HISTORICAL CO_2 EMISSIONS FROM LAND USE AND LAND USE CHANGE FROM THE OIL PALM INDUSTRY IN INDONESIA, MALAYSIA AND PAPUA NEW GUINEA

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ABSTRACT

The CO_2 emissions from land use change (LUC), peat fires and peat oxidation due to the establishment and operations of industrial oil palm plantations were estimated for the major palm oil producing regions of Indonesia (Sumatra, Kalimantan and Papua), Malaysia (Peninsular Malaysia, Sarawak and Sabah) and Papua New Guinea. Measurements of oil palm expansion were based on the visual interpretation of Landsat images from 1990, 2000, 2005, and 2009/2010 that produced a 22 x 22 LUC matrix, which was used in conjunction with emission factors calculated from the differences in the mean value of published reports for above ground carbon (AGC) for each land cover class (e.g., 189 Mg C ha^{-1} for undisturbed forest, 104 Mg C ha^{-1} for disturbed forest, 30 Mg C ha^{-1} for shrub land, 36 Mg C ha^{-1} for oil palm plantations). The emission factor for peat oxidation for oil palm plantations operating on peat soils (43 Mg CO_2 ha^{-1} yr^{-1}) was based on a review of the scientific literature, while the emission factors for peat fires were based on the assumption that fires were used historically to clear land when establishing oil palm plantations in swamp forest (333 Mg CO_2 ha^{-1}) and swamp shrub land (110 Mg CO_2 ha^{-1}).

The total area of oil palm plantations increased from 3.5 to 13.1 Mha between 1990 and 2010 at a mean annual rate of approximately 7%. Over this 20 year period, the direct conversion of natural forest preceded the establishment of approximately 3.5 Mha (36.6%) of new oil palm plantations, with the remainder resulting from the conversion of moderate to low biomass vegetation types, including 1.7 Mha of shrub and grassland habitats (17.6%) and 3.5 Mha of land cover types (37.5%) that had been converted previously to field crops, agroforest or other types of plantations, and 0.9 Mha of other land cover categories (9.5%).

The net emissions of CO_2 from oil palm plantations in the study area resulting from changes in AGC due to LUC, peat fires and peat oxidation increased from 92 to 106 to 184 Tg CO_2 yr^{-1} between the first (1990 – 2000), second (2001 – 2005) and third (2006 – 2009/10) temporal periods. The proportion of CO_2 emissions that originated from AGC due to LUC decreased between the first and second temporal period, but increased in the third (55 to 42 to 67 Tg CO_2 yr^{-1}); the emissions from peat fires linked to LUC tracked those of AGC (12 to 8 to 29 Tg CO_2 yr^{-1}). In contrast, the emissions from the oxidation of peat from plantations operating on partially drained peat soils increased steadily over all three temporal periods (26 to 56 to 88 Tg CO_2 yr^{-1}). Emissions from AGC due to LUC and peat fires are one time emissions that occur at the time of plantation establishment, but peat oxidation results in long-term, annual recurring emissions. By 2010, plantations on peat constituted 18% (2.4 Mha) of the spatial footprint of palm oil, but emission from peat fires and peat oxidation were the source of approximately 64% (118 Tg CO_2 yr^{-1}) of the total emissions from land use linked to industrial scale oil palm plantations.

Finally, we compared the CO_2 emissions from oil palm with the emissions from AGC due to LUC and peat oxidation from other types of land use; emissions from peat fires were excluded due the lack of data on the incidence of fire in other land use categories. We estimate that oil palm was responsible for approximately 13% of the total of these two types of emissions between 2000 and 2005 and 18% between 2006 and 2009/2010, based on total estimated emissions of 698 and 792 Tg CO_2 yr^{-1}, respectively. The largest source of CO_2 emissions originated from a land use trajectory that caused undisturbed forest to be degraded to disturbed forest and then to shrub land, presumably the result of logging and wildfire. Emissions from AGC from this type of forest loss and degradation was estimated at 267 Tg CO_2 yr^{-1} between 2000 and 2005 (39% of the total) and 285 Tg CO_2 yr^{-1} between 2006 and 2009/2010 (36% of the total). The sources of uncertainty in this and other published studies are discussed and represent a potential range that is an order of magnitude smaller or greater than the modeled estimates presented in this study. Prioritizing the use of shrub and grassland on mineral soil and avoiding of the use of peat soils will reduce emission significantly, as will enforcing the ban on fire for land clearing.

Keywords: *Land use change, CO_2 emissions, peat oxidation, low-carbon shrubland rehabilitation*

INTRODUCTION

The palm oil industry has grown from providing less than 5% of the global supply of vegetable oils in 1970 to providing approximately 35% of the global market demand (Teoh, 2010). The rapid growth in the production of palm oil reflects the success of a highly efficient plantation system and the inherent productive capacity of the oil palm (*Elaeis guineensis*). The palm oil industry is expected to expand in the near to medium term in response to the demand for vegetable oil as food in emerging economies and developing countries, and potentially, as a biofuel feedstock in North America and Europe. The plantation model of production is widespread and has existed for more than a century in Africa, Latin America and Southeast Asia (Corley & Tinker, 2003), but it has reached its most sophisticated level of operation in Malaysia and Indonesia, which together produce approximately 85% of global supplies of palm oil. Indonesia is expected to expand the area under cultivation by about 50%, from approximately 8 million ha in 2010 to 12 Mha by 2020 (Teoh, 2010), while Malaysia is expected to increase its oil palm plantations by only 28% due to the limitation of available land resources (Dompok, 2011). Other areas, particularly Papua New Guinea, Thailand, West Africa and South America also are expected to increase oil palm plantations in response to the demand from world markets.

The rapid expansion of oil palm plantations has generated a heated debate about the environmental impacts of palm oil production, particularly as it relates to impacts on climate change, biodiversity and the use of pesticides; social conflicts associated with land disputes and the loss of access to forest resources by local communities have also generate controversy (Panapanaan *et al.,* 2009). The environmental disputes are linked to the widespread assumption that a large proportion of palm oil plantations have been created as a direct consequence of forest clearing. This assumption is challenged by the palm oil industry that asserts that most existing oil pam plantations have been established on lands that were degraded forest, shrub land and rubber plantations (Smith, 2011). Recent studies from Indonesia provide evidence that land cover is dynamic and complex. Deforestation has been associated with the expansion of plantation estates and cropland; however, agroforest landscapes where coffee, cacao, citrus and timber are grown as part of a diversified smallholder production system have decreased gradually since 1990 and so are also likely to be involved. Simultaneously, the loss of forest cover has been linked with the increase in shrub land between 1990 and 2000, presumably due to forest degradation, but this type of land cover decreased between 2000 and 2005, as it was converted to more productive types of land use including oil pam (Ekadinata & Dewi, 2011).

Several studies documenting deforestation have been completed for both Malaysia and Indonesia (Stibig & Malingrea, 2003; Hansen *et al.,* 2009; Miettinen *et al.,* 2011, 2012a) and both governments provide periodic reports to the global database on forest resources (FAO, 2010). However, detailed studies that quantify land use change (LUC) specific for the palm oil sector are nonexistent or incomplete. In Indonesia, Ekadinata & Dewi (2011) analyzed land cover changes for two temporal periods: 1990 – 2000 and 2001 – 2005, but treated all types of industrial plantations as a single category, including oil palm, pulp and paper and rubber. Similarly, the Indonesian Ministry of Forestry (MoF, 2008) analyzed land use change for 2000 – 2003 and 2004 – 2006 and likewise grouped all plantation types into a single category (see WRI, 2008). In Malaysia, a variety of government institutions have tracked forest cover and land use change and have provided detailed information on the expansion of oil palm plantations and changes in forest cover; unfortunately, those studies use different data sources and classification methodologies and lack consistency in the definition of forest between temporal benchmarks making the estimates of change between oil palm expansion and deforestation difficult to verify (Rashid *et al.,* 2013 – this publication). The most widely cited estimate of deforestation attributed to oil palm plantations is based on a reinterpretation of the national reports provided by government ministries to the Forest Resource Assessment program of the Food and Agriculture Organization (FAO, 2010) covering the period between 1990 and 2005. This information has been reinterpreted to provide an estimate that approximately 55 – 59% of oil palm expansion in Malaysia and Indonesia has occurred at the expense of forests (Koh & Wilcove, 2008). It is important to note, however, that this conclusion is based on secondary sources unverified by remote sensing studies, and the FAO database is not considered to be reliable for many tropical forest countries by some remote sensing scientists (Grainger, 2007; Olander *et al.,* 2008).

The controversies surrounding CO_2 emissions and land use are compounded by the uncertainty in the dimensions and variability of above and below ground carbon stocks in natural, degraded, and anthropogenic landscapes. This uncertainty is a function of the variability inherent in any natural ecosystem (Saatchi *et al.,* 2011) and the temporal changes that occur as one class transitions into another (Lambin *et al.,* 2003). Land use change may be abrupt in the case of the conversion of forest habitat to a plantation estate or gradual when primary forest is logged, logged again, and exposed to wildfire prior to its conversion to agriculture. Moreover, the identification of transitional categories is subject to the time span used for the study; for example, a temporal comparison spanning a decade or longer will often document a transition from undisturbed forest to plantation, but a multi-temporal study with shorter periods might reveal that undisturbed forest first become degraded forest and then shrub land, prior to its conversion to some form of productive activity. In addition, the selection of carbon stock values can greatly impact the estimates of net CO_2 emissions, particularly in light of the capacity for plantation landscapes to capture and store significant amounts of carbon (Wautersa *et al.*, 2008; Henson*,* 2009).

Another major controversy is related to the conversion of coastal peat swamps to plantation estates; this type of production strategy requires the partial drainage of these wetland habitats, which leads to the oxidation of peat and the emission of CO_2. Drainage and oxidation causes the peat soils to subside and reduces their capacity to regulate the surrounding hydrology; if the process continues, the underlying mineral soil layer will eventually become exposed or, more likely, the subsidence will approximate the level in adjacent coastal water bodies that are often chemically saline (Hooijer *et al.,* 2010). The dimensions of CO_2 emissions from drained and converted peat swamps are subject to numerous uncertainties and have been a source of contention over the last decade. Estimates of the emission from peat oxidation vary widely, ranging from a low of 26 Mg CO_2 ha^{-1} yr^{-1} (Jauhiainen *et al.,* 2001) in agricultural land to a high of 100 Mg CO_2 ha^{-1} yr^{-1} in oil palm plantations (Hooijer *et al.,* 2012; Page *et al.,* 2011). The uncertainty in these estimates is related to both the physical nature of tropical peat and a lack of studies that adequately address the natural sources of variability, as well as disagreements among soil scientists on how to directly measure CO_2 emissions and the components of a modelling approach that estimates emissions in the absence of direct measurements (Melling *et al.,* 2005; Hooijer *et al.,* 2010; 2012; Agus *et al.,* 2012).

This paper seeks to clarify some of the uncertainties outlined in the previous paragraphs and provide a more robust estimate of CO_2 emissions linked to land use change caused by the palm oil sector. To do this, we documented the full trajectory of the conversion of forest landscapes to oil palm plantations, as well as evaluating how other land cover types have contributed to the expansion of the oil palm plantations. Our primary goal is to provide an objective estimate of the CO_2 emissions from the establishment of new oil palm plantations and to model the emissions from plantations established on peat soils. As part of that process, we provide estimates of the greenhouse gas (GHG) emissions linked to other productive sectors and place the emissions directly linked to palm oil in the broader context of land cover and land use change.

INFORMATION SOURCES AND METHODOLOGIES

This paper represents a synthesis of information that comes largely from two different sources:

1) An original analysis of land cover and land cover change for two decades for the principal palm oil producing regions in Indonesia (Sumatra and Kalimantan) and Malaysia (Peninsular Malaysia, Sabah and Sarawak), as well as the regions most likely to be the focus for future palm oil expansion (Indonesian

Papua and Papua New Guinea)(Gunarso *et al.,* 2013 – this publication).

2) A review of the published literature of carbon stock values for above and below ground biomass for these same geographies and a critical evaluation of the range of values reported for CO_2 emission from peat and the underlying assumptions that are used when estimating them (Agus *et al.,* 2013 – this publication).

Land Cover and Land Use Change

The spatial extent and expansion of oil palm estates was documented for three temporal periods (1990 – 2000, 2001 – 2005 and 2006 – 2009/2010) based on a visual interpretation of Landsat satellite images (Gunarso *et al.,* 2013 – this publication). The land cover stratification is composed of 22 classes, which was based on a harmonization of two similar systems used by the Ministry of Forestry (21 classes) and the Ministry of the Agriculture (23 classes) of the Republic of Indonesia (Table 1). The same system was used for the Malaysian states and Papua New Guinea to ensure uniform criteria for all regions (see Table 1 – Gunarso *et al.,* 2013 – this publication). Experienced GIS technicians visually identified similar groups of pixels based on spectral attributes, geometric patterns, and landscape context to digitally trace polygons on the computer screen. Land use change between each of the different land cover categories was documented and summarized via a 22 x 22 land use change matrix for each temporal period and for each sub-region included in the study. The results were pooled using aggregate categories to facilitate the communication of the results (see first column in Table 1).

Table 1. Emission factors used for the calculation of emission for Indonesia, Malaysia and Papua New Guinea for the above ground (biomass) time average carbon stock and peat oxidation for land use on peat.

Land Cover				Time average above ground carbon stocks		Peat oxidation		Peat fire emissions from conversion
Aggregate	Code	Class	Description	Selected Value (Mg C ha^{-1})	Range (Mg C ha^{-1})	Water Table Depth (cm)	Peat (Mg CO_2 ha^{-1} yr^{-1})	(Mg CO_2 ha^{-1})
Natural Forest	UDF	Undisturbed Upland Forest	Natural forest cover with dense canopy (> 80%), no signs of logging roads; image with high NDVI and infrared channels, lower value in visible channels.	189	61 - 399	n.a.	n.a.	n.a.
	DIF	Disturbed Upland Forest	Natural forest with visible logging roads and clearings visible; image with lower NDVI and infrared channels	104	33 - 250	n.a.	n.a.	n.a.
Degraded Non Forest	SCH	Upland Shrub land	Woody vegetation usually less than 5 m in stature, often regeneration following swidden agriculture activities or intensive logging.	30	27 – 35	n.a.	n.a.	n.a.
	GRS	Upland Grassland	Extensive cover of grasses with scattered shrubs or trees.	3	2 – 4	n.a.	n.a.	n.a.

Table 1. Emission factors for the above ground (biomass) time average carbon stock and peat oxidation (continued).

Land cover				Time average above ground carbon stocks		Peat oxidation		Peat fire emissions from conversion
Aggregate	Code	Class	Description	Selected Value (Mg C ha^{-1})	Range (Mg C ha^{-1})	Water Table Depth (cm)	Peat (Mg CO_2 ha^{-1} yr^{-1})	(Mg CO_2 ha^{-1})
Swamp Forest	USF	Undisturbed Swamp Forest	Natural forest with temporary or permanent inundation.	162	90 – 200	0	0	330
	DSF	Disturbed Swamp Forest	Natural forest cover with indications of logging activity and influence of drainage	84	33 – 155	30	22	330
Open Swamp	SSH	Swamp Shrub land	Woody vegetation less than 5 m in stature, often regeneration following swidden agriculture or logging in areas, mostly affected by drainage	28	18 – 35	30	22	110
	SGR	Swamp Grassland	Extensive cover of grasses with scattered shrubs or trees in inundated area.	2	2	30	22	0
Agroforest & Plantations	TPL	Timber Plantation	Monoculture timber or pulp plantation; canopy cover between 30-50%.	44	29 – 70	50	36	0
	MTC	Mixed Tree Crops (Agroforest)	Agroforest with > 30% of tree cover; usually to settlements and roads; includes rubber, coffee, cacao and home garden.	54	30 – 77	50	36	0
	RPL	Rubber plantation	Traditional and monoculture rubber plantations, sometimes mixed with rubber agroforestry.	55	31 - 89	50	36	0
Oil Palm Plantation	OPL	Oil Palm Plantation	Large Scale Oil Palm Plantation.	36	22 – 60	60	43	0
Bare Soil	BRL	Bare Soil	Exposed soil, gravel, or sand; frequently associated with areas undergoing land use change	36[1]		0	0	0
Agriculture	DCL	Cultivation Land in Upland soils	Open area with herbaceous vegetation; sometimes mixed with shrub land; usually associated with settlements.	11	8 - 12.5	30	22	0
	RCF	Rice Field	Open, flat area subject to inundation; usually associated with settlement and irrigation structure.	2	2	10	7	0

[1]The value of 36 Mg ha^{-1} was used as default carbon stock value in order to avoid introducing artifacts into estimates of oil palm emissions

Table 1. Emission factors for the above ground (biomass) time average carbon stock and peat oxidation (continued).

Land cover				Time average above ground carbon stocks		Peat oxidation		Peat fire emissions from conversion
Aggregate	Code	Class	Description	Selected Value (Mg C ha^{-1})	Range (Mg C ha^{-1})	Water Table Depth (cm)	Peat (Mg CO_2 ha^{-1} yr^{-1})	(Mg CO_2 ha^{-1})
Other	SET	Settlements	Urban areas, towns and villages; associated with road network	7	4 - 10	70	50	0
	MIN	Mining	Open area with mining activities.	0		100	72	0
	UDM	Undisturbed Mangrove	Forest area along the coastline with high density of mangrove tree species; no evidence of logging.	148	85 - 200	n.a.	n.a.	n.a.
	DIM	Disturbed Mangrove	Natural forest along the coast with mangrove species, with evidence of logging.	101	77 - 120	n.a.	n.a.	n.a.
	CFP	Coastal Fish Pond	Open coastal area with block pattern and always inundated.			n.a.	n.a.	n.a.
	WAB	Water bodies	Water bodies; images with low reflectance in all bands.			n.a.	n.a.	n.a.
	NCL	Not Classified Cloud	High reflectance in all bands			n.a.	n.a.	0

Carbon Stocks and Emission Factors

Above ground carbon (AGC) can be either a source or sink of atmospheric CO_2 depending on the difference between the carbon stock of the land prior to and after land use change (LUC). The emission factors from changes in AGC due to LUC are the differences between the mean values of published reports of the carbon stocks for each of the 22 land cover types listed in Table 1 (see review by Agus *et al.,* 2013 - this publication). The variability in the above ground carbon of forest and shrub land vegetation types is due to the interactions of biodiversity and ecological processes, as well as human disturbance from logging and fire. In contrast, crop land and plantation estates are characterized by simple vegetation structure and uniform planting density. Nonetheless, published reports for the carbon stock of oil palm plantations vary by as much as 50%, because different studies include or exclude below ground biomass, ground vegetation, litter and persistent leaf bases that represent short-term carbon pools. The value of 36 Mg ha^{-1} adopted in this study is the mean of several studies that estimate the time-averaged carbon stock of an oil palm plantation that starts near zero to reach more than 155 Mg C ha^{-1} for a 25-yr old plantation (see Agus *et al.,* 2013 - this publication). In the case of bare soils, a transitional category of uncertain origin, we use a value of 36 Mg ha^{-1} as default carbon stock value in order to avoid introducing artifacts into estimates of oil palm emissions. Similarly, obvious errors in land cover classification that produced illogical land use change outcomes (e.g., apparent conversion of water bodies to oil palm) were excluded from the analysis.

The decomposition of peat, also known as peat oxidation, is the most important source of CO_2 emission in oil palm plantations operating on peat soils. Upon partial drainage and conversion, the functional attributes of peat soils change from being a net sink to become a net source of CO_2 (Hooijer *et al*. 2006; Agus & Subiksa 2008; Agus *et al.,* 2012). The rate of emission is primarily a function of the depth of drainage, but other factors such as local climate and peat maturity also influence the rate of decomposition. Estimates of CO_2 emissions from peat oxidation under different conditions remain uncertain, in part due the difficulty of distinguishing between the autotrophic respiration from roots and the heterotrophic respiration from the soil biota that mediates decomposition (see review by Agus *et al.,* 2013 – this publication). We used as a basis the emission factor of 0.91 Mg CO_2 $ha^{-1}cm^{-1}$ (Hooijer *et al*. 2010), but modified that value by a coefficient of 0.79 to correct for the root-related emission based on the studies by Jauhiainen *et al*. (2012). In our model, we assume that oil palm plantations on peat soils have a mean water table depth between 50 and 70 cm, which generates emission estimates between 36 to 50 Mg CO_2 ha^{-1} yr^{-1} with an average value of 43 Mg CO_2 ha^{-1} yr^{-1}.

Peat fires are another major source of CO_2 emissions linked to the cultivation of oil palm on peat. Although the use of fire is on the decline, it was a common management practice throughout the temporal periods described in this study (Schrier-Uijl *et al.,* 2013 – this publication). Peat soils must be drained prior to plantation establishment, but the depth of the water table and the degree of soil dryness varies widely across years: When peat soils are dry, they catch fire and burn. The depth of peat fires range from more than 50 cm during severe drought, such as the mega *El Niño* event of 1997/98 (Page *et al.* 2002), to zero during unusually wet years. We assume that when swamp forest is converted to oil palm, an average of 15 cm of peat is consumed by fire and, because fire is less intense when shrub land is cleared, an average of only 5 cm of peat is lost. In both cases, we assume that peat has a mean carbon content of 0.06 Mg m^{-3}. This combination of peat depth and carbon density were used to calculate an emission factor of 330 Mg CO_2 ha^{-1} for plantations established on forest landscapes and 110 Mg CO_2 ha^{-1} on shrub land (Agus *et al.,* 2012; 2013 – this publication). We assume that fire has not been used and there were no emissions when oil palm plantation were established on cropland, agroforest, other types of plantation or any of the miscellaneous land cover categories. In the case of bare soil, in those areas where this land cover class was documented as being an integral part of the oil palm land use dynamic (Peninsular Malaysia and Sarawak), we treated that proportion of bare soil area as oil palm plantations according to the relative area of bare soils that had been planted to oil palm in the previous temporal period.

Emission Calculation

The estimate of the net carbon emissions was based on IPCC (2006):

*Emission = Activity data*Emission factor*

Activity data is the area under specific land use or undergoing land use change (LUC) within a defined period of time. The Activity data is based on the 22 x 22 LUC matrix for each subregion for each period at national or sub-national level. Emission factor is the change in carbon stock in every major pool or emission rate in case of peat oxidation. The net emission can be calculated as:

$$E = E_a - S_a + E_{bo} + E_{pf}$$

where E is net CO_2 emission, E_a is emission from AGC due to LUC, S_a is sequestration of CO_2 from the atmosphere into crop biomass of the succeeding land uses, E_{bo} is emission from below ground soil organic matter decomposition (peat oxidation), and E_{pf} is emission due to peat fire.

Emissions from AGC due to LUC are calculated based on carbon stock change:

$E_a - S_a$ = (Biomass C stock of the initial land use – Time-averaged plant biomass C stock in the successive land use) * 44/12 * A/t

Emissions from peat oxidation are estimated based on mean depth of drainage and observed rates of CO_2 emission corrected for root respiration:

E_{bo} = 0.91 *0.79 * drainage depth * A/t

Emissions from peat fires are based on carbon density, burn depth and the area of new planting:

E_{pf} = (C density * burn depth) * 44/12 * A/t

The coefficient 44/12 or 3.67 is the conversion factor from C to CO_2, based on atomic weights of C and O of 12 and 16, respectively, t is the period (number of years) of analysis and A is the activity data or area of land use. Quantitative information are expressed using the standard prefixes of the International System of Units (SI): a metric ton is Mg (g $x10^6$), a million metric tons is Tg (g $x10^{12}$) and a million hectares is Mha (ha $x10^6$).

RESULTS

Land Use Change

The total land surface dedicated to the cultivation of oil palm has increased dramatically in Southeast Asia expanding from 3.5 Mha in 1990 to more than 13.1 Mha in 2009/2010 (Table 2); much of that expansion has occurred at the expense of forest. When summed over all regions and for all three temporal periods, forest landscapes were the source of approximately 36.6% of all new oil palm plantations: 25.4% from upland forest and 11% from swamp forests, including both undisturbed and disturbed forest (see Gunarso *et al*., 2013 – this publication). The comparison of soil and land cover maps show the proportion of all oil palm plantations on peat soils at approximately 2.4 Mha in 2009/2010, representing about 18% of all plantations in the study area (see Gunarso *et al*., 2013 – this publication).

Table 2. Oil palm development in Indonesia (Sumatra, Kalimantan and Papua) and Malaysia on peatland and mineral soils (million hectares).

Country, soil	1990	2000	2005	2010
Indonesia	**1.34**	**3.68**	**5.16**	**7.72**
Peat	*0.27*	*0.72*	*1.05*	*1.70*
Mineral	*1.07*	*2.95*	*4.10*	*6.02*
Malaysia	**2.08**	**3.53**	**4.59**	**5.38**
Peat	*0.15*	*0.28*	*0.40*	*0.72*
Mineral	*1.93*	*3.25*	*4.19*	*4.66*
Papua New Guinea	**0.06**	**0.09**	**0.10**	**0.13**
Total	**3.47**	**7.29**	**9.85**	**13.23**

The mean rate of expansion has increased from approximately 373,000 in the 1990s to more than 735,000 ha yr^{-1} in the last temporal period, maintaining an annual growth of approximately 7% over two decades (Figure 1). The development and early expansion of the industry occurred first in Peninsular Malaysia and Sumatra prior to 1990, but expanded over the next two decades to include both the Indonesian and Malaysian regions on the island of Borneo (Gunarso *et al.,* 2013 – this publication). Growth in Malaysia has been more or less constant, but slowed slightly in the last temporal period, and shifted from Peninsular Malaysia to the states of Sabah and Sarawak over time. Indonesia surpassed Malaysia as the world's largest producer of palm oil in 2007 due largely to expansion in Sumatra; however, growth of new plantations in Kalimantan predominated between 2006 and 2009/2010. In the last five year period, expansion slowed in Peninsular Malaysia, Sabah, and Sumatra, but increased dramatically in Kalimantan, while holding steady in Sarawak, Papua and Papua New Guinea (Figure 1).

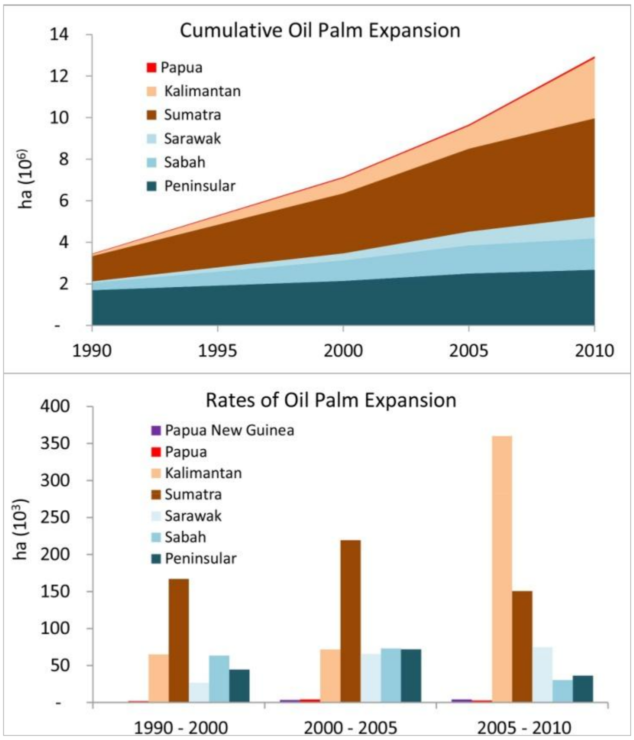

Figure 1. Development of oil palm plantations in Indonesia, Malaysia and Papua New Guinea between 1990 and 2010 (top) and variation in the rate of growth in the different sub-national regions over three temporal periods (bottom).

The trajectory of land use change is fundamentally different in each of the three countries. In Papua New Guinea between 2001 and 2010, only 3% of total deforestation (800,000 ha) was the result of oil palm plantations; nonetheless about 54% of all new oil palm plantations (42,600 ha) originated due to deforestation (see Gunarso *et al.,* 2013 – this publication). In Indonesia, the land use change trajectory is more complex and the forest degradation process is often compounded by wildfire, particularly in Kalimantan, which has led to the development of large areas of quasi-natural habitat dominated by shrubs and grasses (Figure 2). Oil palm plantations have expanded into these so-called "degraded lands" in approximately equal proportions as compared to forest when considering both upland and swamp forest habitats.

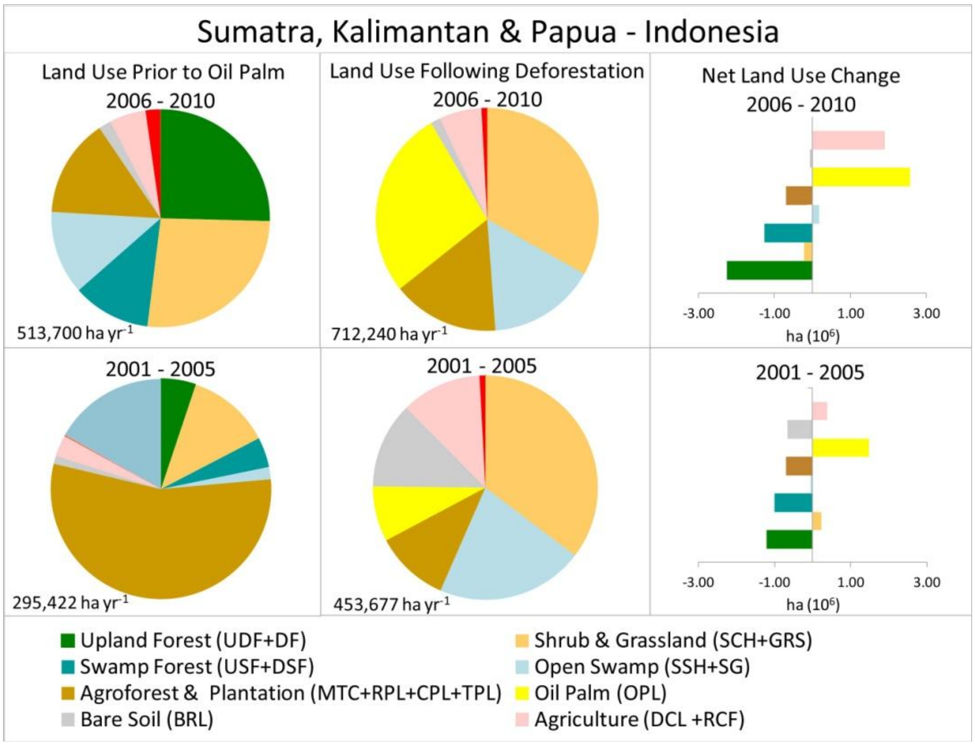

Figure 2. Summary of land use change in the Indonesian territories of Sumatra, Kalimantan and Papua: Left column: land use prior to the establishment of new oil palm plantations (in the lower left corner is the total annual increase in oil palm plantations). Middle column: the fate of land following forest conversion (in the lower left corner is the annual rate of deforestation). Right column: net land use change over each five year period.

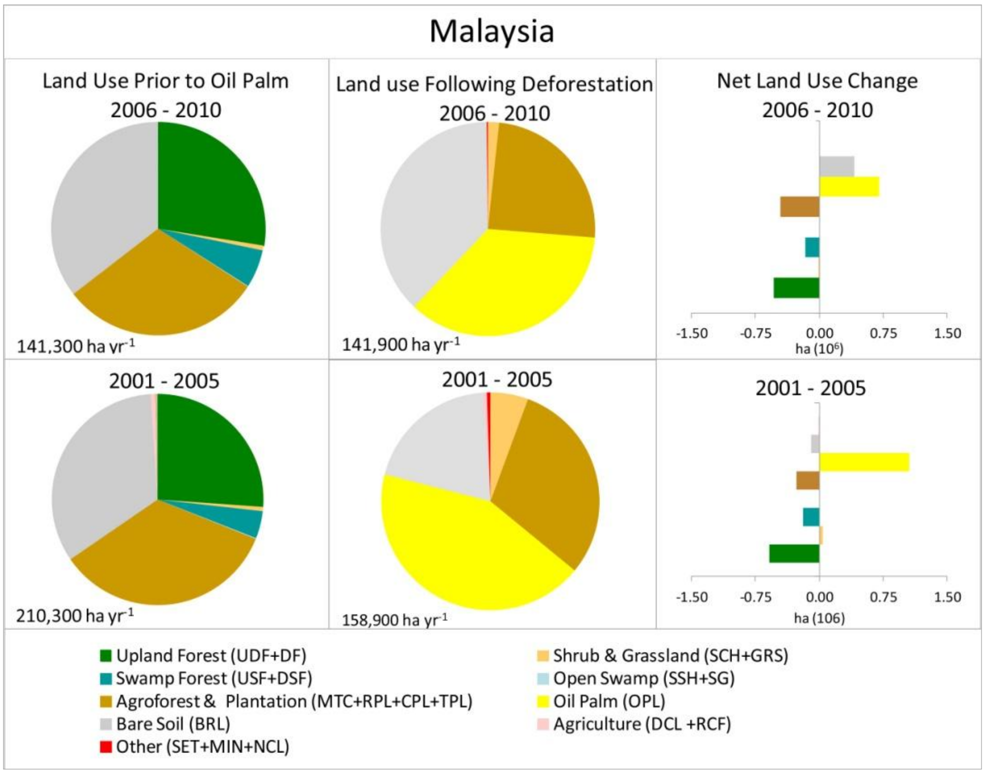

Figure 3. Summary of land use change in the Malaysian territories of Peninsular Malaysia, Sarawak and Sabah. Left column: land use prior to the establishment of new oil palm plantations (in the lower left corner is the total annual increase in oil palm plantations). Middle column: the fate of land following forest conversion (in the lower left corner is the annual rate of deforestation). Right column: net land use change over each five year period.

In Malaysia, the establishment of new plantations tends to be a more straightforward process: Forests are first degraded by intensive logging and although there may be a time lag between logging and conversion, these disturbed forests are then converted directly into oil palm plantations (Figure 3).

In Indonesia and Malaysia, large areas of existing agricultural land and other types of plantation estates were converted to oil palm between 1990 and 2010; at the same time, the agricultural frontier continued to expand at the expense of natural forest landscapes. The total area of the other types of plantations and agroforest decreased, however, because more of these two land cover types were converted to oil palm than were replaced by the conversion of forest (see Figures 2 and 3). The area dedicated to annual crops remained constant in Malaysia, while increasing by about 46% (3.6 Mha) in Indonesia (see Table 6 - Gunarso *et al.,* 2013 – this publication). Land use and land use change is best described as dynamic and complex. Different types of agriculture and plantation production systems are responsible for the conversion of natural forest. A large but variable fraction of deforestation is due to the establishment of new oil palm plantations, which is displacing simultaneously other forms of productive land use. In almost all cases, all forms of agriculture and plantation forestry follow forest degradation, which presumably is initiated by logging and aggravated by wildfire.

The relative proportion of land allocated to oil palm varies among regions. In Malaysia, there is a clear preference to establish oil palm plantations rather than other forms of agriculture and plantation forestry; at the national level, approximately 47% of all productive land (11 Mha) is dedicated to oil palm, a preference that is even more marked in Sabah where 67% of all previously deforested lands (2.3 Mha) are occupied by oil palm (See Figure 4). This trend is reflected also in the land cover category identified as bare soil. Although it is not possible to identify precisely the source and eventual end-use of this land cover type, trends identified in the land use change matrix indicate the preference for oil palm. For example, in Peninsular Malaysia about 9% of bare soil originated from forest landscapes between 2006 and 2009/2010, while 49 % originated from agroforest and other types of plantation landscapes; simultaneously, 6% of bare soils in 2005 were part of the oil palm estate in 2009/2010, a number in line with a replanting cycle of 25 years. In contrast, the previous land cover for bare soil in Sarawak was largely forest habitat, including upland (27%) and swamp habitats (48%). Approximately 50% of all bare soils were eventually planted to oil palm in Malaysia; consequently, the emission estimates for Peninsular Malaysia, Sabah and Sarawak have been adjusted accordingly (see Supplementary Material). In Sumatra, Papua and Papua New Guinea, the category bare soil was employed to identify non-productive land cover types, such as beaches, rock slopes and similar areas, while the bare soils category was not used when classifying land cover in Kalimantan.

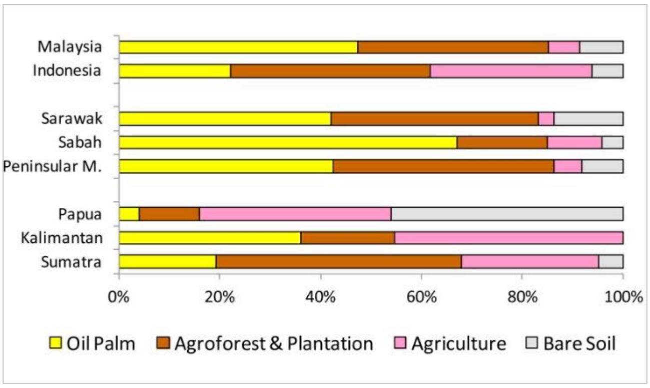

Figure 4. Allocation in 2010 of land dedicated to oil palm, agroforest and other plantations, agriculture and bare soils for Indonesia and Malaysia and the major sub-national regions included in this study. Bare soil is a mixture of exposed substrates, some of which are destined to be converted to one of the other land cover types.

In the three regions of Indonesia included in this study, approximately 24% of productive land cover types dedicated to some type of intensive agriculture, agroforest or plantations estate (32 Mha) have been allocated to oil palm plantations, due mainly to the more diverse productive landscapes that characterize the island of Sumatra (Figure 4). An additional distinguishing characteristics of land cover in Indonesia when compared to Malaysia, is the abundance of quasi-natural non forest habitat categorized as shrub and grassland. These land cover types are often referred to as "degraded lands (Fairhurst & McLaughlin, 2009; Fairhurst *et al.,* 2010) and in 2009/2010 covered an estimated 20% (10.5 Mha) of the total surface area of Kalimantan compared to 5.4% (2.9 Mha) occupied by large scale oil palm plantations (Gunarso *et al.,* 2013 – this publication).

The conversion and drainage of peat soils for the production of palm oil also varies across the region. Sumatra has the largest area of peat soils and the largest area that has been converted to oil palm production (Figure 5).

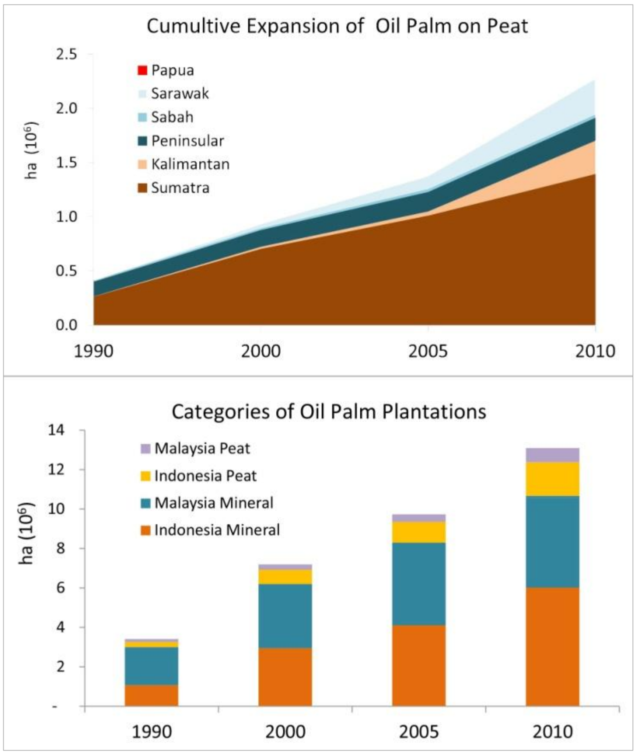

Figure 5. Development of oil palm plantations on peat soils in Indonesia and Malaysia between 1990 and 2010 (top) and the proportion of oil palm on both peat and mineral soils in Indonesia and Malaysia (bottom).

There were about 1.4 Mha or 29% of the total oil palm plantation area in 2009/2010, representing approximately 19% of all the peat soils in Sumatra. Although the overall rate of growth of oil palm in Sumatra decreased in the last temporal period, the rate of conversion of peat swamps increased with an annual rate of conversion that grew from 44,000 in the 1990s to almost 77,000 ha yr^{-1} between 2006 and 2009/2010 (Gunarso *et al.,* 2013 – this publication). Sarawak has the largest proportion (41%) of its total peat swamp area converted to plantations with about 476,000 ha, which also happens to be about 36% of the total oil palm plantation area in the state. Plantations on peat expanded at 59,520 ha yr^{-1} in the last temporal period, translating into an annual loss of 7% of the remaining peat forest habitat in Sarawak (see Supplementary Material, Gunarso *et al.,* 2013 – this publication). Kalimantan converted relatively small areas of peat soil prior to 2005, but converted more than 307,000 ha in the last temporal period, a 10-fold increase in area that represented 11% of all the oil palm plantations on the Indonesian sector of Borneo Island in 2009/2010. Only about 2% of all oil palm plantations in Papua occur on peat, although between 6 and 8 Mha of peat soils have been reported for the region (Wahyunto *et al.,* 2011). Only small areas of peat soils have been reported for Papua New Guinea and there are no reports of oil palm plantations occurring on any of them.

CO_2 Emissions

Net annual emissions from land use change and emissions from peat soils linked to the expansion of oil palm plantations in the study area were estimated at approximately 92 Tg CO_2 yr^{-1} in the first temporal period, which increased to 106 Tg CO_2 yr^{-1} in the second, and then increased markedly to 184 Tg CO_2 yr^{-1} in the most recent period (Figure 6).

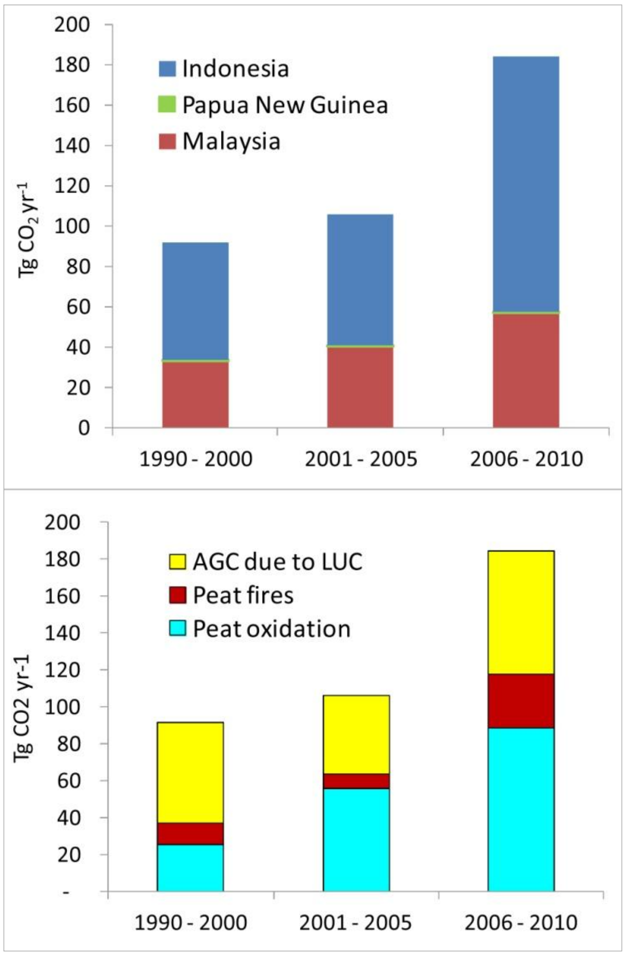

Figure 6. Mean annual emissions stratified by country between temporal periods (top) and (bottom) the same information stratified by source (AGC is above ground carbon and LUC is land use change). Information for Indonesia includes only that for Sumatra, Kalimantan and Papua.

In the three regions of Indonesia included in the study, total net annual emissions from land use in the oil palm sector for the same periods ranged from 58 Tg CO_2 yr^{-1} in the first period, 65 Tg CO_2 yr^{-1} in the second and 127 Tg CO_2 yr^{-1}in the last period. In Malaysia, total net annual emissions for oil palm and land use for the same periods ranged from 33 Tg CO_2 yr^{-1} in the first period, 40 Tg CO_2 yr^{-1} in the second and 57 Tg CO_2 yr^{-1} in the last period. Emissions from Papua New Guinea were estimated at 0.5 Tg CO_2 yr^{-1} between 1990 and 2000, which increased to 0.6 Tg CO_2 yr^{-1} between 2000 and 2010.

The relative importance of the emission source varied over the twenty year period (Figure 6). Between 1990 and 2000 emissions from above ground carbon due to land use change (AGC due to LUC) represented about 60% of total emissions, but emissions from peat oxidation represented 53% of total emissions by the last temporal period. Deforestation as a source of land for the expansion of oil palm became more important in the last temporal period; nonetheless, the incremental emissions originating from existing plantations operating on peat had come to dominate the emission profile. Emissions from peat fires varied over the three temporal periods, essentially tracking land use change on peat soils.

As expected, the total emission profile varied among regions and over time. Sabah, Papua and Papua New Guinea were all characterized by emission profiles dominated by above ground carbon due to land use change, although Sabah's were large when compared to those of Papua and Papua New Guinea (Figure 7). In contrast, the largest source of emissions in Peninsular Malaysia and Sumatra were due to the oxidation of peat, the consequence of declining rates of land use change, but also due to the incremental expansion of oil palm plantations operating on peat soil. Low rates of land use change have stabilized the emissions profile in Peninsular Malaysia, but in Sumatra the relatively large incidence of peat fires indicates that emissions from peat oxidation will continue to increase in the near future. Sarawak and Kalimantan both had emissions profiles that changed over time: AGC due to LUC was the major source of CO_2 emissions in the first period, but the importance of peat oxidation increased as plantations expanded on that soil type. As in Sumatra, the large component of estimated emissions from peat fires is an indication that emissions from peat oxidation will increase over the near term in both Kalimantan and Sarawak (Figure 7).

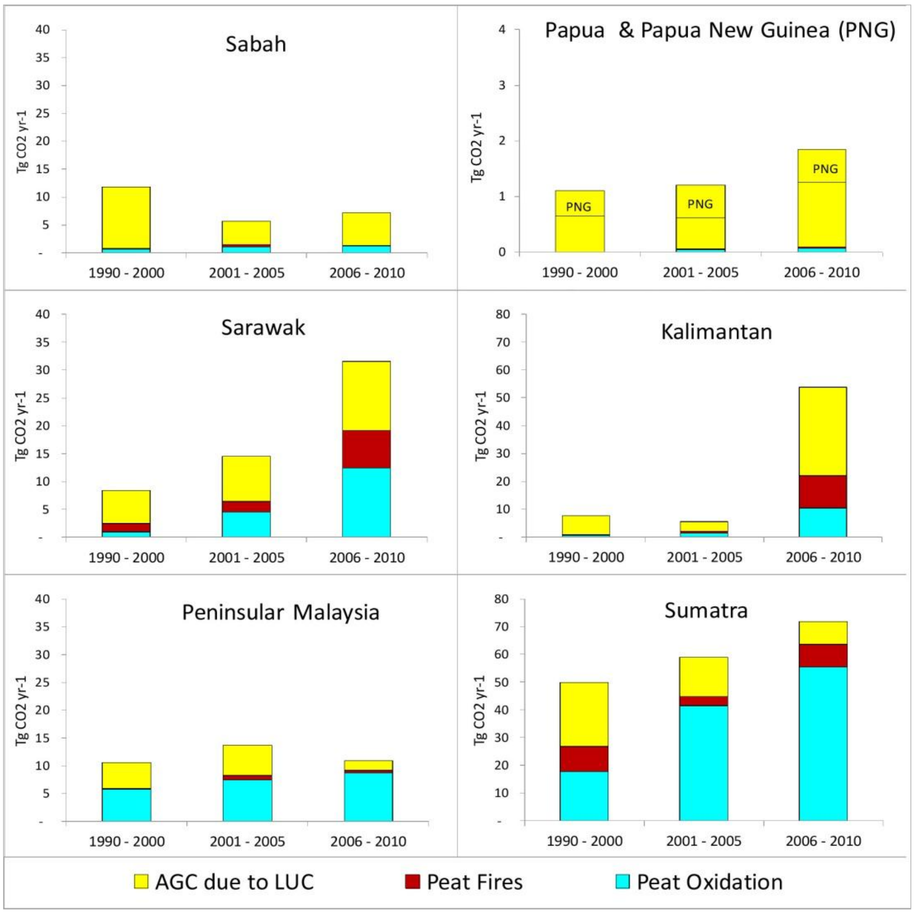

Figure 7. Mean annual emissions stratified by sub region, temporal period and source (AGC is above ground carbon and LUC is land use change); information for Indonesia includes only that for Sumatra, Kalimantan and Papua.

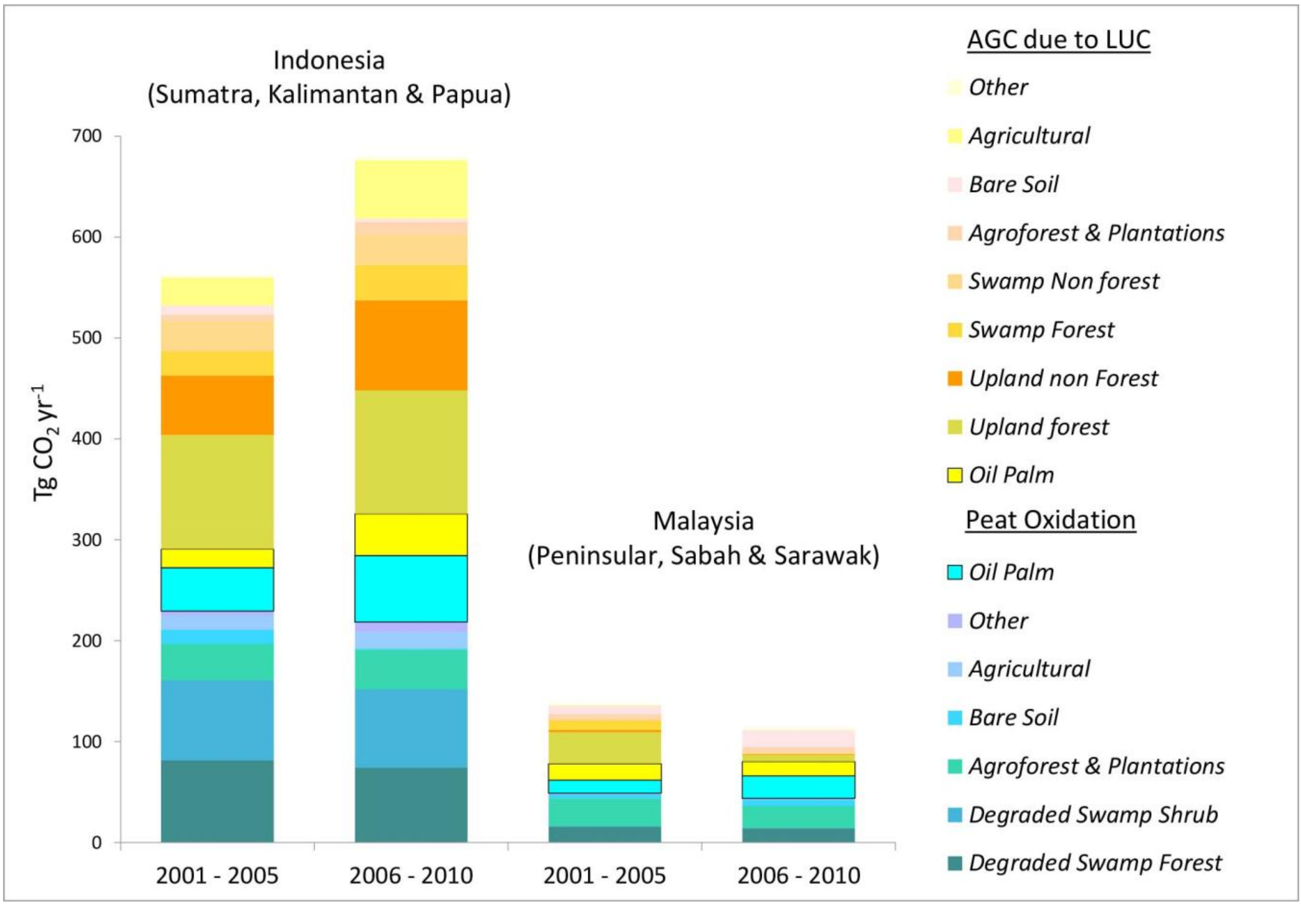

Figure 8. Total mean annual emissions stratified by source of emissions for above ground carbon (AGC) due to land use change (LUC) and the oxidation of peat soils due to drainage and conversion; excludes emissions from peat fires due the lack of fire data for all land cover types.

To evaluate the relative importance of oil palm as a source of CO_2 emissions in the land use sector, we compared emission estimates for oil palm plantations to similar emission estimates for other major land use categories in Malaysia and in the Indonesian study area (Figure 8). This comparison was restricted to emissions from AGC due to LUC and peat oxidation; the impact of peat fires was excluded because of lack of data and a logical framework for developing a model to estimate those emissions. Similarly, only the second and third temporal periods are considered, because we lacked data on land cover change for the other sectors between 1990 and 2000.

Over all, emissions in Indonesia increased from 562 Tg CO_2 yr^{-} in the second temporal period to 679 Tg CO_2 yr^{-1} in the third, with oil palm plantations representing approximately 11% (61Tg CO_2 yr^{-1}) and 16% (107 Tg CO_2 yr^{-1}) of the total from AGC due to LUC and peat oxidation. The largest source of CO_2 emissions came from AGC due to forest degradation with 226 Tg CO_2 yr^{-1} (40%) between 2000 and 2005 and 277 Tg CO_2 yr^{-1} (41%) between 2006 and 2009/2010. The second largest source was peat oxidation from disturbed swamp forests and shrub land, which typically have lower water tables than undisturbed swamp forests due to the construction of canals built to extract timber; our model showed these emissions decreased between the second and third temporal periods from161 Tg CO_2 yr^{-}1 (29%) to 152 Tg CO_2 yr^{-1}(22%), a decline that can be attributed to the conversion of these areas to oil palm plantations, a type of land use change that essentially transfers pre-existing emissions to the palm oil sector (Figure 2). Mean annual emissions from agroforestry and other types of plantations represented about 8% in both periods (43 and 53 Tg CO_2 yr^{-1}), while those from intensive agriculture increased from 7% (42 Tg CO_2 yr^{-1}) to 11% (74 Tg CO_2 yr^{-1}).

Over all, emissions in Malaysia decreased from 136 Tg CO_2 yr^{-1} in the second temporal period to 112 Tg CO_2 yr^{-1} in the third, with oil palm plantations representing approximately 21% (29 Tg CO_2 yr^{-1}) and 32% (36 Tg CO_2 yr^{-1}) of the total amount from both AGC due to LUC and peat oxidation combined. Changes in AGC due to forest degradation were the source of 32% (43 Tg CO_2 yr^{-1}) of total emissions between 2000 and 2005, but decreased to about 8% (8.5 Tg CO_2 yr^{-1}) between 2006 and 2009/2010. Emissions from peat oxidation on degraded swamp forest and shrub habitats decreased from 16 Tg CO_2 yr^{-1} (12%) to 14 Tg CO_2 yr^{-1} (13%); the consequence of these land cover types being converted to oil palm plantations. Annual emissions from agroforestry and other types of plantations declined from 34 Tg CO_2 yr^{-1} (25%) to 27 Tg CO_2 yr^{-1} (24%). The emissions from the AGC due to LUC and peat oxidation linked to intensive agriculture decreased from 0.8 to 05 Tg CO_2 yr^{-1}.

The impact from peat oxidation on the emission profile of oil palm production is becoming increasingly important. Unlike emissions from peat fires and AGC both of which track land use change (Figure 7), the increase in emissions from peat oxidation has been consistent, linear and unidirectional (Figure 6 and 7). The impact of peat oxidation is particularly evident in the case of Sarawak, where it represented less than 11% (0.9 Tg CO_2 yr^{-1}) of total palm oil emissions in the first temporal period, but represented 40% (12.5 Tg CO_2 yr^{-1}) by 2009/2010. Moreover, these statistics do not include the future emissions from an additional 98,000 ha of bare soils on peat documented in the last temporal period (Gunarso *et al.,* 2013 – this publication); historical patterns predict that approximately 80% will be planted to oil palm plantations. Once these lands are incorporated into the oil palm estate, our models predict that emissions from peat oxidation will increase by approximately 30% in Sarawak. Sumatra has an even greater legacy of long-term CO_2 emissions from peat oxidation, which represented 77% (56 Tg CO_2 yr^{-1}) of total emissions linked to oil palm plantations for the island by 2009/10.

In Peninsular Malaysia, where approximately 8% of oil palm are operating on peat soils (Gunarso *et al*. 2013 – this publication) they are now the source of about 84% (9 Tg CO_2 yr^{-1}) of the emissions profile of oil palm linked to land use, a statistic that is not likely to change significantly over the short term. In the case of Kalimantan, AGC due to LUC remains the predominant source of emissions, but emission of peat oxidation will increase in the short term. Only Sabah shows consistently low levels of emissions from peat oxidation, due to the relative scarcity of peat soils in that state. Over all seven regions, plantations operating on peat soils occupied about 18% (2.4 Mha) of the spatial footprint of large-scale oil palm plantations, but peat oxidation from these plantations represented 48% (88 Tg CO_2 yr^{-1}) of the total emission profile in 2009/10.

DISCUSSION

This report provides the first sector-wide estimate of CO_2 emissions linked to land use and land use change for the palm oil industry in the geographic region that produces 85% or more of the world supply of palm oil and palm oil products (Teoh, 2010). The primary objective of this report was to estimate the sources, dimensions, and trends of emissions over the past twenty years; as a secondary objective, we compared these emissions in the broader context of emissions caused by other types of land use. Previous reports of CO_2 emissions linked to land use and palm oil have either been based on bottom up models that estimate emissions as a function of palm oil mass or unit of energy (Reijnders & Huijbregts, 2008; Wicke *et al.,* 2008) or on landscape-scale analyses that do not provide a global estimate of emissions, nor capture the geographic variability characteristic of the industry (Uryu *et al.,* 2008; Koh *et al.,* 2011; Carlson *et al.,* 2012a; 2012b; Miettinen *et al.,* 2012a, 2012b). This report provides detailed information on the historical emissions linked to the expansion and operations of oil palm plantations stratified according to land cover source, soil type, geographic region, and temporal period. This information is essential for establishing the industry's baseline emissions and for developing future scenarios to evaluate the impact of different development options (see Harris *et al.* 2013 – this publication).

Land Cover Classification

Like all studies that document the complex phenomenon of land use and land use change, our study addressed the challenges linked to the quality of available data and the difficulties of interpreting dynamic processes that change over time. These challenges, and the decisions on how to manage them, are sources of variation and uncertainty inherent in a study of this nature. For example, the stratification of land cover types into undisturbed forest, disturbed forest, shrub land and grassland is an approach used by ecologists to qualitatively describe a continuous gradient; however, deciding where one category ends and the next begins is imprecise, and sometimes arbitrary, particularly when relying on satellite imagery covering large heterogeneous areas characterized by varying levels of human activity. Many academic studies choose to manage this challenge by using automatic classification techniques based on the spectral signature of image pixels (Hansen *et al.,* 2009; SarVision, 2011; Broich *et al.,* 2011; Carlson *et al.,* 2012b; Miettinen *et al.,* 2012a; Margono *et al.* 2012), but that approach limits the number of categories that can be discriminated and excludes useful information that can be reasonably interpreted from the landscape context. Moreover, as the number of strata increase, automatic procedures require extensive human editing, which in terms of labour and objectivity, are not unlike visual recognition techniques. Fortunately, oil palm plantations are easy to identify in satellite imagery and the results from Gunarso *et al.* (2013 – this publication) are similar to other studies that have been conducted on shared landscapes (see below). The same cannot be said for the ability to distinguish among other natural, quasi-natural and human-derived land cover types, however, and the level of confidence in the transitions among these different land cover types is less robust. To improve accuracy and facilitate communication, we aggregate similar types of land cover categories based on edaphic attributes (upland vs. swamp), vegetation type (forest vs. shrub and grassland), and land use (plantation and agroforest vs. agriculture).

Land Use Change and Above Ground Carbon

One of the largest sources of uncertainty in estimating the emissions from land use change linked to oil palm plantations is the variability in carbon stock estimates in above ground carbon for the different land cover types. The source of this variability has three origins: 1) natural spatial variability of AGC in forest and non forest land cover types, 2) the impact of logging and fire on above ground carbon in intact but disturbed forest habitats, and 3) the temporal period which is used to calculate emissions from land use change.

For forest, shrub and wetland categories, we use the mean value of all published reports from Indonesia, Malaysia and Papua New Guinea, while values for agriculture, agroforest and other plantation categories were based on scientific and technical publications (see Agus *et al.,* 2013 – this publication). Agroforest, which is sometimes referred to as mixed tree crops in the Indonesian classification system, is a heterogeneous category of different land use intensities, including secondary forests, small farms, pastures, coffee and cocoa, and even small-scale oil palm plantations. The border between agroforest, disturbed forest and shrub land is subject to interpretation and, consequently, a source of uncertainty in emissions estimates.

The estimates of the carbon stock in oil palm plantations, which represent a uniform cropping system and a species with simple allometry, have also been the subject of discussion among workers who seek to estimate the GHG footprint of palm oil as part of a life cycle analyses. For example, a fully mature 25-yr old plantation can have as much as 155 Mg C ha^{-1}, while time-averaged estimates range from 23 to 50 Mg C ha^{-1} (Dewi *et al*., 2009; Khasanah *et al.,* 2011). The time-averaged value adopted in this study (36 Mg C ha^{-1}) does not account for differences among new high yielding dwarf varieties or short rotation cycles favored by some companies, nor low stand densities in poorly managed plantations, senile plantations on peat soils, or smallholder’s crops that might have a low carbon stock value.

Soil type and climate influence plant growth and lead to differences in AGC in humid, semi-humid and dry forest formations (Saatchi *et al.,* 2011). Carbon stocks are also influenced by species composition and the *Dipterocarpaceae*, a plant family that dominates many forests in Southeast Asia, is characterized by tall trees with high wood density which endows undisturbed forests in the study area with unusually high values for above ground carbon (Slik *et al.,* 2009). The relative abundance of this family, which is also known for its high quality timber, also influences logging intensity; and timber extraction rates in Borneo have been estimated at 230 m^3 ha^{-1} — an order of magnitude greater than is common to Amazonian forests (Butler, 2009). This level of logging intensity reduces the carbon stocks in a standing forest, and is a major cause of forest degradation that is magnified by conventional logging practices (Sist *et al.,* 2003). In spite of the loss of above ground carbon, the logged forests in Southeast Asia retain much of their original biodiversity and as many as 75% of the original complement of birds and dung beetles persist in disturbed forests (Edwards *et al.,* 2010). The innate value of this biodiversity, coupled with the inherent capacity of these forests to regenerate and restore carbon stocks, motivate some ecologists and environmental advocates to refer to these disturbed forest as “natural forests” or “intact tropical forests” or “primarily intact forests” or even the oxymoronic “degraded primary forests.”

Some ecologists and many foresters use the term "secondary forest" to describe disturbed and degraded forests; this term has its origin in classic ecological theory that describe how ecological processes mediate a succession of vegetation types following severe disturbance (Clements, 1916). The terms "secondary forest" and "degraded forest" are used by advocates of the palm oil sector to emphasize that palm oil expansion has not occurring at the expense of "primary forests," an affirmation supported by the land use change study that underpins this report (Gunarso *et al.,* 2013 – this publication). This view emphasizes the economic advantages of palm oil production in the context of the low residual economic value of intensively logged forests, the contribution of palm oil to national GDP and its benefits to rural livelihoods (Cramb & Cury, 2012).

We avoid these pitfalls in terminology by using the terms "disturbed" and "undisturbed" forest, as well as document the transition from undisturbed forest to disturbed forest, and then to shrub and grassland, with separate categories for both upland and wetland habitats (Table 1). In addition, we relied on five year temporal comparisons to capture the intermediate stages that distinguishes our study from others that used longer temporal periods (Koh & Wilcove 2008; Carlson *et al.,* 2102b; see Discussion in Gunarso *et al.,* 2013 – this publication). Unfortunately, we were not able to fully document the changes in land cover change between 1990 and 2000 in Indonesia when both logging and forest conversion were at their highest (Hansen *et al.,* 2009); nonetheless, evidence from the two subsequent periods shows that the oil palm sector is not responsible for the loss of the largest part of the carbon stocks of the original forest cover in these regions (Figure 9). Forest loss via degradation was greatest in Kalimantan where 40% of forest loss between 2006 and 2009/2010 was caused by the degradation of approximately 0.9 Mha of forest to shrub land and the release of 155 Tg CO_2 yr^{-1}, almost 52% of total emissions for the region excluding all emissions from peat fires. The historical emissions from above ground carbon due to forest degradation, presumably due to logging and wildfire, were more than four times greater than emissions from above ground carbon due to land use change caused by the establishment of new oil palm plantations in the same temporal period (32 Tg CO_2 yr^{-1}).

Emissions from Peat

Emissions from peat oxidation and peat fires have increased in both absolute and relative terms over the 20 year period and now represent a total of 64% (118 Tg CO_2 yr^{-1}) of all emissions from land use and land use change linked to the palm oil sector. If the one-time emissions from peat fires are excluded, then emissions from peat oxidation represent 48% (88 Tg CO_2 yr^{-1}) of total emissions. Moreover, CO_2 emissions from peat oxidation are not subject to the temporal fluctuations linked to land use change and the establishment of new plantations. Unless these plantations are abandoned and restored as wetlands, they represent a long-term attribute of the palm oil production system (Schrier-Uijl *et al.,* 2013 – this publication). Although the direction and trend of CO_2 emissions from peat oxidation are clear, the actual dimensions of these emissions remain uncertain. This uncertainty is the consequence of four factors: 1) the spatial extent of peat soils, 2) the depth of drainage, 3) the rate of oxidation of peat, and 4) the incidence of fire at the time of plantation establishment (see Agus *et al.,* 2013; Schrier-Uijl *et al.,* 2013 – this publication).

The spatial data used to model emissions in this and other studies are based on soil maps derived from satellite imagery, and thus are subject to the uncertainty linked to that technology. Gunarso *et al.* (2013 – this publication) had access to two sources of information on the distribution of forest wetland: a peat soil map distributed by Wetlands International for Indonesia (Wahyunto & Subagjo, 2003; Wahyunto & Suparto, 2004; Wahyunto *et al.,* 2006) and data from the Harmonized World Soil Database for Malaysia (FAO 2009). However, a more recent study for Sumatra and Kalimantan has reduced the spatial extent of peat swamps by approximately 15% (Wahyunto *et al.,* 2011), while a study using official soil maps developed for Malaysia reported that peat formations were 5% greater (Omar *et al.,* 2011). Since the emissions from peat are dependent on a model that uses data derived from these information sources, improvements in the accuracy and precision will impact estimation of emissions from peat fires and peat oxidation.

Assumptions made regarding the depth of drainage impacts the outputs from models that estimate CO_2 emissions due to peat oxidation. According to better management practices recommended by the Roundtable for Sustainable Palm Oil, the recommended depth of drainage is 60 cm, a level which both maximizes plant productivity and minimizes CO_2 emissions. In many plantations, water table depths are not actively managed and often fall below 80 cm during the annual dry season, particularly during periods of severe drought (Lim *et al.,* 2012). Since the models used to estimate emissions from peat oxidation are simple linear correlations, the mean level of drainage used in those equations will directly impact emissions estimates.

The heterotrophic respiration linked to the degradation of the peat, here referred to as peat oxidation, is perhaps the most uncertain of all the emission factors used to model emission estimates from oil palm plantations. Studies conducted over the past decade have generated estimates of heterotrophic respiration that range from 20 to 95 Mg CO_2 ha^{-1} yr^{-1} (see review in Agus *et al.,* 2013 – this publication). The differences stem from methodological challenges associated with the two main experimental approaches employed to measure peat oxidation. One approach correlates soil subsidence with peat oxidation, a method that can confound soil compaction with peat degradation and, consequently, requires research protocols that document bulk density (weight per volume) and carbon density (% carbon content). The other approach directly measures CO_2 flux on the soil surface using closed chamber systems; however, this method must discount for autotrophic respiration from plant roots, which produce CO_2 while consuming carbohydrates produced by photosynthesis in the leaves of living plants. Failure to adequately account for autotrophic respiration will inflate estimates of CO_2 emissions from peat oxidation. The selection of 43 Mg CO_2 ha^{-1} yr^{-1} was based on a review of recent studies and is near the median value of the range of these values (see Agus *et al.,* 2013 – this publication); other recent studies have based their models on a substantially higher emission factor of approximately 95 CO_2 ha^{-1} yr^{-1} (Uryu *et al.,* 2008; Koh *et al.,* 2011; Carlson *et al.,* 2012a; 2012b; Miettinen *et al.,* 2012a, 2012b)

Peat fires are an important source of CO_2 emissions in Southeast Asia and the haze linked to those fires is an important transboundary issue within the region. Estimation of historical emissions from peat fires has high uncertainty, because of the difficulty in documenting the intensity, depth and spatial extent of fire data collected by satellite sensors. For example, modeled estimates of CO_2 emissions during the unusually severe *El Niño* event of 1997/98 produced values between 2.9 and 9.4 Pg CO_2 when extrapolated across all of Indonesia (Page *et al.,* 2002). A similar approach that included fires in both mineral and peat soils reported emissions of 3.5 Pg CO_2 for the same event, as well as estimating annual emissions from fire in Southeast Asia that fluctuated between 0.09 and 1.3 Pg CO_2 between 2000 and 2009 (van der Werf *et al.,* 2010). We did not calculate region-wide estimates of peat fire emissions due to lack of data on the distribution and severity of peat fires across all land cover types. Our modeled estimates of historical emissions from peat fires for oil palm plantations are based on the assumption that differential amounts of peat are consumed by fire at the time of plantation establishment from forest and shrub (see Agus *et al.,* 2013 – this publication). Our estimates of emissions from peat fires on oil palm plantation correspond to 2% of total mean annual fire emissions between 2000 and 2005 (481 Tg CO_2 yr^{-1}) and 6% between 2005 - 2009/2010 (467 Tg CO_2 yr^{-1}) (van der Werf *et al.,* 2011 and Supplementary Material).

The Impact of Uncertainties

Taken individually, the variability of any single emission factor can lead to relatively large differences in the final estimate of the CO_2 emissions; taken together, these uncertainties become multiplicative and lead to very different estimates of the carbon footprint of palm oil (Reijnders & Huijbregts, 2008). Based on published reports, the range of potential carbon stock values in forest land cover types is from 74 to 360 Mg C ha^{-1}, the emission from peat oxidation may be half as much smaller or twice as large, and the potential depth of burning can vary from zero to as much as 50 cm depending on the severity of seasonal drought. The values selected for the modelled estimates presented here are based on the mean value of all published peer reviewed studies (above ground carbon), a critical evaluation of peer reviewed studies (peat oxidation) and recommendations from informed individuals (peat fire depth).

A comparison of a subset of our results based on land use change data from Kalimantan (Gunarso *et al.* 2013 – this publication) with a similar study focusing on palm oil and CO_2 emissions from the same region (Carlson *et al.,* 2012b) provides an opportunity to evaluate how different emission factors, land cover stratification methodologies, and temporal perspectives impact model outputs. Both studies were based on land use change data derived from similar satellite imagery covering two decades between 1990 to 2009/10. Both are in close agreement as to the rate of growth of oil palm plantations (293% for Gunarso *et al.* vs. 278%, for Carlson *et al.*). Both have similar estimates of the spatial footprint of oil palm plantations in 2009/10 (2.9 vs. 3.2 Mha), and both arrive at similar estimates of the total area of oil palm plantations established on peat soils in 2009/10 (307,000 vs. 402,000 ha). However, the two studies have very different emission estimates (Table 3). Understanding the source of these differences is essential for organizing emission monitoring protocols that will allow the palm oil sector to accurately quantify its CO_2 emissions, as well as identifying strategies to reduce those emissions.

Table 3. Emissions from land use and land cover change from oil palm plantations in Kalimantan

	Carlson *et al.* 2012 Mg CO_2	Agus *et al.* 2013 Mg CO_2
1990 - 2000		
AGB from LUC	309,138,862	65,802,767
Peat oxidation	18,219,572	6,062,943
Peat fires	17,360,229	4,230,649
Total	**344,718,663**	**76,096,360**
2000 - 2010		
AGB from LUC	906,122,095	176,767,485
Peat oxidation	250,194,189	59,466,820
Peat fires	257,480,905	61,354,254
Total	**1,413,797,189**	**297,588,558**

In the first temporal period, the expansion of oil palm plantations on peat soil was relatively small; consequently, the difference in the emissions estimates is due largely to assumptions regarding how land cover classes were defined and how land use change was quantified. Carlson *et al.* (2012b) recognized two forest classes, agroforest and non forest, while Gunarso *et al.* (2013 – this publication) recognized four forest types and four non forest types, as well as separate agroforest and plantation categories. The relative abundance of these categories and their associated carbon stock values was the source of 91% of the variance in the emissions profiles between the two studies (see discussion in Gunarso *et al.,* 2013 – this publication). There is an element of subjectivity to any land cover classification, particularly when attempting to stratify a continuous gradient, which in this case is a transition from undisturbed forest to grassland. In that context, Carlson *et al.,* (2012b) recognized more area as forest along that gradient, while Gunarso *et al.* (2013 – this publication) recognized more area as shrub and grassland.

An alternative methodology is to use pixel-based estimates of carbon density that reflect the variability of ecological gradients (Saatchi *et al.,* 2011). In a companion study, Harris *et al.* (2013 – this publication) used this type of information to model future emissions scenarios for different oil palm development strategies. As part of that effort, they used the polygons developed by Gunarso *et al.* (2013 – this publication) in combination with the pixel-based data from Saatchi *et al.* (2011); their objective was to train the forward looking model using historical land use change data between 2000 and 2010 (see Table 4 in Harris *et al.,* 2013- this publication). That training exercise revealed that the AGC stock values selected for the four forest habitats were similar to the mean values derived from the pixel-based map of carbon density (see Table 4, Harris *et al.,* 2013 – this publication). In contrast, the mean values selected for AGC for shrub categories were about 50% lower for upland habitats and 25% lower for swamp habitats. If we had used mean carbon stock values for shrub land similar to those derived from pixel-based values, the modelled emission estimate from above ground carbon due to land use change in Kalimantan would have increased by about 35 Tg CO_2 yr^{-1} (a 40% increase) between 2000 and 2005 and 86 Tg CO_2 y^{-1}(a 50% increase) between 2006 and 2009/10. Nonetheless, these modified values would still be less than 50% of the modelled estimates reported by Carlson *et al.* (2012b) (see Table 3).

In the temporal period spanning 2001 to 2009/2010, the source of variance is more complex with 65% of the difference attributed to AGC due to LUC with the remaining variance originating from the use of different emissions factors for peat: 17% from peat oxidation and 18% due to peat fire. In the case of peat oxidation, the major factor was the selection of an emission factor of 95 Mg CO_2 ha^{-1} yr^{-1} by Carlson *et al.* (2012b) versus a value of 43 Mg CO_2 ha^{-1} yr^{-1} recommended by Agus *et al.* (2013 – this publication). Similarly, Carlson *et al.* (2012b) assume that on average 203 Mg C ha^{-1} are lost during a fire event on peat soils, while Agus *et al.* (2013 – this publication) recommended values of 90 Mg C ha^{-1} lost from peat soil fires from forest conversion and 30 Mg C $ha^{-1}$from peat soil fires on shrub land. The difference in the modelled estimates are the consequence of the assumption made concerning the depth of peat fires: Carlson *et al.* (2012) assumed a mean burn depth of 33 cm based on studies documenting the impact of fire during *El Niño* drought years (Ballhorn *et al.,* 2009), while *Agus et al.* (2013 – this publication) assumed that on average 15 cm are lost when forest is cleared and burned and 5 cm when shrub land is cleared and burned.

Finally, the time frame in which the comparison is made is an additional factor that can influence the estimation of CO_2 emissions and, subsequently, allocating those emissions to the appropriate economic or social actor. Between 2000 and 2010, Gunarso *et al.* (2013 – this publication) stratified LUC into two five year periods (2000 to 2005 and 2006 to 2009/2010), while Carlson *et al.* (2012b) evaluated change between 2000 and 2010. As the authors point out in the supplementary information of their article: "Due to the 10-year interval between the land cover product and the oil palm coverage, our analysis likely overestimates the amount of intact forest converted to oil palm" (see Supplementary Information, page 7 from Carlson *et al.,* 2012). The adoption of two five year periods allowed Gunarso *et al.* (2013 – this publication) to document the sequential degradation of undisturbed forest to disturbed forest and then to shrub land prior to its conversion to oil palm plantations (see Figure 10, Gunarso *et al.,* 2013 – this publication). The recognition that land is degraded and partially depleted of carbon stocks prior to its conversion to oil palm plantations should be taken into account when estimating the CO_2 emission profile of palm oil. At least some of those historical emissions are more properly allocated to the forest sector due to the intensive logging regimes that characterize the region (Putz *et al.,* 2008) and the impact of forest fires on peat soils that are a combination of bad luck due to drought and the difficulty in fighting wildfires in remote regions of Indonesia (van der Werff *et al*, 2010).

CONCLUSIONS

The rate of expansion of oil palm plantations has been remarkably constant at approximately 7% per annum from 3.5 to 13.1 Mha between 1990 and 2010. The growth in the spatial extent of oil palm plantations has been accompanied by a concomitant increase in the CO_2 emissions, which including all CO_2 emissions from AGC due to LUC, peat oxidation and peat fires, has grown from 92 Tg CO_2 yr^{-1} between 1990 and 2000 to 106 Tg CO_2 yr^{-1} between 2001 and 2005 and 184 Tg CO_2 yr^{-1} between 2006 – 2009/2010. In the third temporal period, 67 Tg CO_2 yr^{-1} (36%) originated from AGC due to LUC and about 90% of these emissions came from deforestation, which has been the source of about 3.5 Mha of the land that has been used for the establishment of new plantations. A smaller area of approximately 3.3 Mha originated on landscapes classified as agroforest or other types of plantations, while 1.7 Mha was developed on land that had been covered by forest in 1990, but which had been degraded to shrub and grassland prior to its conversion to oil palm plantations between 2000 and 2010.

The documentation of this land use trajectory, which includes the transition from undisturbed forest to disturbed forest to shrub land and eventually grassland, dominates the historical CO_2 emissions of the region. Forest degradation, presumably due to intensive logging and its subsequent conversion to shrub land due to wildfire, contributed approximately five times greater emissions (285 Tg CO_2 $yr^{-}1$) between 2006 and 2009/2010 than the AGC due to LUC component of the palm oil emissions profile (55 Tg CO_2 yr^{-1}) for the same period. This explains, in part, why our estimates of oil palm emissions from AGC due to LUC are less than a third of other studies whose models assume that oil palm plantations are established on forests landscapes of high carbon density. The results from a companion article (e.g., Gunarso *et al.,* 2013 – this publication) show that the land cover types used for oil palm plantation expansion has varied over time and among geographic regions; emissions from AGC due to LUC, not surprisingly, track those differences. Emissions from AGC due to LUC can be reduced by promoting oil palm plantation expansion on landscapes with low to moderate levels of AGC, such as the approximately 9 Mha of shrub and grassland in Kalimantan and 8 Mha of agroforest in Sumatra (see Gunarso *et al.,* 2013 – this publication).

Plantations on peat soils now represent about 18% of the spatial footprint of the palm oil industry (2.4 Mha), but represented almost 64% (118 Tg CO_2 yr^{-1}) of the total CO_2 emissions profile in the last temporal period. About 16% (29 Tg CO_2 yr^{-1}) are linked to peat fires, while almost 48% (88 Tg CO_2 yr^{-1}) originate from peat oxidation from existing oil palm plantations operating on peat soils. The emissions from peat fires are one-time events that occurred in the past when forests and shrub land were cleared for new oil palm plantations; these fires are now illegal and unlikely to contribute to future emission profiles. In contrast, emissions from peat oxidation will continue to grow in absolute terms as oil palm companies develop new plantations on existing concessions on peat soils in Sumatra, Kalimantan and Sarawak. Even if the industry acts to halt new development on peat soils, the existing oil palm plantations on peat soils will continue to emit CO_2 at approximately these levels for the foreseeable future. Emissions from peat oxidation can only be terminated by restoring the natural hydrological and ecological conditions that cause peat to form in the first place. Similarly, enforcing the ban the use of fire for land clearing will significantly reduce emissions, especially on peat land.

Just as CO_2 emissions from AGC due to forest degradation are greater than those linked to land use change from the palm oil sector, emissions from peat oxidation from degraded swamp forest with altered hydrological regimes are greater than similar emissions from oil palm plantations (166 vs. 88 Tg CO_2 yr^{-1}). Emissions from degraded swamp forests have declined in the last temporal epoch, in part because logging of remnant swamp forests already has declined, but also because this land cover type is being converted into oil palm plantations. Consequently, CO_2 emissions from degraded swamp forests are being transferred from that category to the oil palm plantation sector.

Finally, by comparing our results with other recently published studies, we show that the uncertainties in estimating CO_2 emissions are subject to the methodological approaches and assumptions used to model emissions from land use and land use change (see review by Agus *et al.,* 2013 – this publication). In spite of the differences in the dimensions of the CO_2 emissions between our models and those employed by other studies (see Carlson *et al.,* 2012b; Page *et al.,* 2011), the overall trends are nearly identical. The rapid expansion of palm oil sector over the last two decades has been responsible for the emissions of several gigatons (Pg) of CO_2 from land use and land use change. Understanding the sources of these emissions, which have been variable in time and space, is a necessary first step in identifying strategies for reducing, eliminating or even reversing the net CO_2 emissions of the industry.

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Published in November 2013
www.rspo.org