Towards robust subsidence-based soil carbon emission factors for peat soils in south-east Asia, with special reference to oil palm plantations

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SUMMARY

Oil palm and *Acacia* pulpwood plantations are being established at a rapid rate on drained peatland in south-east Asia. Accurate measurements of associated carbon losses are still scarce, however, due mainly to difficulties of excluding autotrophic carbon fluxes from chamber-based flux measurements and uncertainties about the extent of waterborne losses. Here, we demonstrate a simple approach to determining total net carbon loss from subsidence records that is applicable to steady state conditions under continuous land use. We studied oil palm and *Acacia* plantations that had been drained for 5–19 years. Very similar subsidence rates and dry bulk density profiles were obtained, irrespective of crop type or age of the plantation, indicating that the peat profiles were in a steady state. These are conditions that allow for the deduction of net carbon loss by multiplying the rate of subsidence by the carbon density of the peat below the water table. With an average subsidence rate of 4.2 cm y^{-1} and a carbon density of 0.043 g cm^{-3}, we arrive at a net carbon loss of ~18 t ha^{-1} y^{-1} (~66 t CO_2-eq ha^{-1} y^{-1}) for typical oil palm and *Acacia* plantations more than five years after drainage, without large differences between the plantation types. The proposed method enables calculation of regional or project-specific carbon loss rates to feed into mitigation schemes of the UN Framework Convention on Climate Change.

KEY WORDS: tropical peatlands; *Acacia*; subsidence; carbon loss; CO_2 emission

INTRODUCTION

In south-east Asia, the expansion of oil palm and pulpwood plantations on peatland is taking place at a rapid and increasing rate. By 2010, industrial plantations on peatlands in Malaysia and Indonesia covered around 3.1 million hectares (Mha) but this area may almost double by 2020 (Miettinen *et al*., 2012).

Reliable carbon emission factors for drained tropical peat soils are needed to help countries such as Indonesia and Malaysia to measure, report and verify (MRV) their greenhouse gas emissions from land use and land-use change within the framework of climate mitigation programmes (Reducing Emissions from Deforestation and Forest Degradation, REDD+; Nationally Appropriate Mitigation Actions, NAMAs). Dependable emission estimates are also required to determine whether palm oil produced from oil palm grown on peatland meets the sustainability criteria for 'renewable biofuels' as set, for example, by the United States and the European Union.

Deriving emission factors from tropical peatlands converted to plantations is a scientific challenge. Direct measurements of gas fluxes are expensive, complicated and have technical constraints (Joosten & Couwenberg 2009, Page *et al*. 2011a). As a result, very few scientifically sound and indisputable greenhouse gas flux measurements are currently available. Detailed 'Tier 3' (i.e. advanced) model-based approaches (IPCC 2006) are not yet feasible due to a lack of accurate data for all relevant ecosystem fluxes in and out of peat soil.

Monitoring of peat subsidence is a long-established method of assessing carbon losses caused by microbial oxidation of drained peat soils (Armentano & Menges 1986, Kasimir-Klemedtsson *et al*. 1997, Oleszczuk *et al*. 2008). Besides oxidation, other processes that do not result in carbon loss also contribute to peat height loss, however. We need to know the relative contribution of these different processes if carbon losses are to be quantified reliably. Such assessments, and hence reliable emission estimates, have been rare for tropical peatlands.

This article derives emission factors for tropical peat soils based on a robust and simplified approach that does not necessitate quantification of the relative contributions of the various processes involved in peat subsidence. The method is a simplified version of the one used to assess the relative contributions of compaction and oxidation to peat thickness loss in drained sub-tropical and tropical peatlands (Stephens & Speir 1969; Driessen & Soepraptohardjo 1974; Wösten *et al*. 1997; Hooijer *et al*. 2012b) and in warm and temperate climates (van der Molen & Smits 1962; Schothorst 1977, 1982; Ewing & Vepraskas 2006). We apply the method using data from *Acacia* and oil palm plantations established on peat in Sumatra, Indonesia.

METHODS

Study sites

Two oil palm plantations and a group of *Acacia* plantations were studied. The oil palm plantations are situated on the large peat dome complex that also supports Berbak National Park in the Province of Jambi (Sumatra, Indonesia) and were drained 4–7 and 15–20 years, respectively, prior to the start of monitoring. We refer to these sites as '5OP' and '19OP', respectively. The *Acacia* plantations were drained 3–8 years prior to the start of monitoring and are located on the Kampar Peninsula in the Province of Riau, Sumatra, Indonesia. This location is referred to as '6A'. All sites are on peat > 6 m thick (Table 1). Fire was used for land clearance in the oil palm plantations but not in the *Acacia* plantations. The data for the 6A area were presented previously by Hooijer *et al*. (2012b), as were part of the data for the 19OP site.

Table 1. Study sites information. 'OP' in the site identifier indicates oil palm, 'A' *Acacia*.

Site	5OP	19OP	6A
Province (Indonesia)	Jambi	Jambi	Riau
Latitude (decimal)	-1.680	-1.709	0.595
Longitude (decimal)	103.828	103.898	102.334
Years since drainage (range)	5 (4–7)	19 (15–20)	6 (3–8)
Peat thickness (mean ± SD, m)	6.3±0.7	7.7±0.7	9.0±2.6
Number of subsidence poles	17	34	125
Number of soil pits	8	10	19

All sites experience very similar climatic conditions, with an average long-term annual rainfall of ~2500 mm, a dry season from July to October with a rainfall deficit (< 100 mm month^{-1}) in some years, and a mean annual air temperature just below 30 °C. During the study (2007–2012), the period from July to October 2010 was exceptionally wet with rainfall more than double the long-term average (Figure 1). Rainfall during the remainder of the study period did not deviate much from the long-term average.

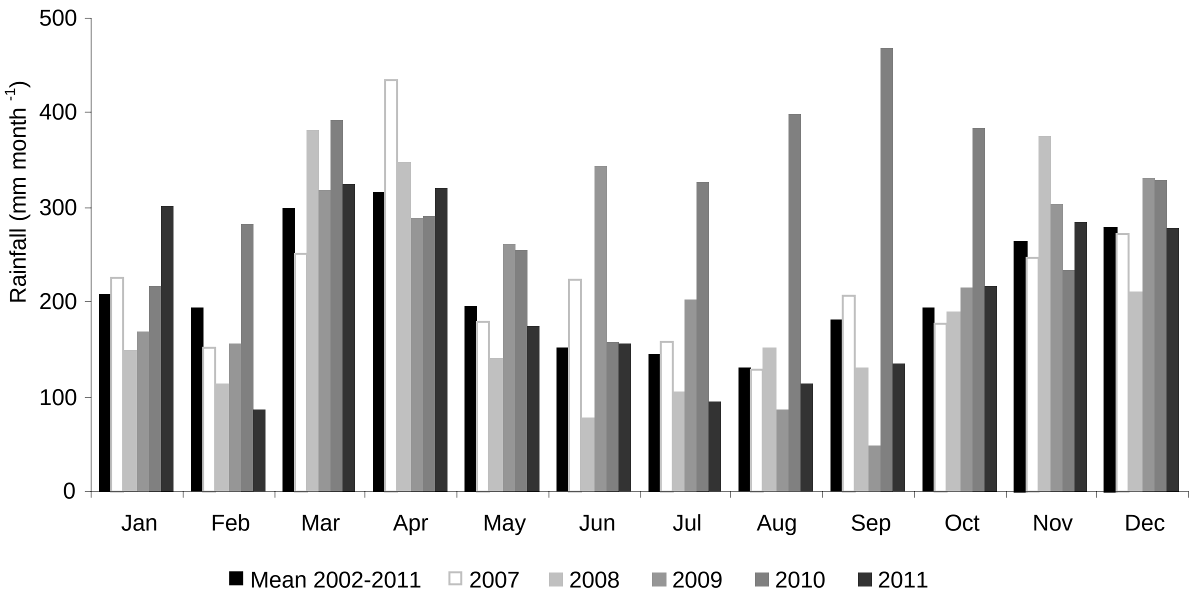

Figure 1. Monthly rainfall at the Jambi OP sites during the study period compared with average monthly rainfall (2002–2011), based on TRMM satellite data (Vernimmen *et al*. 2012).

Monitoring subsidence and water table depth

Subsidence rate and water table depth were monitored over three years, at fortnightly intervals in the two oil palm plantations and monthly in the *Acacia* plantations. The record for the *Acacia* plantations started in September 2007, the record for 19OP in March 2009, and for 5OP in June 2009. Subsidence monitoring poles consisting of perforated PVC tubes were anchored into the mineral subsoil below the peat using augers, thus enabling measurement of peat thickness and water table depth at the same locations. Thin metal marker rings were placed around the poles for measurement accuracy. Care was taken not to disturb the immediate surroundings of the subsidence poles. Locations where disturbance was evident were excluded from analysis.

Measuring dry bulk density

Peat sampling pits, dug using spades, were distributed through all sites. During sampling, pumps were used to remove water flowing into the pits from the adjacent peat. Peat samples were removed horizontally from the sides of the pits using sharpened metal cylinders (8 cm diameter and length) to minimise compression. Samples were oven dried at 105 °C until weight, measured at 24-hour intervals, had stabilised (up to 96 hours), and dry bulk density (*DBD*) was determined. In oil palm plantations the peat was sampled to at least 1.5 m depth at 0.1 or 0.2 m intervals; in the *Acacia* plantations this was done to a depth of 1.2 m at 0.15–0.3 m intervals. Three replicate samples were taken 0.1 m apart at each vertical interval, the average of which was used in data analysis. Further details of sampling methods are available in Hooijer *et al*. (2012b).

Calculating carbon loss

Carbon loss was calculated from subsidence rates and peat dry bulk density below the water table following the method developed by van den Akker (in Kuikman *et al*. 2005) and recently applied to derive carbon losses from drained peatlands in The Netherlands and Switzerland by van den Akker *et al*. (2008) and Leifeld *et al*. (2011). The basic assumption is that, after the end of the consolidation phase which follows immediately after drainage, compaction and oxidation above the water table are the only causes of surface height loss. In contrast to other methods, this approach does not require estimation of the relative contributions of these two processes to subsidence. Under unchanged land use with associated water tables maintained by regulation and periodic deepening of ditches, processes in the upper oxic peat layer may be assumed to be in a steady state.

As compaction and oxidation affect the upper layer, leading to subsidence and progressive elevation of the water table relative to the peat surface, regular lowering of the water table (by regulation of canal water tables or deepening of drainage channels) transfers un-decomposed peat from the anoxic layer below the water table to the upper oxic layer. This process takes place continuously at a steady rate and the thickness of the oxic layer remains constant. As the processes of peat subsidence and adjustment of water tables continue, un-decomposed peat is progressively incorporated into the oxic layer, becoming more and more oxidised towards the surface. The result is a *de facto* constant peat profile in the upper layer, with the peat going from a relatively un-decomposed condition just above the water table to a strongly decomposed (oxidised) state at the surface. Because of this dynamic equilibrium the upper oxic peat layer need not be considered when deriving carbon losses from the peat column, even though it is here that actual losses take place. Instead, peat (and carbon) losses can be calculated from only two variables: surface height loss and characteristics of the lower peat layer (Figure 2; van den Akker *et al*. 2008). A formal presentation is given in Equation 1:

$$V_{ox} = S_t \times DBD_l \qquad [1]$$

in which:
V_{ox} = annual peat loss (kg m^{-2} y^{-1});
S_t = total annual surface height loss (m y^{-1}); and
DBD_l = dry bulk density of the peat below the water table (kg m^{-3}).

The amount of carbon lost, C_{loss} (kg m^{-2} y^{-1}), is calculated by multiplying surface height loss S_t by volumetric carbon density of the peat below the water table, C_{vol} (kg m^{-3}) (Equation 2). Volumetric carbon density is the product of dry bulk density and carbon concentration in the peat on a dry weight basis, C_{dw} (kg kg^{-1}).

$$C_{loss} = S_t \times C_{vol} = S_t \times DBD_l \times C_{dw} \qquad [2]$$

The peat at the study sites has very low mineral content (Hooijer *et al*., 2012b), and carbon concentration of the peat below the water table is estimated from literature values to amount to 55 % (see Dommain *et al*. 2011, Page *et al*. 2011b, Warren *et al*. 2012). Then, referring to Equation 1,

$$C_{loss} = V_{ox} \times 0.55 \qquad [3]$$

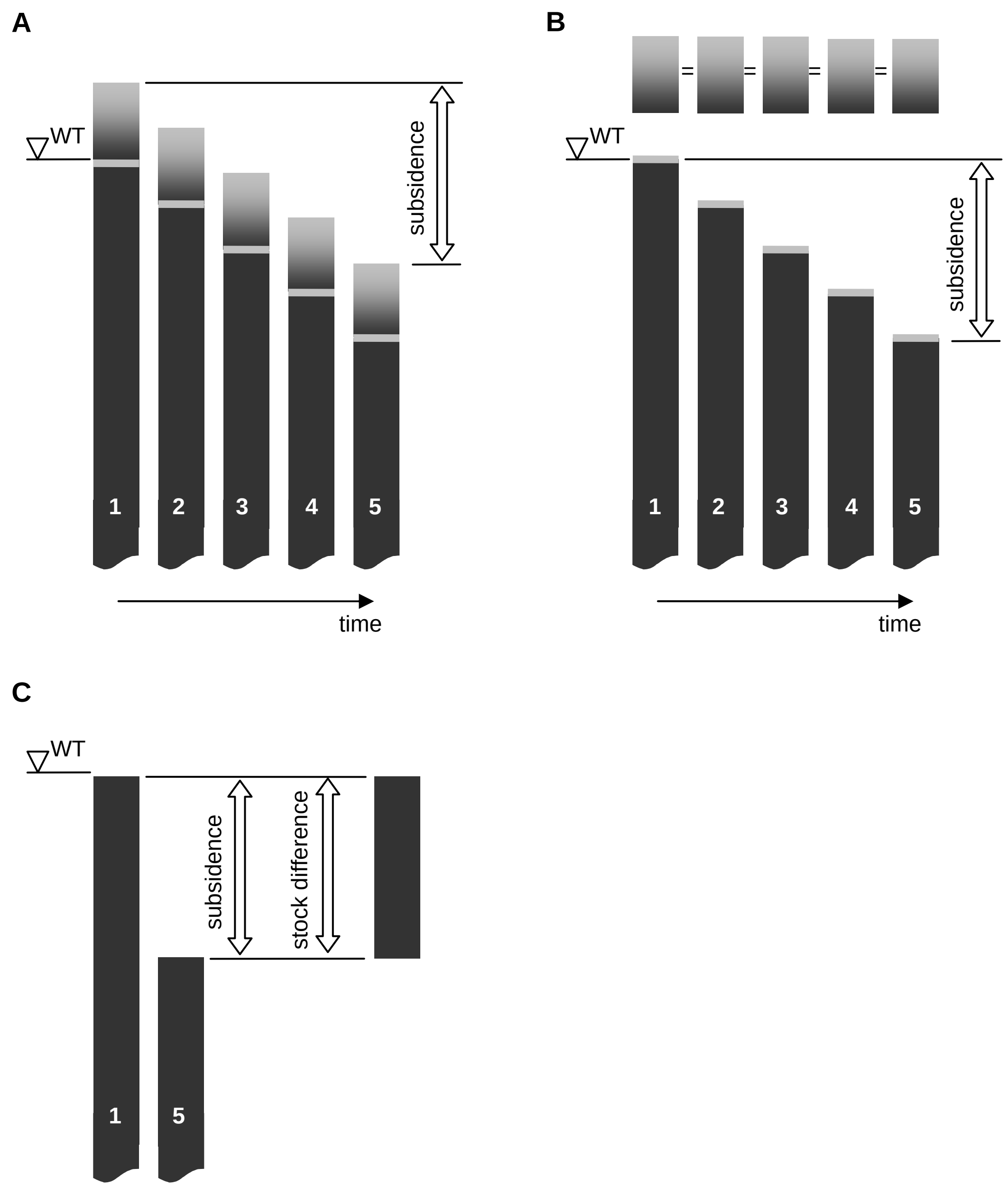

Figure 2. Derivation of peat loss from subsidence data. (A) In a drained peatland under continuous land use, the peat subsides over time (1, 2, …5). The water table is kept stable relative to the peat surface by regulation of water levels in the drainage canals. (B) As a result, the character of the upper oxic peat layer does not change and surface height losses can be thought of as affecting the lower anoxic layer only. (C) Peat (and carbon) losses can then be calculated using peat characteristics of the lower layer only.

RESULTS

Water table depth

Water tables vary considerably in time (Hooijer *et al*. 2012a,b). Average water table depths at the three sites ranged from 0.7 m (6A) and 0.64 m (19OP) to 0.44 m (5OP) below the peat surface. During 2009, 2011 and 2012 rainfall rates and water table depths in the OP sites were close to the long-term averages (Figure 1). During the exceptionally wet year of 2010, they were considerably higher. Therefore, our results represent conditions with rainfall and water levels that are somewhat higher than typical.

Subsidence rate

Subsidence between 3.7 and 5.0 cm y^{-1} on average occurred at all sites, irrespective of land cover or time since drainage (Table 2, Hooijer *et al*. 2012a,b). The average rate of subsidence in the two oil palm plantations would be about 10 % larger if the exceptionally wet year of 2010 were not taken into account. Whereas spatial variation in subsidence rates was small, considerable variation was observed over time, ranging from almost zero in some months to more than 1 cm in others (Figure 3). Low subsidence rates were associated with high and rising water tables, while highest rates

Table 2. Water table depth, dry bulk density (DBD) and subsidence rates; all values are presented as mean ± SD. The top layer is considered to extend from 0 m to 0.65 m below the surface; data for the lower layer extend from 0.7 m to 1.5 m depth. For sites 5OP and 19OP, water tables and subsidence rates are given for mid-2009 to mid-2012. The study period for 6A was 2007–2010.

Site	5OP	19OP	6A[1]
Water table depth (m)	-0.56 ± 0.06	-0.65 ± 0.25	-0.70 ± 0.20
DBD at 0.1 m depth (g cm^{-3})	0.124 ± 0.02 (n=99)	0.128 ± 0.02 (n=105)	0.144 ± 0.02 (n=162)
DBD of top layer (g cm^{-3})	0.106 ± 0.02 (n=297)	0.096 ± 0.02 (n=465)	0.111 ± 0.03 (n=504)
DBD of lower layer (g cm^{-3})	0.082 ± 0.01 (n=450)	0.078 ± 0.01 (n=537)	0.074 ± 0.02 (n=246)
Subsidence rate (cm y^{-1})	3.9 ± 0.5	3.7 ± 0.5	5.0 ±2 .2

[1] From Hooijer *et al*. (2012b).

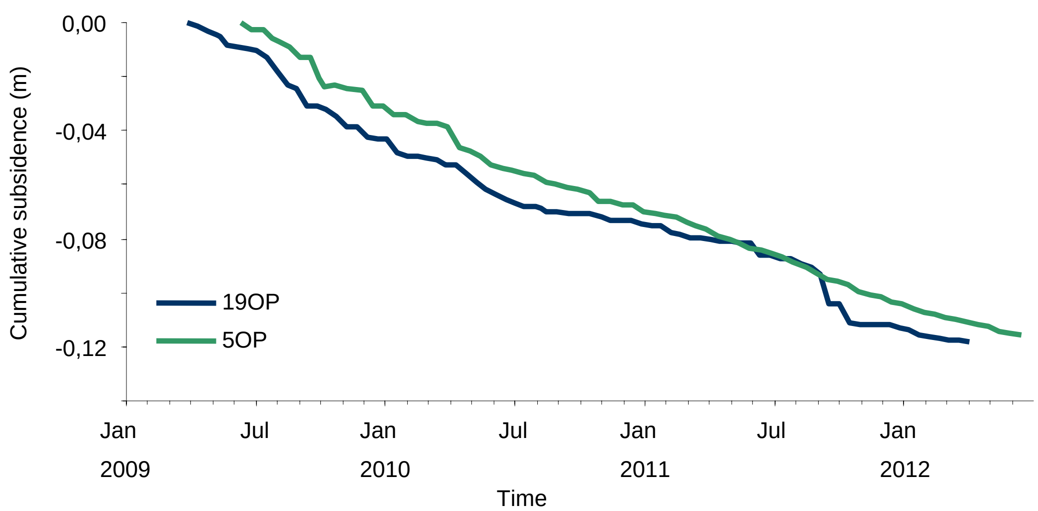

Figure 3. Subsidence measured between March/June 2009 and March/June 2012 in the 5OP and 19OP sites, averaged over 17 and 34 monitoring locations respectively.

were obtained when water tables were dropping sharply in periods of low rainfall.

Dry bulk density profiles and peat characteristics

The peat below the water table at all locations was fibric to hemic, with recognisable wood fragments and fine fibrous root material surrounded by a matrix of more decomposed organic particles. Ash content was on average < 2 % for all sites, and < 5 % for all samples.

Dry bulk density (DBD) decreases with depth below the peat surface (Figure 4). For consecutive samples below the surface, we define the start of the lower peat layer when change in DBD remains less than 5 %. For all sites this is the case for samples ≥ 0.7 m below the surface, which corresponds well with the position of dry-season water table. Mean DBD of the top layer (< 0.7 m) is ~0.10 g cm^{-3} for all sites, with highest values of ~0.135 g cm^{-3} found at 0.1 m depth (Table 2). The mean of all DBDs in the lower layers of the two OP sites is 0.080 g cm^{-3}, and 0.078 g cm^{-3} for all three sites together, with respective relative standard errors < 1 %. Standard error of all layer-specific DBD values is < 0.004, relative standard error < 4 % (< 2 % for the two OP sites). DBD differs significantly between the upper and lower layers for all sites (t-test, $P < 0.001$), but not between either the upper or lower layers of the different sites (paired t-test, $P < 0.001$).

Carbon loss

Applying a subsidence rate of 3.8 cm y^{-1}, a DBD of the lower peat layer of 0.080 g cm^{-3} and a carbon concentration of 55 %, we find an annual carbon loss of 16.7 t ha^{-1} y^{-1} for the two OP sites. With a subsidence rate of 5.0 cm yr^{-1} and a DBD of the lower peat layer of 0.074 g cm^{-3}, annual carbon loss from site 6A (*Acacia*) is 20.3 t ha^{-1} y^{-1} (Table 3). Averaged over all three study sites, a subsidence rate of 4.2 cm combined with a DBD of the lower peat layer of 0.078 g cm^{-3} (Table 2), results in an annual carbon loss of 18 t ha^{-1} y^{-1}.

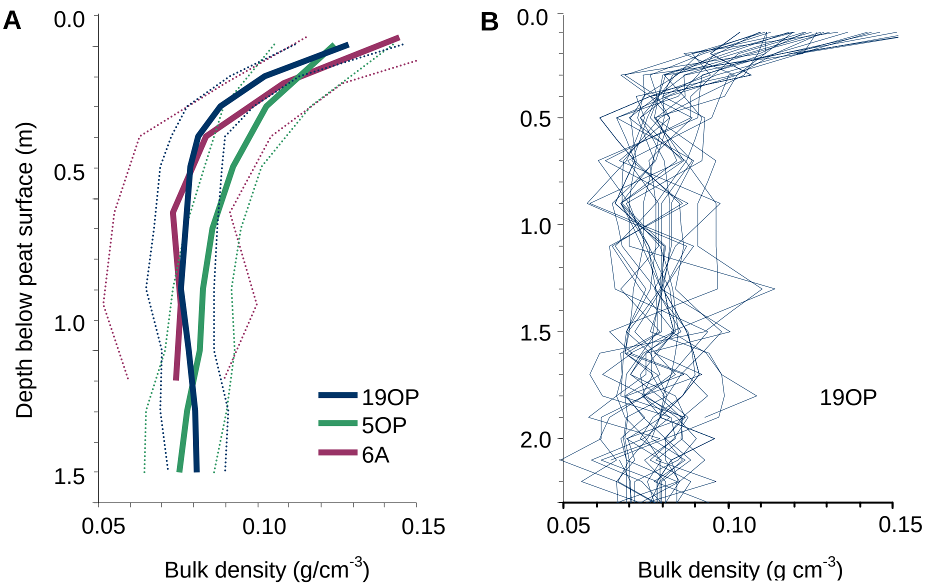

Figure 4. Dry bulk density profiles of the three study sites. (A) Mean ± SD for each 10 cm interval of the upper 1.4 m. (B) Individual profiles for the 19OP site from ten pits, each with three replicates (total n=30 at each sampling depth). Note the difference in vertical scale.

Table 3. Subsidence and carbon loss from drained tropical peatlands in south-east Asia with (re)calculated carbon loss following Equations 1–3. Volumetric carbon density of the lower peat is the product of dry bulk density and carbon content (% dry weight). We excluded data from shallow peat (< 1.6 m), peat with high mineral content (> 5 %), subsidence records < 1 year long and areas that were (potentially) drained < 3 years ago. OP indicates oil palm. Note that default values for dry bulk density and carbon concentration of the lower peat layer were used where publications were unclear or inconsistent (see footnotes).

Reference	Land use	Years since drainage / measuring duration (y) / no. of measurement sites	Water table depth (m)	Subsidence rate (cm y^{-1})	Volumetric C density (g cm^{-3})	Calculated C loss (t ha^{-1} y^{-1})
DID & LAWOO (1996)	OP (Phase I)	> 12 / 17–21 / 16	-	2.7	0.042[1]	12.0
	OP (Phase II)	> 28 / 4 / 10	0.53	3.8	0.042[1]	16.0
Maswar (2011)	OP	> 15 / 1.2 / 5	0.60	5.0	0.041[2]	20.4
Othman *et al*. (2011)	OP	2–6 / 7–8 / 2–10	0.41	4.5	0.044[3]	19.8
This study	*Acacia* (6A)	3–8 / 2 / 125	0.70	5.0	0.041[4]	20.3
	OP (5OP)	4–7 / 3 / 29	0.56	3.9	0.045[4]	17.6
	OP (19OP)	15–20 / 3 / 42	0.65	3.7	0.043[4]	15.9
Overall mean			0.58	4.1	0.042	17.4

[1] DBD (0.07 g cm^{-3}) and C concentration (60 %) from the same area (Salmah *et al*. 1992).
[2] Assumed DBD 0.08 g cm^{-3} and C concentration 51 %; DBD from auger samples (~0.01 g cm^{-3}) discarded.
[3] Assumed DBD 0.08 g cm^{-3} and C concentration 55 %; Othman *et al*. (2011) report DBD and C concentration of the upper peat only.
[4] Assumed C concentration of 55 %.

DISCUSSION

Measuring the DBD (dry bulk density) of tropical peat is not straightforward. Coarse woody fragments may obstruct auger sampling, resulting in incomplete recovery and underestimation of peat DBD or in compaction of peat, giving rise to overestimation. To avoid inaccurate sampling, we took large numbers of peat samples from vertical profiles in soil pits, with horizontal replicates. In addition, multiple pits were dug at each site to determine spatial variability in DBD profiles. The DBD of wood remains at the 19OP site was < 10 % higher than that of the surrounding peat material, with coarse wood fragments making up < 20 % of the peat volume even well below the water table (Hooijer *et al*. 2012b). Undersampling of coarse woody fragments will, therefore, not significantly affect the accuracy of the DBD values presented here. DBD profiles of the study sites show little variation, independent of time since drainage, crop type or location. Although the 6A *Acacia* sites are hundreds of kilometres distant from the two OP sites, the DBD profiles are very similar, suggesting that peat characteristics are uniform across the larger region. The DBD profiles measured by Salmah *et al*. (1992) in Johore (Malaysia) also compare well with those in Figure 4. The DBDs in the uppermost part of the peat profiles ($\bar{x}$ = 0.134 g cm^{-3}) are similar to measurements made on drained peat soils throughout other parts of Western Malesia (Sundaland) (Page *et al*. 2011b); values for the lower layer of the peat profiles ($\bar{x}$ = 0.078 g cm^{-3}) also fit well with other measurements from the region (Driessen & Rochimah 1976; Diemont & Supardi 1987; Cameron *et al*. 1989; Neuzil 1997; Page *et al*. 2004; Sumawinata *et al*. 2007).

Consolidation is generally considered to end within a few years after drainage (Kasimir-Klemedtsson *et al*. 1997). Applying material coefficients measured in Indonesian peatlands to plantation drainage scenarios typical for south-east Asia, den Haan *et al*. (2012) concluded that consolidation was completed within a few months after the main plantation canals were opened, and that from then onwards the peat below the water table could be considered over-consolidated and stable, leaving all subsequent subsidence to be explained by oxidation and compaction above the water table only. These findings confirm a broader assessment by Mesri & Ajlouni (2007) who reported that 94 % of consolidation in fibrous peat was caused by fast 'primary' processes and only 6 % by slow 'secondary' ones.

Once plantations are established, water tables may be controlled using weirs and periodic deepening of ditches (Lim *et al*. 2012), resulting in a relatively constant water table depth below the surface (*cf*. Melling *et al*. 2005; Othman *et al*. 2011; Hooijer *et al*. 2012b) and associated uniform thickness of the upper, oxic peat layer. After drainage, the loss of supporting pore water pressure, combined with shrinkage and decreased structural strength following decomposition of the peat, result in physical compaction and increased DBD of the upper peat. The DBD profiles of the upper peat layer soon stabilise (Figure 4; *cf*. Ywih *et al*. 2009; Anshari *et al*. 2010).

The concept of a stable upper peat layer under conditions of continued land use is analogous to the acrotelm or 'active horizon' in undisturbed boreal and temperate peatlands (Romanov 1968, Clymo 1984). Both concepts treat the upper peat layer as a 'black box' in which several simultaneous processes take place that result in changes to the catotelm, or 'inactive horizon' below. In undisturbed peatlands, as the peat surface and absolute height of the water level (a.s.l.) rise, the lower saturated peat layer receives organic matter continuously from the unsaturated layer above, sequestering it long term. By contrast, subsidence in a drained peatland under unchanging land use results in decrease of the absolute height of the water level (a.s.l.). As the upper unsaturated peat layer loses organic material because of oxidation (decomposition), it constantly incorporates peat from the saturated lower layer. In undisturbed peatlands, the rate of peat (and carbon) accumulation can be determined by quantifying all gains and losses in the upper acrotelm layer; but it is more commonly, and more robustly, determined by focusing on the lower, catotelm layer only. Likewise, the rate of peat (and carbon) loss from the upper unsaturated peat layer can be determined by quantifying all gains and losses, but as this upper layer is in a steady state the loss of peat carbon can be determined more easily by focusing on the lower saturated peat layer.

The method used here to derive carbon losses from drained tropical peat soils has been applied to European peatlands by van den Akker *et al*. (2008) and Leifeld *et al*. (2011). The results obtained from the subsidence approach to carbon loss for temperate peatlands correspond well with independent closed chamber measurements in similar locations (Figure 5), demonstrating the reliability of the technique. The subsidence based carbon losses derived by van den Akker *et al*. (2008) are used in the Dutch reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol (van den Wyngaert *et al*. 2009), confirming international acceptance of the method.

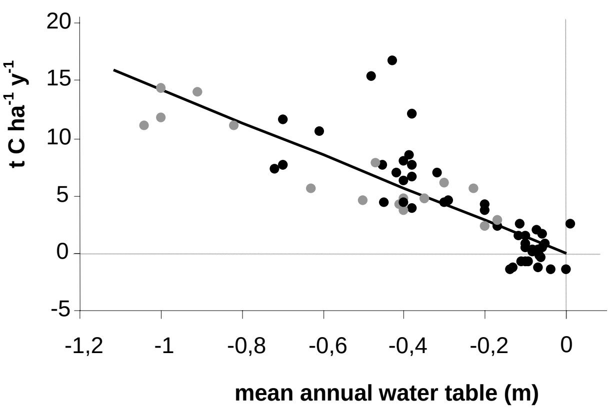

Figure 5. Relationship between annual carbon flux rates from temperate European peatlands and mean annual water table depth. Flux values derived using the subsidence based method described in this paper (●) correspond well with flux values derived from closed chamber measurements (●). The linear regression ($y = -14.2\,x$; $r^2 = 0.84$; $P < 0.001$) applies to all data points. Subsidence based data from van den Akker *et al*. (2008), closed chamber based data from references in Couwenberg *et al*. (2011), Elsgaard *et al*. (2012) and Kandel *et al*. (2012).

For tropical peatlands in south-east Asia, comparison of the subsidence based method used in this paper with closed chamber measurements is possible in only a few instances. Most of the published chamber flux data present total soil respiration rates, which include autotrophic (plant root) respiration and do not provide appropriate insight on net carbon losses from peat (Couwenberg *et al*. 2010). Chamber design and measurement methods are often poorly described, preventing rational judgement of their accuracy (*cf*. Pumpanen *et al*. 2004). In addition, chamber flux measurements rarely cover multiple years, whereas most subsidence measurements do so (Table 3). The few adequately derived and described chamber based measurements on south-east Asian peatlands (Melling *et al*. 2007, as adjusted in Couwenberg *et al*. 2010; Jauhiainen *et al*. 2012) are in line with the carbon loss values derived in this paper, and applying the method to existing subsidence records increases the number of carbon loss estimates from drained tropical peatlands under plantation management considerably (Table 3).

Whereas we calculate carbon loss on the basis of the lower saturated peat only, this does enable assessment of the relative importance of the physical (shrinkage and compaction) and oxidative (decomposition) components of surface height losses from the upper unsaturated peat layer. The magnitude of the oxidative component of peat subsidence can be calculated from the established carbon loss and the volumetric carbon density of the upper peat layer; the remainder of the height loss is caused by physical peat shrinkage and compaction. With a volumetric carbon density of ~0.055 g cm^{-3} (*cf*. Table 2), oxidative losses for the two oil palm sites (5OP and 19OP) amount to ~80 % and 70 % for the *Acacia* site (6A). The remaining 20–30 % can be attributed to physical compaction. Using the more elaborate method that assesses the relative importance of compaction and oxidation to overall subsidence from DBD changes in vertical profiles, Hooijer *et al*. (2012b) arrived at values of 92 % for the cumulative oxidative contribution to subsidence in the 19OP and of 75 % for the 6A site. Our current findings are in agreement with these estimates, further confirming the validity of the method. Assumptions of the peat DBD prior to drainage are not required, which overcomes an uncertainty associated with the more complex method applied by Hooijer *et al*. (2012b) and others. Values around or above 70 % are common in the literature for the oxidative contribution to subsidence, not only in (sub-)tropical peatlands (e.g. Stephens & Speir 1969; Kyuma *et al*. 1992), but also in boreal and temperate climates (van der Molen & Smits 1962, Eggelsman 1976, Schothorst 1977, Deverel & Leighton 2010), and this value has been applied as a default factor in Europe (Kasimir-Klemedtsson *et al*. 1997, Oleszczuk *et al*. 2008). It should be noted, however, that most published values refer to the cumulative contribution of oxidation since the start of drainage, including the initial period during which compaction is dominant (but excluding consolidation), and that the relative contribution of oxidation beyond that period increases (Bouman & Driessen 1985; Hooijer *et al*. 2012b). Most published oxidation rates should, therefore, be seen as (historical) minimum values rather than applying to conditions many years after drainage. The method applied here addresses carbon losses from only long-term sustained land use, when the upper peat layer is in a steady state. Carbon losses that occur before this steady state is achieved are not accounted for. These include the very large losses of carbon that occur during land use change (e.g. deforestation and drainage) on peatland owing to microbial oxidation (Bouman & Driessen 1985; Hooijer *et al*. 2012b) and clearance fires (*cf*. Page *et al*. 2002; Couwenberg *et al*. 2010). Emission factors that address land use change must take these initial high losses into account.

We have presented here a straightforward method to assess carbon losses from drained tropical peatlands, based on subsidence records and carbon density of the peat. In contrast to more complex methods hitherto applied, this does not need to address the various processes that contribute to subsidence in the upper oxic, unsaturated peat layer. Instead, we consider this layer to be in a steady state and focus on changes to carbon stock in the lower anoxic, saturated peat layer, thereby reducing assumptions and measurement efforts. The DBD profiles vary little and are independent of time since drainage, crop type and location, which supports the steady state assumption and suggests that our findings are applicable over the larger south-east Asian region. Average carbon losses amount to ~18 t ha^{-1} y^{-1} (~66 t CO_2 ha^{-1} y^{-1}) for the oil palm and *Acacia* plantations studied, without apparent differences between plantation types. These rates explain 70–80 % of total subsidence, which is in line with oxidation rates reported by other studies in temperate and tropical climates. Applying the same method, subsidence data reported by earlier studies in oil palm plantations in south-east Asia suggest similar carbon loss rates. Losses do not differ much between different plantation types with similar peat thickness, drainage depth and subsidence rates.

The carbon losses derived here apply to drained systems under continuous established land uses. Losses associated with land use change from hitherto undrained peatland to plantation involve forest biomass and clearance fire losses and higher initial microbial oxidation rates, which are not covered by this approach. Our findings apply to peat with a mineral content below 5 %, which includes the majority of plantations in south-east Asia. There are also plantations on shallower peat with higher ash concentration, but further studies are needed to determine carbon losses from these.

At the simplest Tier 1 (default) level of IPCC emission factors, our findings are sufficiently precise to be applied. Moreover, the proposed method provides simple and effective ways of upgrading emission factors to a more detailed (Tier 2, intermediate) level by adopting regional, land use type or site-specific subsidence rates and carbon concentration values. Subsidence may be measured by large ground-based networks or by remote sensing (LIDAR), and this could offer spatially diverse data on carbon losses from peatland conversion and degradation over large areas that would greatly assist countries such as Indonesia in measuring, reporting and verifying (MRV) carbon emissions within the framework of climate mitigation programmes (REDD+, NAMAs) under the UNFCCC.

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REFERENCES

Anshari, G.Z., Afifudin, M., Nuriman, M., Gusmayanti, E., Arianie, L., Susana, R., Nusantara, R.W., Sugardjito, J. & Rafiastanto, A. (2010) Drainage and land use impacts on changes in selected peat properties and peat degradation in West Kalimantan Province, Indonesia. *Biogeosciences*, 7, 3403–3419.

Armentano, T.V. & Menges, E.S. (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology*, 74, 755–774.

Bouman, S.A.M. & Driessen, P.M. (1985) Physical properties of peat soils affecting rice-based cropping systems. *Proceedings of Workshop on Soil Physics and Rice*, International Rice Research Institute (IRRI), Manila, 71–83.

Cameron, C.C., Esterle, J.S. & Curtis, A.P. (1989) The geology, botany and chemistry of selected peat-forming environments from temperate and tropical latitudes. *International Journal of Coal Geology*, 12, 105–156.

Clymo, R.S. (1984) The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London B*, 303, 605–654.

Couwenberg, J., Dommain, R. & Joosten, H. (2010) Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology*, 16, 1715–1732.

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A. & Joosten, H. (2011) Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia*, 674, 67–89.

den Haan, E.J., Hooijer, A. & Erkens, G. (2012) *Consolidation Settlements of Tropical Peat Domes by Plantation Development*. Report, Deltares, Delft, The Netherlands, 44 pp.

Deverel, S.J. & Leighton, D.A. (2010) Historic, recent, and future subsidence, Sacramento-San Joaquin Delta, California, USA. *San Francisco Estuary and Watershed Science,* 8(2), 1–23.

DID & LAWOO (1996) *Western Jahore integrated Agricultural Development Project. Peat Soil Management Study*. Department of Irrigation and Drainage (DID), Kuala Lumpur, Malaysia and Land and Water Research Group (LAWOO), Wageningen, The Netherlands, 100 + 171 pp.

Diemont, W.H. & Supardi, M.N.N. (1987) Accumulation of organic matter and inorganic constituents in a peat dome in Sumatra, Indonesia. In: *International Peat Society Symposium on Tropical Peat and Peatlands for Development*, Yogyakarta, Indonesia, February 9–14, 1987, Abstracts, 698–708.

Dommain, R., Couwenberg, J. & Joosten, H. (2011) Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability. *Quaternary Science Reviews*, 30, 999–1010.

Driessen, P.M. & Rochimah, L. (1976) The physical properties of lowland peats from Kalimantan and their significance for land suitability appraisal. In: *Peat and Podzolic Soils and Their Potential for Agriculture in Indonesia*. Soil Research Institute, Bogor, 56–73.

Driessen, P.M. & Soepraptohardjo, M. (1974) *Soils for Agricultural Expansion in Indonesia*. Bulletin 1, Soil Research Institute, Bogor, Indonesia, 63 pp.

Eggelsman, R. (1976) Peat consumption under influence of climate, soil condition and utilization. *Proceedings of the Fifth International Peat Congress, Poznań, Poland*, 1, 233–247.

Elsgaard, L., Görres, C.-M., Hoffmann, C.C., Blicher-Mathiesen, G., Schelde, K. & Petersen, S.O. (2012) Net ecosystem exchange of CO_2 and carbon balance for eight temperate organic soils under agricultural management. *Agriculture, Ecosystems and Environment*, 162, 52–67.

Ewing, J.M. & Vepraskas, M.J. (2006) Estimating primary and secondary subsidence in an organic soil 15, 20, and 30 years after drainage. *Wetlands*, 26, 119–130.

Hooijer, A., Lee, W.A., Lu, X.X, Idris, A., Sugino, Jauhiainen, J. & Page, S. (2012a) Subsidence as an accurate measure of carbon loss in drained peatlands in SE Asia. *Proceedings of the 14th International Peat Congress, Stockholm, Sweden*. Extended Abstract No. 177, 6 pp.

Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A. & Anshari, G. (2012b) Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences*, 9, 1053–1071.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Agriculture, Forestry and Other Land Use*. IGES, Japan, 561 + 117 pp.

Jauhiainen, J., Hooijer, A. & Page, S.E. (2012) Carbon dioxide emissions from an *Acacia* plantation on peatland in Sumatra, Indonesia. *Biogeosciences*, 9, 617–630.

Joosten, H. & Couwenberg, J. (2009) *Are Emission Reductions from Peatlands MRV-able?* Report to Wetlands International, Ede, The Netherlands, 14 pp.

Kandel, T.P., Elsgaard, L. & Lærke, P.E. (2012) Measurement and modelling of CO_2 flux from a drained fen peatland cultivated with reed canary grass and spring barley. *GCB Bioenergy*, doi: 10.1111/gcbb.12020.

Kasimir-Klemedtsson, A., Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J. & Oenema, O. (1997) Greenhouse gas emissions from farmed organic soils: a review. *Soil Use and Management*, 13, 245–250.

Kuikman, P.J., van den Akker, J.J.H. & de Vries, F. (2005) *Emissie van N_2O en CO_2 uit organische landbouwbodems* (*Emission of N_2O and CO_2 from Organic Agricultural Soils*). Alterra Report 1035-2, Alterra, Wageningen, 66 pp. (in Dutch).

Kyuma, K., Kaneko, N., Zahari, A.B. & Ambak, K. (1992) Swamp forest and tropical peat in Johore, Malaysia. In: Aminhuddin, B.Y. (ed.) *Tropical Peat. Proceedings of the International Symposium on Tropical Peatland, 6–10 May 1991, Kuching, Sarawak, Malaysia.* Malaysian Agricultural Research and Development Institute, 300–306.

Leifeld, J., Müller, M. & Fuhrer, J. (2011) Peatland subsidence and carbon loss from drained temperate fens. *Soil Use and Management*, 27, 170–177.

Lim, K.H., Lim, S.S., Parish, F. & Suharto, R. (eds.) (2012) *RSPO Manual on Best Management Practices (BMPs) for Existing Oil Palm Cultivation on Peat*. RSPO, Kuala Lumpur, Malaysia, 214 pp.

Maswar, M. (2011) *Kajian cadangan karbon pada lahan gambut tropika yang didrainase untuk tanaman tahunan* (*Carbon Stock Study on Drained Tropical Peatland for Perennial Crops*). PhD thesis, Institut Pertanian Bogor (IPB), 157 pp. (in Bahasa Indonesia).

Melling, L., Goh, K.J., Beauvais, C. & Hatano, R. (2007) Carbon flow and budget in a young mature oil palm agroecosystem on deep tropical peat. In: Rieley, J.O., Banks, C.J. & Radjagukguk, B. (eds.) *Carbon–Climate–Human Interaction on Tropical Peatland: Proceedings of the International Symposium and Workshop on Tropical Peatland, Yogyakarta, 27–29 August 2007.* CARBOPEAT, Department of Geography, University of Leicester, UK, 153–157.

Melling, L., Hatano, R. & Goh, K.J. (2005) Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. *Tellus B*, 5, 1–11.

Mesri, G. & Ajlouni, M. (2007) Engineering properties of fibrous peats. *Journal of Geotechnical and Geoenvironmental Engineering*, 133, 850–866.

Miettinen, J., Hooijer, A., Shi, C., Tollenaar, D., Vernimmen, R., Liew, S.C., Malins, C. & Page, S.E. (2012) Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections. *Global Change Biology Bioenergy*, doi: 10.1111/j.1757-1707.2012.01172.x.

Neuzil, S.G. (1997) Onset and rate of peat and carbon accumulation in four domed ombrogenous peat deposits, Indonesia. In: Rieley, J.O. & Page, S.E. (eds.), *Biodiversity and Sustainability of Tropical Peatlands*. Samara Publishing, Cardigan, United Kingdom, 55–72.

Oleszczuk, R., Regina, K., Szajdak, L., Höper, H. & Maryganowa, V. (2008) Impacts of agricultural utilization of peat soils on the greenhouse gas balance. In: Strack, M. (ed.) *Peatlands and Climate Change*, International Peat Society, Jyväskylä, Finland, 70–97.

Othman, H., Mohammed, A.T., Darus, F.M., Harun, M.H. & Zambri, M.P. (2011) Best management practices for oil palm cultivation on peat: ground water-table maintenance in relation to peat subsidence and estimation of CO_2 emissions at Sessang, Sarawak. *Journal of Oil Palm Research*, 23, 1078–1086.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D.V., Jaya, A. & Limin, S. (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, 420, 61–65.

Page, S.E., Morrison, R., Malins, C., Hooijer, A., Rieley, J.O. & Jauhiainen, J. (2011a) *Review of Peat Surface Greenhouse Gas Emissions from Oil Palm Plantations in Southeast Asia*. ICCT White Paper 15, International Council on Clean Transportation, Washington DC, USA, 77 pp.

Page, S.E., Rieley, J.O. & Banks, C.J. (2011b) Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, 17, 798–818.

Page, S.E., Wüst, R.A.J., Weiss, D., Rieley, J.O., Shotyk, W. & Limin, S.H. (2004) A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. *Journal of Quaternary Science*, 19, 625–635.

Pumpanen, J., Kolari, P., Ilvesniemi, H., Minkkinen, K., Vesala, T., Niinistö, S., Lohiha, A., Larmola, T., Morero, M., Pihlatie, M., Janssens, I., Curiel Yuste, J., Grünzweig, J.M., Reth., S., Subke, J.-A., Savage, K., Kutsch, W., Østreng, G., Ziegler, W., Anthoni, P., Lindroth, A. & Hari, P. (2004) Comparison of different chamber techniques for measuring soil CO_2 efflux. *Agricultural and Forest Meteorology*, 123, 159–176.

Romanov, V.V. (1968) *Hydrophysics of Bogs*. Israel Program for Scientific Translations, Jerusalem, 299 pp.

Salmah, Z., Spoor, G., Zahari, A.B. & Welch, D.N. (1992) Importance of water management in peat soil at farm level. In: Aminhuddin, B.Y. (ed.) *Tropical Peat. Proceedings of the International Symposium on Tropical Peatland,* 6–10 May 1991, Kuching, Sarawak, Malaysia. Malaysian Agricultural Research and Development Institute, 228–238.

Schothorst, C.J. (1977) Subsidence of low moor peat soils in the western Netherlands. *Geoderma*, 17, 265–291.

Schothorst, C.J. (1982) Drainage and behaviour of peat soils. In: de Bakker, H. & van den Berg, M.W. (eds.) *Proceedings of the Symposium on Peat Soils below Sea Level, 24–28 August 1981*, ILRI, Wageningen, The Netherlands, 130–168.

Stephens, J.C. & Speir, W.H. (1969) *Subsidence of Organic Soils in the USA*. IAHS-AIHS Publication 89, 523–534.

Sumawinata, B., Mulyanto, B., Djajakirana, G. & Pulunggono, H.B. (2007) Some considerations of tropical peat for energy. In: Rieley, J.O., Banks, C.J. & Radjagukguk, B. (eds.) *Carbon–Climate–Human Interaction on Tropical Peatland: Proceedings of the International Symposium and Workshop on Tropical Peatland, Yogyakarta, 27–29 August 2007.* CARBOPEAT, Department of Geography, University of Leicester, UK, 243–248.

van den Akker, J.J.H., Kuikman, P.J., de Vries, F., Hoving, I., Pleijter, M., Hendriks, R.F.A., Wolleswinkel, R.J., Simões, R.T.L. & Kwakernaak, C. (2008) Emission of CO_2 from agricultural peat soils in the Netherlands and ways to limit this emission. In: Farrell, C. & Feehan, J. (eds.) *Proceedings of the 13th International Peat Congress “After Wise Use – The Future of Peatlands”, Vol. 1 Oral Presentations*. International Peat Society, Jyväskylä, 645–648.

van den Wyngaert, I.J.J., Kramer, H., Kuikman, P. & Lesschen, J.P. (2009). *Greenhouse Gas Reporting of the LULUCF Sector, Revisions and Updates Related to the Dutch NIR 2009.* Alterra Report 1035-7, 104 pp.

van der Molen, W.H. & Smits, H. (1962) Die Sackung in einem Moorgebiet in Nordgriechenland (Subsidence in a peatland area in northern Greece). In: Baden, W., Grospietsch, T., Lachmann, H., Operschal, E. & Stöber, O.

(eds). *Bericht über den 8. Internationalen Kongreß für universelle Moor- und Torfforschung*. Internationale Gesellschaft für Moor-Forschung, Vaduz, 69–72 (in German).

Vernimmen, R.R.E., Hooijer, A., Mamenun, Aldrian, E. & van Dijk, A.I.J.M. (2012) Evaluation and bias correction of satellite rainfall data for drought monitoring in Indonesia. *Hydrology and Earth System Sciences*, 16, 133–146.

Warren, M.W., Kauffman, J.B., Murdiyarso, D., Anshari, G., Hergoualc'h, K., Kurnianto, S., Purbopuspito, J., Gusmayanti, E., Afifudin, M., Rahajoe, J., Alhamd, L., Limin, S. & Iswandi, A. (2012) A cost-efficient method to assess carbon stocks in tropical peat soil. *Biogeosciences*, 9, 4477–4485.

Wösten, J.H.M., Ismail, A.B. & van Wijk, A.L.M. (1997) Peat subsidence and its practical implications: a case study in Malaysia. *Geoderma*, 78, 25–36.

Ywih, C.H., Ahmed, O.H., Majid, N.M.A. & Jalloh, M.B. (2009) Effects of converting secondary forest on tropical peat soil to oil palm plantation on carbon storage. *American Journal of Agricultural and Biological Sciences*, 4, 123–130.

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