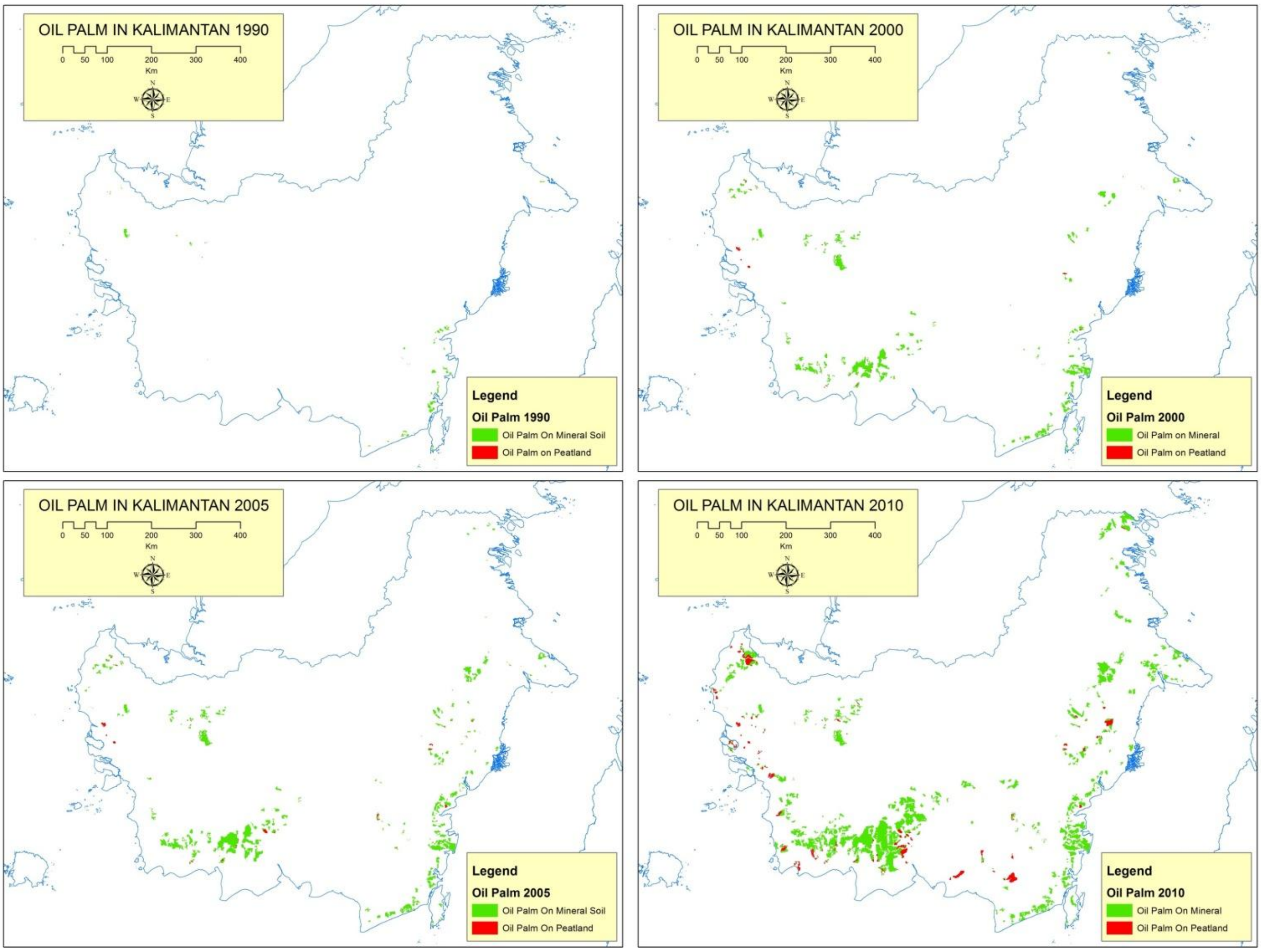

Figure 9. The expansion of oil palm plantations in Kalimantan between 1990 and 2010.

Table 11. Prior land use of all new oil palm plantations established in Kalimantan between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 -2005		2005 -2010		1990 - 2010	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest	1.3	0.2	1.1	0.3			2.4	0.1
Disturbed Upland Forest	298	45.8	74	20.7	614	34	986	35.1
Upland Shrub & Grasslands	254	39.0	192	53.4	675	38	1,122	39.9
Undisturbed Swamp Forest					2.4	0.1	2.4	0.1
Disturbed Swamp Forest	32	4.9	25	6.9	179	10.0	236	8.4
Swamp Shrub & Grasslands	4.2	0.6	21	5.9	193	10.7	219	7.8
Agroforest & Plantation	9.2	1.4	27	7.4	52	2.9	88	3.1
Intensive Agriculture	12	1.9	19	5.4	85	4.7	116	4.1
Bare Soil								
Others	40	6.2		0.0			40	1.4
Total New Plantations	**652**		**359**		**1,801**		**2,811**	

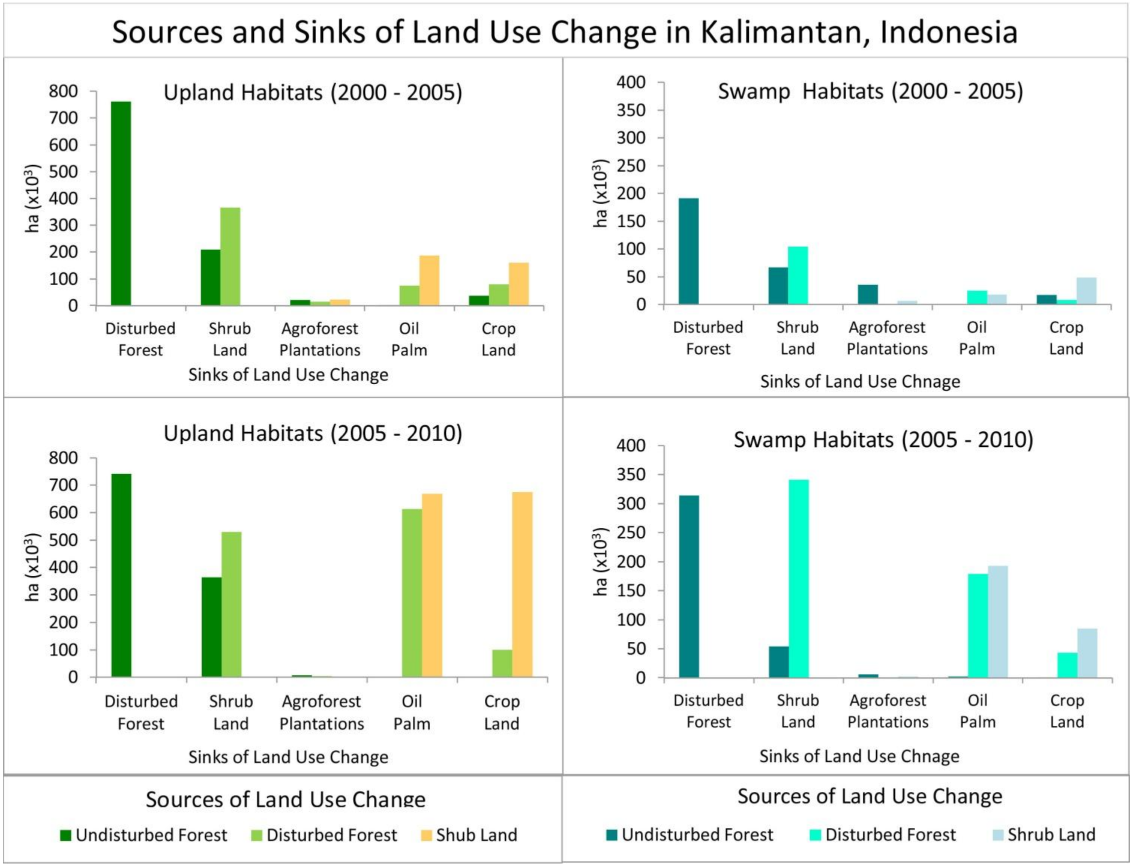

Figure 10. The conversion of forest in Kalimantan is a step-wise process where undisturbed forest is impacted by logging, which is sometimes followed by wildfire that further degrades areas into shrub land. The establishment of plantations or crops is largely the consequence of the conversion of disturbed forest or shrub land; this trajectory of degradation prior to conversion occurs on both upland and swamp habitats.

Papua (West Papua and Papua Provinces)

Total oil palm plantations in Papua reached 83,600 ha by 2010, with only about 1,700 ha located on peat soils (Figure 11 and 12). Unlike Sumatra and Kalimantan, the expansion of oil palm in Papua remains limited and more than 79% of the island remains covered by intact forest ecosystems (Table 12). Nevertheless, between 2000 and 2010, undisturbed upland forest in Papua declined by 2.1 Mha, while the extent of undisturbed swamp forest declined by about 690,000 ha (Table 12). Since the absolute numbers linked to the expansion of oil palm plantations are relatively small in any one temporal period, the relative contributions of the different land cover types to that expansion vary greatly (Table 13). When summed over the total twenty year period, the largest single source of new plantations was the aggregate category agroforest and other plantations; nonetheless, when the various forest categories are combined they sum to approximately 61% (Table 13).

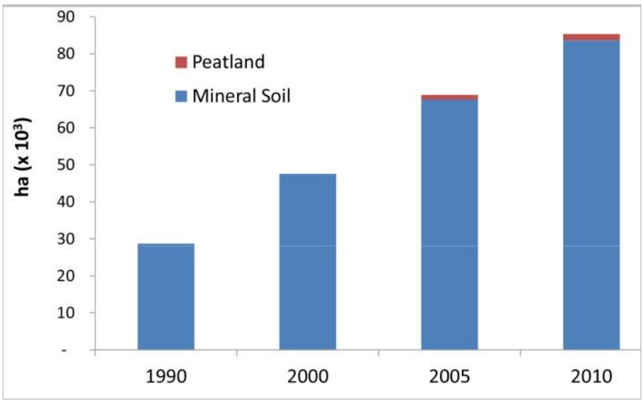

Figure 11. The area planted to oil palm in 1990, 2000, 2005 and 2010 on mineral and peat soil in Papua.

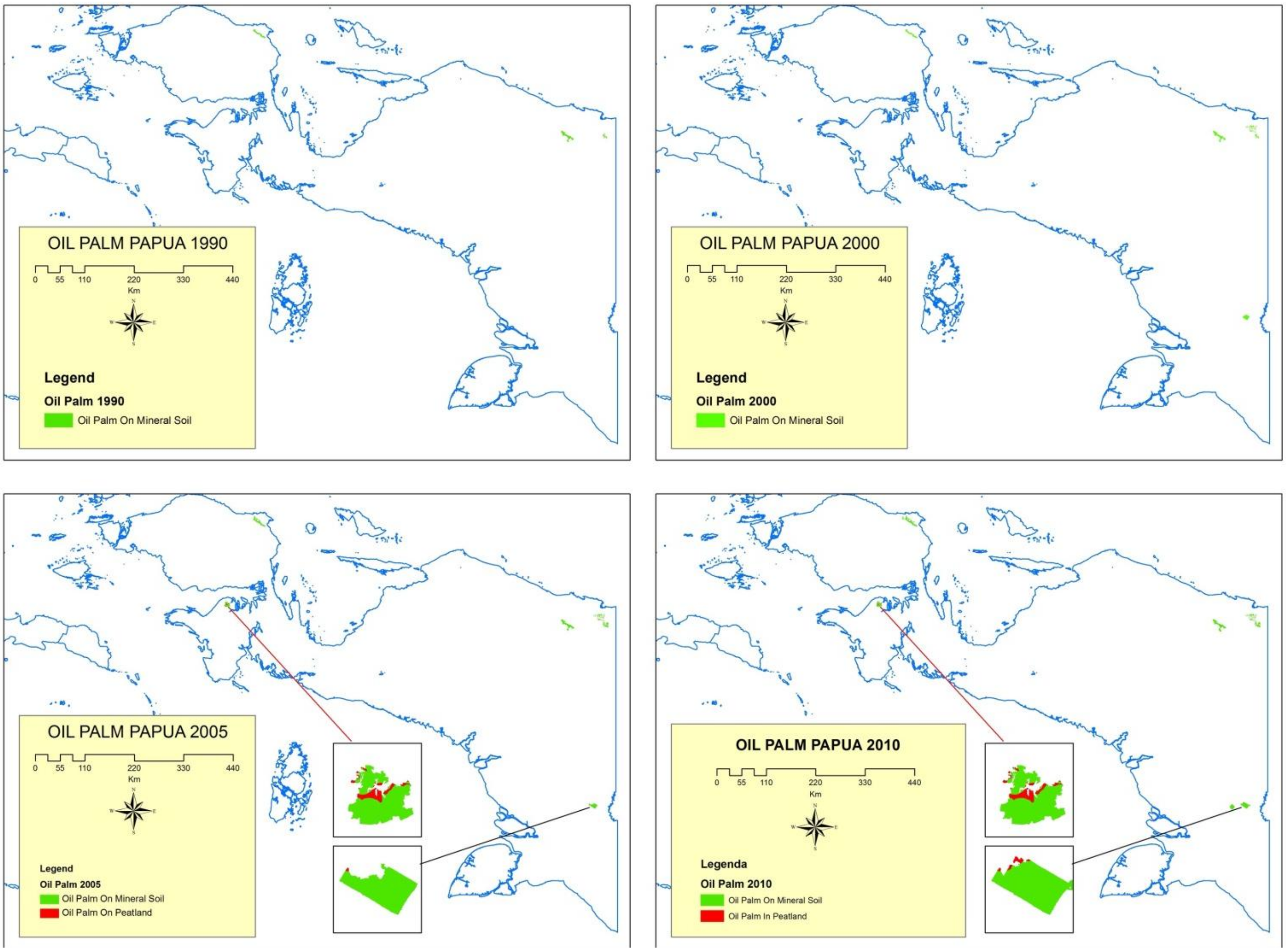

Figure 12. The expansion of oil palm plantations in Papua between 1990 and 2010.

Table 13. Prior land use of all new oil palm plantations in Papua between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 - 2005		2006 - 2010		1990 - 2010	
	ha	%	ha	%	ha	%	ha	%
Undisturbed Upland Forest	-		1,545	7.2	8,738	59.4	10,283	18.7
Disturbed Upland Forest	7,136	37.9	2,936	13.8	2,288	16	12,361	22.5
Upland Shrub & Grasslands	-		1,131	5.3	125	1	1,256	2.3
Undisturbed Swamp Forest	10,178	54.1	67	0.3	481	3	10,726	19.5
Disturbed Swamp Forest	-		53	0.2	137	0.9	191	0.3
Swamp Shrub & Grasslands	-		-		258	1.8	258	0.5
Agroforest & Plantation	1,505	8	14,876	69.7	2,064	14.0	18,446	33.6
Intensive Agriculture	-							
Bare Soil	-		156	0.7	621	4.2	778	1.4
Others	-		585	2.7	-	-	585	1.1
Total New Plantations	**18,820**		**21,350**		**14,713**		**54,883**	

Table 12. Land cover area (hectares) in 2000, 2005, and 2010 in Papua.

Aggregate Class	2000	2005	2010
Undisturbed Upland Forest	23,121	21,851	20,977
Disturbed Upland Forest	2,731	3,763	4,518
Upland Shrub and Grassland	1,611	1,695	1,753
Undisturbed Swamp Forest	6,932	6,557	6,241
Disturbed Swamp Forest	425	652	895
Swamp Shrub and Grassland	1,267	1,402	1,632
Agroforest and Plantation	262	245	257
Oil Palm Plantations	48	69	84
Intensive Agriculture	733	925	976
Bare soil	827	865	803
Others	3,295	3,230	3,116
Total	**41,252**	**41,252**	**41,252**

Malaysia

Malaysia has the second largest extent of oil palm plantations in the world, which in 2010 covered approximately 5.2 Mha or 16% of the total land area of the country, up from 6.4 % in 1990 (Table 14 and Figure 13). The rate of growth of new oil palm plantations has been decreasing over the past twenty years; it reached a high of 6.4% (134,926 ha) in the first period, but declined slightly to 6.1 % (210,261 ha) between 2001 and 2005 and then dropped to 3.1% (141,326 ha) annual growth in the last five year period (Table 15). Expansion during the first period was largely the result of the conversion of disturbed upland forest, followed by agroforest and plantations (Table 15), but during the second temporal period (2001-2005) the conversion of disturbed upland forest decreased markedly. In the last temporal period (2006-2010) the largest single source of young plantations was bare soil, which includes large areas of recently cleared forest in Sarawak and Sabah, as well as the conversion of rubber plantations and the renovation of older oil palm plantations in Peninsular Malaysia (see Supplementary Materials). To better understand the dynamics of the growth in oil palm development in Malaysia, we analyzed separately the expansion of oil palm plantations in the three geographical regions: Peninsular Malaysia, the state of Sabah, and the state of Sarawak.

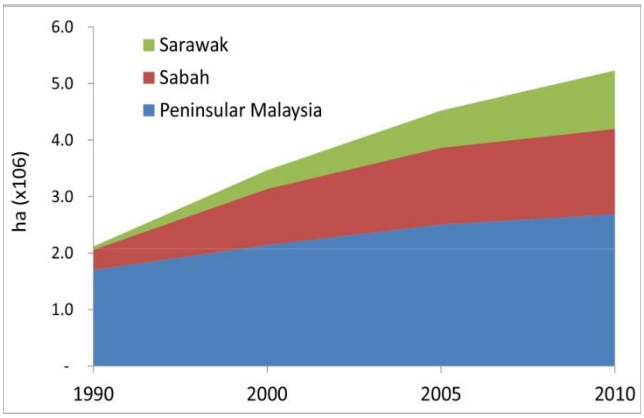

Figure 13. The expansion of oil palm plantations between 1990 and 2010 in Malaysia.

Table 14. Land cover area (10^3 ha) in Malaysia (Peninsular, Sarawak, Sabah) in 2000, 2005, and 2010.

Aggregate Class	2000	2005	2010
Undisturbed Upland Forest	3,710	3,153	3,150
Disturbed Upland Forest	16,901	16,875	16,340
Upland Shrub and Grassland	104	144	142
Undisturbed Swamp Forest	189	18	7
Disturbed Swamp Forest	928	904	746
Swamp Shrub and Grassland	44	46	51
Agroforest and Plantation	4,800	4,592	4,175
Oil Palm Plantations	3,467	4,521	5,230
Intensive Agriculture	684	681	682
Bare soil	624	527	937
Others	1,632	1,622	1,624
Total	**33,084**	**33,084**	**33,084**

Table 15. Prior land use of all new oil palm plantations established in all regions of Malaysia (Peninsular, Sarawak, Sabah) between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 - 2005		2006 - 2010		1990 - 2010	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest			0.2	0.0			0.2	0.0
Disturbed Upland Forest	744	53.3	289	26	207	27.5	1,239	38.1
Upland Shrub & Grasslands	2.6	0.0	7.2	0.7	5.5	0.7	15	0.5
Undisturbed Swamp Forest	0.5	0.0					0.5	0.0
Disturbed Swamp Forest	36	2.6	46	4.2	43	5.8	126	3.9
Swamp Shrub & Grasslands	2.9	0.2	1.3	0.1	0.7	0.1	5.0	0.2
Agroforest & Plantation	511	37	380	34.3	228	30.4	1,119	34.4
Intensive Agriculture			8.4	0.8	0.1	0.0	8.5	0.3
Bare Soil	94	6.7	371	33.5	266	35.4	731	22.5
Others	3.9	0.3	3.2	0.3	0.1	0.0	7.0	0.2
Total New Plantations	**1,394**		**1,106**		**751**		**3,252**	

Peninsular Malaysia

The oldest oil palm plantations established in the country are located in Peninsular Malaysia with about 1.7 Mha existing in 1990, which by 2010 had increased to approximately 2.7 Mha, representing about 20% of the total area of the peninsula (Figure 14 and Table 16). There has been no direct conversion of undisturbed forest on the peninsula throughout the twenty year period, but the conversion of disturbed forest represented more than 38% of all new plantations in the first temporal period, but this then declined in the next two temporal periods (Table 17). The largest source of young oil palm plantations in all three temporal periods was from the conversion of agroforest and plantations. An evaluation of the bare soil category in the change matrix showed that a variable amalgam of different land types, including forest, rubber and oil palm plantations, were converted into this transitional category, prior to being replanted as oil palm plantations. The percentage of oil palm plantations on peat soils stayed relatively constant throughout, expanding proportionally with the sector, constituting about 8.1% of all oil palm plantations in 1990 and 7.9% in 2010 (Figure 15). If the forest conversion statistics are modified to reflect the proportion of bare soils that originated from forest habitats and that were allocated to oil palm plantations over the entire 20 year period, then approximately 28% of all plantations or 318,000 ha have originated due to forest conversion (see Supplementary Material).

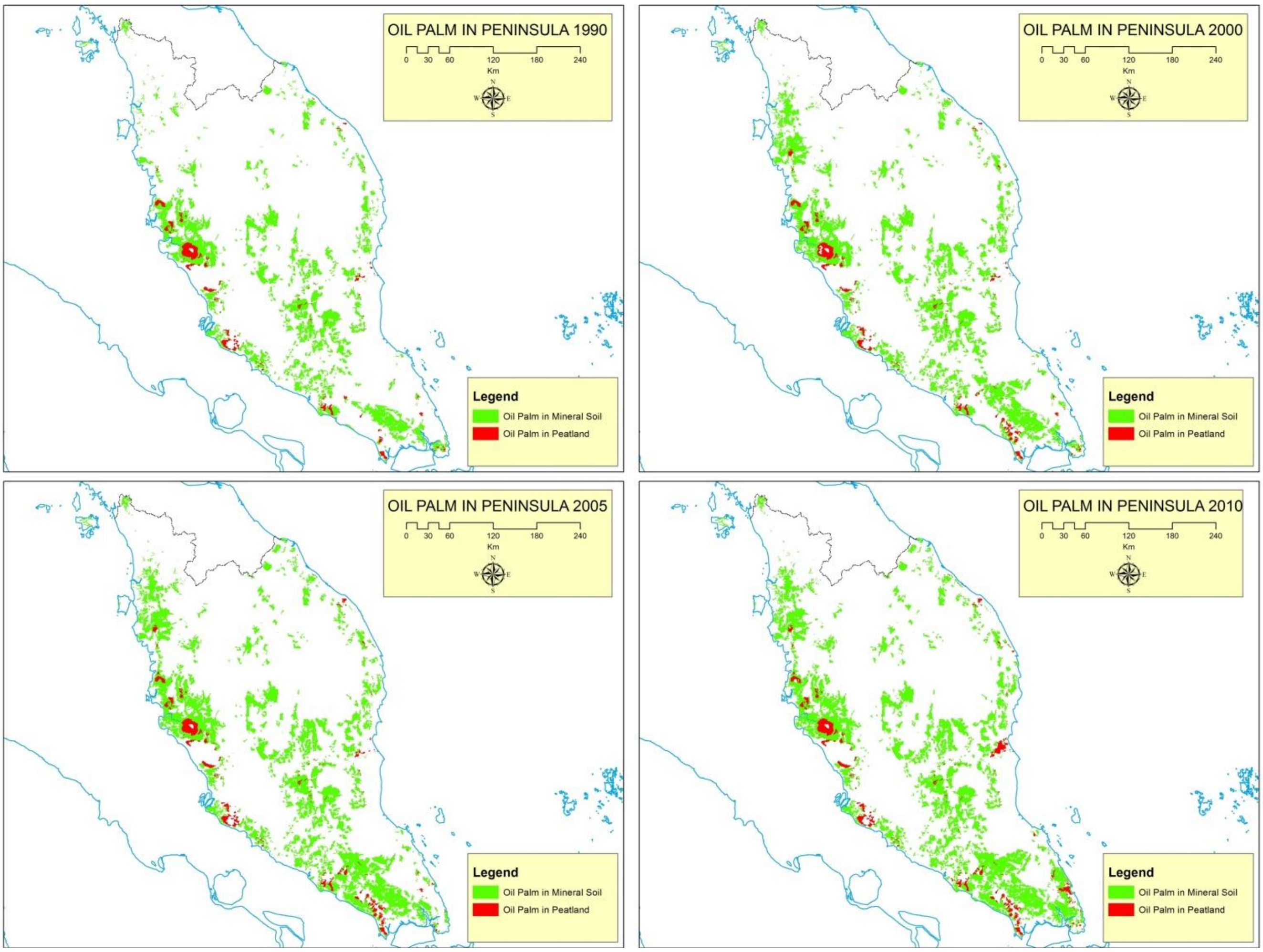

Figure 14. The expansion of oil palm plantations in Peninsular Malaysia between 1990 and 2010.

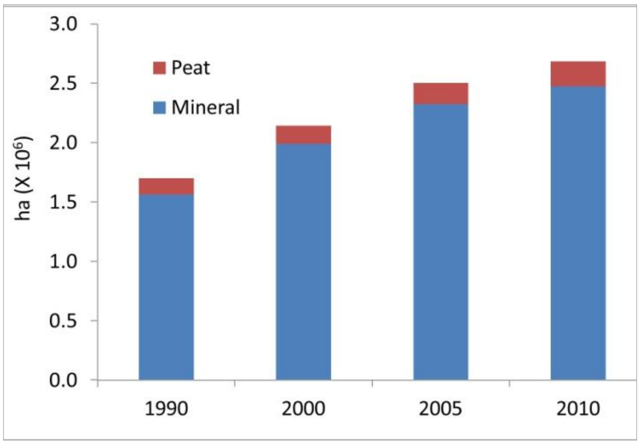

Figure 15. The area planted to oil palm in 1990, 2000, 2005 and 2010 on mineral and peat soil in Peninsular Malaysia.

Table 16. Land cover are (10^3 ha) in 2000, 2005 and 2010 in Peninsular Malaysia.

Aggregate Class	2000	2005	2010
Undisturbed Upland Forest	3,442	3,000	3000
Disturbed Upland Forest	2,416	2,670	2,578
Upland Shrub and Grassland	91	107	97
Undisturbed Swamp Forest	170	1	1
Disturbed Swamp Forest	270	346	338.99
Swamp Shrub and Grassland	22	22	23
Agroforest and Plantation	3,134	3,062	2,763
Oil Palm Plantations	2,144	2,504	2,686
Intensive Agriculture	359	355	357
Bare soil	306	287	511
Others	850	850	851
Total	**13,205**	**13,205**	**13,205**

Table 17. Prior land use of new oil palm plantations established in Peninsular Malaysia between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 - 2005		2006 - 2010		1990 - 2010	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest								
Disturbed Upland Forest	174	35.5	63	15.4	14	6.2	251	22.4
Upland Shrub & Grasslands	0	0.0	6.6	1.6	4.9	2.2	12	1.0
Undisturbed Swamp Forest								
Disturbed Swamp Forest	9.7	2.0	20	4.9	0.1	0.1	30	2.7
Swamp Shrub & Grasslands								
Agroforest & Plantation	260	53.0	125	30.8	101	46.3	487	43.6
Intensive Agriculture	-	0.0	5.9	1.4			5.9	0.5
Bare Soil	43	8.8	185	45.4	99	45.2	327	29.3
Others	3.5	0.0	1.8	0.5			5.9	0.5
Total New Plantations	**491**		**407**		**219**		**1,118**	

Sabah

Sabah is situated on the northeast corner of Borneo with a total land area of 7.4 Mha; oil palm plantations covered 358,000 ha in 1990 and grew to more than 1.5 Mha by 2010 (Table 18). Most of this growth occurred between 1990 and 2000 when annual growth rates approached 10%; the rate of expansion then declined over time, and between 2006 and 2010 was 2.2% annually. By 2010, the area dedicated to oil palm corresponded to about 20% of the total area of Sabah (Figure 16). The largest single source of new plantations in Sabah over two decades has been disturbed, presumably logged, upland forest; nonetheless, during the period between 2001 and 2005, the conversion of agroforest and other types of plantations was nearly equivalent to the area converted from forest (Table 19). Sabah lacks extensive swamp forest formations and, consequently, the amount of oil palm on peat soils is minimal (Figure 17). If the forest conversion statistics are modified to reflect the proportion of bare soils that originated from forest habitats and that were allocated to oil palm plantations over the entire 20 year period, then approximately 62% of all plantations, or 714,000 ha, have originated due to forest conversion (see Supplementary Material).

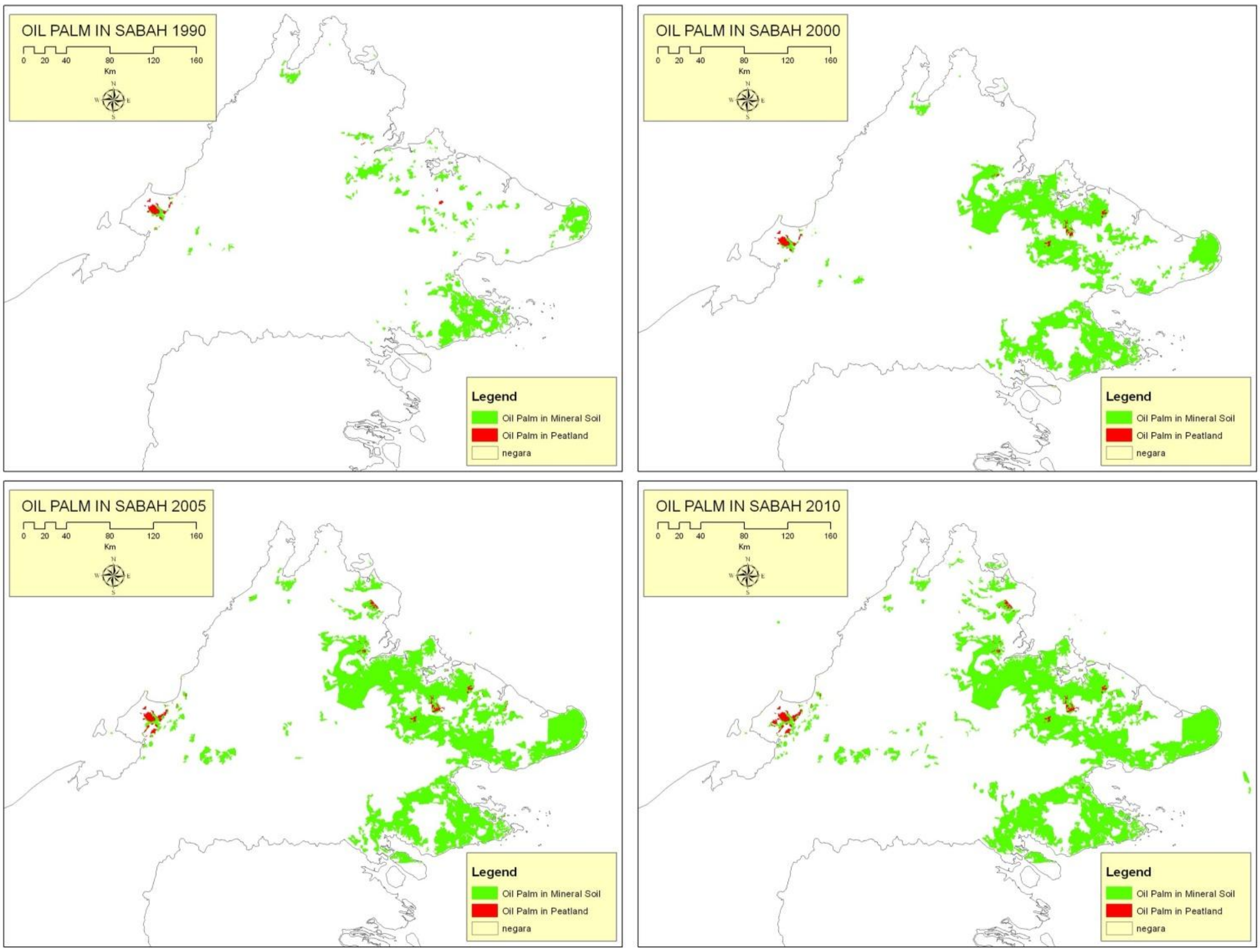

Figure 16. The expansion of oil palm plantations in Sabah between 1990 and 2010.

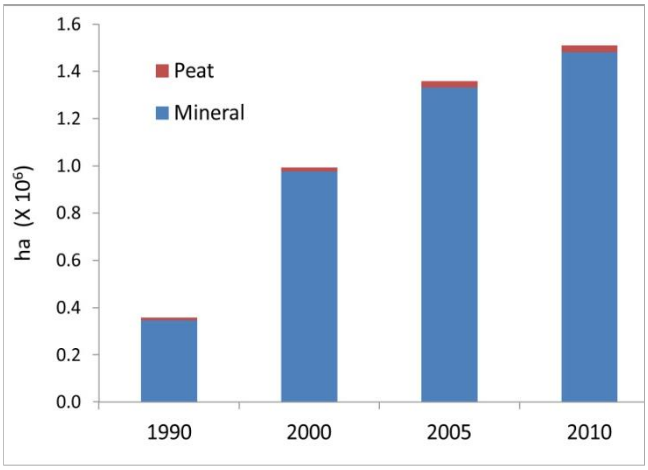

Figure 17. The area planted to oil palm in 1990, 2000, 2005 and 2010 on mineral and peat soil in Sabah.

Table 18. Land cover area (10^3 ha) in 2000, 2005 and 2010 in Sabah.

Aggregate Class	2000	2005	2010
Undisturbed Upland Forest	245	130	127.04
Disturbed Upland Forest	4,789	4,714	4,482
Upland Shrub and Grassland	7	9	10
Undisturbed Swamp Forest	17	15	4
Disturbed Swamp Forest	47	37	39
Swamp Shrub and Grassland	19	23	26
Agroforest and Plantation	404	350	405
Oil Palm Plantations	994	1,359	1,511
Intensive Agriculture	249	247	246
Bare soil	170	60	92
Others	489	487	487
Total	**7,431**	**7,431**	**7,431**

Table 19. Prior land use of all new plantations established in Sabah, Malaysia between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 - 2005		2006 - 2010		1990 - 2010	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest	-	0.0	0	0.0	-	0.0	0	0.0
Disturbed Upland Forest	435	68.4	126	34.5	116	75.5	677	58.6
Upland Shrub & Grasslands	1.7	0.3	0.6	0.2	0.3	0.2	2.6	0.2
Undisturbed Swamp Forest	-	0.0	-	0.0	-	0.0	-	0.0
Disturbed Swamp Forest	5.0	0.8	6.2	1.7	0.6	0.4	12	1.0
Swamp Shrub & Grasslands	2.9	0.5	1.3	0.4	0.7	0.5	5.0	0.4
Agroforest & Plantation	163	25.7	125	34.2	7.8	5.1	296	25.6
Intensive Agriculture	-	0.0	0.4	0.1	-	0.0	0.4	0.0
Bare Soil	28	4.4	106	28.8	28	18.4	162	14.0
Others			0.4	0.1	-	0.0	0.4	0.0
Total New Plantations	**636**		**366**		**153**		**1,155**	

Sarawak

The development of the oil palm sector in Sarawak lagged behind both Sabah and Peninsular Malaysia; in 1990, the state had less than 61,000 ha of industrial scale plantations. Expansion occurred at the rate of 16.5% in the 1990s and 20% between 2001 and 2005 and remained at the relatively high level of 11.4% between 2006 and 2010. By 2010, the total extent of oil palm plantations had reached 1.03 Mha, or about 6% of the total area of Sarawak (Figure 18 and Table 20). The expansion of oil palm plantations has occurred largely as a consequence of the conversion of disturbed upland forest; other important sources of land cover include rubber and timber plantations and disturbed swamp forest (Table 21). Coastal Sarawak is characterized by large areas of peat swamp and the expansion of oil palm plantations on peat soils has become increasingly important over time; in 1990 only about 8% of the total oil palm plantation area was located on peat soils, but this value increased to more than 32% in 2010 (Figure 18 and 19).

As stated previously, the category identified as bare soil is a combination of the clearing of land cover types and examination of the change matrix for Sarawak reveals that approximately 29% originated from upland forest landscapes and 16% from swamp forest habitats, while between 77% and 88% of bare soils were eventually planted with oil palm (see Supplementary Material). If the forest conversion statistics are modified to reflect the proportion of bare soils that originated from all types of forest habitats (disturbed and undisturbed, plus upland and wetland) and the proportion of bare soils that were allocated to oil palm plantations in the same temporal period, then approximately 48% (471,000 ha) of all plantations would have originated due to forest conversion. Moreover, if the area classified as bare soil within the peat polygon is included, then the area of oil palm plantations operating on peat soils in Sarawak would be approximately 476,000 ha (41% of all oil palm plantations in the state), which represents about 36% of all peat soils (~1.3 Mha) in the state (see Supplementary Material).

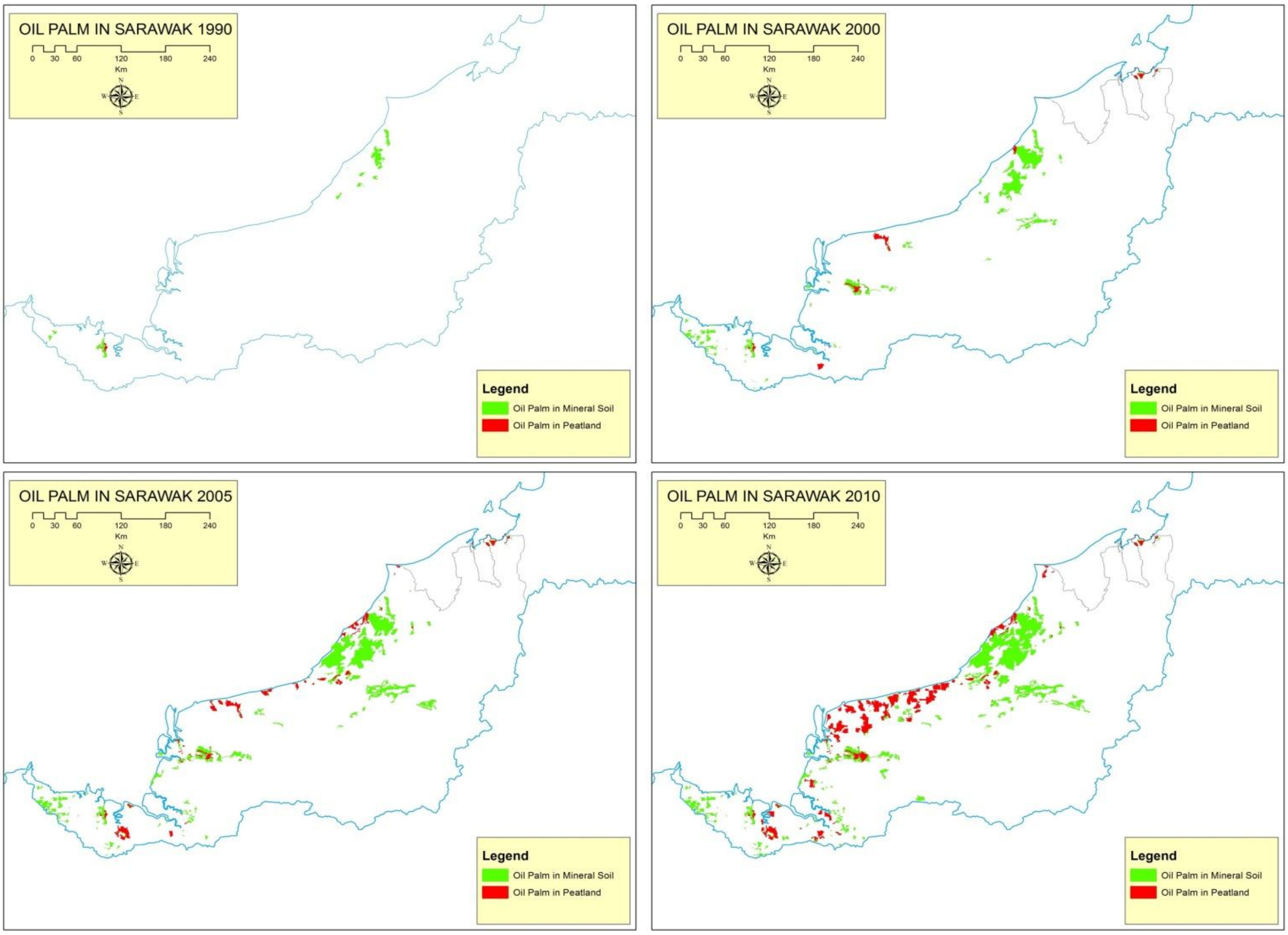

Figure 18. The expansion of oil palm plantations in Sarawak between 1990 and 2010.

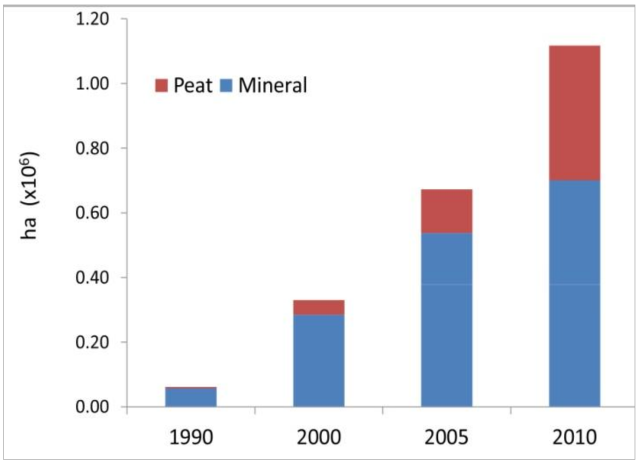

Figure 19. The area planted to oil palm in 1990, 2000, 2005 and 2010 on mineral and peat soil in Sarawak.

Table 20. Land cover area (10^3 ha) in 2000, 2005 and 2010 in Sarawak.

Aggregate Class	2000	2005	2010
Undisturbed Upland Forest	23	23	23
Disturbed Upland Forest	9,696	9,491	9,281
Upland Shrub and Grassland	6.2	27	34
Undisturbed Swamp Forest	1.7	1.4	1.4
Disturbed Swamp Forest	610	520	368
Swamp Shrub and Grassland	3.9	1.6	1.5
Agroforest and Plantation	1,263	1,180	1,007
Oil Palm Plantations	330	658	1,033
Intensive Agriculture	76	79	79
Bare soil	148	181	334
Others	290	285	286
Total	**12,448**	**12,448**	**12,448**

Table 21. Prior land use of new oil palm plantations established in Sarawak between 1990 and 2010.

Aggregate Class	1990 - 2000		2001 - 2005		2006 - 2010		1990 - 2010	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Undisturbed Upland Forest	0.0	0.0	-	0.0	-	0.0	0	0.0
Disturbed Upland Forest	135	50	100	30.0	78	20	312	31.8
Upland Shrub & Grasslands	0.7	0.3	-	0.0	0.3	0.1	1.0	0.1
Undisturbed Swamp Forest	0.5	0.2	-	0.0	-	0	0.5	0.1
Disturbed Swamp Forest	21	7.8	20	6.2	43	11.3	84	8.6
Swamp Shrub & Grasslands	-	0	-	0.0	-	0.0	-	0.0
Agroforest & Plantation	87	33	129	38.9	120	31.4	336	34.3
Intensive Agriculture	-	0	2	0.6	-	0.0	2.1	0.2
Bare Soil	23	9	80	24.2	140	36.8	243	24.8
Others	0.4	0.2	0.7	0.2	0.0	0.0	1.2	0.1
Total New Plantations	**267**		**333**		**381**		**981**	

Papua New Guinea

The expansion of oil palm plantations in Papua New Guinea is similar to that documented for the Papua region of Indonesia. Large-scale plantations were established in the 1960s, largely on the island of New Britain, and by 2010 the country had a total of 133,516 ha (Figure 20 and Table 22). Growth in plantation area has fluctuated between 3 to 6% annually (2,440 to 4,261 ha) over the three temporal periods. The largest source of land cover type for this expansion has been disturbed upland forest (Table 23). Peats swamps are largely absent and no oil palm plantations were documented for that soil type in Papua New Guinea (Figure 20 and 21).

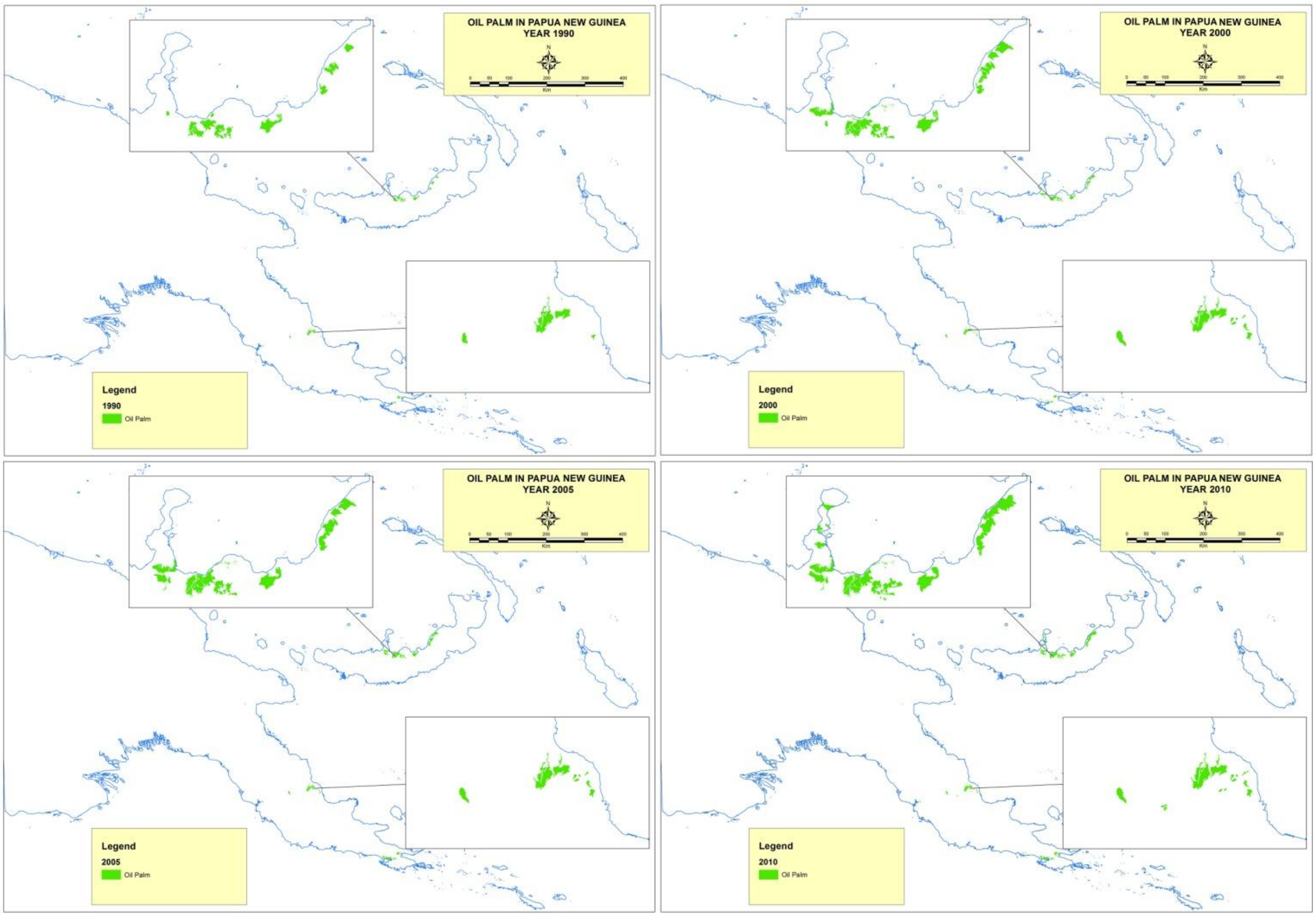

Figure 20. The expansion of oil palm plantations in Papua New Guinea between 1990 and 2010.

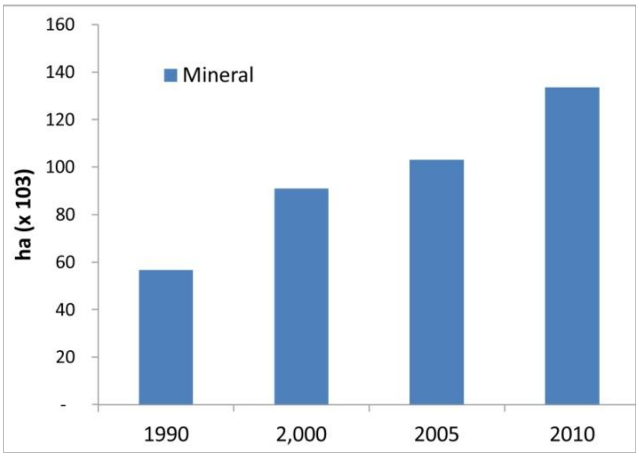

Figure 21. The area planted to oil palm in 1990, 2000, and 2010 on mineral soil in Papua New Guinea.

Table 22. Land cover area (10^3 ha) in 1990, 2000 and 2010 in Papua New Guinea.

Aggregate Class	1990	2,000	2010
Undisturbed Upland Forest	24,618	23,452	22,678
Disturbed Upland Forest	6,879	7,588	7,589
Upland Shrub and Grassland	5,307	5,680	6,292
Undisturbed Swamp Forest	1,538	1,533	1,521
Disturbed Swamp Forest	2,798	2,791	2,786
Swamp Shrub and Grassland	4,047	4,059	4,074
Agroforest and Plantation	302	302	304
Oil Palm Plantations	57	91	134
Intensive Agriculture	152	201	325
Bare Soil	81	77	73
Settlements, Mines and clouds	295	299	317
Mangroves	986	986	985
Water	289	289	273
Total	**47,349**	**47,349**	**47,349**

Table 23. Prior land use of new oil palm plantations established in Papua New Guinea between 1990 and 2010.

	1990 - 2000		2001 - 2005		2006 - 2010	
	ha	%	ha	%	ha	%
Undisturbed Upland Forest	4,302	12.6	316	0.7	4,618	6.0
Disturbed Upland Forest	11,854	34.6	25,045	58.8	36,899	48.0
Upland Shrub & Grasslands	16,123	47.0	11,789	27.7	27,912	36.3
Undisturbed Swamp Forest						
Disturbed Swamp Forest			169	0.4	169	0.2
Swamp Shrub & Grasslands			3,320	7.8	3,320	4.3
Agroforest & Plantation						
Intensive Agriculture	1,995	5.8	1,968	4.6	3,963	5.2
Bare Soil						
Others						
Total New Plantations	**34,274**		**42,607**		**76,881**	

DISCUSSION

Southeast Asia has the highest relative rate of deforestation in the humid tropics (Achard *et al.,* 2004; Sodhi *et.al*., 2005; Hansen, *et al.,* 2009; Houghton *et al.,* 2012) and the rapid development of the palm oil sector in Indonesia and Malaysia has contributed to this phenomenon. The expansion of oil palm plantations in Malaysia and Indonesia is one of several drivers of deforestation, however, and it is a misconception to allege that all oil palm plantations originate from forest conversion. This was recognized by Koh and Wilcove (2008) who estimated that between 1990 and 2005 between 55 to 59% of oil palm expansion in Malaysia and at least 56% in Indonesia were established as a direct result of forest conversion. That study did not differentiate between undisturbed and disturbed forests, although the authors did recognize that forest landscapes are often degraded by intensive logging and wildfire prior to their conversion to oil palm plantations. In a more comprehensive study (Wicke *et al*., 2011), the palm oil sector was identified as a major driver of forest cover loss in Sumatra and Kalimantan; these authors similarly recognized the complex nature of land cover change and the role of the forest sector as part of that dynamic. In both cases, the results and conclusions were limited by a reliance on secondary data derived largely from ministerial and sector reports (e.g., FAO, 2006; FAOSTAT, 2008).

Our study is based on a direct interpretation of satellite imagery for the entire region and shows that for the period between 1990 and 2010 approximately 36.5% of all oil plantations were established directly on some type of forest landscape, including both undisturbed and disturbed forest from both upland and swamp habitats (Table 5). If shrub land habitats are also included, and we assume that many of these are essentially highly degraded forest landscapes, then our results approach those reported by Koh and Wilcove (2008).

The distinction between primary and degraded or secondary forest has been one point of confusion when understanding the role of forest conversion in oil palm development. For example, the palm oil sector has made a point of emphasizing that they do not clear primary forests to establish plantations, a point which is essentially validated by our results. Nonetheless, disturbed forests also have biodiversity value (Hammer *et al.*, 2003; Peh *et al.*, 2005, 2006; Edwards *et al.,* 2010) and maintain significant carbon stocks (Pinard & Putz, 1996; Putz *et al.*, 2012) and this has motivated some authors to use terminology such as “primarily intact forests” (Carlson *et al.,* 2012b) or the oxymoronic “primary degraded forests” (Margono, *et al,* 2012). The definition of what constitutes “degraded” varies widely among authors, but in Indonesia it is assumed that areas classified as degraded land are a direct consequence of forest degradation (Wicke *et al.*, 2011; Margono, *et al.,* 2012). To avoid this type of terminological confusion, we delineate different types of land cover classes based on a combination of vegetation structure, degree of disturbance, and drainage (see Table 1 and 2); this allows us to document and track the transition between these categories so as to facilitate comparison and foster effective communication (Table 5 and Figure 10).

Our results also highlight the temporal and geographic variability associated with land use change and the oil palm sector. Forest conversion was much more important as a source of land for plantation expansion in the first and third temporal periods, but was less important between 2001 and 2005 when the sector converted an approximately equivalent area from rubber plantations and agroforest (Table 5). This trend was particularly notable in Sumatra where 85% of all new plantations established during the second temporal period occurred on existing “production” landscapes (Table 9) and in Peninsular Malaysia, where the conversion of plantations and agroforest landscapes over all three periods averaged 44% (Table 17). By contrast, other regions consistently converted large areas of forest landscapes to oil palm across all periods, particularly in Kalimantan, Sabah and Sarawak (Tables 11, 19 and 21).

Our results also show that the relatively low biomass landscapes that are converted to oil palm are themselves the consequence of forest degradation and conversion due to logging practices that are often compounded by the impact of wildfire. This dynamic is best described as a land use trajectory, and other studies have documented the impact of logging on forest cover prior to land clearing (Hansen *et al*., 2009; Margono *et al*., 2012). In Kalimantan, the transitional category is shrub land (see Figure10), while in Sumatra it was identified as mixed tree crops, which is a synonym for agroforest. Oil palm plantations have been established at multiple points along this trajectory.

Whether forest clearing is attributed to the oil palm sector or to the forest sector is partially dependent upon the time frame of the analysis; for example, if the analysis spans 10 years or more, the tendency is to

allocate forest loss to the oil palm sector rather than to logging and fire. The impact of fire has been particularly large in Kalimantan, as evidenced by the conversion of degraded forest to shrub land between 1990 and 2000 linked to extensive and severe fires that occurred during the *El Niño* event of 97/98 (Hansen *et al.,* 2009). Our data show that this dynamic of forest degradation also occurred in the second temporal period, when approximately 50% of all forest loss occurred because areas classified as disturbed forest in 2000 were recognized as shrub land in 2005 (see Figure 10 and Supplementary Material). In Malaysia, the direct conversion of forest to oil palm was more common, particularly in Sabah and Sarawak (Tables 19 and 21), but the conversion of other land cover types, such as rubber plantations, was more important in Peninsular Malaysia (Table 17).

Comparison with other remote sensing studies

Due to the impact of deforestation and its threat to biodiversity conservation and climate change, land use change has been the focus of numerous studies in Southeast Asia (Stibig & Malingreau 2003; Miettinen *et al.,* 2012a, Hansen *et al.,* 2009, Broich *et al,.* 2011, Ekadinata & Dewi, 2011; Margono *et al.,* 2012). Our principal objective was to evaluate land use change linked to the expansion of oil palm plantations, but our results can also be used to estimate overall levels of deforestation (Table 24). Our results are both similar and distinct from other studies, an outcome that is to be expected when using different types of remote sensing data, classification methodologies, and definitional criteria when evaluating change on complex landscape mosaics (see Supplementary Material).

For example, our results differ significantly from a study that relied on moderate resolution MODIS images that compared two land cover maps for 2000 and 2010 covering Indonesia, Malaysia and Brunei (Miettinen *et al.,* 2012a). Their estimates of forest cover loss are 10% to 16% greater for Borneo and the Malay Peninsula, but are about 64% and 66% greater for Sumatra and Papua. A visual comparison of the maps shows that the greatest source of variance can be attributed to the nature of the output from an automatic pixel-based classification methodology when compared to an on-screen visual interpretation procedure. The automatic procedure identifies tens of thousands of small to medium patches of forest loss that are scattered across an otherwise intact forest matrix. In contrast, our visual interpretation grouped both types of pixels into a broad category defined as disturbed forest. The automatic procedure is efficient and objective when considering a limited number (e.g. 5) of land cover strata, but is impractical for developing a land cover classification with multiple types (e.g., 22).

Similar differences in data sources and classification methodologies likewise explain the differences between our study and a recent analysis based on high resolution radar images for Sarawak (SarVision, 2011). As in the MODIS-based study, an automated classification procedure produced an impressively accurate and precise high resolution map of forest cover that identifies the loss of tens of thousands of small deforestation patches, as well as hundreds of remnant forest patches that persist on agroforest landscapes. However, that study treats all forest pixels as equal entities, including those that are located in highly impacted landscapes with numerous logging roads and those located in protected areas with no visible disturbance: thus being precise in terms of forest change, but not necessarily accurate with respect to forest degradation. In contrast, we accurately, but imprecisely, lump these landscapes into categories of disturbed forest, which we assume has a lower carbon stock value than undisturbed forest (see Agus *et al.*, 2013a, 2013b – this publication). The combination of both pixel based methodologies and on-screen manual interpretation can provide both an accurate and precise estimate of disturbed and undisturbed forest cover types (Margono *et al.,* 2012).

Two studies used a combination of moderate resolution satellite imagery (MODIS) and Landsat images to track annual forest cover change in Indonesia between 2000 to 2005 (Hansen *et al.,* 2009) and between 2000 and 2008 (Boisch *et al.,* 2011). The combination of satellite imagery allowed the authors to take advantage of the high frequency of MODIS images and the higher resolution of Landsat imagery to produce estimates of forest conversion of greater temporal and spatial resolution. Nonetheless, these studies recognize only forest and non forest classes and lack the detail provided by multiclass land cover stratifications.

Table 24. Estimates of all types of deforestation in Indonesia and Malaysia based on a summation of the loss of all types of undisturbed and disturbed forest categories, including upland, swamp and mangrove habitats, either by conversion to some form of agriculture or plantation forestry or by the degradation of forest categories to scrub or grassland in both upland and swamp land cover types.

All types of forest (UDF+DIF+USF+DSF+UMF+DMF)	2000 – 2005				2005 – 2010			
	annual rate of deforestation		OP LUC as % total deforestation	% new OP	annual rate of deforestation		OP LUC as % total deforestation	% new OP
	10^3ha yr^{-1}	%			10^3ha yr^{-1}	%		
Indonesia*	**454**	**0.53**	**7.7**	**12**	**712**	**0.85**	**27**	**37**
Sumatra	*152*	*0.96*	*9.2*	*10*	*207*	*1.37*	*15*	*20*
Kalimantan	*225*	*0.66*	*8.9*	*28*	*454*	*1.37*	*35*	*44*
Papua	*85*	*0.25*	*1.2*	*23*	*42*	*0.12*	*5.6*	*79*
Malaysia	**159**	**0.71**	**60**	**34**	**142**	**0.66**	**68**	**35**
Peninsular	*57*	*0.89*	*56*	*28*	*20*	*0.33*	*56*	*12*
Sabah	*42*	*0.76*	*70*	*38*	*49*	*0.93*	*66*	*77*
Sarawak	*50*	*0.57*	*56*	*38*	*73*	*0.72*	*74*	*41*

Table 25. Comparisons of forest cover loss from three different studies using different satellite imagery, classification methodologies and temporal time periods for Sumatra and Kalimantan; values in parenthesis indicate increases in cover for that category.

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)[1]	68.9	55.7	52.7			1,320	600			
Sumatra + Kalimantan (Broich)[2]		57.8		57.8					653	
Sumatra + Kalimantan (Gunarso)[3]		50.1	48.2		44.9		377	668*		523
Sumatra (Margono)[4]		15.7			13.6					211
Sumatra (Gunarso)		15.9	15.1		14.1		152	206		179
Other tree-dominated types (Gunarso)										
Sumatra Agroforest[5]		2.9	2.2		2.1		141	13		77
Sumatra Shrub[6]		6.2	6.2		6.3		(5)	(21)		(13)
Kalimantan Agroforest		0.6	0.7		0.4		(14)	65*		25
Kalimantan Shrub		13.3	13.5		13.2		(48)	76*		14

[1]Hansen *et al., Environmental Research Letters,* 4, 034001 (2009)
[2]Broich *et al., Environmental Research Letters,* 6, 014010 (2011)
[3]Gunarso et al., (2013)- this publication, includes all forest classes: UDF, DIF, USF, DSF, UMF, DMF
[4]Margono *et al., Environmental Research Letters*, 7, 034010(2012)
[5]Includes MTC class only
[6]Includes SCH and SSH
* a mosaic images from 2009 and 2010

In addition, different definitional criteria may have caused them to incorporate agroforest areas into their forest class; for example, our decision to classify highly degraded forests as shrub land may overlap with their definition of forest. Not surprisingly, the differences among the three studies are less evident when other tree based systems (all types of forest, shrub land and agroforest) are aggregated in the results (Table 25).

Table 26. A comparison of two studies in Kalimantan between 2000 and 2009/2010 based on similar data, somewhat different classification methodologies and distinct classification criteria.

Carlson *et al.* (2012)		This study	
Land cover types	Source of OP plantations (%)	Land cover types	Source of OP plantations (%)
Primarily Intact Forest	47	Undisturbed Upland Forest	0.09
Logged Forest	22	Disturbed Upland Forest	35.1
Agroforest	21	Upland Shrub Land	38.8
Non Forest	10	Upland Grasslands	1.1
		Undisturbed Swamp Forest	0.1
		Disturbed Swamp Forest	8.4
		Swamp Shrub Land	7.6
		Swamp Grassland	0.1
		Rubber Plantations	1.3
		Pulp Plantations	0.3
		Mixed Tree Crops	0.3
		Rice Paddy Agriculture	0.01
		Upland Agriculture	4.1

A more recent study documented the extent and rate of oil palm expansion in Kalimantan between 1990 and 2010 (Carlson *et al.,* 2012b). That study documented approximately 3.1 Mha of oil palm plantations in the study area, a value slightly greater than the 2.9 Mha documented by our results. In both cases, the spatial area occupied by oil palm plantations was digitized manually on-screen and the difference between the two values may be the result of the use of several satellite images from 2009 in our study (vs. 2010) and the documented rate of change in Kalimantan of approximately 360,000 ha yr^{-1}, which would account for the difference between the two statistics. Other differences between the two studies were: 1) the use of an automated classification and change detection procedure to create four land cover types/change categories compared to our visual recognition of 22 land cover types, and 2) different definitional criteria for stratifying disturbed and undisturbed forest, versus primarily intact and logged forest (Table 26). Moreover, these authors classified only landscapes that fell within the polygons identified as oil palm plantations in 2010, which can be interpreted as the "plantation frontier" while we conducted a wall-to-wall classification for all of Kalimantan, which included the plantation frontier, as well as other areas that had been impacted by logging and fire, but have not (yet) been targeted for plantation development. Finally, Carlson *et al.* (2012b) applied the rates and sources of land cover change documented for the period between 1990 and 2010 to the period between 2000 and 2010, and assumed that the patterns of land use change in the first period would be the same as in the second period. In contrast, we documented the sources of land cover and rates of change for oil palm plantations separately for the periods: 1990 – 2000, 2001 – 2005 and 2006 – 2009/2010.

At first glance, results for the two studies are markedly dissimilar. Much of that difference, however, can be attributed to the use of different definitions and criteria for stratifying land cover classes (Table 26), particularly our decision to recognize a distinct tree-based, non forest "shrub land" category. Although almost 1.1 Mha of this category was converted into oil palm (see Table 11), it was simultaneously replenished by the ongoing degradation of disturbed forest (Figure 10), which we assume was due to the ongoing degradation caused by unsustainable logging practices and wildfire. Although we did not document the change between 1990 and 2000, massive wildfires caused the conversion of between 4.5 – 9 Mha of forests during the drought of the extreme *El Niño* event of 1997/98 (UNCHS, 2000; Hansen *et al*., 2009; van der Werff *et al.,* 2010). This phenomenon continues, as documented by our wall-to-wall study of land cover change in Kalimantan (Figure 10). Apparently, Carlson *et al.* (2012b) did not track land cover change between primarily intact or logged forest to either agroforest or non-forest, and assumed that change from any forest

category to oil palm plantation was direct and did not include transitional degradation as a form of land cover change. The assumption by Carlson *et al.* (2012b) that the sources of land cover types for conversion to oil palm plantations in the 1990s would be the same in the next decade are not supported by our results (see Table 11), which show that relative proportion of forest conversion declined between 2001 and 2005, to then increase again in the last temporal period. A similar trend was documented by Hansen *et al.* (2009) who tracked annual changes in deforestation using MODIS images.

Differences in temporal periods and classification criteria limited our ability to compare the results of the Landsat based study for Malaysia (Rashid *et al.,* 2013 – this publication). Nonetheless, the results from the two studies broadly conform when evaluated for the extent and distribution of oil palm plantations, including those on peat soils, particularly if a significant portion of the category bare soil is assumed to be destined as oil palm plantations. However, there was less agreement concerning the land cover types that were the source of new oil palm plantations, in part because of less stratification in the data set (e.g., an "other" category that included at least 10 of the categories detailed in the Indonesian land cover classification). There were also discrepancies regarding the conversion of forest and rubber plantations; in the case of the former, the data set compiled by the Forest Research Institute of Malaysia showed increases in forest area between temporal periods.

Drivers of Deforestation

The differences in methodological approaches, including the use of different temporal periods, land cover definitions, and classification protocols, impacts on how the causes of deforestation are characterized and, consequently, attributed to different economic sectors. The definition of what constitutes a forest is precisely defined by foresters (FAO, 2007), but delineating forest cover from satellite images incorporates an element of subjectivity, particularly when visual techniques are employed, but also when pixel-based procedures use predefined cut-off points based on spectral indices. A large part of the differences among the various studies can be explained by differing definitions of forest and, more importantly when it comes to calculating GHG emissions (see Agus *et al*., 2013 – this publication), how to stratify the forest into different levels of disturbance. The potential for error is greatest on dynamic landscapes characterized by intermediate or even overlapping land cover types.

The drivers of land cover change are also usually not independent of one another. For example, timber exploitation almost always precedes plantation establishment and, in some cases, the two may be linked, as with wood salvage operations carried out as part of the land clearing process. In other cases, demonstrating a causal linkage is difficult, particularly if timber exploitation and plantation establishment are separated by several years or longer. In some regions, oil palm concessions have been used to fraudulently exploit timber resources with no intention of developing them as oil palm plantations (Sandker *et al.,* 2007). The impact of fire must also be considered, especially if it is sufficiently intense to create a tipping point that shifts a land cover from forest to a non forest over a period of a few weeks. Logging creates the conditions for fire by increasing forest litter and necromass, as well as opening the forest canopy to allow increased solar radiation to reach the forest floor and desiccate combustible material. Wildfires during periodic droughts can spread across large areas and have been particularly damaging to peat swamps where soil fires can damage root systems. Fire has been traditionally used to facilitate the development of oil palm plantations and carelessness may lead to uncontrolled fires that impact neighboring forest landscapes and cause them to shift from continuous forest to shrub land or agroforest.

The challenges linked to documenting land use change on highly dynamic landscapes can be managed by using short temporal periods to track change and by combining automatic pixel-based classification methodologies with visual interpretation to identify the economic and social actors that drive land use change (Margono *et al.,* 2012). In the specific case of Indonesia, our results show that there are multiple drivers of deforestation and that selection of temporal periods and the definitions of the parameters that define a forest can influence the allocation of deforestation to different economic sectors.

Oil palm plantations on peat in Malaysia and Indonesia

A total of approximately 2.43 Mha of oil palm plantations were established on peat soils in Indonesia and Malaysia by 2009/2010; this represents more than

9% of the total area of peat soils in these two countries if Papua is included, but almost 15% of the total area of peat in Peninsular Malaysia, Borneo and Sumatra. Sumatra leads in absolute areas of converted peat (Figure 7) and has converted approximately 19% (1.4 Mha) of its total peat area to oil palm plantations. The island also has large plantation areas dedicated to the cultivation of timber and cellulose, most of which is likewise planted on peat soils (Miettinen *et al.,* 2012c). Sarawak follows in absolute area with about 330,000 ha of oil palm plantation on peat in 2010 (25% of the total peat swamp area). However, if bare soils are included within this statistic, and in the case of Sarawak these are largely early stage oil palm plantations (88% between 2005 and 2010), then the total area of oil palm on peat in Sarawak surpasses 417,000 ha (37% of the total peat swamp area). The rate of change in the last temporal period of swamp forest in Sarawak was approximately 7% annually (59,620 ha) and nearly all of the loss of peat forest can be directly attributed to establishment of new oil palm plantations (see Supplementary Material).

Table 27. Comparison of three studies focusing on oil palm plantations on peat (10^6 ha).

	This study	Omar *et al.* (2010)	Miettinen *et al.* (2012)
Total Peat Area			
Malaysia	2.15	2.43	2.49
Peninsular	*0.72*	*0.72*	*0.85*
Sabah	*0.12*	*0.12*	*0.19*
Sarawak	*1.31*	*1.59*	*1.44*
Indonesia (excluding Papua)	13.04		13.00
Sumatra	*7.21*		*7.23*
Kalimantan	*5.83*		*5.77*
Total	**15.19**		**15.49**
Oil palm in 2010			
Malaysia	0.72	0.76	0.84
Peninsular	*0.21*	*0.30*	*0.26*
Sabah	*0.03*	*0.02*	*0.05*
Sarawak (including bare soil)	*0.48*	*0.44*	*0.53*
Indonesia (excluding Papua)	1.71		1.29
Sumatra	*1.40*		*1.03*
Kalimantan	*0.31*		*0.26*
Total	**2.42**		**2.13**

In contrast, in neighboring Kalimantan large areas of peat have been degraded and abandoned without any productive use or effort to restore their ecological functionality (Figure 10). Our results documenting the extent of oil palm plantations are similar to two other studies that used high resolution SPOT images (Table 27). All relied on soil maps to delineate the spatial extent of peat swamps and the extent of oil palm plantations were all derived by a manual on-screen digitizing methodology. The differences among the studies are most probably due to the spatial area defined by different peat soil polygons.

CONCLUSIONS

The historical trend in oil palm plantation development in the region has stayed remarkably steady between 7 and 7.7% annual growth rate over twenty years. There have been short term variations and we document one of these in the second temporal period when there was a tendency to convert previously cleared lands and other forms of plantations to oil palm. Similarly, there are measurable differences among the various sub national units: Sumatra, Peninsular Malaysia, and Sabah all showing rates that have decreased considerably in the last temporal period. The absolute area of new plantations in Sumatra remains large, but the annual rate of growth has declined from 7.6% initially to 3.8% in the last five year period. Even in Sarawak, which had annual growth rates between 15 and 20% between 1990 and 2005, growth has slowed somewhat, although there is no indication that the rates of change on peat soils is decreasing. Kalimantan continues to expand at near exponential rates of growth, a trend that we believe will moderate in the near future; as in other regions, the conversion of peat soils in Kalimantan has increased over time. If past history is a reliable guide and demand for palm oil continues to grow, it is likely that expansion will continue at 7% annual rates over the short term, however future expansion might shift to the frontier landscapes of Papua and Papua New Guinea.

The production of palm oil is only one driver of deforestation. In Indonesia, the largest single cause of historical forest loss is probably due to intensive logging and the impact of fire, which in combination have led to the progressive degradation of large areas of forest landscapes into agroforest or shrub land. In Malaysia, the direct conversion of forest to oil palm was more common, particularly in Sabah and Sarawak, but the

conversion of other types of land use, such as rubber was more important in Peninsular Malaysia.

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