Biogeosciences, 9, 1053–1071, 2012
www.biogeosciences.net/9/1053/2012/
doi:10.5194/bg-9-1053-2012

Biogeosciences

Subsidence and carbon loss in drained tropical peatlands

A. Hooijer[1], S. Page[2], J. Jauhiainen[3], W. A. Lee[4], X. X. Lu[5], A. Idris[6], and G. Anshari[7]

[1]Deltares, P.O. Box 177, Delft 2600 MH, The Netherlands
[2]Department of Geography, University of Leicester, UK
[3]Department of Forest Sciences, University of Helsinki, Finland
[4]Singapore Delft Water Alliance, National University of Singapore, Singapore
[5]Department of Geography, National University of Singapore, Singapore
[6]University of Jambi, Jambi, Indonesia
[7]Center for Wetlands People and Biodiversity, Tanjungpura University, Pontianak, Indonesia

Correspondence to: A. Hooijer (aljosja.hooijer@deltares.nl)

Received: 4 July 2011 – Published in Biogeosciences Discuss.: 15 September 2011
Revised: 6 February 2012 – Accepted: 9 February 2012 – Published: 20 March 2012

Abstract. Conversion of tropical peatlands to agriculture leads to a release of carbon from previously stable, long-term storage, resulting in land subsidence that can be a surrogate measure of CO_2 emissions to the atmosphere. We present an analysis of recent large-scale subsidence monitoring studies in *Acacia* and oil palm plantations on peatland in SE Asia, and compare the findings with previous studies. Subsidence in the first 5 yr after drainage was found to be 142 cm, of which 75 cm occurred in the first year. After 5 yr, the subsidence rate in both plantation types, at average water table depths of 0.7 m, remained constant at around 5 cm yr^{-1}. The results confirm that primary consolidation contributed substantially to total subsidence only in the first year after drainage, that secondary consolidation was negligible, and that the amount of compaction was also much reduced within 5 yr. Over 5 yr after drainage, 75 % of cumulative subsidence was caused by peat oxidation, and after 18 yr this was 92 %. The average rate of carbon loss over the first 5 yr was 178 $t\ CO_{2eq}\ ha^{-1}\ yr^{-1}$, which reduced to 73 $t\ CO_{2eq}\ ha^{-1}\ yr^{-1}$ over subsequent years, potentially resulting in an average loss of 100 $t\ CO_{2eq}\ ha^{-1}\ yr^{-1}$ over 25 yr. Part of the observed range in subsidence and carbon loss values is explained by differences in water table depth, but vegetation cover and other factors such as addition of fertilizers also influence peat oxidation. A relationship with groundwater table depth shows that subsidence and carbon loss are still considerable even at the highest water levels theoretically possible in plantations. This implies that improved plantation water management will reduce these impacts by 20 % at most, relative to current conditions, and that high rates of carbon loss and land subsidence are inevitable consequences of conversion of forested tropical peatlands to other land uses.

1 Introduction

More than half (24.8 Mha) of the global area of tropical peatland is in SE Asia (56 %), mostly in Indonesia and Malaysia. Owing to the considerable thickness (mean >5 m) of the peat in these two countries they contain 77 % of the entire tropical peat carbon store (Page et al., 2011). In Peninsular Malaysia and the islands of Sumatra and Borneo, some 60 % of peat swamps were partly or completely deforested by 2007, usually accompanied by some form of drainage, and only 10 % remained in pristine condition (Miettinen and Liew, 2010). Some 5 Mha were under agricultural use in 2007, of which 45 % (2.3 Mha) was large-scale oil palm and pulpwood (*Acacia*) plantations. A recent inventory by Miettinen et al. (2012) shows that the area of large-scale industrial plantations had increased to 3.15 Mha by 2010 (12 % increase per yr since 2007; excluding smallholder plantations and other forms of land conversion), and that this high expansion rate is likely to continue unless the implementation of land use planning policies is changed.

Published by Copernicus Publications on behalf of the European Geosciences Union.

It has long been known that drainage of peatlands causes irreversible lowering of the surface (subsidence) as a consequence of peat shrinkage and biological oxidation, with the latter resulting in a loss of carbon stock. In peatland areas as different as the Fenlands of the UK, the Netherlands, Venice Lagoon in Italy, the Everglades and Sacramento Delta in the United States and Lake Hula in Israel, a total subsidence of 200 to 600 cm occurred over 40 to 130 yr, bringing surface levels close to or below sea level (Schothorst, 1977; Hutchinson, 1980; Stephens et al., 1984; Hambright and Zohary, 1998; Gambolati et al., 2003; Deverel and Leighton, 2010). In all of these cases, peat oxidation is reported to be the main cause of subsidence. In recent years, rapidly increasing peat carbon losses from drained SE Asian peatlands have been found to contribute substantially to global greenhouse gas emissions (Hooijer et al., 2006, 2010; Couwenberg et al., 2010; Murdiyarso et al., 2010). Estimates of net carbon losses and resultant CO_2 emissions from peatland drained for agriculture range from $< 40\,t$ CO_2 ha^{-1} yr^{-1} (Melling et al., 2005; Murdiyarso et al., 2010; Herchoualc'h and Verchot, 2011), to $> 60\,t$ ha^{-1} yr^{-1} at water table depths around 0.7 m (applying relations between water table depth and emission as proposed by DID Sarawak, 2001; Hooijer et al., 2006, 2010; Couwenberg et al., 2010), excluding forest biomass and fire losses.

The uncertainty in the rate of carbon emission from drained tropical peatland is caused partly by the reliance on measurements of gaseous CO_2 emissions that are difficult to conduct and interpret. Unless CO_2 emission studies are carried out on a large scale (i.e. a large number of measurements conducted over a long time period at a large number of monitoring locations) and over a range of environmental conditions (in terms of water table, vegetation cover and temperature), data uncertainty is considerable (Couwenberg et al., 2010; Murdiyarso et al., 2010; Jauhiainen et al., 2012). For example, widely quoted estimates of CO_2 emission from oil palm plantations on peat have been based on fewer than 50 observations, including replicates, at single locations (Murayama and Bakar, 1996; Melling et al., 2005). Moreover, few studies have estimated net CO_2emissions resulting from peat oxidation alone, excluding root respiration. Also, gas flux measurements do not account for carbon losses in discharge water (DOC and POC), that leave the peatland in drainage water (Alkhatib et al., 2007; Baum et al., 2007; Moore et al., 2010). Recent efforts to calculate the net change in peat carbon stock from the difference between all estimated fluxes into and out of the peat, including changes in biomass (Herchoualc'h and Verchot, 2011), have been inconclusive because of the limited data available and the cumulative uncertainties associated with each component.

There is a need, therefore, for a simple and reliable approach to determining net carbon losses from drained tropical peatlands, especially in view of the urgent requirement for land use planning policies that reduce CO_2 emissions from SE Asian peatlands, which form a substantial part of global emissions (Hooijer et al., 2006, 2010; Malhi, 2010). Measurements of land subsidence, in combination with data on peat characteristics, provide a direct approach to carbon loss assessment that is relatively straightforward to conduct in the field and to interpret. All impacts on the peat carbon stock are integrated over time without requiring instantaneous measurements, thereby providing a more accurate value for total carbon loss even if the individual loss components (CO_2, CH_4, DOC and POC) can not be separated using this method alone. The use of this approach on SE Asian peatlands has been hampered by a scarcity of reliable long-term subsidence data and adequate information on bulk density and carbon content of the peat (cf. review by Couwenberg et al., 2010).

When determining carbon loss from subsidence data, it is necessary to know the extent to which subsidence is the result of peat oxidation compared to physical volume reduction. The following subsidence components need to be separated:

- Oxidation: decomposition of peat in the aerated zone above the water table owing to breakdown of organic matter, resulting in carbon loss through release of gaseous CO_2 to the atmosphere (Neller et al., 1944; Jauhiainen et al., 2005, 2008; Hirano et al., 2009), and removal as DOC and POC in drainage water (Alkhatib et al., 2007; Baum et al., 2007; Moore et al., 2010). This process, acting alone, does not increase bulk density of the peat and could in fact decrease it.

- Compaction and shrinkage: volume reduction of peat in the aerated zone above the water table. Compaction results from the pressure applied on the peat surface by heavy equipment; shrinkage occurs through contraction of organic fibres when drying. These two processes can often not be separated in practice and they are considered together as "compaction" in this paper. Both processes lead to an increase in peat bulk density.

- Consolidation: the compression of saturated peat below the water table owing to loss of buoyancy of the top peat, increasing strain on the peat below. Primary consolidation is caused by loss of water from pores in the peat; it occurs rapidly when groundwater is removed fast, especially where a dense drainage system is implemented in peat of high permeability. Secondary consolidation is a function of the resistance of the solid peat material itself to compression; this is a slow process that makes up only a small fraction of total consolidation (Berry, 1983; Mesri and Aljouni, 2007). Both processes increase peat bulk density.

Fire and erosion of peat particles by water flow both remove peat from near the surface. Their impact on the bulk density of the remaining peat is unknown.

In this study, we investigated in detail the parameters involved in subsidence and carbon loss from tropical peatlands, aiming to reduce uncertainties by better quantifying the oxidation component. Our main objectives were to determine (1) the rate of peat subsidence and changes over time, (2) the contribution of oxidation to subsidence, (3) carbon loss from peat oxidation, and (4) the relationship between carbon loss and environmental factors especially water table depth and land cover. We were able to carry out a much larger number of subsidence measurements (at over 200 locations) than earlier reported studies (at less than 30 locations), across a wider range of conditions, and compared the results with findings on subsidence and carbon loss from previous studies of tropical and sub-tropical peatlands, and with CO_2 emissions that were measured in parallel on the same sites (Jauhiainen et al., 2012).

2 Methods

2.1 Measurement locations, climate and land conversion history

The monitoring sites were located on large peat domes in Indonesia, in *Acacia* tree (for paper production) plantations and adjacent natural forest in the province of Riau and in mature oil palm plantations (for palm oil production) in the province of Jambi. All sites experienced similar climatic conditions, with an average long-term annual rainfall of around 2500 mm and a mean annual air temperature just below 30 °C. During the study period (2007–2010), dry season rainfall was somewhat above the long-term average in the years 2007, 2008 and 2010, with rainfall deficits (broadly defined as rainfall below 100 mm month^{-1}; Vernimmen et al., 2012) only occurring in one or two months at any location. The rainfall regime in 2009 was about average.

All plantation sites are drained by a network of canals, 5 to 8 m wide, over 3 m deep and spaced 500 to 800 m apart, to lower the groundwater table to a level suitable for growth of the plantation crops. Fire was used for land clearance prior to planting oil palms but not in the *Acacia* plantations. Except for 14 locations where monitoring started 1 yr after drainage, in 2002, monitoring in *Acacia* plantations started 3 to 8 yr after drainage; the average period after drainage over the study period was 6 yr. *Acacia* crop rotations at study locations over the measurement period varied mostly from immature to mature, with open conditions occurring in a minority of locations where harvesting took place. In such cases, care was taken not to disturb the immediate surrounding of subsidence poles. Locations where disturbance was evident from the record were excluded from analyses. Study locations in oil palm plantation were drained for 14 to 19 yr when subsidence monitoring started, with an average of 18 yr over the study period, and nearly all locations had mature oil palm cover.

Monitoring locations were established along 16 transects between 0.5 and 12 km long, located perpendicular to drainage canals and covering a wide range of peat thickness and water table depths (Table 1, Fig. 1). Distances between monitoring locations varied from 50 to 400 m depending on site conditions. Transects in *Acacia* plantation were extended 2 km into adjacent peat swamp forest where this still remained. Data used in this analysis were obtained from a total of 218 monitoring locations (125 in *Acacia* plantation, 42 in oil palm plantation and 51 in peat swamp forest adjacent to *Acacia* plantation).

2.2 Peat surface subsidence measurements

At all study locations, the peat surface level was measured using 5 cm diameter, perforated PVC tubes as subsidence poles, inserted vertically through the peat and anchored firmly to at least 0.5 m in the underlying mineral substrate. To minimize measurement error, permanent markers made of light thin metal or wood were placed on the peat surface. Compression of the surface peat was avoided by ensuring field staff did not step within a 0.5 m radius around pole locations, and only on planks during installation. As a further precaution the initial period after installation, from 3 months to more than a year (as much as the data series length allowed while still maintaining a full 2 yr record), was excluded from analyses. Peat subsidence was monitored at intervals of 1 to 3 months in the *Acacia* plantation. A full 2 yr data series for use in analyses was selected for each transect from the 3 yr data collection period of September 2007 to August 2010 on the basis of data availability (some transects were periodically inaccessible due to external factors), with all records overlapping by at least 1 yr. Included in the 125 study locations in *Acacia* plantation were the 14 subsidence poles that had been installed one year after drainage, providing data for a longer period (2002–2010).

For the oil palm plantation, a one-year data series (July 2009 to June 2010), monitored at 2-weekly intervals, was available for analysis. Cumulative subsidence at all locations in both *Acacia* and oil palm plantations was recalculated to annual mean values that allowed comparison.

As no monitoring data from subsidence poles were available for the first year after drainage, we used company records of repeated elevation surveys along transects across *Acacia* plantations, before and approximately 1 yr after drainage, for this period.

2.3 Water table depth measurements

The depth of the water table below the peat surface was monitored in the perforated PVC subsidence tubes at 2-weekly to 3-monthly intervals at the same 218 locations as subsidence. Average water table depths were calculated from records over the same period as the subsidence records used in analyses.

Table 1. Summary of measurement site characteristics. Averages are provided with standard deviations.

		Acacia plantation 6 yr after drainage	Oil palm plantation 18 yr after drainage	Plantation mean 6–18 yr after drainage	Drained forest[2]
Site location (Lat/Long)		102.334/0.595	103.601/−1.566	–	102.334/0.595
Number of measurement locations		125	42	167	51
Peat depth	m	9 ± 2.6	7.7 ± 1.4	8.4	9.9 ± 3.2
Peat bulk density of top 1 m	g cm^{-3}	0.089 ± 0.018	0.087 ± 0.018	0.088	–
Peat bulk density > 1 m depth[1]	g cm^{-3}	0.073 ± 0.015	0.078 ± 0.007	0.075	–
Water table depth	m	0.7 ± 0.2	0.73 ± 0.23	0.71	0.33 ± 0.16

[1] Measured at 1 to 2.3 m depth; affected by initial consolidation.
[2] Natural forest strip up to 2 km from plantation boundary; affected by drainage.

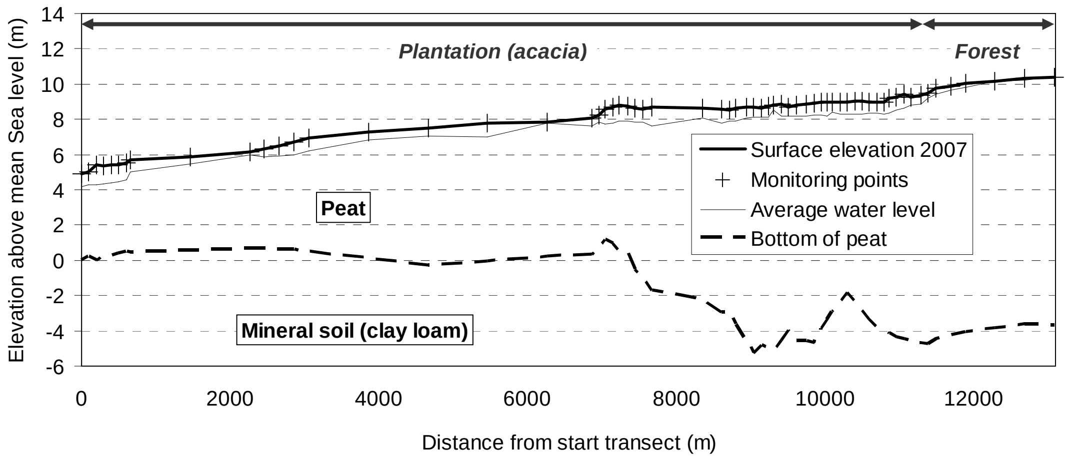

Fig. 1. Cross section along typical study transect in Sumatra, 6 yr after drainage, showing variation in peat depth, average water level, land use and monitoring location density.

2.4 Peat characteristics

Peat thickness and type (fibric, hemic or sapric) were determined at the time of pole installation using locally produced augers and visual interpretation.

Bulk density (BD) was determined at 22 locations in the *Acacia* plantation, 19 that were drained 4 to 7 yr before and 3 about two years after drainage, and at 10 locations in the oil palm plantation. Peat samples were collected from the sides of pits excavated in peat, using sharpened steel cylinders to avoid peat compression that may result from using a vertical corer. This was done quickly after pit construction, to avoid deformation or drying of the peat. To further avoid compression and to ensure inclusion of smaller wood remains, relatively large cylinders of 8 cm diameter and 8 cm length (402 cm^3) were used. All pits were at least 1 m away from trees or palms, where the presence of tree roots was found to be minimal. Water was pumped from deeper pits to facilitate sampling. In the *Acacia* plantation, pits of 1 m diameter were up to 1.2 m deep and three replicate samples were taken at intervals of 0.15 to 0.3 m starting at 0.075 m below the surface. In the oil palm plantation, pits were 2 to 2.5 m deep and samples were collected at intervals of 0.1 m, commencing 0.1 m below the surface (Fig. 2). A total of 1201 peat samples were oven dried at 105 °C for up to 96 h (as long as necessary to ensure that dry weight of samples had fully stabilized) to remove moisture, and weighed to calculate BD.

Large wood remains could not be collected in the cylinders, so additional checks were carried out to determine if undersampling of such remains would affect the BD values. A total of 20 samples of partly decomposed wood taken in 3 soil pits from peat below 1 m depth in oil palm plantations, with an average volume (± SD) of 326 ± 104 cm^3, were dried and weighed following the same protocol as cylinder samples. In addition, the wood content of the peat in oil palm plantation sites was assessed visually on 10 cleaned pit sides, through detailed descriptions of peat surfaces of 0.1 by 0.3 m at 0.1 m depth intervals, prior to sampling.

Ash content in 223 subsamples from *Acacia* plantation sites was determined by loss on ignition in a muffle furnace.

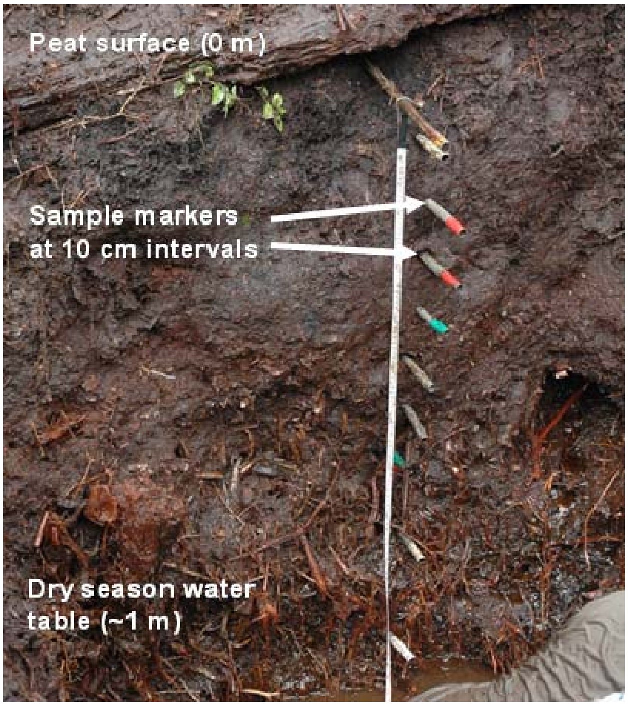

Fig. 2. Peat profile in an oil palm plantation, 18 yr after drainage. The top peat is amorphous without visible plant remains, indicating advanced decomposition, while the peat below 0.3 m is increasingly fibric going downwards, with abundant remains of wood and roots.

2.5 Determining the compaction component of subsidence

The contribution of compaction (including shrinkage) and oxidation to subsidence was calculated by determining the net increase in BD of the peat above the water table caused by compaction, and the total amount of subsidence in that period (e.g. Stephens and Speir, 1969; Schothorst, 1972; Ewing and Vepraskas, 2006; Leifeld et al., 2011). We used a variation modified from Driessen and Soepraptohardjo (1974), as follows:

$$V_{ox} = ((V_1 \times BD_1) - (V_{rest} \times BD_2))/BD_1$$

and:

$$V_{comp} = V_{rest} \times (BD_2 - BD_1)/BD_1$$

and:

$$P_{ox} = V_{ox} \times BD_1 / \left((V_{ox} \times BD_1) + (V_{comp} \times BD_1)\right)$$

where:

- V_{ox} = peat volume loss due to oxidation (cm^3),
- V_{comp} = volume loss due to compaction (cm^3),
- V_{rest} = peat volume after subsidence, above deepest groundwater level (cm^3),
- V_1 = peat volume before subsidence, above deepest groundwater level (cm^3),
- BD_1 = original bulk density above deepest groundwater level (g cm^{-3}),
- BD_2 = new bulk density above deepest groundwater level, after subsidence (g cm^{-3}),
- P_{ox} = percentage of subsidence caused by oxidation.

This method may be demonstrated by taking two extreme conditions as examples: if the height and volume of a peat column above the water table is reduced by 50 %, and the BD of the peat has doubled over the same period, all subsidence can be explained by compaction alone. If on the other hand no change in BD is observed, it may be concluded that there has been no compaction and all subsidence is fully explained by oxidation (assuming consolidation can be excluded). In practice, compaction and oxidation usually both explain a part of total subsidence.

The method ideally requires data on peat BD at the start and end of a subsidence record of many years, at the same site, or data from a nearby undrained reference site. However pre-drainage BD data were not available for the study sites, and truly intact forest areas on deep peat were not accessible close to the study areas. Therefore, two alternative approaches were followed. First, it was assessed whether the current BD of the peat below the lowest average water table depth, which is about 1 m for our sampling locations, could be considered representative for the BD of the upper peat layer at the start of drainage, i.e. for the original peat before subsidence started. Secondly, BD profiles above the water table in the *Acacia* and oil palm plantations, at 2, 4–7 and 18 yr after drainage respectively, were compared. This approach assumed that the pre-drainage peat profiles at the different sampling locations were sufficiently similar to allow such comparison, considering the very similar bulk densities below the water table at the locations (Fig. 3) and their comparable settings on deep peat domes in the same climate region.

2.6 Determining the consolidation component of subsidence

The rate and timing of primary consolidation in the first year was estimated by evaluating the shape of the subsidence curve in the first years after drainage. The contribution of secondary consolidation to subsidence was determined from the relation between subsidence rate and peat depth, 6 yr on average after drainage. If consolidation has occurred, the physics of soil compression determine that the rate of surface lowering it causes is proportional to the thickness of the saturated peat layer (i.e. below the water table) that is being compressed (Berry, 1983; Mesri and Aljouni, 2007). There is also a relationship with the depth of the surface peat unsaturated zone, which determines the loss of buoyancy (i.e.

the increase in strain on the saturated peat below), but in our assessment of secondary consolidation this effect was minimized by only selecting locations with average water table depths within a range of 0.5 to 1 m.

2.7 Determining the oxidation component of subsidence and carbon loss

The contribution of oxidation to subsidence was obtained as the remainder after subtracting the consolidation and compaction components from total subsidence. Carbon loss is calculated from the thickness of peat that is lost as a result of oxidation by applying a BD for peat below the water table, measured as described above, and a carbon concentration for the original peat of 55 % by dry weight, as reported by Suhardjo and Widjaja-Adhi (1977) for a peatland site near the *Acacia* plantation. This value is nearly identical to the value of 56 % found to be representative for hemic and fibric tropical peat in SE Asia by Page et al. (2011).

3 Results

3.1 Subsidence rates

Subsidence in the first year after drainage, along two transects in the *Acacia* plantation, was found to be 60 and 90 cm (75 cm on average), from repeated elevation surveys over that period. Over the subsequent 4 yr a further subsidence of 67 ± 11 cm (average $\pm$ SD) was observed at 14 locations, with an average in the second and third year of 19 ± 4 cm (Fig. 4). On the basis of these two datasets, total subsidence over the first 5 yr after drainage was determined to be 142 cm on average. At around 6 yr after drainage, average subsidence as measured at 125 locations stabilized at around $5 \pm 2.2\ \mathrm{cm\,yr^{-1}}$ (Figs. 4 and 5). In the oil palm plantation the average subsidence was $5.4 \pm 1.1\ \mathrm{cm\,yr^{-1}}$; 18 yr after drainage. On this basis, we conservatively applied an annual subsidence rate of $5\ \mathrm{cm\,yr^{-1}}$ in further calculations of subsidence more than 5 yr after drainage. In the natural forest average subsidence was $2.4 \pm 1.6\ \mathrm{cm\,yr^{-1}}$ at the forest-plantation edge, reducing to 0–$1\ \mathrm{cm\,yr^{-1}}$ at a distance of 2 km inside the forest from the plantation boundary.

For *Acacia* plantations, a subsidence record over 8 yr (2002–2010) was assembled from 3 sources: field elevation surveys before and after the first year after drainage, data from 14 subsidence poles for years 2–5, and data from 125 poles for 6 yr on average after drainage. For oil palm plantations, no accurate subsidence measurements were available prior to our monitoring which commenced more than 14 yr after initial drainage. We therefore applied the *Acacia* plantation record of 142 cm subsidence over the first 5 yr to the oil palm plantation sites, on the basis that the two types of sites were shown to be very similar in terms of peat type, peat depth, water table depth and subsidence rate (comparing rates after 6 and 18 yr on average). To this was added an annual subsidence rate of $5\ \mathrm{cm\,yr^{-1}}$ for the period of 6 to 18 yr after drainage, resulting in a total subsidence of 212 cm over 18 yr. This number was supported by field evidence including the observation that the peat surface had dropped by between 1.2 and 1.5 m relative to the overflow of a weir that was constructed one to two years after drainage and that was anchored in the underlying mineral subsoil (resulting in the overflow being "dry" 16 yr after construction, and the weir no longer operational).

3.2 Water table depths

The average water table depth in the *Acacia* plantation was 0.7 m (Table 1), with a range of values between the 10th and 90th percentiles of 0.47 to 0.98 m. In the oil palm plantation the water table depth regime was similar with an average of 0.73 m and a 10-percentile range of 0.33 to 1.03 m. In the drainage-impacted forest the average water table depth was 0.33 m decreasing to zero (i.e. at the peat surface as defined by the bottom of hollows in the surface hummock-hollow topography) at a distance of 2 km away from plantation perimeter canals, inside the forest.

3.3 Peat bulk densities and other characteristics

Bulk density profiles determined for both *Acacia* and oil palm plantations (Fig. 3) provided average values around $0.15\ \mathrm{g\,cm^{-3}}$ near the peat surface, declining to a constant value of around $0.075\ \mathrm{g\,cm^{-3}}$ at depths below 0.5 m. A small set of data collected at a *Acacia* plantation site 2 yr after drainage showed that the near surface BD was $0.085 \pm 0.01\ \mathrm{g\,cm^{-3}}$ ($n = 36$). The average BD ($\pm$ SD) of the top metre of peat was $0.089 \pm 0.018\ \mathrm{g\,cm^{-3}}$ ($n = 228$) and $0.087 \pm 0.018\ \mathrm{g\,cm^{-3}}$ ($n = 330$) in the *Acacia* plantation sites (4–7 yr after drainage) and oil palm plantation sites (18 yr after drainage), respectively (Table 1). At depths of 1–1.2 m in the *Acacia* plantation and 1–2.5 m in the oil palm plantation these values were $0.073 \pm 0.015\ \mathrm{g\,cm^{-3}}$ ($n = 171$) and $0.078 \pm 0.007\ \mathrm{g\,cm^{-3}}$ ($n = 436$), respectively (Fig. 3).

In the oil palm plantation, the average dry BD ($\pm$ SD) of larger wood remains in peat at depths below 1 m was $0.083 \pm 0.036\ \mathrm{g\,cm^{-3}}$ ($n = 20$), only $0.005\ \mathrm{g\,cm^{-3}}$ above that of the non-woody peat matrix and far below the BD of fresh wood which is generally above $0.4\ \mathrm{g\,cm^{-3}}$ (confirming that the wood remains in this peat are in fact largely decomposed even if they may look quite fresh). The content of larger wood remains in peat below 1 m depth was visually estimated to be 15 % on average, compared to 5 % over the top metre of peat (10 % at 0.6–1 m depth and 0 % at 0–0.5 m). Given the relatively small difference between BD of the wood remains and the peat matrix, and the relatively limited occurrence of large wood remains by volume, there was no need to correct BDs as measured in cylinder samples for the undersampling of larger wood remains.

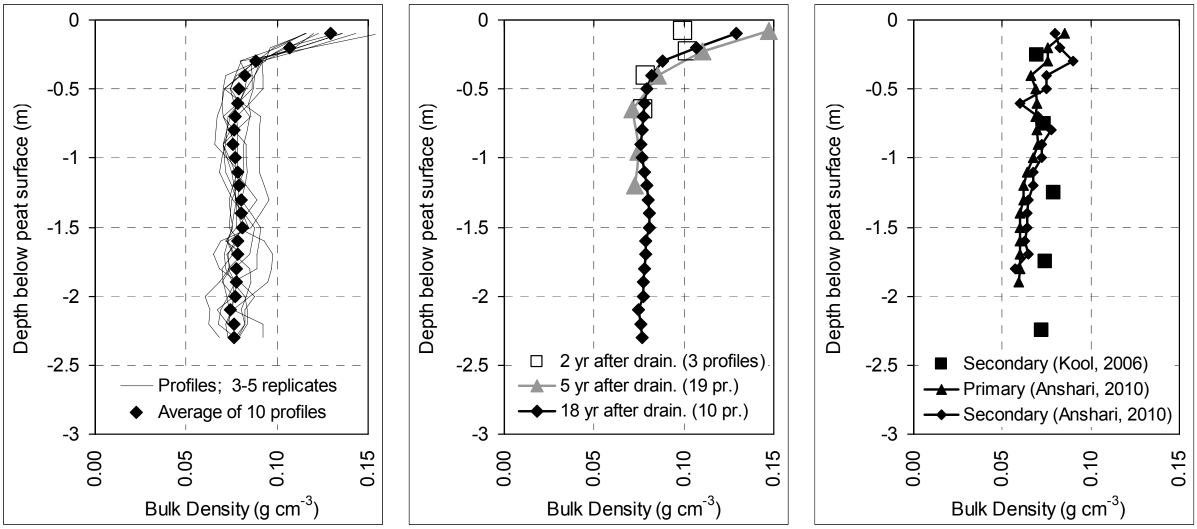

Fig. 3. Vertical profiles of bulk density in SE Asian peatlands. Left: individual profiles (with 3 to 5 replicates at each depth) in Sumatra oil palm plantations (this study), 18 yr after drainage. Middle: average profiles for Sumatra *Acacia* and oil palm plantations at 2, 5 and 18 yr after drainage respectively; each location represents the average of 3 to 19 profiles that all have 3 to 5 replicate samples at each depth (this study). Right: average profiles in undrained secondary natural peatland forest in Kalimantan (Indonesia) as reported by Kool et al. (2006; average of 9 profiles with peat depths over 4 m) and in primary and secondary forest as provided by Gusti Anshari (averages of 4 and 6 profiles per site). The latter data are also reported, in summary, by Anshari et al. (2010).

The average ash content of 223 subsamples was 1.2 % by weight, with a standard deviation of 1.13 %. No relationship between ash content and sampling depth was apparent.

3.4 Peat thickness and type

Values for peat thickness in the *Acacia* plantation varied from 3.8 to 16.9 m, with an average ($\pm$ SD) of 9 ± 2.6 m (Table 1). The range in oil palm plantation was 5.6 to 10.7 m, with an average of 7.7 ± 1.4 m. The overall average peat thickness for both plantation types was 8.4 m. The top 0.3 m to 0.5 m of peat in oil palm plantation sites was generally hemic (with limited plant remains visible; Fig. 2), with some fibric peat (abundant plant remains visible) and sapric peat (no plant remains visible). In *Acacia* plantation sites, that were drained more recently, the top layer of peat was mostly described as more fibric, but going towards hemic. Peat at greater depth was nearly always fibric, and often woody, except the lowest few metres where peat was often hemic or sapric and sometimes described as "muddy", indicating higher mineral content.

3.5 The effect of consolidation on peat bulk density

On the assumption that all or nearly all primary peat consolidation occurs in the first year after drainage (Andriesse, 1988), we estimated the consolidation amount by subtracting a subsidence value of 0.19 m (25 %), obtained for the second and third year, from a total subsidence of 0.75 m in the first year, providing a consolidation component of 0.56 m. This amounts to 7 % of the average peat thickness of 8.4 m at our study sites, implying that the BD of 0.075 g cm^{-3} that is now found below the lowest water table at the study sites, results from the consolidation of a peat column with a "pre-drainage" BD of around 0.07 g cm^{-3}.

No statistically significant relation between subsidence rate and peat thickness ($R^2 = 0.002$, with subsidence being around 5 cm yr^{-1} for all peat thickness values) was evident 6 yr after drainage, confirming that secondary consolidation is negligible in these peatlands.

3.6 The oxidation component of subsidence, and resulting carbon loss

Accounting for consolidation, a total of 0.86 m of the total subsidence of 1.42 m at the *Acacia* plantation sites, over the first five years, was caused by a combination of compaction and oxidation. Following the method described in Sect. 2.5, the BD profile indicates an oxidative peat loss that is equivalent to an average CO_2 emission of 178 *t* ha^{-1} yr^{-1} (Table 2, Fig. 6), which explains 75 % of cumulative subsidence at the *Acacia* plantation monitoring sites over this period. Applying the same method to the oil palm plantation data, assuming the same subsidence of 1.42 m over the first 5 yr and a subsidence of 5 cm yr^{-1} in the subsequent 13 yr, an equivalent average peat oxidative CO_2 emission of 119 *t* ha^{-1} yr^{-1} is obtained, which explains 92 % of subsidence over 18 yr.

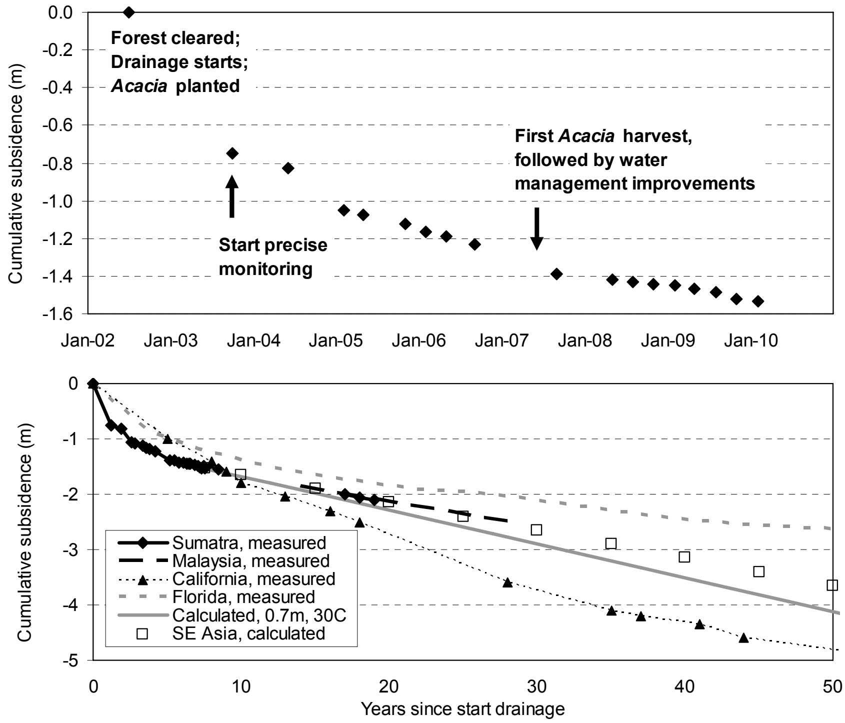

Fig. 4. Top: average subsidence rates as measured at 14 locations in *Acacia* plantations, over the first 9 yr after drainage. Bottom: as measured at a larger number of drained peatland locations in Sumatra (this study), Malaysia (from Wösten et al., 1997, based on DID Malaysia, 1996), Mildred Island in the California Sacramento Delta (Deverel and Leighton, 2010) and Florida Everglades. The Everglades record is averaged from three records presented by Stephens and Speir (1969); as the first two years after completing the drainage system in 1912 were missing from the subsidence record, which started in 1914, we added a subsidence of 22.5 cm yr^{-1} for those years, which is the average subsidence rate over 1914 and 1915 and therefore almost certainly an underestimate of actual initial subsidence. Also shown are long-term calculated subsidence rates for SE Asia, applying both the relation determined for Florida Everglades (Stephens et al., 1984), assuming a water depth of 0.7 m and an average temperature of 30 °C, and the relation found for SE Asia in this paper.

Applying 92 % oxidation to the average subsidence rate measured in the *Acacia* plantation, 6 yr on average after drainage, the resulting carbon loss is 68 t CO_{2eq} ha^{-1} yr^{-1} (CO_2 equivalents, i.e. assuming in this calculation that no carbon is lost as CH_4, DOC or TOC). For the oil palm site, 18 yr after drainage, this value is 78 t CO_{2eq} ha^{-1} yr^{-1}. For these plantations in general, 6 yr or more after drainage, an average minimum loss of 73 t ha^{-1} yr^{-1} may be accepted at an average water table depth of 0.71 m (Table 2).

When calculating total cumulative carbon loss from plantations, both the very high loss in the first 5 yr and the lower loss in the subsequent period must be accounted for. Over a 25 yr period, the average annual carbon loss thus becomes 90 t CO_{2eq} ha^{-1} yr^{-1} for *Acacia* plantation and 109 t ha^{-1} yr^{-1} for oil palm plantation, with an average of 100 t ha^{-1} yr^{-1} for all plantations. Over a 50 yr period, these values become 79 t ha^{-1} yr^{-1} and 94 t ha^{-1} yr^{-1} respectively, with an average of 86 t ha^{-1} yr^{-1}.

3.7 Relationships between subsidence rate and water table depth

Linear correlation regressions between subsidence rate and average water table depth were determined separately for *Acacia* plantation and drained natural forest. The relationship between water table depth and subsidence in *Acacia* plantation, 6 or more years after drainage, is as follows (see Fig. 5):

$$S = 1.5 - 4.98 \times \mathrm{WD}$$

where:

- Regression: $N = 125$, $F = 33.38$, $p < 0.001$, $R^2 = 0.21$,
- Intercept = 1.50, SE = 0.63, $p = 0.02$,
- Slope = −4.98, SE = 0.86, $p < 0.001$,
- S = annual subsidence of the peat surface (cm yr^{-1})
- WD = average water table depth below the peat surface (−m; negative).

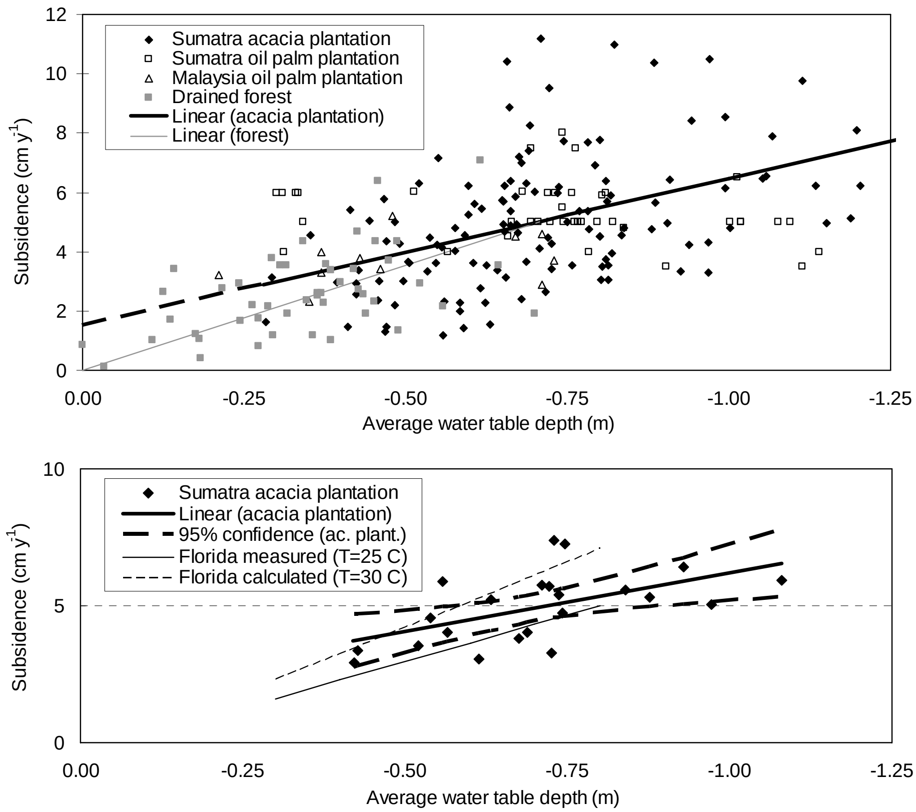

Fig. 5. Subsidence rates and water table depths as measured in *Acacia* plantations, oil palm plantations and adjacent forest in Sumatra, Indonesia. Top: data for individual monitoring locations. Measurements in Malaysian oil palm plantations are shown for comparison (from DID Malaysia, 1996). The linear relations shown are for *Acacia* plantations (excluding oil palm oil plantations) and forest. Bottom: averages for the Sumatra plantation data, grouped by (sub-) transects of 5 to 9 adjacent monitoring locations. Linear relations for Florida Everglades are also shown (adapted from Stephens et al., 1984).

Table 2. Subsidence rates and carbon loss over different time periods, as determined from subsidence and bulk density data.

		Acacia plantation sites	Oil palm plantation sites	Plantation average
Total subsidence in first 5 yr after drainage	(m)	1.42	–	–
Average subsidence and SD, >5 yr after drainage	$cm\,yr^{-1}$	5 ± 2.2	5.4 ± 1.1	5.2
Carbon loss 0–5 yr after drainage (measured)	$t\,CO_{2eq}\,ha^{-1}\,yr^{-1}$	178	–	–
Carbon loss 0–18 yr after drainage (measured)	$t\,CO_{2eq}\,ha^{-1}\,yr^{-1}$	–	119	–
Carbon loss 5–8 yr after drainage (measured)	$t\,CO_{2eq}\,ha^{-1}\,yr^{-1}$	68	–	–
Carbon loss 18 yr after drainage (measured)	$t\,CO_{2eq}\,ha^{-1}\,yr^{-1}$	–	78	–
Carbon loss 0–25 yr after drainage (calculated)	$t\,CO_{2eq}\,ha^{-1}\,yr^{-1}$	90	109	100
Carbon loss 0–50 yr after drainage (calculated)	$t\,CO_{2eq}\,ha^{-1}\,yr^{-1}$	79	94	86

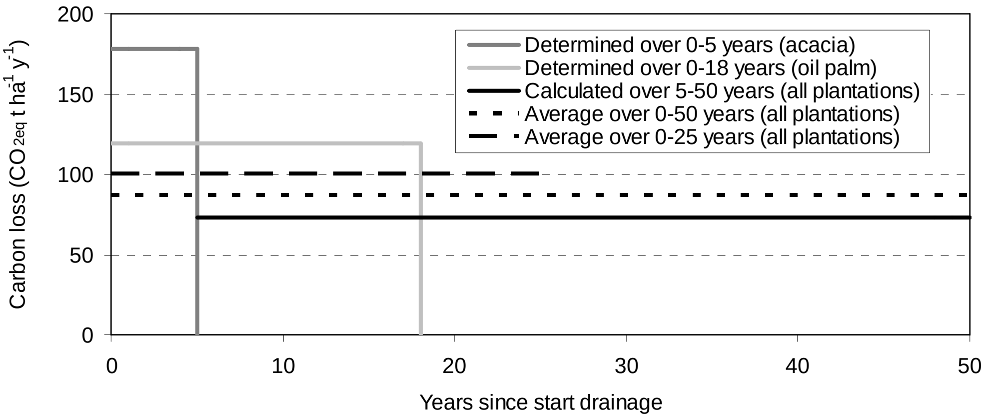

Fig. 6. Development in carbon loss over time in the *Acacia* and oil palm plantations studied.

The analysis of variance confirms that the linear relationship between peat subsidence rate and peat water table depth is statistically valid at the <0.05 significance level. Based on the t-test on coefficients, the intercept is found to differ significantly ($p = 0.02$) from zero.

The relationship for drained forest, at water table depths of 0–0.7 m, is:

$$S = 0.41 - 6.04 \times \mathrm{WD}$$

where:

– Regression: $N = 51$, $F = 26.43$, $p < 0.001$, $R^2 = 0.35$,

– Intercept = 0.41, SE = 0.43, $p = 0.34$,

– Slope = −6.04, SE = 1.17, $p < 0.001$.

This analysis, too, confirms that there is a statistically valid linear relationship between the peat subsidence rate and peat water table depth. The t-test on coefficients suggests that the intercept does not differ significantly ($p = 0.34$) from zero. Therefore, we may recommend a somewhat modified relation with an intercept of zero for use in applications where a water table depth at the peat surface (i.e. of zero) is assumed in emission calculations for intact natural peatland forest:

$$S = -7.06 \times \mathrm{WD}$$

where:

– Regression: $N = 51$, $F = 197.12$, $p < 0.001$, $R^2 = 0.80$,

– Slope = −7.06, SE = 0.50, $p < 0.001$.

The correlations found for these regression relationships including intercept are not high, partly due to data limitations and partly because factors other than water table depth also influence subsidence (see Discussion), but also as a consequence of splitting the dataset into "*Acacia* plantation" and "forest" subsamples with limited water table depth ranges. If a relation is fitted through the combined "*Acacia* plantation" and "forest" data set, resulting in an "intermediate" relation that may be applied where peatland land cover conditions are not clear, a stronger relationship is obtained:

$$S = 0.69 - 5.98 \times \mathrm{WD}$$

where:

– Regression: $N = 176$, $F = 128.42$, $p < 0.001$, $R^2 = 0.43$,

– Intercept = 0.69, SE = 0.34, $p < 0.05$,

– Slope = −5.98, SE = 0.53, $p < 0.001$,

This analysis again confirms a valid linear relationship between the peat subsidence rate and peat water table depth. Based on the t-test on coefficients, the intercept is found to differ significantly ($p < 0.05$) from zero.

3.8 Relationships between carbon loss and water table depth

The CO_2 emissions equivalent to peat subsidence losses caused by drainage in *Acacia* plantation and natural forest (Fig. 7) were determined by applying an oxidation percentage of 92 %, a carbon content of 55 % and a bulk density of 0.075 g cm^{-3}. For plantations, the resulting relationship with average water table depth is:

$$\mathrm{CL} = 21 - 69 \times \mathrm{WD}.$$

For drained natural forest (using the subsidence relation with an intercept through zero):

$$\mathrm{CL} = -98 \times \mathrm{WD}.$$

Combined (for deforested unproductive peatlands):

$$\mathrm{CL} = 9 - 84 \times \mathrm{WD}$$

where:

CL = carbon loss, in $t\,\mathrm{CO_{2eq}\,ha^{-1}\,yr^{-1}}$.

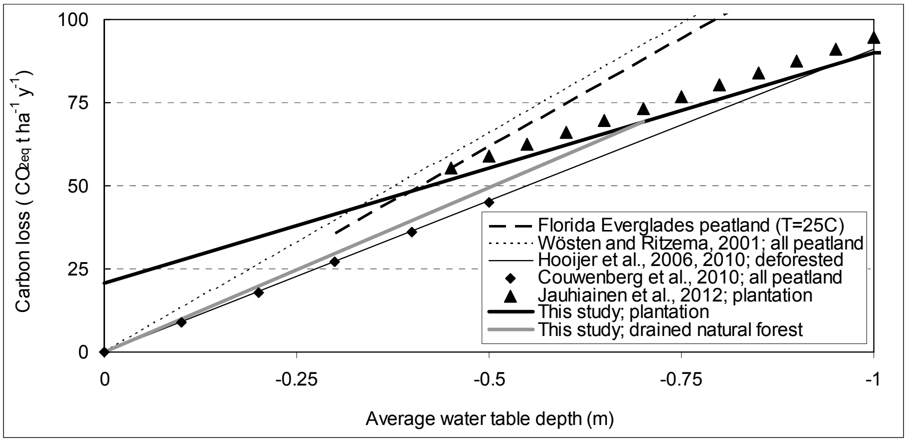

Fig. 7. Comparison of the relation between carbon loss (CO_{2eq}) and water table depth in tropical peatlands, more than 5 yr after drainage, as determined in this and other studies. The Florida Everglades relation is calculated from data in Stephens and Speir (1969), that may also have been used to calculate the relation in Wösten and Ritzema (2001). The relations by Hooijer et al. (2006, 2010) and Couwenberg et al. (2010) were based on partly different sets of literature sources. The relation by Jauhiainen et al. (2012) is based on daytime CO_2 flux measurements in the same *Acacia* plantation as the current study, excluding root respiration and corrected for diurnal temperature fluctuation.

4 Discussion

4.1 Comparison with other published tropical and sub-tropical peat subsidence rates

The average subsidence rate of 5 cm yr^{-1} found for *Acacia* and oil palm plantations, more than 5 yr after initial drainage, is close to most literature values. Subsidence rates reported for a Johor (Malaysia) oil palm plantation, between 14 and 28 yr after drainage, were 4.6 cm yr^{-1} on average at 17 locations for which water table depth data are not available (Wösten et al., 1997), and 3.7 cm yr^{-1} at 11 other locations with an average water table depth of 0.5 m (DID Malaysia, 1996). Mohammed et al. (2009) report, on the basis of field monitoring in oil palm plantations on peat of 3 to 4 m in thickness, that subsidence stabilizes at 4.3 cm yr^{-1} after 15 years under best practice management with average water depths of 0.4 m. DID Sarawak (2001) reported a constant average subsidence rate of 5 cm yr^{-1} in Sarawak after the initial two years following drainage, at a water table depth of 0.6 m, but also proposed that the rate of annual subsidence increased by 1 cm for every 10 cm lowering of the water table, which would result in 7 cm yr^{-1} subsidence at a water table depth of 0.7 m. Andriesse (1988) suggested a stabilization of subsidence at long-term rates of up to 6 cm yr^{-1}, based on observations in a number of locations in SE Asia. In the Everglades, USA, an average subsidence rate of 3 cm yr^{-1} was reported over more than 50 yr after the initial year (Stephens and Speir, 1969; Fig. 4), but this was for a different peat type in a sub-tropical region with a lower surface peat temperature of 25 °C, compared to 30 °C in plantation sites in Indonesia (Jauhiainen et al., 2012), and for higher water table levels. Applying an equation that relates subsidence to temperature and water table depth, based on long-term controlled field plot experiments, Stephens et al. (1984) calculated that the Everglades peat would have subsided by 8 cm yr^{-1} in the long term had it been in fully tropical conditions with a peat surface temperature of 30 °C. In peatland with an initial organic content of around 80 % in the Sacramento Delta, California, subsidence after the initial 5 yr proceeded at a constant rate of 7.5 cm yr^{-1} for over 50 yr (Deverel and Leighton, 2010; Fig. 4).

These studies support our finding that subsidence rates stabilize between 4 cm yr^{-1} and 5.5 cm yr^{-1} in drained SE Asian peatlands, at average water table depths around 0.7 m, after an initial phase of more rapid subsidence. The variation in reported subsidence rates in tropical peat seems to be small compared to temperate peats (Couwenberg et al., 2010). This may be related to the effect of soil temperature, which is more constant in time and space in the tropics (at around 30 °C) compared to temperate climates, on peat oxidation.

The studies in SE Asia mentioned above apply to deep deposits of fibric peat with a pre-drainage BD of around 0.07 to 0.1 g cm^{-3} and low mineral content. Where lower subsidence rates are reported, this is usually for shallower peat with higher BD and mineral content. Murayama and Bakar (1996) reported that subsidence rates in drained peatlands in Peninsular Malaysia, with bulk densities between 0.1 and 0.35 g cm^{-3}, were 2 to 4 cm yr^{-1} after the initial year, and that subsidence decreased as BD increased. Dradjad et al. (2003) reported a subsidence range of 2.4 to 5.3 cm yr^{-1} over a 14 yr period, in peaty swamp soil around 2 m thick with a mineral content as high as 73 to 86 % (i.e. not really peat). Deverel and Leighton (2010) also found a strong relationship between soil organic content and subsidence rate in the Sacramento Delta, with subsidence rates some 100 yr after initial drainage having declined to less than 1 cm yr^{-1}

in areas where the organic content of the top soil was below 10 %, but still as high as 3.5 cm yr^{-1} where the organic content remained 60 %, corresponding to an original organic content of around 80 %.

4.2 Subsidence rates in relation to water table depth and other environmental variables

The relationships between subsidence and water table depth found in this study for peatlands that have been drained for 6 yr on average (Sect. 3.7) are not very different from the relations reported for the drained subtropical Everglades peatlands in Florida on the basis of long-term field experiments (Stephens et al., 1984; Fig. 5), or by Couwenberg et al. (2010) in a review of limited data for SE Asia. While it is possible that non-linear relationships apply, our data do not suggest that these would be more appropriate because they do not yield higher goodness of fit (R^2) values. Non-linear relations are not apparent either from data presented by Stephens et al. (1984), so we conclude that applying a linear regression is appropriate for the current purpose.

It has been suggested that no further increase in peat subsidence and CO_2 emission rates occurs when the water table falls below a threshold depth (Couwenberg et al., 2010). Our data do not indicate such a threshold within the range of water table depths observed in this study (0 to 1.2 m) and we suggest that the linear relationship applies to water table depths up to at least 1 m, while acknowledging that the relationship for greater water table depths may be different.

In contrast with relationships published to date, the regression in this study for *Acacia* plantation does not intercept with the origin, indicating that substantial subsidence would occur in these drained peatlands even if average water tables could be maintained near to the peat surface. It is probable that the higher temperatures and increased peat surface aeration, resulting from reduced vegetation cover and increased peat soil disturbance in plantations, enhance peat oxidation regardless of the position of the water table. Only part of the variation in subsidence and carbon loss can therefore be explained by the relationship with water table depth, and part of it must be attributed to other factors.

In the oil palm plantation, subsidence is virtually constant at all locations (Table 2, Fig. 5), with no relationship with water table depth. This difference with *Acacia* plantation may be because the oil palm sites were continuously fertilized with large amounts of nitrogenous fertilizer ($\sim$600 kg ha^{-1} yr^{-1} urea), whereas the *Acacia* received a small amount of fertilizer during the planting phase only. Inorganic nitrogen increases the rate of microbial breakdown of organic matter (Berg, 2000; Berg and Laskowski, 2006). Therefore, the relationship obtained for *Acacia* plantations can provide a tentative minimum estimate for oil palm plantations until further studies enable determination of a more specific relationship for the latter.

The intercept of the relationship for drained forest, at water table depths of 0–0.7 m, does not differ significantly from zero, confirming that in natural forest the peat carbon store is stable if the water table is close to the peat surface. At 0.7 m water table depth, the "*Acacia* plantation" and the "forest" subsidence rates are the same (Fig. 5) and the "*Acacia* plantation" relationship may be applied to drained natural peatland forest when average water table depths are below 0.7 m.

The difference between the "*Acacia* plantation" and "forest" relationships, especially at high water levels, demonstrates that the presence of an intact natural forest cover reduces oxidation, even if the water table is lowered. Since plantations and natural forest are at opposite ends of the spectrum of land use impacts on peatlands, in terms of vegetation cover and soil disturbance, the two relationships may be assumed to represent extremes of a range from relatively undisturbed to highly disturbed peatlands. The "intermediate" relation may therefore be tentatively applied to degraded natural forest and deforested unproductive peatlands, that experience intermediate levels of disturbance.

4.3 Changes in subsidence rate over time and the role of consolidation

Several studies of SE Asian peatlands report a rapid and major drop by around 100 cm in the peat surface in the first one to two years after drainage, followed by stabilization at a lower, constant rate (Andriesse, 1988; DID Sarawak, 2001), similar to that found in the current study (Fig. 4). Values of this order also occur in other regions of the world, e.g. a primary subsidence of 60 to over 100 cm (Drexler et al., 2009; Deverel and Leighton, 2010) was reported immediately after drainage of the Sacramento Delta peatlands. All studies agree that this initial drop can be attributed mostly to primary consolidation of the peat, while it is generally concluded that secondary consolidation after this initial phase is negligible (Stephens and Speir, 1969; Andriesse, 1988), as found in the current study. Indeed all previous studies applying subsidence measurements to estimate peat oxidation and carbon loss (Schothorst, 1977; Stephens et al., 1984; Wösten et al., 1997; Couwenberg et al., 2010; Deverel and Leighton, 2010; Leifeld et al., 2011) have explicitly or implicitly assumed the effect of consolidation, after an initial "dewatering" phase, to be negligible.

The near absence of consolidation after the first year of plantation drainage can be explained by the high hydraulic conductivity of fibrous tropical peat (10 to over 100 m d^{-1}; DID Sarawak, 2001; Hooijer et al., 2009) that allows the primary consolidation process in intensively drained areas to be completed rapidly as water is removed easily from the peat, and by the small amount of secondary consolidation that occurs in fibrous peat in general (6 % of total consolidation; Mesri and Aljouni, 2007).

For the Florida Everglades, Stephens and Speir (1969) concluded that subsidence continued at a constant rate for over 50 yr after the initial phase. Constant subsidence is also observed in the Sacramento Delta (Deverel and Leighton, 2010; Fig. 4). Whilst a gradual reduction to a subsidence rate of 2 cm yr^{-1}, beyond 28 yr after drainage, was suggested by Wösten et al. (1997), it should be noted that this value was based on an estimated projection rather than only on measurements. Subsidence rates presented in this study, as well as those presented by Wösten et al. (1997), are all around 5 cm yr^{-1} after 6, 18 and 14–28 yr respectively, suggesting a constant subsidence rate rather than a clear gradual decrease.

On the basis of the evidence available we conclude that subsidence rates in *Acacia* and oil palm plantations in SE Asia, more than 5 yr after drainage at constant water table depths, are likely to remain constant or nearly constant at around 5 cm yr^{-1} as long as there is "fresh" peat available for oxidation (Fig. 4). When the peat deposit is nearly depleted and all remaining peat is compacted and drained, the subsidence rate would be expected to decline. This also applies when, as oxidation has removed the upper layers, lower peat layers are being accessed that may have higher BD and mineral content. We therefore emphasize that the current assessment applies to fibric to hemic peat with very low mineral content and low BD.

4.4 Unexplained variation in subsidence rates and water table depths

Subsidence rates determined at individual monitoring locations show considerable variation, with values varying from 1.2 to 11.2 cm yr^{-1} (Fig. 5). However, when values are averaged over subgroups of 5 to 9 adjacent monitoring locations over relatively short distances along transects, this range narrows to 2.9–7.4 cm yr^{-1} (Table 3, Fig. 5). The standard deviation in subsidence rates, expressed as a percentage of the mean value, is still considerable at 42 % on average at the subgroup level (Table 3). This variation in subsidence is not matched by variation in water table depth or peat thickness, with standard deviations of 21 % and 9 % of the mean, respectively, over the same subgroups. This suggests that the variation within these groups, between individual measurements, is related partly to highly localized variations in physical conditions, including heterogeneity in the near-surface peat and in canopy cover, with the latter affecting peat surface temperature.

It follows that accurate subsidence and water table depth measurement requires a large number of locations monitored over long periods to cover not only the obvious variations in land cover and water management, but also the unknown random heterogeneities. In the end, however, substantial unexplained variation in measured subsidence is likely to always remain as some physical conditions that may affect carbon loss and subsidence can not or hardly be measured. For example, it is not possible to measure the variation in peat characteristics (BD, wood content) at the micro-scale without sampling the peat in a pit, which destroys the monitoring location.

The nature of water table depth measurements may also explain part of the variation. The 2-year subsidence records used in this study did not all cover the same period, although all overlap by at least 1 yr, introducing differences in rainfall and soil moisture regime experienced by the different locations; moreover data gaps occurred on some of the records, which affected the average water table depth numbers but not the subsidence numbers.

4.5 Study site bulk density compared to literature values

The average "original" BD value of 0.075 g cm^{-3} found in peat below 1 m depth in this study, translating to a value of 0.07 g cm^{-3} prior to consolidation, is at the low end of values for SE Asian peats presented by Page et al. (2011), who find that average values reported by 15 individual studies, in both intact and deforested peatlands, are between 0.08 and 0.13 g cm^{-3} with an average of 0.09 g cm^{-3}. Lower-range values reported by individual studies are below 0.06 g cm^{-3} in only 3 out of 15 studies, and all 15 report average values above 0.07 g cm^{-3}. In deforested peatlands, Page et al. (2011) find BD values of near-surface peat to be higher than at greater depth, but in forested peatlands no consistent increase or decrease with depth was identified. This lack of a clear trend with depth, at depths between 0 and 4 m, is also confirmed by peat profiles in primary and secondary forest in Kalimantan (Indonesia) (Kool et al., 2006; Anshari et al., 2010) (Fig. 3).

The value of 0.061 g cm^{-3} over 1–2 m depth derived from data used by Anshari et al. (2010) is the lowest average reported for any group of peat profiles in undrained peatland forest in SE Asia. By contrast, data for intact forest presented by Kool et al. (2006) yield an average of 0.074 g cm^{-3} over 1–4 m, which is higher than the pre-consolidation value of 0.07 g cm^{-3} applied in the current study.

On the basis of the above assessment of literature values, and noting that the BD values below 1 m at the different locations in the current study are all very similar, we conclude that our BD values below 1 m are indeed representative of the pre-drainage conditions, somewhat increased by primary consolidation. Therefore, total compaction since the start of drainage, after the initial 1 yr consolidation phase, may be estimated by comparing the current BD of peat below 1 m depth with that above it as explained in Sects. 2.5 and 3.6.

4.6 Determining the carbon loss from oxidation, as a percentage of total subsidence

Very few studies have separated the oxidation and compaction components of subsidence in tropical and subtropical peatlands using BD profiles. Stephens and

Table 3. Summary statistics of water depth, peat thickness and subsidence rate along all plantation transects, as calculated over groups of 5 to 9 adjacent measurement locations each. Mean, maximum and minimum values are calculated from average values for individual locations. The "Riau" locations are in *Acacia* plantation, the "Jambi" locations in oil palm.

(Sub-) transect code		No of mon. points	Water table depth					Peat thickness					Subsidence				
			Mean m	Min m	Max m	SD m	SD % mean	Mean m	Min m	Max m	SD m	SD % mean	Mean $cm\,yr^{-1}$	Min $cm\,yr^{-1}$	Max $cm\,yr^{-1}$	SD $cm\,yr^{-1}$	SD % mean
A	Riau	6	−0.56	−0.72	−0.41	0.11	20	−5.3	−5.7	−4.6	0.4	8	5.9	4.2	9.5	1.9	32
B	Riau	6	−0.63	−0.77	−0.47	0.10	16	−6.7	−7.2	−6.2	0.5	7	5.2	3.4	7.7	2.1	40
C	Riau	6	−0.54	−0.80	−0.29	0.11	21	−7.8	−10.2	−7.1	0.6	8	4.5	2.2	7.8	2.1	46
D	Riau	5	−0.72	−0.91	−0.65	0.10	14	−7.8	−8.6	−6.9	0.5	7	5.7	3.1	7.4	2.4	42
E	Riau	6	−0.84	−1.05	−0.56	0.10	11	−8.1	−8.4	−7.8	0.5	7	5.6	2.3	10.4	2.1	38
F	Riau	6	−0.56	−0.69	−0.43	0.11	19	−8.6	−9.1	−8.1	0.6	7	4.0	1.5	6.3	1.9	48
G	Riau	5	−0.43	−0.56	−0.28	0.11	26	−11.6	−11.8	−11.5	0.7	6	3.4	1.6	5.1	2.0	59
H	Riau	5	−0.42	−0.50	−0.35	0.11	25	−11.8	−11.9	−11.6	0.5	4	2.9	1.5	4.6	1.5	51
I	Riau	5	−0.67	−0.97	−0.47	0.11	17	−6.0	−7.7	−5.1	0.4	6	3.8	1.3	6.2	1.4	37
K	Riau	5	−0.74	−0.83	−0.62	0.11	15	−8.3	−9.3	−7.7	0.3	3	4.7	1.6	11.0	1.7	36
L	Riau	5	−0.61	−0.71	−0.55	0.12	19	−12.2	−13.1	−11.6	0.2	2	3.1	1.2	4.1	1.7	57
M	Riau	5	−0.52	−0.60	−0.46	0.13	24	−14.6	−16.9	−13.3	0.1	1	3.5	2.3	4.5	1.9	53
N	Riau	5	−0.74	−0.80	−0.66	0.10	14	−12.8	−14.7	−10.2	0.1	1	5.4	4.5	6.2	1.8	34
O	Riau	9	−0.71	−0.99	−0.49	0.12	17	−12.7	−14.4	−10.5	0.3	3	5.8	4.3	8.5	1.9	32
P	Riau	5	−0.88	−1.07	−0.78	0.13	15	−8.7	−9.3	−8.4	0.3	4	5.3	3.0	7.9	2.0	38
Q	Riau	5	−0.73	−0.81	−0.62	0.13	18	−8.8	−9.4	−8.4	0.4	4	3.3	2.3	4.5	2.3	69
R	Riau	6	−0.69	−0.81	−0.58	0.21	31	−9.0	−10.0	−8.5	1.4	15	4.0	1.4	5.7	2.4	61
S	Riau	5	−0.73	−0.81	−0.66	0.26	35	−4.6	−5.9	−3.8	1.5	33	7.4	3.1	11.2	2.4	32
T	Riau	7	−0.75	−0.97	−0.55	0.26	34	−8.3	−10.1	−7.5	1.5	18	7.3	3.7	10.5	2.4	33
U	Riau	7	−0.93	−1.26	−0.65	0.21	23	−8.6	−9.0	−8.0	1.3	15	6.4	4.7	8.4	2.2	34
V	Riau	6	−1.08	−1.19	−0.97	0.22	20	−8.0	−8.0	−8.0	1.1	13	5.9	4.3	9.8	2.2	37
1	Jambi	9	−0.75	−0.84	−0.66	0.19	25	−6.4	−7.2	−6.0	1.0	16	5.3	4.5	6.0	2.0	38
2	Jambi	8	−1.06	−1.14	−1.00	0.19	18	−6.5	−8.1	−6.0	1.0	16	4.9	3.5	6.5	2.0	41
3	Jambi	9	−0.73	−0.90	−0.51	0.22	31	−6.9	−8.5	−5.6	1.2	18	4.8	3.5	6.0	1.9	40
4	Jambi	9	−0.73	−0.77	−0.69	0.12	16	−9.2	−10.7	−8.8	0.7	7	6.1	5.0	8.0	1.9	31
5	Jambi	7	−0.32	−0.34	−0.30	0.11	33	−9.2	−9.9	−8.7	0.6	6	5.9	4.0	8.0	1.8	31
All Riau		125	−0.70	−0.86	−0.56	0.14	20	−8.89	−9.81	−8.17	0.62	8	4.92	2.76	7.51	1.99	43
All Jambi		42	−0.72	−0.80	−0.63	0.17	25	−7.64	−8.87	−7.01	0.91	13	5.40	4.10	6.90	1.93	36
All		167	−0.71	−0.85	−0.57	0.14	21	−8.66	−9.63	−7.95	0.67	9	5.01	3.01	7.40	1.98	42

Speir (1969) calculated that oxidation accounted for 78 % of subsidence in the Everglades peatlands over a period of more than 50 yr since drainage; this was confirmed by CO_2 flux measurements at the same sites (Neller, 1944) and under laboratory conditions (Volk, 1973). In a reassessment of the same data, Stephens et al. (1984) estimated that the increase in BD in field plots reported by Neller (1944) explained only 10 to 15 % of subsidence, implying that 85 to 90 % could be attributed to carbon loss. Deverel and Rojstaczer (1996) and Deverel and Leighton (2010) found that oxidation accounted for 68 % of subsidence in Californian peatlands more than 70 yr after drainage, based on CO_2 flux measurements and a carbon balance model. This value applies, however, to peat with a mineral content that is 20 % higher than in the Everglades or SE Asia, which is expected to reduce the relative contribution of oxidation to subsidence. Based on CO_2 flux measurements, Murayama and Bakar (1996) concluded that oxidation caused 50 % to 70 % of subsidence at sites in Malaysia; however this was also for shallow peat with high mineral content. In peatland plantations in Johor, Malaysia a cumulative value of 61 % was reported (DID Malaysia, 1996; Wösten et al., 1997); however, the authors do not explain over what period after drainage this value applies. Moreover, the same study also reports complete loss of the peat layer, i.e. 100 % oxidation, at up to one third of the subsidence monitoring locations where peat was thin at the start of monitoring. Couwenberg et al. (2010) assumed a minimum oxidation percentage of 40 %, but this was based mostly on studies in temperate climates whereas others (Volk, 1973; Stephens et al., 1984; Brady, 1997) have shown that peat oxidation increases at higher temperatures, causing a doubling of subsidence rate for every 10 °C increase. Assuming an average peat surface temperature of 10 °C in temperate peatlands and 30 °C in the tropics, the oxidation rate would be expected to be four times higher in the latter and make up a far larger proportion of subsidence. Peat temperature and its potential impact on tropical peat oxidation is discussed in more detail in Jauhiainen et al. (2012).

While the oxidation contribution to peat subsidence increases over the first few years after drainage as primary consolidation and compaction diminish, the net carbon loss in fact decreases over this period, before stabilizing. It may be that a finite pool of the most labile carbon compounds decomposes rapidly, leaving only recalcitrant carbon compounds that are more resistant to decomposition (Berg, 2000). In addition, a lower water table in this initial "dewatering phase", applied to rapidly consolidate the peat surface before planting, may further increase oxidation. A similar finding of an initial "spike" in carbon loss was reported for the Sacramento Delta by Deverel and

Leighton (2010), who calculated that emissions reduced from 154 *t* CO_{2eq} ha^{-1} yr^{-1} a few years after drainage to 55 *t* ha^{-1} yr^{-1} 80 yr later, at an average water table depth of 1 m (Drexler et al., 2009).

The fact that the BD profiles in our study sites at 3–7 and 18 yr after drainage are very similar (Fig. 3) indicates that not only primary consolidation but also compaction may in fact have become negligible after the first 5 yr, at which point nearly 100 % of subsidence appears to be caused by oxidation. After the initial year of subsidence, rates of compaction and oxidation may achieve equilibrium. Compaction continues as uncompacted peat from the saturated zone enters the unsaturated, oxidative zone. However this compaction appears to be balanced by oxidation in an unsaturated peat profile of constant thickness and bulk density that moves progressively downwards over time as the water table is lowered to match surface subsidence. The combined result of the two processes is a peat bulk density profile that is stable in time.

The long-term oxidation contribution to subsidence of 92 % in oil palm plantations, 18 yr after drainage, is at the high end of earlier estimates. Our study confirms, however, that the contribution of oxidation to peat subsidence increases in time while consolidation and compaction are major contributors only in the initial period. It should be noted that most published percentage oxidation values, including the 61 % reported by DID Malaysia and Wösten et al. (1996, 1997) and the 85–90 % suggested by Stephens et al. (1984), are averages of the cumulative oxidation since the start of drainage, and therefore systematically underestimate the percentage oxidation after the initial period. The longer the period after drainage that is considered, the greater the cumulative contribution of oxidation to subsidence that will be found. For calculations of long-term carbon emissions we therefore recommend use of the figure of 92 % oxidation that we find for oil palm plantation 18 yr after drainage, rather than the 75 % that we found for *Acacia* plantations 6 yr after drainage.

4.7 Sensitivity assessment

The calculation of the percentage oxidation contribution to subsidence, and the resulting carbon loss, is sensitive to the value used for the original pre-drainage BD, corrected for consolidation immediately after drainage. In Sect. 4.5 we have shown that the pre-drainage BD values around 0.075 g cm^{-3} used in our analysis, resulting from a value of 0.07 g cm^{-3} allowing for primary consolidation immediately after drainage, are at the low end of published values. We have also shown that the lowest average pre-drainage value reported in any study is 0.061 g cm^{-3} (using data of Anshari et al., 2010). This would increase to around 0.065 g cm^{-3} allowing for consolidation. Using the latter value instead of the 0.078 g cm^{-3} on average applied to the oil palm plantation in this study would have yielded an oxidation percentage of 77 % at 18 yr after drainage instead of 92 %, suggesting that carbon loss more than 5 yr after drainage could be at the very most 20 % lower than the average value of 73 *t* CO_{2eq} ha^{-1} yr^{-1} proposed in this paper, i.e. around 60 *t* CO_{2eq} ha^{-1} yr^{-1}. However, this low-end figure is unlikely to apply, as such low BD values appear to be exceptional.

For assessing the spike in carbon loss in the first year after drainage, the estimate of primary consolidation in the first year is also a sensitive parameter. If we would assume all the 75 cm of subsidence in the first year is caused by primary consolidation only, rather than allowing for 19 cm being caused by oxidation and compaction (Sect. 3.5), the average carbon loss over the first 5 yr becomes 132 *t* CO_{2eq} ha^{-1} yr^{-1} rather than 178 *t* CO_{2eq} ha^{-1} yr^{-1}. This would also decrease the percentage oxidation that is calculated over the period, from the 75 % now calculated for *Acacia* plantation over 5 yr after drainage (Sect. 3.6) to 69 %, and from 92 % for oil palm plantation over 18 yr to 90 %. While we deem the underlying assumption of an absence of oxidation in the first yr to be unrealistic, these values of 132 *t* ha^{-1} yr^{-1} emission over the first 5 yr and a long-term oxidation percentage of 90 % may be seen as the lowest possible estimates on the basis of the evidence available.

The value for carbon content used has a proportional effect on the carbon loss calculated from subsidence. Assuming carbon content of 50 % or 60 % instead of 55 %, which covers the range reported in literature for fibric and hemic peat with low mineral content, would reduce or increase carbon loss by 10 %.

4.8 Comparison of carbon loss in subsidence with CO_2 emission measurements

Gaseous CO_2 emissions at the peat surface in the same *Acacia* plantation landscape have been measured using the closed chamber technique at 144 locations (Jauhiainen et al., 2012). Measures were taken to exclude root respiration so the results only represent CO_2 emissions from peat oxidation. After correction for diurnal temperature fluctuations, these measurements from the same peatland yield a value of 80 *t* ha^{-1} yr^{-1} at an average water table depth of 0.8 m, which is very close to the 76 *t* CO_{2eq} ha^{-1} yr^{-1} yielded by the subsidence method for the same water table depth. Moreover, the slope of the relationship between water table depth and CO_2 emission presented by Jauhiainen et al. (2012) is nearly identical to that using the subsidence method presented in this paper (Fig. 7). We conclude that the results of the two independent approaches are mutually supportive.

4.9 Comparison with other published CO_2 emissions from tropical peatland

At water table depths between 0.5 and 1 m, that are most common in plantations, the emission relations found for *Acacia* plantations and drained forest are similar to the

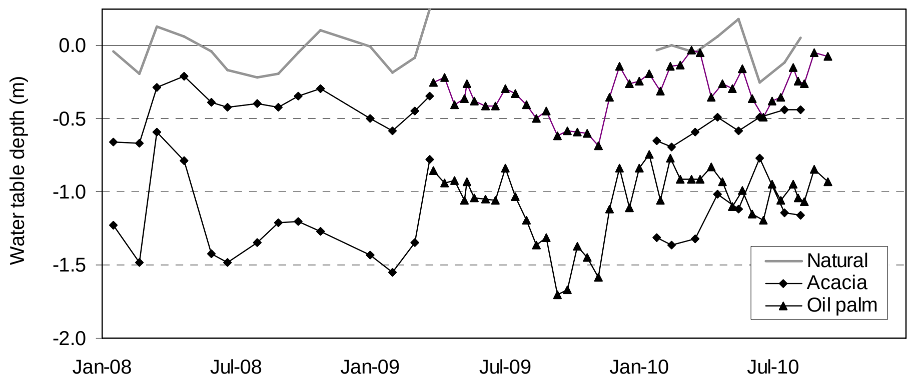

Fig. 8. Time series of water table depth as measured at individual locations in the studied *Acacia* and oil palm plantations, and in nearby natural forest at 2 km from the *Acacia* plantation, over a 3-years period. In plantations, the records nearest the lower and upper 10-percentile average water levels were selected.

linear relationship reported by Hooijer et al. (2006, 2010) and Couwenberg et al. (2010), that were based on meta-data assessments of studies carried out in deforested tropical peatlands (Fig. 7). A similar CO_{2eq} emission value was also obtained by DID Sarawak (2001) and Wösten and Ritzema (2001) who proposed that every 1.0 cm of subsidence results in a CO_{2eq} emission of 13.3 t ha^{-1} yr^{-1}, equating to a total CO_{2eq} emission of 66 t ha^{-1} yr^{-1} at the subsidence rate of 5 cm yr^{-1} reported in the same publications.

We conclude that the carbon losses found in this study, more than 5 yr after drainage, are in agreement with most earlier studies, for water table depths that are common in plantations and for the period beyond the initial years after drainage. At lesser water table depths, the difference with existing relationships increases, suggesting higher emissions from drained peatlands than have been assumed to date and a stronger relationship with vegetation cover, and perhaps with fertilization and peat disturbance as well. Moreover, we found that carbon loss in the initial year is higher than in subsequent years, resulting in considerably higher long-term average emissions than have been reported to date.

4.10 Predicting subsidence and carbon loss under different water management regimes

The average water table depths encountered in this study are similar in both *Acacia* and oil palm plantations, at 0.7 and 0.73 m respectively, which is less than those reported in some earlier studies (e.g. 0.95 m in Hooijer et al., 2006, 2010) and close to the target of 0.7 m specified for the *Acacia* plantations studied (Hooijer et al., 2009) and of 0.6 m for oil palm plantations in general (DID Sarawak, 2001). However, this does not suggest that high and well-controlled water levels are the norm in such plantations. The limited options for effective water level control are illustrated by the wide range of levels encountered in the study, with 10-percentile values for annual averages ranging between 0.33 and 1.03 m and for individual measurements between 0 and 1.6 m (Fig. 8). Water table depth can vary by up to a metre over a few kilometres in each type of plantation, and also over time within the dry and wet seasons. It should also be noted that our measurements were obtained in a relatively "wet" year with high rainfall even in the dry season, and in plantations that are relatively well managed compared to others in the region. Water table depth variations in normal years, and in other areas, are likely to be greater.

The implication of the relatively low slope of the regression between water table depth and subsidence found in this study, is that the benefit of raising water tables to reduce carbon emissions in plantations may be smaller than earlier assumed. Even if an average water table depth of 0.6 m could be achieved in the plantations now studied, which is not guaranteed, subsidence would still be 4.5 cm yr^{-1} over the long term, and the carbon loss 63 t CO_{2eq} ha^{-1} yr^{-1} more than 5 yr after drainage. This would be a reduction of no more than 20 % relative to the average emissions currently occurring. Moreover, it should be noted that this reduction in annual subsidence and emission merely means they are postponed to a later date, unless natural conditions could be restored in these plantations.

5 Conclusions

We show, for a much larger number of locations than all previous studies in SE Asia on this subject combined, that measurements of subsidence and bulk density can yield accurate soil carbon loss values for tropical peatlands, if the contributions from the different processes of oxidation, compaction and consolidation contributing to subsidence are accounted for. This reduces the uncertainty of carbon loss estimates compared to earlier peat subsidence and gaseous emission studies. This study is also the first to determine carbon loss from tropical peatland from subsidence in parallel with direct

CO_2 gas emission measurements at the same locations (see Jauhiainen et al., 2012); the close agreement between the results of the two independent approaches further confirms their validity. We recommend that this subsidence approach is adopted in future studies of carbon loss from tropical peatlands, alone or in combination with direct CO_2 gas emission measurements.

The subsidence rate of 142 cm over the first 5 yr, and 5 cm yr^{-1} over subsequent decades at water table depths around 0.7 m, is supported by findings of most smaller-scale studies published earlier. However the accompanying carbon loss, of 100 t CO_{2eq} ha^{-1} yr^{-1} on average over 25 yr after drainage, is higher than other published estimates. This is largely because earlier studies have assumed that peat oxidation and carbon loss are constant from the start of plantation development, whereas we confirmed substantially higher loss rates in the first few years after drainage. Another reason for the underestimation of CO_2 losses from tropical peatland is the use of oxidation percentages from temperate and boreal peatland studies that do not take into account the temperature dependence of the decomposition processes involved.

The average emission in the plantations studied more than 5 yr after drainage, for *Acacia* and oil palm combined, is found to be 73 t CO_{2eq} ha^{-1} yr^{-1} at water depths around 0.7 m. This is at the high end of earlier estimates. Our sensitivity analysis shows that for emissions to be 20 % lower, we would have to apply the lowest pre-drainage BD reported for SE Asian peatlands. We therefore believe our carbon loss calculations to be conservative. The relatively small difference for carbon loss from *Acacia* plantations 6 yr after drainage and oil palm plantations 18 yr after drainage, of 68 and 78 t CO_{2eq} ha^{-1} yr^{-1} respectively, suggests that the overall range in long-term carbon emissions from these types of plantations in this region may be limited.

The carbon emission estimates and relations presented in this paper, as well as the improved ability to project long-term emissions, may help REDD projects (Reduced Emissions from Deforestation and Degradation) to better quantify the actual carbon emission reduction that can be achieved through rehabilitation and conservation of tropical forested peatlands, compared to a "Business as Usual" scenario of deforestation and drainage that is now evident in most tropical peatlands. Reduced uncertainty in these calculations is essential for REDD projects to be economically viable and verifiable (Murdiyarso et al., 2010; Asner, 2011). Our findings support a conservative approach as they suggest that bringing up water tables to near-natural levels alone, without restoring a near-natural vegetation cover which may take a long time, will still allow substantial carbon emissions.

With a subsidence rate of around 1.5 m over the first five years after drainage, followed by a nearly constant rate of 5 cm yr^{-1} in subsequent years, subsidence typically amounts to 2.5 m in 25 years and could well be over 5 m within 100 years if peat thickness allows it, even excluding the effect of fires. Such substantial lowering of the land surface in coastal lowlands will affect drainability, as has been seen in other parts of the world, and may cause loss of agricultural production in many areas of deep peat in SE Asia unless an alternative to gravity drainage would be technically and economically possible. This issue has received little attention to date, as the focus in the discussion on the future of peatlands in SE Asia has so far been on carbon emissions and biodiversity loss. We recommend that the effect of subsidence on drainability and agricultural production should be quantified and considered in land use planning, as it is likely to affect the longer-term economic viability of establishing agriculture on peatlands.

Where plantations on tropical peatland are inevitable, investment in water management is needed to achieve water levels that reduce subsidence and reduce carbon loss, while at the same time protecting forest and peat resources in the surrounding peatland. However the finding that considerable carbon loss and subsidence occur even at the highest possible water levels in and around peatland plantations, leads to the conclusion that carbon emission and land subsidence are an inevitable consequence whenever tropical peatlands are drained, regardless of management regime.

Acknowledgements. We thank the plantation companies, as well SDWA (Singapore Delft Water Alliance) and the Deltares R&D programme, for supporting different parts of the research. The University of Jambi field team is thanked for data collection.

Edited by: D. Zona

References

Alkhatib, M., Jennerjahn, T. C., and Samiaji, J.: Biogeochemistry of the Dumai river estuary, Sumatra, Indonesia, a tropical blackwater river, Limnol. Oceanogr., 52, 2410–2417, 2007.

Andriesse, J. P.: Nature and management of tropical peat soils, FAO Soils Bulletin, 59, 248 pp., 1988.

Anshari, G. Z., Afifudin, M., Nuriman, M., Gusmayanti, E., Arianie, L., Susana, R., Nusantara, R. W., Sugardjito, J., and Rafiastanto, A.: Drainage and land use impacts on changes in selected peat properties and peat degradation in West Kalimantan Province, Indonesia, Biogeosciences, 7, 3403–3419, doi:10.5194/bg-7-3403-2010, 2010.

Asner, G. P.: Painting the world REDD: addressing scientific barriers to monitoring emissions from tropical forests, Environ. Res. Lett., 6, 021002, doi:10.1088/1748-9326/6/2/021002, 2011.

Baum, A., Rixen, T., and Samiaji, J.: Relevance of peat draining rivers in central Sumatra for the riverine input of dissolved organic carbon into the ocean, Estuar. Coast. Shelf S., 73, 563–570, 2007.

Berg, B.: Litter decomposition and organic matter turnover in northern forest soils, Forest Ecol. Manag., 133, 13–22, 2000.

Berg, B. and Laskowski, R.: Litter decomposition: a guide to carbon and nutrient turnover, Woods Hole Oceanographic Institute, Massachusetts, USA, 449 pp., 2006.

Berry, P. L.: Application of consolidation theory for peat to the design of a reclamation scheme by preloading, Q. J. Eng. Geol., 16, 103–112, 1983.

Brady, M. A.: Organic matter dynamics of coastal peat deposits in Sumatra, Indonesia, Ph.D. thesis, University of British Columbia, Vancouver, 258 pp., 1997.

Couwenberg, J., Dommain, R., and Joosten, H.: Greenhouse gas fluxes from tropical peatlands in southeast Asia, Global Change Biol., 16, 1715–1732, 2010.

Deverel, S. J. and Rojstaczer, D. A.: Subsidence of agricultural lands in the Sacramento-San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes, Water Resour. Res., 32, 2359–2367, 1996.

Deverel, S. J. and Leighton, D. A: Historic, recent, and future subsidence, Sacramento-San Joaquin Delta, California, USA, San Francisco Estuary and Watershed Science, 8, 23 pp., 2010.

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

DID Sarawak: Water management guidelines for agricultural development in lowland peat swamps of Sarawak, Report of the Department of Irrigation and Drainage, Sarawak, Malaysia, 78 pp., 2001.

Dradjad, M., Soekodarmodjo, S., Hidayat, M. S., and Nitisapto, M.: Subsidence of peat soils the tidal swamplands of Barambai, South Kalimantan, Jurnal Ilmu Tanah dan Lingkungan, 4, 32–40, 2003.

Drexler, J. Z., DeFontaine, C. S., and Deverel, S. J.: The legacy of wetland drainage on the remaining peat in the Sacramento-San Joaquin Delta, Journal of the Society of Wetlands Scientists, 29, 372–386, 2009.

Driessen, P. M. and Soepraptohardjo, M.: Soils for agricultural expansion in Indonesia, Publication of Soil Research Institute, Bull. 1, Bogor, Indonesia, 41–63, 1974.

Ewing, J. M. and Vepraskas, M. J.: Estimating primary and secondary subsidence in an organic soil 15, 20, and 30 yr after drainage, WETLANDS, 26, 119–130, 2006.

Gambolati, G., Putti, M., Teatini, P., and Stori, G. G.: Subsidence due to peat oxidation and its impact on drainage infrastructure in a farmland catchment south of Venice Lagoon, RMZ – Materials and Geoenvironment, 50, 125–128, 2003.

Hambright, K. D. and Zohary, T.: Lakes Hula and Agmon: destruction and creation of wetland ecosystems in northern Israel, Wetl. Ecol. Manag., 6, 83–89, 1998.

Hergoualc'h, K. and Verchot, L. V.: Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review, Global Biogeochem. Cy., 25, GB2001, doi:10.1029/2009GB003718, 2011.

Hirano, T., Jauhiainen, J., Inoue, T., and Takahashi, H.: Controls on the carbon balance of tropical peatlands, Ecosystems, 12, 873–887, 2009.

Hooijer, A.: Hydrology of tropical wetland forests: recent research results from Sarawak peat swamps, in: Forests-Water-People in the Humid Tropics, edited by: Bonell, M. and Bruijnzeel, L. A., Cambridge University Press, 447–461, 2005.

Hooijer, A., Silvius, M., Wösten, H., and Page, S.: PEAT-CO_2 Assessment of CO_2 emissions from drained peatlands in SE Asia, Delft Hydraulics report Q3943, 36 pp., 2006.

Hooijer, A., Page, S., and Jauhiainen, J.: Kampar Peninsula Science Based Management Support Project, Interim Summary Report 2007–2008; first findings on hydrology, water management, carbon emissions and landscape ecology, Deltares report, 37 pp., 2009.

Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wösten, H., and Jauhiainen, J.: Current and future CO_2 emissions from drained peatlands in Southeast Asia, Biogeosciences, 7, 1505–1514, doi:10.5194/bg-7-1505-2010, 2010.

Hutchinson, J. N.: The record of peat wastage in the East Anglian Fenlands at Holme Post, 1848–1978 AD, J. Ecol., 68, 229–49, 1980.

Jauhiainen, J., Takahashi, H., Heikkinen, J. E. P., Martikainen, P. J., and Vasander, H.: Carbon fluxes from a tropical peat swamp forest floor, Glob. Change Biol., 11, 1788–1797, 2005.

Jauhiainen, J., Limin, S., Silvennoinen, H., and Vasander, H.: Carbon dioxide and methane fluxes in drainage affected tropical peat before and after hydrological restoration, Ecology, 89, 3503–3514, 2008.

Jauhiainen, J., Hooijer, A., and Page, S. E.: Carbon dioxide emissions from an *Acacia* plantation on peatland in Sumatra, Indonesia, Biogeosciences, 9, 617–630, doi:10.5194/bg-9-617-2012, 2012.

Koh, L. P., Miettinen, J., Liew, S. C., and Ghazoul, J.: Remotely sensed evidence of tropical peatland conversion to oil palm, Proc. Natl. Acad. Sci. USA, 108, 5127–5132, 2011.

Kool, D. M., Buurman, P., and Hoekman, D. H.: Oxidation and compaction of a collapsed peat dome in Central Kalimantan, Geoderma, 137, 217–225, 2006.

Leifeld, J., Müller, M., and Fuhrer, J.: Peatland subsidence and carbon loss from drained temperate fens, Soil Use Manage., 27, 170–176, 2011.

Malhi, Y.: The carbon balance of tropical forest regions, 1990–2005, Environmental Sustainability, 2, 237–244, 2010.

Melling, L., Hatano, R., and Goh, K. J.: Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia, Tellus B, 57, 1–11, 2005.

Mesri, G. and Aljouni, M.: Engineering properties of fibrous peats, J. Geotech. Geoenviron., 133, 850–866, 2007.

Miettinen, J. and Liew, S. C.: Degradation and development of peatlands in Peninsular Malaysia and in the islands of Sumatra and Borneo since 1990, Land Degrad. Dev., 21, 285–296, 2010.

Miettinen, J., Hooijer, A., Tollenaar, D., Page, S., Malins, C. Chenghua Shi, C., and Soo Chin Liew, S. C.: Historical analysis and projection of oil palm plantation expansion on peatland in SE Asia, White Paper no. 17 of the International Council of Clean Transportation, Washington, 2012.

Mohammed, A. T., Othman, H., Darus, F. M., Harun, M. H., Zambri, M. P., Bakar, I. A., and Wösten, H.: Best management practices on peat: water management in relation to peat subsidence and estimation of CO_2 emission in Sessang, Sarawak, Proceedings of the PIPOC 2009 International Palm Oil Congress (Agriculture, Biotechnology and Sustainability), 2009.

Moore, S., Gauci, V., Evans, C. D., and Page, S. E.: Fluvial organic carbon losses from a Bornean blackwater river, Biogeosciences, 8, 901–909, doi:10.5194/bg-8-901-2011, 2011.

Murayama, S. and Bakar, Z. A.: Decomposition of tropical peat soils, estimation of in situ decomposition by measurement of CO_2 flux, JARQ-JPN. Agr. Res. Q., 30, 153–158, 1996.

Murdiyarso, D., Hergoualch, K., and Verchot, L. V.: Opportunities for reducing greenhouse gas emissions in tropical peatlands, P. Natl. Acad. Sci. USA, 107, 19655–19660, 2010.

Neller, J. R.: Oxidation loss of lowmoor peat in fields with different water tables, Soil Sci., 58, 195–204, 1944.

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

Page, S. E., Rieley, J. O., and Banks, C. J.: Global and regional importance of the tropical peatland carbon pool, Global Change Biol., 17, 798–818, 2011.

Schothorst, C. J.: Subsidence of low moor peat soils in the Western Netherlands, Geoderma, 17, 265–291, 1977.

Stephens, J. C. and Speir, W. H.: Subsidence of organic soils in the USA, IAHS-AIHS Publication, 89, 523–534, 1969.

Stephens, J. C., Allen, L. H., and Chen, E.: Organic soil subsidence, Geological Society of America, Reviews in Engineering Geology, Vol. VI, 107–122, 1984.

Suhardjo, H. and Widjaja-Adhi, I. P. G.: Chemical characteristics of the upper 30 cm of peat soils from Riau, Sumatra (Indonesia), in: Final Report, Agricultural Technical Assistance Programme (Indonesia – The Netherlands) 1974–1977, 74–92, Lembaga Penelitian Tanah, Bogor, Indonesia, 1977.

Vernimmen, R. R. E., Hooijer, A., Mamenun, Aldrian, E., and van Dijk, A. I. J. M.: Evaluation and bias correction of satellite rainfall data for drought monitoring in Indonesia, Hydrol. Earth Syst. Sci., 16, 133–146, doi:10.5194/hess-16-133-2012, 2012.

Volk, B. G.: Everglades histosol subsidence – Part 1: CO_2 evolution as affected by soil type, temperature and moisture, Proceedings Soil and Crop Science Society of Florida, 32, 132–135, 1973.

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

Wösten, J. H. M. and Ritzema, H. P.: Land and water management options for peatland development in Sarawak, Malaysia, International Peat Journal, 11, 59–66, 2001.