REVIEW OF EMISSION FACTORS FOR ASSESSMENT OF CO_2 EMISSION FROM LAND USE CHANGE TO OIL PALM IN SOUTHEAST ASIA

Fahmuddin Agus[1], Ian E. Henson[2], Bambang Heru Sahardjo[3], Nancy Harris[4], Meine van Noordwijk[5] and Timothy J. Killeen[6]

[1]Indonesian Agency for Agricultural Research and Development, Jakarta, Indonesia
[2]Independent Consultant in Tropical Agriculture, Amberwood House, 6 Beaufort Road, Clifton, Bristol BS8 2JZ, UK
[3]Bogor Agricultural University, Bogor, Indonesia
[4]Winrock International, 2101 Riverfront Drive, Little Rock, AR 72202, USA
[5]World Agroforestry Centre (ICRAF), United Nations Avenue, Gigiri PO Box 30677. Nairobi, 00100, Kenya
[6] World Wildlife Fund, 1250 24th St NW, Washington, DC 20037

ABSTRACT

This paper reviews published reports of carbon stocks, emission factors and approaches for estimating CO_2 emissions from land use change and peat soils. Above ground carbon stock values were based on studies representative of major land cover types for Indonesia, Malaysia and Papua New Guinea and include undisturbed upland forests, undisturbed swamp forest, disturbed upland forests, disturbed swamp forest, shrub land and swamp shrub land, with average above ground carbon stock values of 189, 162, 104, 84, 30 and 28 Mg C ha^{-1}, respectively. The time-averaged above ground carbon stock for oil palm plantations, rubber plantations, timber plantations, mixed tree crops (agroforest) and agricultural crop land was estimated at 36, 56, 44, 54 and 11 Mg C ha^{-1}, respectively. The emissions factors linked to land use change among these land cover types is the difference in carbon stocks between any two of these values converted to Mg CO_2 ha^{-1}.

Emissions from the oxidation of peat soils can be estimated by measuring the amount of CO_2 released from the soil surface over discrete time periods (closed chambers), or from the net changes of soil carbon measured over one or several time periods (subsidence studies). Emissions factors are expressed in Mg of CO_2 per unit area per unit of time (Mg CO_2 ha^{-1} yr^{-1}) and vary between 20 to 95 Mg CO_2 ha^{-1} yr^{-1} due to natural variability and disturbance, as well as to uncertainties in the methodological protocols used to measure or model emissions. We recommend 43 Mg CO_2 ha^{-1} yr^{-1} as a time-averaged default value for estimating emissions caused by the oxidation of peat for oil palm plantations operating on peat soils that have a mean water table depth of 60 cm.

Emissions from fires that impact peat soils when used to clear vegetation during plantation establishment vary depending on weather conditions, and can range from zero in wet years to up to more than 50 cm deep during extreme drought linked to *El Niño* events. We recommend using an average value of 15 cm depth of burnt peat soils for estimating emissions from plantations established on forest landscapes and 5 cm depth when clearing shrub land. Emissions from peat fires are similar to those from land use change, because both are one-time emissions generated while establishing a new plantation. In contrast, emissions from the oxidation of peat recur annually throughout the life time of a plantation that operates on partially drained peat soils.

Keywords: *land cover, land use change, carbon stock, above ground biomass, emissions factor, soil carbon, peat, peat oxidation, fire.*

INTRODUCTION

The rapid expansion of oil palm over the past two decades has led to the transformation of large areas of forest and plantation landscapes throughout Southeast Asia and is believed to be one of the major sources of greenhouse gas (GHG) emissions linked to land use in the region (Agus *et al.,* 2010, Ekadinata & Dewi, 2011, Wicke *et al.,* 2011). Demand for palm oil continues to grow and the sector continues to invest in expanded production through multiple strategies, including by increasing yield and avoiding waste, but also by expanding the area under cultivation.

The ongoing and future expansion of oil palm plantations may, or may not, result in future emissions of CO_2, the most significant GHG linked to land use, depending on the type of land cover that is converted for new plantations. For example, if expansion occurs on forest landscapes with high above- and below-ground carbon stocks, then net emissions linked to the sector will be proportionally large. In contrast, if the source of land for new plantations has low C stock value, such as shrub land or agroforest, then future expansion could be considered carbon neutral. In some cases, expansion might actually be carbon positive if the initial carbon stock is less than that of oil palm as is the case with grassland and most types of annual crops.

In addition to land cover change, the conversion and drainage of peat soils creates an additional source of CO_2 emissions (Wösten *et al.,* 2008; Hooijer *et al.,* 2010; Page *et al.,* 2011a; Parish *et al.,* 2007). A major component of emissions originating from peat formations is the result of fire used as a management tool when establishing new plantations; however, CO_2 is also released via anaerobic decomposition once the anoxic conditions of the peat soil profile are modified to facilitate the cultivation of oil palm. Peat swamps form when input from photosynthesis is greater than decomposition leading to the accumulation of partially decayed organic matter (e.g., peat); drainage reverses this equilibrium leading to a gradual decline in the amount of peat stored in the soil. Water management is an important factor in determining the level of CO_2 emissions from oil palm plantations operating on peat soils and has direct implications locally in the form of peat subsidence, which increases susceptibility to floods and droughts, and affects the general environment in the form of CO_2 emission and loss of biodiversity. Emissions caused by the oxidation of peat are recurrent and will continue until the plantation is removed from production and re-flooded to create the anoxic conditions that favor peat formation.

The absolute and relative magnitude of CO_2 emissions from land use change and the conversion of peat soils have been subject to much speculation and vigorous debate because of the uncertainty and variability associated with published reports. This paper provides a review of the scientific and technical literature in order to provide representative values for general use and explains the method of emission calculation associated with land use changes.

METHODOLOGY OF EMISSION CALCULATION

Net emission from land use and land use changes can be estimated based on equations provided by IPCC (2006):

$$\Delta C = \Sigma \text{ (Activity data * Emission factor)} \qquad [1]$$

Where ΔC is the change in carbon stock, *Activity data* is the area undergoing a specific type of land use change that emits carbon, and *Emission factor* is the total loss of carbon stock per unit land area during the specific type of land use change. Carbon emissions can be expressed in terms of C loss or can be converted to CO_2 by multiplying with a factor of 44/12 which is the molecular weight of CO_2 per unit atomic weight of C. If the activity data account for all possible land use changes within a classification system, equation [1] can be rewritten as:

$$\Delta C = \sum_{ij} A_{ij} \left[\Delta C_{ij\,LB} + \Delta C_{ij\,DOM} + \Delta C_{ij\,SOIL}\right] / T_{ij} \qquad [2]$$

Where

ΔC	= the change in all carbon pools in a unit of time
A_{ij}	= the activity data or area of land use under land cover type *i* that change to type *j* during an observation period
$\Delta C_{ij\,LB}$	= change in carbon stock in the living biomass (above + below ground)
$\Delta C_{ij\,DOM}$	= change in carbon stock in dead organic matter, especially dead vegetation (above + below ground)
$\Delta C_{ij\,SOIL}$	= the change in carbon stock in the soil
T_{ij}	= the length of the observation period and time scale of calculation

The living biomass (LB), dead organic matter (DOM) or necromass, and soil organic matter (SOIL) are the main carbon pools. There are more published emission data for living biomass and soil but below ground biomass and necromass are rarely assessed (Hairiah *et al.,* 2001). Secondary forests and newly planted agricultural lands may have high amounts of above ground necromass (Hairiah & Rahayu, 2007), but this decomposes on the ground within a few years resulting in a lower C stock when time-averaged. Due to the few data available necromass is not included in the national or sub-national calculations shown in Agus *et al*. (2013 – this publication).

Carbon in above ground biomass and in necromass together constitutes the total above ground carbon stock. The below ground biomass can be estimated from root/shoot ratios. Default values for the root/shoot ratio of tree biomass are around 1/4. However, the ratio varies depending on species, soil and climatic conditions (Hairiah & Rahayu, 2007).

CARBON STOCK ESTIMATES

There is a wide range of estimates in the literature of carbon stock in plant biomass and we provide a review of those values for the 22 land cover types used in the companion studies (Table 1: see Gunarso *et al.,* 2013 and Agus *et al.,* 2013, this publication). The sources mainly include only the carbon in above ground biomass as there is very little reliable data for below ground biomass and soil organic matter for most land cover types, a data deficiency that is compounded by very high levels of natural variability in both natural and human altered ecosystems. Carbon stock estimates for undisturbed natural vegetation types represent values from habitats assumed to be at equilibrium and, as such, are effectively equivalent to time-averaged values; however, values from disturbed habitat types represent their status at the time of conversion and are not equivalent to a time-averaged value. Values for all human altered categories, such as oil palm, rubber plantations, timber and pulp plantations, agroforest and intensive agricultural are time-averaged values that reflect the life cycle of individual production systems.

Above Ground Biomass

Published reports on forest carbon have evolved over time. Early papers tended to have relatively high estimates of plant biomass carbon stock in undisturbed forest, while more recent ones tend to have much lower estimates as the scientific community has become more interested in the global carbon cycle and the impact of disturbance on ecosystem function. For example, Palm *et al*. (1999) estimated carbon stocks in the plant biomass of primary (undisturbed) forest that ranged from 207 to 405 Mg C ha^{-1}, while secondary (disturbed) forest in Kalimantan stores between 58 to 203 Mg C ha^{-1} (Brearly *et al.*, 2004; Rahayu *et al.*, 2005; Harja *et al.*, 2011). Laumonier *et al.* (2010) working in South Sumatra found above ground forest carbon stocks to be between 135-240 Mg C ha^{-1}, with an average of 183 Mg C ha^{-1}. Most of these estimates were based on the non-destructive measurement of tree girth with reference to a wood density database maintained at the World Agroforestry Centre (ICRAF), resulting in tree biomass and carbon stock estimates based on only one of a few allometric relationships. The estimates of Harja *et al.* (2011) used the allometry of Chave *et al.* (2005) which is more conservative compared to those of Basuki *et al.* (2009), Brown *et al.* (1989) and Ketterings *et al.* (2001).

A recent study derived from the National Forest Inventory of Indonesia, covering more than 2000 forest plots scattered across the country and stratified by ecological zone. has provided a significantly, and surprisingly, lower estimate of average forest C stock, ranging from 93 Mg ha^{-1} for undisturbed forests to 74 Mg ha^{-1} for low density disturbed forests (Ekadinata & Dewi, 2011; Harja *et al.*, 2011). The level of replication for undisturbed forest, however, was lower than that for other types of forest cover, and quality control of forest inventory data, required by allometric equations that depend on wood density, may be insufficient. Consequently, we recommend using mean values from all listed results (Table 1). Estimates for rubber plantations ranged from 25 to 143 Mg C ha^{-1} (Ziegler *et al.*, 2011) with a mean time-averaged estimate of 56 Mg C ha^{-1}. Estimates for timber and pulp plantations (Table 1) are lower due to the shorter life cycle that characterizes that industry, while mixed tree crops or agroforest landscapes are highly heterogeneous, reflecting age of settlements and population density.

For oil palm plantations, the carbon stock data are surprisingly variable considering the oil palm is a tree with relatively simple allometry and is cultivated in uniform stands comprised of equal age cohorts. Differences occur largely due to the assumptions and components included in the modeling or measurement protocol, with only some studies including persistent leaf bases, dead fronds (e.g., necromass), ground cover and roots. On average, necromass on the surface will decompose within 12-18 months (Khalid *et al.*, 2000) and, in some cases, may increase soil carbon stock (Mathews *et al.*, 2010; Haron *et al.*, 1998) and nutrient supply (Chiew & Rahman, 2002; Salétes *et al.*, 2004). If data are provided for necromass, however, the decomposition rate should be taken into account when calculating time-averaged necromass stock; otherwise, the accounting for the decomposing necromass will result in double accounting in a carbon stock assessment. Estimates of time-averaged above ground carbon stock for oil palm range from 23 to 60 Mg C ha^{-1}. We recommend using the mean value of 36 Mg C ha^{-1} (Table 1).

Table 1. Above ground carbon stocks (AGC) of different land use classes. Estimates for undisturbed natural vegetation types represent values from habitats assumed to be at equilibrium, while values from disturbed habitat types represent their status at the time of conversion. Values for all human altered categories, such as oil palm, rubber plantations, timber and pulp plantations, agroforest and intensive agricultural are time-averaged values that reflect the life cycle of individual production systems. Unless otherwise stated, data are for above ground biomass only and were obtained in Indonesia.

Land use type and description [(1)]	AGC (Mg ha^{-1})	Reference; remarks
UNDISTURBED UPLAND FOREST Natural forest with dense canopy; no signs of logging roads.	399	Proctor *et al.* (1983), in Malaysia
	306	Palm *et al.* (1999), Tropical rainforests
	300	World Agroforestry Centre (2011), Southeast Asia
	252	Prasetyo *et al.* (2000), Indonesia
	250	Houghton (1999); DeFries *et al.* (2002), the tropics
	230	Rahayu *et al.* (2005), Nunukan , East Kalimantan, Indonesia
	229	Omar (2010), Malaysia
	225	IPCC (2006), tropical Asia
	202	Hoshizaki *et al.* (2004), Primary dipterocarp forest in Pasoh Forest reserve, Peninsular Malaysia
	195	BAPPENAS (2010), Indonesia
	180	Laumonier *et al.* (2010); Southern Sumatra, Indonesia, disturbed and undisturbed forests
	177	Morel *et al.* (2011), Sabah, Malaysia
	164	Gibbs *et al.* (2007), for tropical Asia
	150	IPCC (2006) general data for tropical rainforest
	121	Griscom *et al.* (2009), pre-logged forest, Indonesia.
	55	Bryan *et al.* (2010), pre-logged forest, Papua New Guinea
	104	Stanley (2009), pre-logged forest, Indonesian territory of Papua
	93	Harja *et al.* (2011), Indonesia
	83	Pinard & Putz (1996), pre-logged forest, Malaysia
	61	Fox *et al.* (2010), pre-logged forest, Papua New Guinea
Average	189±87	

Table 1. Above ground carbon stocks (AGC) of different land use classes (continued).

Land use type and description [(1)]	AGC (Mg ha^{-1})	Reference; remarks
DISTURBED UPLAND FOREST Natural forest area with logging roads and forest clearings.	250	World Agroforestry Centre (2011), logged forest, high density, Indonesia
	203	Rahayu *et al.* (2005), Nunukan , East Kalimantan, Indonesia
	180	IPCC (2006), for tropical Asia
	170	MoF (2008), Indonesia
	153	Saatchi *et al.* (2011) average of 43 M ha PNG forests with 30% canopy cover threshold
	150	World Agroforestry Centre (2011), logged forest, low density
	134	Omar *et al.* (2010), Malaysia
	132	Morel *et al.* (2011), average of 1970-2007 logged forest in Sabah, Malaysia.
	93	Palm *et al* (1999), logged forest, the tropics
	91	Griscom *et al.* (2009), above ground C pre-logging minus C lost from logging, the tropics
	87	Henson (2005a, 2009), logged forest, Malaysia
	74	Harja *et al.* (2011), Indonesia
	71	Stanley (2009), logged forest, PNG
	65	Morel *et al.* (2011), early secondary forest, Sabah, Malaysia
	60	Pinard & Putz (1996), logged forest, Malaysia
	57	Morel *et al.* (2011), medium disturbance secondary forest, Sabah, Malaysia
	55	Morel *et al.* (2011), late secondary forest, Sabah, Malaysia
	45	Fox *et al.* (2010), logged over forest, PNG
	43	Pinard & Putz (1996), logged over forest, Malaysia
	40	Bryan *et al.* (2010), logged over forest, PNG
	37	Bryan *et al.* (2010), logged over forest, PNG
Average	104±59	
UNDISTURBED SWAMP FOREST Forest wetland with temporary or permanent inundation	200	World Agroforestry Centre (2011), undisturbed swamp forest, Indonesia
	196	MoF (2008), Indonesia
	90	Harja *et al.* (2011), Indonesia
Average	162±51	
DISTURBED SWAMP FOREST Swamp forest with signs of logging canals, or degradation.	155	MoF (2008), Indonesian Forest Carbon Alliance study, Indonesia
	120	World Agroforestry Centre (2011), logged swamp forest, Indonesia
	78	Harja *et al.* (2011), Indonesia
	64	Morel *et al.* (2011), Sabah, Malaysia, low disturbance forest
	52	Morel *et al.* (2011), Sabah, Malaysia, high disturbance peat forest
	33	Morel *et al.* (2011), Sabah, Malaysia, medium disturbance swamp forest
Average	84±42	

Table 1. Above ground carbon stocks (AGC) of different land use classes (continued).

Land use type and description (1)	AGC (Mg ha^{-1})	Reference; remarks
UNDISTURBED MANGROVE Area along the coastline with high density of mangrove trees.	200	World Agroforestry Centre (2011), Indonesia
	170	Komiyama *et al.* (2008), Indonesia
	135	Putz & Chan (1986), study in Malaysia
	85	Harja *et al.* (2011), Indonesia
Average	148±43	
DISTURBED MANGROVE Logged-over and partly degraded mangrove area.	120	Komiyama *et al.* (2008), Indonesia
	105	Ong *et al.* (1982), Malaysia
	100	World Agroforestry Centre (2011), logged mangrove forest, Indonesia
	77	Harja *et al.* (2011), Indonesia
Average	101±15	
RUBBER PLANTATION Including rotational agroforestry rubber	97	Lasco & Pulhin (2004), rubber monoculture, Southeast Asia
	89	Palm *et al.* (1999), permanent agroforestry (jungle) rubber, the tropics
	46	Palm *et al.* (1999), rotational agroforestry (jungle) rubber the tropics
	53	Corpuzm *et al.,* (2011), monoculture, Philippines
	36	Prasetyo *et al.,* (2000), (jungle) rubber, Jambi, Indonesia
	31	World Agroforestry Centre (2011), estate on peat, Indonesia
Average	58	
OIL PALM PLANTATIONS Large-scale plantations recognizable in satellite images	60	Rogi (2002), Indonesia
	47	Syahrinudin (2005), recalculated based on biomass curve, Indonesia
	47	World Agroforestry Centre (2011), various kinds of estate, mainly rubber and oil palm
	40	van Noordwijk *et al*. (2010), averaged over 25 years, based on observations in Sumatra and Kalimantan, Indonesia
	40	Henson (2005b), estimated using OPRODSIM based on medium sized fronds, including oil palm roots and shoot, ground cover, pruned frond piles, shed frond base piles and male inflorescence piles, national average over 30 year
	36	Henson (2009), Malaysian national average over 30 year including the palm components as in Henson (2005b)
	31	World Agroforestry Centre, (2011), estate on peat (mainly oil palm), Indonesia
	30	Germer & Sauerborn (2008), the tropics
	29	Recalculated from Henson & Dolmat (2003) from a study of 1 to16 year old oil palm on peat in Malaysia: trunk (16 Mg C ha^{-1}), fronds (5.6 Mg C ha^{-1}), and male inflorescence (7.5 Mg C ha^{-1}) for a planting density of 160 palms ha^{-1}.
	26	Morel *et al.* (2011), Sabah, Malaysia
	23	Kheong (MPOC, unpublished), 45.3 t C ha^{-1} at 20 years after planting is considered to be the peak C stock; time-average C stock calculated as half of the peak C stock, Malaysia.
	23	Corley & Tinker (2003), Malaysia
Average	36±11	

Table 1. Above ground carbon stocks (AGC) of different land use classes (continued).

Land use type and description [(1)]	AGC (Mg ha^{-1})	Reference; remarks
TIMBER PLANTATION Monoculture timber plantations	70	World Agroforestry Centre (2011), timber plantation, Indonesia
	60	World Agroforestry Centre (2011), timber plantation, Indonesia
	40	Matsumura *et al.* (2008), a study in Java of a 10-yr Acacia cycle interpolated from an 8-yr cycle, the most common cycle currently used.
	37.5	Nurwahyudi & Tarigan (2001) for *Acacia* 7 yr old, Indonesia
	37	Palm *et al.* (1999), for pulp trees in the tropics
	35	Matsumura *et al.* (2008), Peninsular Malaysia
	29	Morel *et al.* (2011), Sabah, Malaysia
Average	44±14	
MIXED TREE CROPS Also known as agroforestry.	77	World Agroforestry Centre (2011), agroforest on peat, Indonesia
	30	Rahayu *et al.* (2005), Nunukan , East Kalimantan, Indonesia
Average	54±24	
UPLAND SHRUB LAND Upland (well drained sols), small trees and shrubs	35	IPCC (2006) for tropical shrub land
	30	Istomo *et al.* (2006), Indonesia
	29	Jepsen (2006), Sarawak, Malaysia
	27	World Agroforestry Centre (2011), Indonesia
Average	30±3	
SWAMP SHRUB LAND Wetland (periodically or permanently inundated), small trees and shrubs	35	IPCC (2006) for tropical shrub land
	30	Istomo *et al.* (2006), Indonesia
	29	Jepsen (2006), Sarawak, Malaysia
	18	World Agroforestry Centre (2011), shrub on peat, Indonesia
Average	28±6	
INTENSIVE AGRICULTURE Open area, usually intensively managed for annual row crops.	12.5	Hashimotio *et al.*, (2000) based on biomass estimates of 50 Mg ha^{-1} for 10-12 yr fallow rotation in Kalimantan, Indonesia
	12	World Agroforestry Centre (2011), cropland, Indonesia
	10	Murdiyarso & Wasrin (1996), Indonesia
	8	World Agroforestry Centre (2011), cropland on peat, Indonesia
Average	11±2	
SETTLEMENTS Homestead, urban, rural, harbor, airports, industrial areas.	10	BAPPENAS (2010), assuming one third of the homestead area is allocated for home gardens (mixed tree crops and agriculture), Indonesia
	4	World Agroforestry Centre (2011), Indonesia
Average	7±3	
GRASSLAND Upland (well drained soils), dominated by grasses.	4	Rahayu *et al.* (2005), Nunukan, East Kalimantan, Indonesia
	2	World Agroforestry Centre (2011), time-averaged value, Indonesia
Average	3±1	

Table 1. Above ground carbon stocks (AGC) of different land use classes (continued).

Land use type and description [1]	AGC (Mg ha^{-1})	Reference; remarks
SWAMP GRASSLAND Wetland (periodically or permanently inundated) dominated by grasses	2	Palm *et al.* (1999), the tropics
RICE FIELD Paddy field usually irrigated.	2	Palm *et al.* (1999), the tropics
COASTAL FISH POND Open area on coast always inundated	0	Assumed
BARE SOIL Area with little or no woody vegetation	36	Recommended as a default value when modeling CO_2 emissions from land use change linked to oil palm, because it is a transitional category with various original land cover source [2]
MINING Open area with mining activities.	0	Assumed

[1] The detailed description is provided by Gunarso *et al.* (2013, this publication).
[2] Assumed to be the same as that of oil palm plantation. The C stock is mostly in the form of necromass.

Carbon Stock in Mineral Soils

Globally, soils store about 3.3 times the amount of C present in the atmosphere and about 4.5 times the C found in above ground terrestrial biota. The soil carbon stock varies with land use and land management systems; hence, the uncertainty in soil carbon stock data is high. Despite the advances in soil survey around the world, data on soil bulk density is scarce relative to that on soil organic carbon content. Both variables are needed for the calculation of volume-based soil organic C stock and its possible change; consequently, a modeling approach is required to fill the gap between the available soil data in order to produce a soil carbon assessment.

Carbon stock in the top 30 cm of soil in humid tropical forests ranges from 5 to 180 Mg ha^{-1} (IPCC, 2006) and changes in soil carbon content are influenced by various factors such as soil tillage and organic matter inputs. Mean estimates of carbon stock for humid tropical soils suitable for oil palm may be as high as 120 ± 60 Mg C ha^{-1} (Germer & Sauerborn, 2008) and as much as 30% of soil organic matter may be lost when forest is converted to plantations (Murty *et al.*, 2002). This would translate into an initial carbon loss of about 36 ± 18 Mg C ha^{-1} when the land is converted to a plantation, but when low biomass land cover types are converted to plantations, soil carbon stock might increase. However, there are many inconsistencies and uncertainties associated with soil carbon stock change as affected by land use change in mineral soils, especially from land use change from forest to oil palm plantations (Table 2). Most problematic is the fact that data for initial carbon stock are generally not available. Consequently, it is not possible to make reliable conclusions regarding the dimensions of CO_2 emissions from mineral soil carbon, and hence this component of CO_2 emissions is not considered in the analysis by Agus *et al.* (2013 – this publication).

Table 2. Reported change in carbon stock in mineral soil as affected by land use change

Initial land use	Subsequent land use	Change in C stock, references
Logged forest	Oil palm	32% and 15% increase of soil organic carbon in the 0-45 cm layer, in the first and second cycles respectively, of oil palm under intensive organic matter management Mathews *et al*. (2010).
Oil palm, 5 years after planting	Oil palm, 20 years after planting	Increase of soil organic carbon (C_{org}) in the avenue and weeded circles from 0.82% to 2.21%. Increase of C_{org} from 0.82% to 3.09% in the pruned frond windrows occupying 20% of the area and receiving an equivalent of 4.8 Mg C ha^{-1} yr^{-1} from palm fronds. (Haron *et al*. 1998).
Primary forest	Secondary forest, and oil palm plantations	C_{org} was 29±9 g kg^{-1} and 21±8 g kg^{-1} under the canopy and gap areas respectively of a primary forest, 17±3 g kg^{-1} and 14±4 g kg^{-1} under the canopy and gap area of a secondary forest and 16 ±8 g kg^{-1} under an oil palm plantation. The three land cover types were adjacent to each other in Pasoh, Peninsular Malaysia (Adachi *et al*. 2006).
Secondary forest, 30 years after logging	Oil palm 9 and 19 years old, rubber 30 years old	No significant change from about 33 g kg^{-1} in 0 – 10 cm soil depth (Tanaka *et al*. 2009).
Forest	Long term agricultural cultivation	30% decrease in soil C stock (Murty *et al*. 2002) in soils suitable for oil palm with 120±60 Mg C/ha (IPCC, 2006)
Forest	Degraded land	50% decrease in soil C stock (Murty *et al*., 2002; Germer & Sauerborn, 2008).
Forest	No tillage system	Increase of 0-10% organic C with crop residue recycling (Murty *et al*., 2002; Germer & Sauerborn, 2008).
Forest	Plantation	30% decrease in soil C stock (Murty *et al*. 2002; Germer & Sauerborn, 2008).
Degraded land	Plantation	30% increase in soil C stock (Murty *et al*., 2002).

EMISSIONS FROM PEAT SOILS

Distribution and Carbon Stock of Peat Soil

Peat soil is one of the most important sites for carbon storage under tropical forest conditions. Carbon is stored in plant biomass above and below ground, in necromass and in the soil, the largest stock of carbon in peat soil being in the below-ground peat itself. For example, a one meter layer of peat stores between 300-700 Mg C ha^{-1} (Page *et al*., 2002; Agus & Subiksa, 2008); in contrast, the above ground biomass of a primary forest stores only 90-200 Mg C ha^{-1} (Table 1). The carbon rich organic matter in peat builds up under the anoxic conditions characteristic of swamp forests over 3000 to >8000 years. Once the forest is cleared and drained, however, peat will be decomposed by oxidization and a peat formation can disappear within decades (Parish *et al*., 2007; Hooijer *et al*., 2006; Rieley & Page, 2008). The wide-scale conversion of peat formations and the resultant oxidation of peat soils represent a very large source of actual and potential CO_2 emissions.

The earlier estimate of Indonesian peat soil area was about 21 Mha (Wahyunto *et al*., 2004, 2005, 2006), which is equivalent to about 83% of the reported peat soil of Southeast Asia and which stores an estimated 37.2 Pg of carbon (Hooijer *et al*., 2006; Wahyunto *et al*., 2004, 2005, 2006). However, these estimates were based on maps generated using Landsat TM images with little ground truth data, especially for Papua. Soil surveys have progressed in Indonesia and field data have been plotted against an alternative map of peat soils to produce a revised estimate of Indonesian peat soil area of 14.9 Mha (Ritung *et al*., 2011). The greatest reduction in area was in Papua where soil survey data were poor and the estimated extent of peat was reduced by more than 50% (Table 3). The extent of peat soils in Sumatra and Kalimantan each showed a reduction of around one million hectares, estimates that are in line with other recently published values of 13.0 Mha (Miettinen *et al*., 2012).

A study of two peat domes in South Sumatra (Airsugihan and Telukpulai), three in Central Kalimantan (Sebangau, Block B and Block C) and one in West Papua (Teminabuan) used a 3D modeling approach using optical images from Landsat ETM+ and synthetic aperture radar data from the NASA Shuttle Radar Topographic Mission (Jeanicke *et al*., 2008). The sites in Central Kalimantan and South Sumatra were selected because of their representative character and the availability of around 750 peat thickness measurements; Teminabuan was chosen to extend the geographical range of the study and to include another type of Indonesian peat dome in the modeling process, even though detailed peat thickness data were lacking for that locality. The results from this five dome study were then extrapolated across the nation based on three key assumptions: average peat depth of 4.5±0.85 m, total peat soil area of 21 Mha as projected by Wetlands International (Wahyunto *et al*., 2004; 2005; 2006), and average carbon content of 58 kg m^{-3}. The total carbon store in Indonesian peat formations was then estimated to be 55±10 Pg (Jaenicke *et al*., 2008).

Subsequently, field based verification of the Wetlands International peat soil maps led to a revised and stratified peat soils map with 5.2 Mha of shallow peat (50-100 cm), 3.9 Mha of medium deep peat (100-200 cm), 2.9 Mha of deep peat (200-300 cm) and 3.0 Mha of very deep peat (>300 cm), giving a total of 15 Mha (Ritung *et al*., 2011). The very deep peat may reach beyond 800 cm at the center of some domes, but the overall average peat thickness is unlikely to exceed 300 cm (Ritung *et al*., 2011), although some authors estimate mean thickness at between 550 and 700 cm (Miettinen *et al*., 2012). If one assumes 300 cm is the average peat depth and 60 kg C m^{-3} the average carbon content (Page *et al*., 2002), then the estimated carbon storage for the 15 Mha of Indonesian peat formations would be approximately 27 Pg (1800 Mg C ha^{-1}), about one half the 46.6 Pg C estimated by Page *et al*. (2011b) and almost a third of the 55±10 Pg estimated by Jeanicke *et al*. (2008).

In Malaysia, a recent estimate of peat soil area is 2.4 Mha (Table 4), with about two thirds of the total being found in Sarawak; estimates of the carbon stored in Malaysian peat soil ranges from 7.9 to 9.2 Pg (Page *et al*., 2011a). In Papua New Guinea, the distribution and extent of peat soil is not well documented, ranging from 0.05 to 2.9 Mha, with the best estimate around 1.1 Mha and peat carbon stock estimated at about 1.4 Pg, and ranging between 0.6 to 1.7 Pg (Page *et al.,* 2011b).

Table 3. Areas (Mha) of peatland in Sumatra, Kalimantan and Papua, Indonesia as reported by three sources.

Region	Wahyunto *et al.* (2003, 2004, 2006)	Ritung *et al.* (2011)	Miettinen *et al.* (2012)
Sumatra	7.2	6.4	7.2
Kalimantan	5.8	4.8	5.8
Papua	7.8	3.7	n.a.
Total	20.8	14.9	>12.0

n.a. : Not available

Table 4. Extent of peat soils for the three regions of Malaysia as reported by three sources

Region	Gunarso *et al.* (2013)	Omar *et al.* (2010)	Miettinen *et al.* (2012)
Peninsular	719,909	716,944	854,884
Sarawak	1,308,086	1,588,142	1,442,845
Sabah	117,035	121,514	191,330
Total	2,145,030	2,426,600	2,489,059

Greenhouse Gas Emission Due to Peat Oxidation

Land use change from peat forest to plantation, especially for those plantations requiring relatively deep drainage, will change the function of the peat soil from a net carbon sequester to a net carbon emitter (Parish *et al*., 2007; Agus & Subiksa, 2008). Numerous studies have shown that peat oxidation due to drainage is a long-term process that will create a long-term source of CO_2 emissions (Stephen & Johnson, 1951; Stephen, 1956; Wösten *et al.*, 1997). Data on the dimensions of these emissions vary widely as there are many interacting factors influencing this process. The most frequently reported factor determining CO_2 emission from peat is the depth of the groundwater table, which is affected by drainage (Hooijer *et al*., 2010, 2012; Couwenberg *et al*., 2010; Jauhiainen *et al*., 2005, 2012; Page *et al*., 2011a; Husnain *et al*., Pers. Comm.; Dariah *et al.* Pers.Comm.). The stored carbon may be lost from biomass, necromass and peat soil by burning and/or decomposition, and deep drainage (i.e., greater than 60 cm) greatly increases the rate of peat oxidation and the risk of peat fire (Page *et al*., 2002; van der Werf *et al*., 2008).

In addition to CO_2, methane (CH_4) and nitrous oxide (N_2O) are also emitted during land conversion particularly during fire events; nonetheless, CO_2 dominates the GHG emission profiles linked to land use on peat soils due to the total volumes of CO_2 emitted, even though CH_4 and N_2O have greater global warming potentials (GWPs): 21 for CH_4 and 296 for N_2O in comparison with CO_2 (IPCC, 2006). For example, CH_4 emissions occur under anaerobic conditions through the action of methanogenic bacteria (Holzapfel-Pschorn & Conrad, 1985), but when the water table is deeper than 20 cm CH_4 emissions are rarely detectable. The availability of easily decomposable material such as leaf litter, which is abundant on the surface in relatively undisturbed sites, is an important factor promoting CH_4 emission (Jauhainen *et al.,* 2008). These CH_4 fluxes in undrained forest represent only about 0.9% of GHG emission in the form of CO_2-e (Jauhiainen *et al.,* 2005; Inubushi *et al.,* 2003), while in drained forests and agricultural areas CH_4 emission levels represent only 0.01% to 0.2% relative to that of CO_2 (Melling *et al.,* 2005; Jauhiainen *et al.,* 2008).

Similarly, N_2O is emitted as a by-product of nitrification (conversion of NH_4^+ to NO_3^-) and denitrification (conversion of NO_3^- to N_2O or N_2) under low O_2 availability (Inubushi *et al.,* 2003). Increased availability of NO_3^- enhances N_2O emissions from soils (Yanai *et al.,* 2007) and the relative contribution of N_2O released from agricultural land can be very high. Nonetheless, the range of measured N_2O emission varies widely depending on many factors linked to management practices and transient weather events; thus, any modeled estimate of GHG emission based on regional or landscape level assumptions are inherently uncertain. Consequently, N_2O emissions were not considered as part of a regional effort to estimate GHG emissions linked to palm oil production (see Agus *et al.*, 2013 – this publication). It should be noted, however, that by only focusing on CO_2, the total GHG emissions will be somewhat underestimated.

In some instances CO_2 emission from the surface of peat forest can be higher than that from peat under oil palm, which can be attributed to the contribution of CO_2 by root-related respiration that is higher under forest due to higher root density and activity (Melling *et al.*, 2005). However, this increased emission represents recycled CO_2 fixed by photosynthesis and thus does not represent a net increase in atmospheric CO_2. In the rhizosphere, a term used to describe the soil zone dominated by the roots, bacterial and fungal respiration is dependent on inputs from the living roots and, although it is not 'autotrophic' in the original meaning of the term, many researchers who study peat refer to all respiration linked to current and recent photosynthesis as being 'autotrophic'. The proportion of plant-based respiration (e.g., autotrophic) to peat-based respiration (heterotrophic) is presently a source of uncertainty. Two approaches can be taken to address this problem.

(i) Separation of plant-based from peat-based respiration by the use of root exclusion or isotope labeling techniques and;
(ii) Monitoring carbon stock change (bulk density and carbon content changes with peat depth) of different land use/land cover types.

Without consistent use of such approaches there will continue to be uncertainty concerning the precise effects of agricultural operations and oil palm expansion on peat CO_2 emission.

Research in temperate zones has found that 55-65% of peat respiration was generated via root+rhizosphere interactions, which are considered to be autotrophic, and that only about 35-45% of the soil respiration could be classified as a GHG emission due to the decomposition of peat (Knorr *et al*., 2008). In another study, the contribution of peat-related decomposition was shown to be as high as 42%, while root+rhizosphere respiration was 41% and the remainder, 17%, was the consequence of above ground litter decomposition (Mäkiranta *et al*., 2008). Root-related respiration in oil palm plantations in Southeast Asia has been found to be 38% and 40% of the total measured at the soil surface by closed chambers (Agus *et al*., 2010; Melling *et al*., 2007). In transects established in *Acacia* plantations in Riau province, Indonesia, CO_2 emission near the trees was about 21% higher than at the midpoint between trees, a difference that was attributed to autotrophic respiration linked to roots (Jauhiainen *et al*., 2012). Unlike oil palm plantations, however, planting density in *Acacia* plantations is high (2 m x 2 m) and all areas in these plantations are probably influenced by roots. The root-related autotrophic component of different land cover types is therefore uncertain, and adopting total CO_2 efflux data will overestimate net CO_2 emissions.

For oil palm plantations on peat, published reports from closed chamber measurements of soil surface flux range from 20 to 57 Mg CO_2 ha^{-1} yr^{-1}, with an average value of 38 Mg CO_2 ha^{-1} yr^{-1} (Reijnders & Huijbregts, 2008; Wicke *et al.,* 2011; Murdiyarso *et al.,* 2010; Murayama & Bakar, 1996; Jauhiainen *et al.,* 2001; Melling *et al.,* 2005; Melling *et al.,* 2007; Agus *et al.,* 2010). Recent studies in Jambi, Sumatra fall within the middle of this range, with mean values corrected to discount for plant-based, or autotrophic, respiration of 38±2 Mg CO_2 ha^{-1} yr^{-1} for 6 year old oil palm and 34±3 Mg CO_2 ha^{-1} yr^{-1} for 15 year old oil palm (Dariah *et al.,* Pers. Com.). Similarly, new studies from Sumatra and Kalimantan found CO_2 emissions under oil palm plantations on peat varied widely from 18±13 to 66±24 Mg CO_2 ha^{-1} yr^{-1} with the overall average of 39±19 Mg ha^{-1} yr^{-1}; the highest CO_2 emission was observed in oil palm plantations in Riau (Husnain *et al.,* Pers. Com.).

Another approach for estimating CO_2 emissions from peat soils is based on measurements of subsidence over time, which when coupled with the monitoring of changes in bulk density and carbon content, can provide an independent estimate of peat oxidation. Recent studies in Riau and Jambi Provinces of Indonesia exemplify the subsidence technique and provide a different, and much larger, estimate of net CO_2 emissions (Hooijer *et al.,* 2012). However, the experimental design of this study did not account for potential differences in bulk density within the soil profile and the initial mean bulk density of the soil was assumed to be the same as the bulk density measured just below the average water table depth of the subsequent land use. In addition, the model used to estimate changes in carbon stock assumed a constant carbon content of 55% throughout the soil profile and across all sites—an assumption that disregards spatial variability and changes in carbon content linked to the degradation of peat over time. Carbon content of peat is variable and is the basis of the peat classification system which defines "fibric"," hemic" and "sapric" types of peat; essentially, as peat is oxidized, it becomes more carbon dense (Wurst *et al.,* 2003). In summary, the study by Hooijer *et al.* (2012) estimated soil decomposition to represent about 92% of subsidence and the remaining 8% was attributed to shrinkage and compaction, which produced a modeled emission estimate of 100 CO_2 Mg ha^{-1} yr^{-1} for the first 25 year cycle of an oil palm plantation operating on peat soils, or a value of 95 Mg CO_2 ha^{-1} yr^{-1} when annualized over a 30-year rotation cycle (Page *et al.,* 2011a).

Other studies have shown that the decomposition component of land subsidence was about 60% (Wösten *et al.,* 1997), 60% (Hooijer *et al*., 2010) or 40% (Couwenberg *et al*., 2010). In the Everglades region of Florida, long-term studies of peat subsidence following conversion to agriculture have shown losses of about 40% of their original volume in the 40 years since the onset of drainage (Stephen & Johnson, 1951). Although these studies unequivocally document that peat oxidation following drainage is a long-term source of CO_2 emissions, they have also demonstrated that the initial cause of subsidence after drainage is due to physical compaction (Stephen & Johnson, 1951; Stephen, 1956; Wösten *et al.,* 1997).

As stated previously, all of these estimates are contingent upon water table depth and Hooijer *et al*. (2006, 2010) developed a model that correlates drainage depth with CO_2 emissions such that for each 1 cm of drainage depth there is an emission of about 0.91 Mg CO_2 ha^{-1} yr^{-1}. For a typical oil palm plantation with a water table situated at about 60 cm below the soil surface, the estimated emission would be about 54 Mg CO_2 ha^{-1} yr^{-1}. However, this relationship is based largely on experiments using closed chambers in which there was no separation between autotrophic respiration mediated by roots and heterotrophic respiration linked to microbial decomposition (Hooijer *et al*., 2006). In order to avoid over estimating CO_2 emissions by using total soil respiration, we recommend using the emission factor developed by Hooijer *et al*. (2010) modified by a coefficient of 0.79 to correct for the root-related emission based on the studies of Jauhiainen *et al*. (2012). The complete equation is therefore:

$$E_{bo} \text{ (Mg CO}_2\text{ ha}^{-1}\text{ yr}^{-1}) = 0.91*0.79*\text{ drainage depth (cm)} \quad [3]$$

Using Equation 3 for an oil palm plantation with a water table depth that varies between 50 and 70 cm gives estimated emissions that range between 36 to 50 Mg CO_2 ha^{-1} yr^{-1} with an average of 43 Mg CO_2 ha^{-1} yr^{-1}. This is the value we recommend as a default when estimating emissions from oil palm plantations operating on peat soils.

Emissions Due to Burning

Fires have direct on-site effects resulting in degradation of vegetation, loss of biodiversity, destruction of property and occasional loss of life, while off-site impacts include carbon emissions, smoke and its impacts on human health. Wild fire can be caused by natural phenomena such as lightning, but human activities, particularly land preparation for agriculture and plantation estates, are among the most important causes (FAO, 2011; Herawati & Santoso, 2011.).

The impacts of fire on GHG emissions in Southeast Asia are considered to be of historical significance and loom large in any discussion or estimate of CO_2 emission and land use. The largest single source of emission in recorded history is believed to be the GHG emissions from forest and peat fires in Southeast Asia during the exceptionally strong 1997/98 *El Niño* event, which led to the release of an estimated 2.9 to 9.4 Pg CO_2 (Page *et al.,* 2002). In the last decade, a combination of remote sensing data and top-down models have been used to monitor the annual variation in fire related emissions, which have fluctuated between 0.09 and 1.3 Pg CO_2 yr^{-1} (van der Werf *et al.,* 2008, 2010). Annual estimates are highly variable, and during the average 2006 *El Niño*, fire emission in Kalimantan was more than 30 times greater than those during the 2000 *La Niña*, which is an exceptionally wet episode that alternates with *El Niño* droughts (van der Werf *et al.,* 2010).

Estimates of the impacts of the depth of fire on peat soils are dominated by a limited number of studies that have focused on observations made during *El Niño* years in Central Kalimantan. These values range from approximately 50 cm in 1997 (Page *et. al*., 2002) to 39 cm in 2002 (Usup *et al.*, 2004) and 33 cm in 2006 (Balhorn *et al.,* 2009). These published values should be viewed with caution, because water table depth and the distribution of rainfall both influence the extent and intensity of fire. Nonetheless, fire has been used historically as a management tool when preparing land for new oil palm plantations, in spite of the legal proscriptions limiting its use (Someshwar *et al*., 2011). Unfortunately, precise information as to the intensity and depth of peat fires during average or wet years is not available, but evidence from remote sensing indicates, and our own field experience supports, the supposition that the depth of peat fires during average or wet years is only a fraction of the levels documented during *El Niño* droughts (van der Werf *et al.,* 2010).

Consequently, we recommend using relatively conservative values when estimating the impact of historical fire on peat soils during plantation establishment over decadal time periods that span both wet and dry years. Specifically, we assume that the average depth of a peat fire would be 15 cm for swamp forest and 5 cm for swamp shrub land (Agus *et al.* 2012); the difference between the two values is based on anecdotal accounts that greater levels of above ground biomass lead to more intense fires and deeper burns. Moreover, we assume there is no burning of peat during oil palm replanting or the conversion of other land uses that have already been cleared for agriculture, agroforestry or other forms of plantation agriculture. Calculation of our emission factors for peat fires is based on an average carbon density of 0.06 Mg m^{-3} for peat soils (Page *et al*., 2002), which translates into emissions factors of 330 and 110 Mg CO_2 ha^{-1} for swamp forest and swamp shrub land respectively. The derivations of these emissions factors are based solely on assumptions and logic, but we feel this is preferable to ignoring a significant source of emissions due to the lack of empirical data.

Assessment of Historical Emissions

Based on the discussion in the previous sections, Table 5 summarizes C stock in plant biomass, peat oxidation loss and related water table depths, and emissions from burning. Only emission from above ground biomass, peat soil organic matter oxidation and controlled peat fire were taken into account in our analysis (Agus *et al.* 2013 – this publication). For peat soil, there are more data based on instantaneous CO_2 efflux than calculated from carbon stock change, while for living biomass most data are based on carbon stocks. The emission factor, multiplied by the activity data will give the emission estimate for the land areas of interest. Equation [2] can be rewritten in term of CO_2-e emission as,

$$Total\ Emission = \sum_{ij} A_{ij}\ [Emission_{ij\ LB} + Emissionij\ SOIL]/Tij \quad [4]$$

Where

A_{ij} = the activity data or area of land use under land cover type *i* that changes to type *j*

$Emission_{ij\ LB}$ = change in carbon stock in the living biomass under land cover type *i* that changes to type *j* * 3.67 (to convert C to CO_2). A_{ij} is presented outside the diagonal of the land use change matrix. Land use that is unchanged appears in the diagonal of the land use change matrix and is assumed not to exchange CO_2 from the living biomass with that in the atmosphere. While this is not true in the short term, it holds in the long term (over one plantation cycle or longer). Deviation from this assumption may occur because of changes in land management.

$Emission_{ij\ SOIL}$ = change in peat carbon stock due to oxidation from drainage and burning under land cover type *i* that changes to type *j* * 3.67. For peat soil land uses that remain the same during the analysis period, drainage oxidation is calculated as A_{ii} * peat oxidation rate under that particular land use (in Mg CO_2 ha^{-1} yr^{-1}). Emission from drainage oxidation of peat soil that changes in land use from *i* to *j* = the average of emissions from the two land uses * A_{ij}.

T_{ij} = the time scale of calculation

In a separate paper (Agus *et al.*, 2013 – this publication), estimates of total CO_2 emissions from land use linked to the establishment and operations of oil palm plantations in Malaysia, Indonesia and Papua New Guinea has been carried out by combining land use change matrices that cover three consecutive periods (Gunarso *et al.,* 2013 – this publication) with the emission factors recommended by this paper (Table 5).

Table 5. Mean above ground carbon (AGC) stocks (see Table 1) used for the calculation of CO_2 emissions due to land use change (LUC); the water table depth and associated CO_2 emission factors for peat oxidation and the CO_2 emission factors from peat burning in Indonesia, Malaysia and Papua New Guinea.

Land use/land cover type	AGC (Mg ha^{-1})	Water table depth (cm)	CO_2 emissions from peat oxidation (Mg $ha^{-1}yr^{-1}$)	CO_2 emissions from fire on peat due to land use change (Mg ha^{-1})
Undisturbed Forest	189			
Disturbed Forest	104			
Undisturbed Swamp Forest	162			330
Disturbed Swamp Forest	84	30	22	330
Undisturbed Mangrove	148			
Disturbed Mangrove	101			
Traditional Rubber Plantation	56	50	36	
Oil Palm Plantation	36	60	43	
Timber Plantation	44	50	36	
Mixed Tree Crops	54	50	36	
Shrub land	30			
Swamp Shrub land	28	30	22	110

Table 5. Mean above ground carbon (AGC) stocks (continued)

Land use/land cover type	AGC ($Mg\ ha^{-1}$)	Water table depth (cm)	CO_2 emissions from peat oxidation ($Mg\ ha^{-1}yr^{-1}$)	CO_2 emissions from fire on peat due to land use change ($Mg\ ha^{-1}$)
Annual Upland Crops	11	30	22	
Settlements	7	70	50	
Grassland	3			
Swamp Grassland	2	30	22	
Rice Field	2	10	7	
Coastal Fish Pond	0			
Bare soils	36[1]			
Mining	0	100	72	
Water Bodies	0			
No Classification	0			

[1]Bare soils is a transitional category of unknown precedence and the value of 36 $Mg\ ha^{-1}$ is recommended in order to avoid introducing artifacts into the estimation of net oil palm emissions

CONCLUSIONS

This report reviews the scientific literature on carbon stocks for different land cover types in Southeast Asia; these values can be used to calculate CO_2 emission factors due to land use change (see Agus *et al*, 2013 – this publication). In addition, we provide a review of the dimensions of the recurrent CO_2 emissions due to the oxidation of peat following drainage and provide a framework for estimating the one-time emissions caused by peat fires at the time of plantation establishment (see Table 5). There is a high degree of variation in all of these sources of emission which will contribute to uncertainties in any CO_2 emission analysis.

The reported values for plant biomass carbon stock reflect the inherent variation in natural habitats and disturbance intensities caused by human intervention. The recommended values for calculating emission factors from land use change between any two land cover categories are the differences between the mean carbon stock values for the two categories (Tables 1 and 5). In the case of natural or quasi-natural land cover types, these are not time-averaged values, but are assumed to reflect the carbon stocks at the time of conversion. This is done to avoid confounding CO_2 emissions from degradation due to logging and wildfire with the emissions specifically due to the clearing of land for agriculture. In contrast, the carbon stock values for human modified land cover types are the time averaged values that reflect the cyclical harvest or renovation period characteristic of each production system, which in the case of oil palm is based on the 25 year cycle typical for oil palm plantations.

The source of the uncertainty in the estimates of CO_2 emissions linked to the oxidation of peat is largely the consequence of the methodological limitations of the two major approaches for measuring (closed chamber systems) or modeling (tracking subsidence) the decomposition of peat following drainage. The values produced by the two methodological approaches vary widely and the emission factor recommended as a default value (43 Mg CO_2 $ha^{-1}yr^{-1}$) is based on our evaluation of the various published studies and the assumption that water tables in oil palm plantations are at approximately 60 cm from the soil surface. Unlike the emissions factors from land use change and peat fires, which are one-time events, the emissions from the oxidation of peat recur annually until the active drainage of the land cover type is ended. This is not only true for human managed land cover types, such as oil palm and tree plantations, but also for disturbed swamp forests and shrub lands that have been impacted by logging canals.

The emission factors reported for peat fires are also uncertain, due to the lack of published studies that document the phenomenon, compounded by the variation in fire intensity linked to inter-annual climate variability. Peat fires burn deeper in drought years but occur only superficially or are absent during wet years. We provide emissions factors only for peat fires linked to the conversion of swamp forest and shrub land to oil palm plantation and these values are based on anecdotal evidence that the use of fire to clear biomass has been a standard operating procedure over the last two decades (Table 5). No emissions factors are provided for peat fires that impact other land cover categories or other types of land use change.

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