Biogeosciences Discuss., 8, 9311–9356, 2011
www.biogeosciences-discuss.net/8/9311/2011/
doi:10.5194/bgd-8-9311-2011


Biogeosciences Discussions



# Subsidence and carbon loss in drained tropical peatlands: reducing uncertainty and implications for $CO_2$ emission reduction options

**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, Indonesia
[7]Center for Wetlands People and Biodiversity, Tanjungpura University, Pontianak 78124, Indonesia

Received: 4 July 2011 – Accepted: 31 August 2011 – Published: 15 September 2011

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

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







Subsidence and carbon loss in drained tropical peatlands

A. Hooijer et al.

## 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 years after drainage was found to be 142 cm, of which 75 cm occurred in the first year. After 5 years, the subsidence rate in both plantation types, at average water table depths of 0.7 m, remained constant at around 5 cm $yr^{-1}$. Bulk density profiles indicate that consolidation contributes only 7 % to total subsidence, in the first year after drainage, and that the role of compaction is also reduced quickly and becomes negligible after 5 years. Over 18 years after drainage, 92 % of cumulative subsidence was caused by peat oxidation. The average rate of carbon loss over the first 5 years was 178 t $ha^{-1}$ $yr^{-1}$ $CO_{2eq}$, which reduced to 73 t $ha^{-1}$ $yr^{-1}$ $CO_{2eq}$ over subsequent years, resulting in an average loss of 100 t $ha^{-1}$ $yr^{-1}$ $CO_{2eq}$ annualized over 25 years. Part of the observed range in subsidence and carbon loss values is explained by differences in water table depth, but vegetation cover and 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 table levels theoretically possible in plantations. This implies that improved water management will reduce these impacts by only 20 % at most, relative to current conditions, and that high rates of carbon loss and land subsidence should be accepted as inevitable consequences of conversion of forested tropical peatlands to other land uses.

## 1 Introduction

More than half (24.8 Mhectares) of the global area of tropical peatland is in SE Asia (56 %), mostly in Indonesia and Malaysia. Owing to the considerable thickness (mean





BGD

8, 9311–9356, 2011

>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 Mhectares were under agricultural use in 2007, of which 45 % (2.3 Mhectares) was large-scale oil palm and pulpwood (*Acacia*) plantations. A recent inventory by Hooijer et al. (2011) shows that the area of large-scale plantations had increased to 3.15 Mhectares by 2010 (12 % per year since 2007), and that this high expansion rate is likely to continue unless the implementation of land use planning policies is changed.

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 years 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 significantly 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 $>70\,t\,ha^{-1}\,yr^{-1}$ (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





BGD
8, 9311–9356, 2011

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., 2011). 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 $CO_2$ emissions resulting from peat oxidation alone, excluding root respiration. Also, the $CO_2$ emission method does not account for carbon losses in discharge water (DOC and POC) leaving the peatland catchment in drainage water (Alkhatib et al., 2007; Baum et al., 2007; Moore et al., 2011). 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 biomass (Herchoualc'h and Verchot, 2011), have been inconclusive because of 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 significant part of global emissions (Hooijer et al., 2006, 2010; Malhi, 2010). This can be achieved by determining the change in carbon stock directly, from measurements of land subsidence and peat characteristics that are 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 more accurate peat carbon budgets. 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 (c.f. review by Couwenberg et al., 2010).

When determining carbon loss from subsidence data, it is important to know the extent to which it is the result of peat oxidation compared to physical volume reduction.





BGD
8, 9311–9356, 2011

The following subsidence components need to be separated (Stephens et al., 1984; Andriesse, 1988):

- 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., 2011). 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 during deforestation, drainage and planting operations; shrinkage occurs through contraction of organic fibres when drying. These two processes cannot be separated in practice and they are considered together as "compaction". 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 of water from macropores in the peat; it occurs rapidly when groundwater is removed fast, especially in peat of high permeability where a dense drainage system is implemented. 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.

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 (i) the rate of peat subsidence and changes over time, (ii) the contribution of oxidation to subsidence,

(iii) carbon loss from peat oxidation, and (iv) the relationship between carbon loss and environmental factors especially water table depth and land cover. We carried out a much larger number of measurements than earlier studies, 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., 2011).

## 2 Methods

### 2.1 Measurement locations, climate and land conversion history

The monitoring sites were located on large peat domes in the provinces of Riau and Jambi, Sumatra, Indonesia, in *Acacia* tree (for paper production) and mature oil palm plantations (for palm oil production), and in drainage-impacted natural forest adjacent to the *Acacia* plantation. All sites experienced similar climatic conditions, with an average 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 average in the years 2007, 2008 and 2010, with rainfall deficits (rainfall below 120 yr$^{-1}$; Hooijer, 2005) 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, spaced 500 to 800 m apart, to lower the groundwater table to a level suitable for growth of the plantation crops. Fire was used to facilitate land clearance prior to planting oil palms but not in the *Acacia* plantation. Drainage had commenced on average 5 or 6 years prior to the mid-point of subsidence monitoring in the *Acacia* plantation, varying mostly between 4 and 8 years with a few somewhat younger (3 years) and older locations possibly included where development history was unclear. *Acacia* trees varied mostly from mature first crop to young second crop. In the minority of cases where harvesting took place during the monitoring period, care was taken not to disturb subsidence poles. Locations where





BGD
8, 9311–9356, 2011

disturbance was evident were excluded from analyses. Study locations in oil palm plantation were drained for 19 to 15 years before, with an average of 18 years, and all 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, and *Acacia* plantation transects were extended 2 km into adjacent peat swamp forest where this still remained. Data used in this analysis were obtained from a total of 215 monitoring locations (125 in *Acacia* plantation, 39 in oil palm plantation and 51 in peat swamp forest adjacent to *Acacia* plantation).

## 2.2 Peat surface subsidence measurements

At all locations, the peat surface level was measured using 5 cm diameter, perforated PVC tubes as poles, inserted vertically through the peat and anchored firmly in the underlying mineral substrate. To reduce measurement errors, permanent markers made of light thin metal were placed on the peat surface. Compression of the surface peat during pole installation and monitoring was minimized by ensuring field staff did not step within a 0.5 m radius around pole locations. As a further precaution the initial period after installation, from 3 months to more than a year, was excluded from analyses. Peat subsidence was monitored at intervals of 1 to 3 months in the *Acacia* plantation. A full 2-year data series for use in analyses was selected for each transect from the 3-year data collection period of September 2007 to August 2010 on the basis of data availability (some transects were periodically inaccessible due to external factors). Prior to the main study, 14 subsidence poles had been installed in 2002 in the *Acacia* plantation, one year after drainage (Hooijer et al., 2009), providing data for a longer period (2002–2010). A one-year data series (July 2009 to June 2010), monitored at 2-weekly intervals, was analyzed for the oil palm plantation. Cumulative subsidence was recalculated to annual mean values that allowed comparison between all locations.





BGD
8, 9311–9356, 2011

## 2.3 Peat thickness and type

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

## 2.4 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 locations and times as subsidence. Average water table depths were calculated from time series measurements.

## 2.5 Bulk density measurement and ash content of peat

Bulk density (BD) was determined at 22 locations in the *Acacia* plantation, 19 that were drained 5 to 7 years 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 stainless steel cylinders to avoid peat compression that may result from using a vertical corer. 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 amount of tree roots was found to be minimal. 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, peat samples were collected in pits of 2 to 2.5 m depth from which water was pumped to facilitate sampling at greater depths. Samples were collected from these pits 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 96 h (the period at which it was found that sample dry weight had fully stabilized) to remove moisture, and weighed to calculate BD.





BGD
8, 9311–9356, 2011

Large wood remains could not be collected in the cylinders, so additional checks were carried out at the oil palm sites to determine if the presence of wood affected the BD values. A total of 20 samples of isolated remains of partly decomposed wood taken in 3 soil pits from peat below 1 m depth, with an average volume (±SD) of $326 \pm 104\,\mathrm{cm}^3$, were dried and weighed following the same protocol as cylinder samples. In addition, the wood content of the peat in palm oil 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.

### 2.6 Temperature measurements

Daytime temperatures of the peat at 0.05 m depth were measured at a subsample of monitoring locations in the *Acacia* plantation, with a total number of 1200 measurements, as described by Jauhiainen et al. (2011).

### 2.7 Determining the compaction component of subsidence

The contribution of compaction and oxidation to subsidence was calculated by determining the increase in BD of the peat caused by compaction, estimated from the peat profile, and the total amount of subsidence in that period (e.g. Stephens and Speir, 1969; Schothorst, 1977; Ewing and Vepraskas, 2006; Leifeld et al., 2011). We used a variation modified from Driessen and Soepraptohardjo (1974), as follows:

$$V_{ox} = ((V_1 \times BD_1) - (V_{rest} \times BD_2))/BD_1 \quad (1)$$

and:

$$V_{comp} = V_{rest} \times (BD_2 - BD_1)/BD_1 \quad (2)$$

and:

$$P_{ox} = V_{ox} \times BD_1/((V_{ox} \times BD_1) + (V_{comp} \times BD_1)) \quad (3)$$





BGD
8, 9311–9356, 2011

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 period of many years of subsidence, at the same site or from a nearby 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. Firstly, it was assessed whether the current BD of the peat below the lowest water level, which is about 1 m on average 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





BGD
8, 9311–9356, 2011

above the water table in the *Acacia* and oil palm plantations, at 2, 5–7 and 18 years after drainage, respectively, were compared. This assumed that the pre-drainage peat profiles at the different sampling locations were sufficiently similar to allow 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.

### 2.8 Determining the consolidation component of subsidence

The rate 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, 5 years 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 this effect was minimized by only selecting locations with average water table depths within a range of 0.5 to 1 m.

### 2.9 Determining the oxidation component of subsidence and carbon loss

The contribution of oxidation to subsidence was obtained by 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).





BGD
8, 9311–9356, 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 cm and 90 cm (75 cm on average), through repeated field surveys. Over the subsequent 4 years a further subsidence of 67 ± 11 cm (mean ±SD) was observed at 14 locations, with an average in the second and third years of 19 ± 4 cm (Fig. 4). On the basis of these two datasets, total subsidence over the first 5 years after drainage was determined to be 142 cm on average. At 5 years after drainage, subsidence stabilized at around 5 ± 2.2 cm $yr^{-1}$ (Figs. 4 and 5). In the oil palm plantation the average subsidence was 5.4 ± 1.1 cm $yr^{-1}$ 18 years after drainage. In the natural forest average subsidence was 2.4 ± 1.6 cm $yr^{-1}$ at the forest-plantation edge, reducing to 0–1 cm $yr^{-1}$ at a distance of 2 km inside the forest from the plantation boundary.

### 3.2 Water table depths

The average water table depth in the *Acacia* plantation was 0.7 m, with a 10-percentile range of 0.47 to 0.98 m. In the oil palm plantation average water table depth was 0.73 m and the 10-percentile range was 0.33 to 1.03 m (Table 1). In the drainage-impacted forest the average water table depth was 0.33 m at the forest edge, decreasing to zero (peat surface) at a distance of 2 km away from plantation perimeter canals, inside the forest.

### 3.3 Peat bulk densities and ash contents

Bulk density profiles determined for the *Acacia* and oil palm plantations (Fig. 3) provided average values around 0.15 g $cm^{-3}$ near the peat surface, declining to a constant value of around 0.075 g $cm^{-3}$ at depths below 0.5 m. A small set of data collected at an *Acacia* plantation site 2 years after drainage showed that the near surface BD was 0.085 ± 0.01 g $cm^{-3}$ ($n = 36$). The average (±SD) BD of the top metre of peat



BGD
8, 9311–9356, 2011

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 (5 to 7 years after drainage) and oil palm plantation sites (18 years after drainage), respectively. 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 bulk density (±SD) of wood remains in peat at depths below 1 m was $0.083 \pm 0.036\,\mathrm{g\,cm^{-3}}$. The wood content of peat below 1 m depth was 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 of $0.005\,\mathrm{g\,cm^{-3}}$ between bulk density of the wood remains and the peat matrix, and the relatively limited wood content of the peat, bulk densities as measured in cylinder samples were not corrected for the undersampling of wood remains.

The average ash content of 223 subsamples was 1.2 % by weight, with a standard deviation of 1.13 %. No relationship with 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 (±SD) of $9 \pm 2.6$ m. The range in oil palm plantation was 5.6 to 10.7 m, with an average of $7.7 \pm 1.4$ m. The overall average peat thickness for both plantation types is 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 sapric and sometimes described as “muddy”, indicating higher mineral content.



BGD

8, 9311–9356, 2011

### 3.5 Soil temperature

Soil temperature at 0.05 m depth in the *Acacia* plantation ranged from 25 to 42 °C in the daytime, with an average of around 30 °C (Jauhiainen et al., 2011). Temperature data were not obtained in the oil palm plantation

### 3.6 Consolidation and its effect on peat bulk density

No relation between subsidence rate and peat thickness was evident 5 years after drainage (Fig. 6), confirming that secondary consolidation is negligible in these peatlands. On the assumption that all primary peat consolidation occurs in the first year after drainage (Andriesse, 1988; see also Sect. 4.3), we estimated the amount by subtracting a subsidence value of 0.19 m, obtained for the second 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 (Table 1), 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$^{-3}$.

### 3.7 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 by Driessen and Soepraptohardjo (1974), 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. 7), 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 years and a subsidence of 5.4 cm yr$^{-1}$ in the subsequent 13 years, an equivalent average peat oxidative $CO_2$ emission of 119 t ha$^{-1}$ yr$^{-1}$ is obtained, which explains 92 % of subsidence over 18 years.





BGD
8, 9311–9356, 2011

Applying 92 % oxidation to the average subsidence rate measured in the *Acacia* plantation, 5 years on average after drainage, the resulting carbon loss is 68 t ha$^{-1}$ yr$^{-1}$ $CO_{2eq}$. For the oil palm site, 18 years after drainage, this value is 78 t ha$^{-1}$ yr$^{-1}$. For these plantations in general, 5 years or more after drainage, an average minimum $CO_{2eq}$ 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 years and the lower loss in the subsequent period must be accounted for. Over a 25 year period, the annualized average carbon loss thus becomes 90 t ha$^{-1}$ yr$^{-1}$ $CO_{2eq}$ 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. Annualized over a 50 year 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$^{-1}$.

### 3.8 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, 5 years after drainage, is as follows (see Fig. 5):

$$S = 1.5 - 4.98 \times WD \; (R^2 = 0.21) \quad (4)$$

where:

- S = annual subsidence of the peat surface (cm yr$^{-1}$)
- WD = average water table depth below the peat surface (−m; negative)

The relationship for drained forest, 5 years after drainage at water table depths of 0–0.7 m, is:

$$S = -7.06 \times WD \; (R^2 = 0.34) \quad (5)$$





BGD
8, 9311–9356, 2011

The correlations found for these regression relationships are not high, 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 their own limited water table depth ranges. If a relation is fitted through the combined "*Acacia* plantation" and "forest" data set, resulting in an "intermediate" relation, a stronger relationship is obtained:

$$S = 0.64 - 6.04 \times WD \ (R^2 = 0.45) \tag{6}$$

### 3.9 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. 8) 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:

$$CL = 21 - 69 \times WD \tag{7}$$

For drained natural forest:

$$CL = -98 \times WD \tag{8}$$

Combined (for deforested unproductive peatlands):

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

Where:

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





BGD
8, 9311–9356, 2011

## 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 years after initial drainage, is close to most literature values. Subsidence rates reported for a Johor (Malaysia) palm oil plantation, between 14 and 28 years 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). 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, and proposed that the rate of annual subsidence increased by 1 cm for every 10 cm lowering of the water table, resulting 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 long-term subsidence rate of 3 cm $yr^{-1}$ was reported after the initial years (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 the 28–30 °C in the plantation sites in Indonesia and Malaysia, 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 $yr^{-1}$ 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 years proceeded at a constant rate of 7.5 cm $yr^{-1}$ for over 50 years (Deverel and Leighton, 2010; Fig. 4).

These studies support our findings that subsidence rates stabilize at around 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 subsidence rates in



BGD
8, 9311–9356, 2011

tropical peat seems to be small compared to temperate peats (Couwenberg et al., 2010). This may be related to temperature, which is much higher in the tropics compared to temperate climates, and the effect this has on peat oxidation.

The studies in SE Asia mentioned above apply to fibric peat with a pre-drainage BD of around 0.07 to 0.1 $g\,cm^{-3}$ and mineral content below 3 %. Where lower subsidence rates are reported, this is usually for shallower peat with higher BD and mineral content. Murayama and Bakar (1996), for example, 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 years, 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 year period, in peaty swamp soil around 2 m thick with a mineral content as high as 73 to 86 % (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 years 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 was 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 5 years, although not identical, are not very different from the relation 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. No dataset suggests that non-linear relationships would be more suitable, so we conclude that applying a linear regression is appropriate.





BGD
8, 9311–9356, 2011

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

In contrast with relationships obtained by others, the regression in this study for *Acacia* plantation does not intercept with the origin, indicating that considerable 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, that result 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. A nearly identical relationship was found between $CO_2$ gas emission and water table depth, in a parallel study using closed, gas flux monitoring chambers (Jauhiainen et al., 2011).

In oil palm plantation, subsidence is virtually constant at all locations (Table 2, Fig. 5), with no relationship with water table depth being apparent. This difference from *Acacia* plantation may be because the oil palm sites were fertilized with large amounts of nitrogenous fertilizer (~600 kg ha$^{-1}$ yr$^{-1}$ urea) (Fig. 9), 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) leading to a higher peat oxidation rate. 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.

The relationship for drained forest, 5 years after drainage at water table depths of 0–0.7 m, intercepts through zero, confirming that in natural forest the peat carbon store is stable if the water level is close to the peat surface. At 0.7 m water table depth, the





BGD
8, 9311–9356, 2011

“*Acacia* plantation” and the “forest” subsidence rates are the same (Fig. 5) and the “*Acacia* plantation” relationship can 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 tropical peatlands. The ‘combined’ relationship 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 cm 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) consider the effect of consolidation, after a brief initial “dewatering” phase, to be negligible.





BGD
8, 9311–9356, 2011

The near absence of consolidation after the first year of plantation drainage found by this study can be explained by the high hydraulic conductivity of fibrous tropical peat (over 50 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 can be 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 the subsidence rate reached a "steady state" after the initial phase, and in the Sacramento Delta, subsidence after the initial 5 years also appeared to have been constant (Deverel and Leighton, 2010; Fig. 4). Whilst a gradual reduction to a subsidence rate of 2 cm $yr^{-1}$, beyond 28 years after drainage, was proposed by Wösten et al. (1997), it should be noted that this value was based partly on an estimated projection that was not fully supported by the data.

We therefore conclude that all sources confirm our conclusion that subsidence rates in *Acacia* and oil palm plantations in SE Asia, more than 5 years after drainage at water table depths around 0.7 m, will remain constant at around 5 cm $yr^{-1}$ for decades (Fig. 4).

### 4.4 Variation in subsidence rates in relation to monitoring duration and number of locations

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





BGD
8, 9311–9356, 2011

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 surface peat and in canopy cover, with the latter affecting peat surface temperature. It follows that accurate subsidence measurement requires a large number of monitoring locations to cover not only the known variations in land cover and water table depth, but also these unknown random heterogeneities. The same is likely to apply to direct measurements of $CO_2$ gas emission.

### 4.5 Study site bulk density compared to literature values

The average BD value of 0.075 g cm$^{-3}$ found in peat below 1 m depth in this study, and the estimated value of 0.07 g cm$^{-3}$ prior to consolidation, are within the range of 0.05 to 0.1 g cm$^{-3}$ reported by Andriesse (1988) for relatively undisturbed fibric peat in SE Asia. However, they are 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 values reported by individual studies are below 0.075 g cm$^{-3}$ in only 6 cases. In deforested peatlands, BD of near-surface peat was found to be higher than at greater depth, but in forested peatlands no consistent increase or decrease with depth was apparent. This lack of a trend is also confirmed by peat profiles in primary and secondary forest in Kalimantan (Indonesia) (Kool et al., 2006; Anshari et al., 2010) with BDs in individual cores varying between 0.03 and 0.15 g cm$^{-3}$ at depths from 0 to 3 m, although averages are quite constant with depth (Fig. 3). The value of 0.061 g cm$^{-3}$ over 0–2 m depth derived from data of Anshari et al. (2010) is the lowest average reported for a group of peat profiles in undrained peatland forest in SE Asia. By contrast, data presented by Kool et al. (2006) yield an average of 0.074 g cm$^{-3}$, which is higher than the pre-consolidation value of 0.07 g cm$^{-3}$ applied in the current study.

Following comparison with literature values, and having established that the values from the range of different locations in the current study are very similar, we conclude





BGD
8, 9311–9356, 2011

that our BD values below 1 m are representative of the consolidated but uncompacted peat shortly after plantation establishment. Therefore, total compaction since the start of drainage, after the initial 1-year consolidation phase, may be estimated by comparing the current BD of peat below 1 m depth with that above it.

### 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 sub-tropical peatlands using BD profiles. Stephens and Speir (1969) calculated that oxidation accounted for 78 % of subsidence in the Everglades peatlands over a period of more than 50 years since drainage; this was confirmed by $CO_2$ flux measurements at the same sites (Neller, 1944) and under laboratory conditions (Volk, 1973). In a later study, Stephens et al. (1984) estimated that the increase in BD in field plots reported by Neller (1944) explained only 10 to 15 % of subsidence, and concluded 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 years 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 reduces 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 peat with high mineral content. In peatland plantations in Johor, Malaysia a value of 61 % was reported (DID Malaysia, 1996; Wösten et al., 1997); however, the authors do not explain how this value was determined or how long after drainage it refers to. 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,





BGD
8, 9311–9356, 2011

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 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. (2011).

The long-term oxidation contribution to subsidence of 92 % in plantations on tropical peatland is high compared to most other estimates. Our study shows, however, that the contribution of oxidation to peat subsidence increases in time while consolidation and compaction are major contributors only in the initial period. The fact that the BD profiles in plantations at 5 and 18 years after drainage are nearly identical (Fig. 3) indicates that compaction has become negligible after the first 5 years, at which point nearly 100 % of subsidence is caused by oxidation. After the initial years of subsidence, rates of compaction and oxidation therefore appear to achieve equilibrium. Compaction continues as uncompacted peat from the saturated zone below enters the unsaturated, oxidative zone. However this compaction is 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.

It should be noted that most published percentage oxidation values, including the 61 % reported by DID Malaysia (1996) and the 90 % suggested by Stephens et al. (1984), are averages of the cumulative oxidation since the start of drainage, and therefore underestimate the percentage oxidation after the initial period. We are confident applying the oxidation percentage of 92 % to plantations on drained tropical peat in calculations of long-term carbon losses and equivalent $CO_2$ emissions.

While the oxidation contribution to peat subsidence increases over the first few years after drainage, the net carbon loss decreases over this period, before stabilizing (Fig. 7). It may be that a finite pool of the most labile carbon compounds decomposes rapidly, leaving only carbon compounds more resistant to decomposition (Berg, 2000). In addition, a lower water table in this initial “dewatering phase”, required





BGD
8, 9311–9356, 2011

by plantation managers to consolidate the peat surface before planting, may increase oxidation. A similar finding of an initial peak in carbon loss was reported for the Sacramento Delta by Deverel and Leighton (2010), who calculated that emissions reduced from 154 t $ha^{-1}$ $yr^{-1}$ $CO_{2eq}$ a few years after drainage to 55 t $ha^{-1}$ $yr^{-1}$ 80 years later, at an average water depth of 1 m (Drexler et al., 2009).

### 4.7 Sensitivity assessment

The calculation of the percentage oxidation contribution to subsidence, and the resulting carbon loss, is most sensitive to the value used for the original pre-drainage BD, corrected for consolidation immediately after drainage. On the basis of the data discussed in Sect. 4.5 and shown in Fig. 3, we estimate that the lowest pre-drainage BD value that could apply to our study sites 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 a 7 % consolidation immediately after drainage, as found in the current study. Using the latter value instead of the 0.078 g $cm^{-3}$ on average applied for oil palm plantation after 18 years in this study would have yielded an oxidation percentage after 18 years of 77 % instead of 92 %, suggesting that long-term carbon loss figures could be at the very most 20 % lower than the values proposed in this paper. However, this lower figure is unlikely to apply, as BD values as low as 0.061 g $cm^{-3}$ are exceptional.

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., 2011). 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 $CO_2$ emission 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 ha$^{-1}$ yr$^{-1}$ $CO_{2eq}$ 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. (2011) is nearly identical to that using the subsidence method presented in this paper (Fig. 8). 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 m and 1 m, that are most common in plantations, the emission relations found for *Acacia* plantations and drained forest are similar to the linear relationship reported by Hooijer et al. (2006, 2010) and Couwenberg et al. (2010), that were based on metadata assessments of studies carried out in deforested tropical peatlands (Fig. 8). 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 reported subsidence rate of 5 cm yr$^{-1}$.

We conclude that the carbon losses found in this study 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, although these aspects require further investigation. Moreover, we found that carbon loss in the initial years is higher than in subsequent years (Fig. 7), resulting in considerably higher long-term average emissions than have been reported to date.





BGD
8, 9311–9356, 2011

### 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 are higher than those reported in some earlier studies (e.g. 0.95 m in Hooijer et al., 2006, 2010). However, high and well-controlled water levels are not the norm in these plantations, where the lack of effective water level control is illustrated by the wide range of levels encountered during the monitoring period. (10-percentile values for annual averages ranged between 0.33 and 1.03 m and individual measurements from 0 to 1.6 m (Fig. 10)). 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. Our measurements were obtained in relatively "wet" years 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.

As both *Acacia* and oil palm have low tolerance to inundation and are best grown at water table depths of at least 0.7 and 0.6 m respectively (DID Sarawak, 2001), prevention of high water tables is the highest operational priority for plantation managers. Thus, water management systems are optimized to remove large amounts of discharge water as quickly as possible. In tropical peatland plantations, which have very low surface gradients in a region with high rainfall rates, this requires wide canals and a minimum of water level control structures. As land subsidence continues and the risk of inundation increases, the focus of plantation water management will inevitably shift towards discharge maximization rather than water level optimization. The average water table depth of around 0.7 m measured in our study areas is therefore close to a "best case" situation for large-scale plantations, in which lower water levels are common.





BGD
8, 9311–9356, 2011

## 5 Conclusions

We show 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 determined separately. The study has collected subsidence and peat characteristics data from a much larger number of locations than all previous studies in SE Asia on this subject combined. This has reduced 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., 2011); 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 other methods.

The subsidence rate of 142 cm over the first 5 years, 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 $ha^{-1}$ $yr^{-1}$ $CO_{2eq}$ annualized over 25 years after drainage, is higher than any other published estimate. This is partly because earlier studies have assumed that peat oxidation and carbon loss are constant from the start of plantation development, whereas we found higher loss rates in the first 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 implication of the relatively low gradient of the regression between water table depth and subsidence found in this study, is that the benefit of raising plantation water tables to reduce carbon emissions may be smaller than earlier assumed (Hooijer et al., 2009). Even if an average water table depth of 0.6 m could be achieved, subsidence





BGD
8, 9311–9356, 2011

would still be 4.5 cm $yr^{-1}$ over the long term, and the carbon loss 63 t $ha^{-1}$ $yr^{-1}$ $CO_{2eq}$ after 5 years. This would be a reduction of 10 % to 20 % relative to the emissions around 73 t $ha^{-1}$ $yr^{-1}$ $CO_{2eq}$ currently occurring in the plantations studied, which is not enough to be considered a solution to the problem. Moreover, it should be noted that this reduction in annual emission does not mean these emissions are avoided but merely postponed to a later date unless drainage can be ended altogether and natural conditions restored.

The relationships between water table depth, land cover and land subsidence presented enable prediction of the productive lifespan of plantations on tropical peatland, i.e. of the period before subsidence renders them incapable of further drainage by gravity. This should be included in the integrated cost-benefit analysis required for spatial planning and policy development. It would also enable REDD projects (Reduced Emissions from Deforestation and Degradation) to quantify better 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 full deforestation and drainage that is now evident in many tropical peatlands. Reduced uncertainty in these calculations is essential for REDD projects to be economically viable and verifiable (Murdiyarso et al., 2010; Asner, 2011).

Where plantations on tropical peatland are inevitable, investment in water management is essential to control water table depths that are low enough to enable satisfactory crop growth but sufficiently high to minimise subsidence and reduce carbon loss while, at the same time, protecting forest and peat resources in the surrounding area. However the finding that considerable carbon loss and subsidence occur even at the highest water levels in peatland plantations, and the limited likelihood that much higher levels can be achieved at the larger scale in practice, given crop requirements and water management limitations, leads to the conclusion that carbon emission should be considered an inevitable consequence whenever tropical peatlands are converted to drained agriculture, regardless of water management regime. It is best to separate land uses on peatlands at the landscape level, allocating entire peat domes to conservation





BGD
8, 9311–9356, 2011

where possible and others to agriculture where necessary, in the latter case accepting high carbon emissions and high rates of land surface subsidence that are likely to eventually result in increased flood frequency and loss of agricultural productivity.

*Acknowledgements.* We thank APRIL (Asia Pacific Resources International Limited), SDWA (Singapore Delft Water Alliance) and the Deltares R&D programme for financially supporting parts of the research. The APRIL and University of Jambi field teams are thanked for data collection.

## 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. London, 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.





BGD

8, 9311–9356, 2011

Subsidence and carbon loss in drained tropical peatlands

A. Hooijer et al.

Couwenberg, J., Dommain, R., and Joosten, H.: Greenhouse gas fluxes from tropical peatlands in southeast Asia, Glob. 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(8), 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(2), 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 Drainage and Irrigation Department, 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(1), 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, J. Soc. Wetl. Scientists, 29, 372–386, 2009.
Driessen, P. M. and Soepraptohardjo, M.: Soils for agricultural expansion in Indonesia, Publication of Soil Research Institute, Bulletin 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 years after drainage, WETLANDS, 26(1), 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(1), 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





BGD
8, 9311–9356, 2011

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-CO2 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.
Hooijer, A., Miettinen, J., 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. Report of the International Council of Clean Transportation, Washington, 2011.
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., Hooijer, A., and Page, S. E.: Carbon dioxide emissions from an *Acacia* plantation on peatland in Sumatra, Indonesia, Biogeosciences Discuss., 8, 8269–8302, doi:10.5194/bgd-8-8269-2011, 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 Manag., 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, Tellus B, 57, 1–11, 2005.
Mesri, G. and Aljouni, M.: Engineering properties of fibrous peats, J. Geotech. Geoenviron., 133(7), 850–866, 2007.
Miettinen, J. and Liew, S. C.: Degradation and development of peatlands in Peninsular Malaysia





BGD
8, 9311–9356, 2011

Subsidence and carbon loss in drained tropical peatlands

A. Hooijer et al.

and in the islands of Sumatra and Borneo since 1990, Land Degrad. Dev., 21, 285–296, 2010.

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(46), 19655–19660, 2010.

Neller, J. R.: Oxidation loss of lowmoor peat in fields with different water tables, Soil Science, 58(3), 195–204, 1944.

Page, S. E., Rieley, J. O., and Banks, C. J.: Global and regional importance of the tropical peatland carbon pool, Glob. 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, Volume 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, Lembaga Penelitian Tanah, Bogor, Indonesia, 74–92, 1977.

Volk, B. G.: Everglades histosol subsidence: 1. $CO_2$ evolution as affected by soil type, temperature and moisture, in: 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.

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

| | | *Acacia* plantation 5 yr after drainage | Oil palm plantation 18 yr after drainage | Plantation mean 5–18 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 | 39 | 164 | 51 |
| Peat depth | m | $9 \pm 2.6$ | $7.7 \pm 1.4$ | 8.4 | $9.9 \pm 3.2$ |
| Peat bulk density of top 1 m | $g\,cm^{-3}$ | $0.089 \pm 0.018$ | $0.087 \pm 0.018$ | 0.088 | – |
| Peat bulk density >1 m depth[1] | $g\,cm^{-3}$ | $0.073 \pm 0.015$ | $0.078 \pm 0.007$ | 0.075 | – |
| Water table depth | m | $0.7 \pm 0.2$ | $0.73 \pm 0.23$ | 0.71 | $0.33 \pm 0.16$ |

[1] Measured at 1 to 2.3 m depth, 5–18 years after drainage; affected by initial consolidation.

[2] Natural forest strip up to 2 km from plantation boundary; affected by drainage.





BGD

8, 9311–9356, 2011

**Table 2.** Subsidence rates and carbon loss over different time periods 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) | $t\,ha^{-1}\,yr^{-1}\,CO_{2eq}$ | 178 | – | – |
| Carbon loss 0–18 yr after drainage (measured) | $t\,ha^{-1}\,yr^{-1}\,CO_{2eq}$ | – | 119 | – |
| Carbon loss 5–8 yr after drainage (measured) | $t\,ha^{-1}\,yr^{-1}\,CO_{2eq}$ | 68 | – | – |
| Carbon loss 18 yr after drainage (measured) | $t\,ha^{-1}\,yr^{-1}\,CO_{2eq}$ | – | 78 | – |
| Carbon loss 0–25 yr after drainage (calculated) | $t\,ha^{-1}\,yr^{-1}\,CO_{2eq}$ | 90 | 109 | 100 |
| Carbon loss 0–50 yr after drainage (calculated) | $t\,ha^{-1}\,yr^{-1}\,CO_{2eq}$ | 79 | 94 | 86 |





BGD
8, 9311–9356, 2011

**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.

| (Sub–)transect | | No of 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 | –0.97 | –1.20 | –0.80 | 0.12 | 13 | 5.2 | 5.3 | 5.0 | 0.3 | 7 | 5.1 | 3.3 | 8.1 | 1.5 | 30 |
| J | 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 |

*Mean/Max/Min values of individual means per location.
**The range is the difference between min and max values, expressed as a percentage of the mean.



BGD
8, 9311–9356, 2011
Subsidence and carbon loss in drained tropical peatlands
A. Hooijer et al.

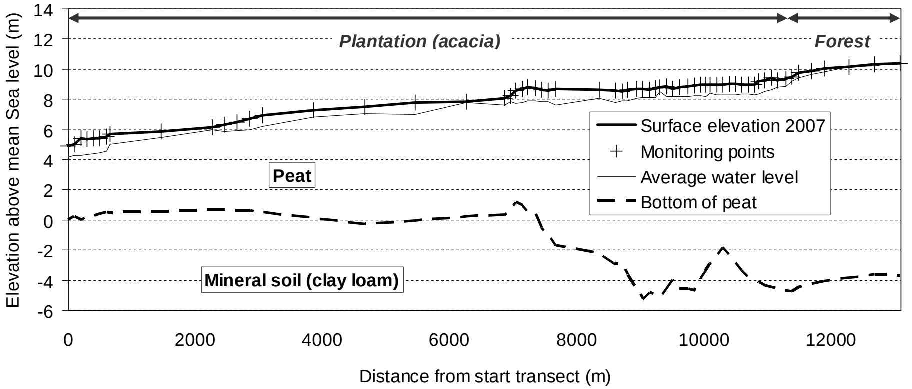


**Fig. 1.** Cross section along typical study transect in Sumatra, 6 years after drainage, showing variation in peat depth, average water level, land use and monitoring location density.





BGD

8, 9311–9356, 2011

Subsidence and carbon loss in drained tropical peatlands

A. Hooijer et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

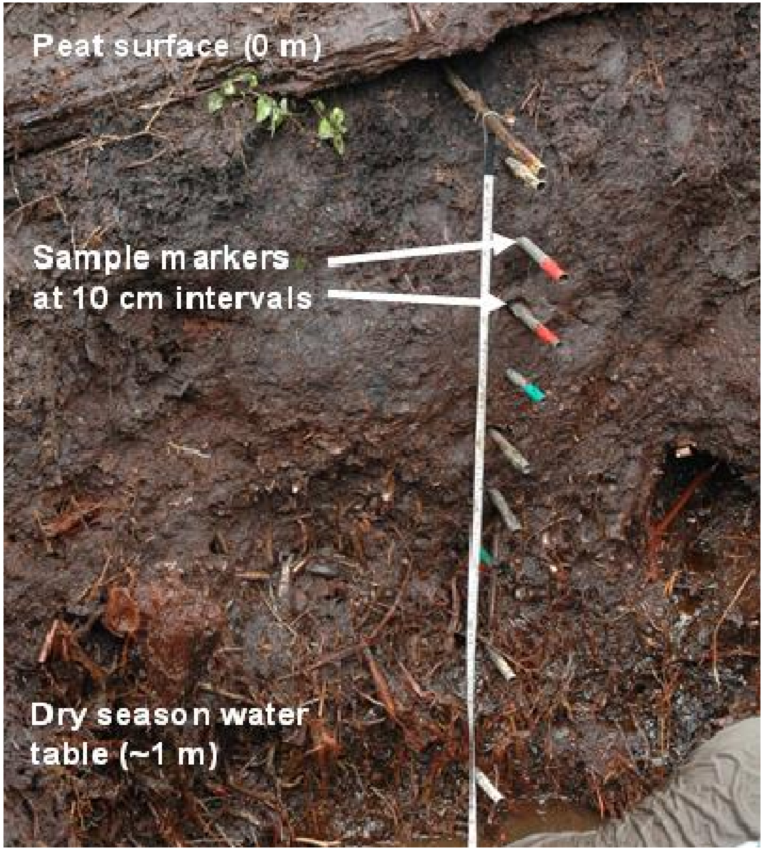


**Fig. 2.** Peat profile in an oil palm plantation, 18 years after drainage. The top peat is amorphous without visible plant remains, indicating advanced decomposition, while the peat below 0.3 m is increasingly fibric going downwards, with abundant remains of wood and roots.





BGD
8, 9311–9356, 2011

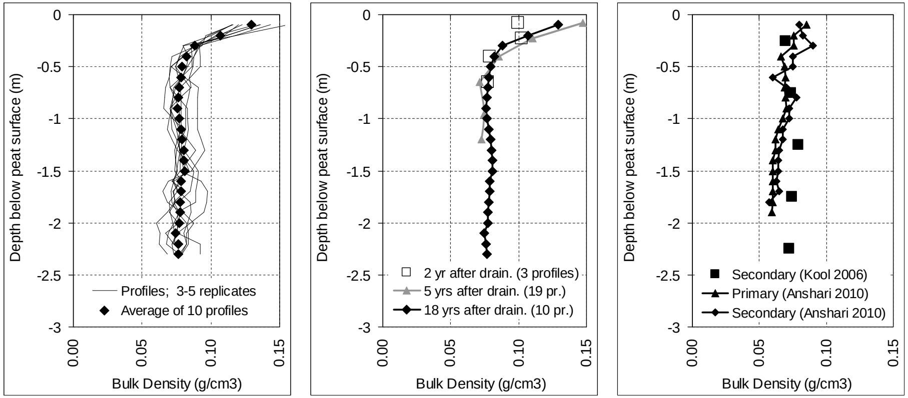


**Fig. 3.** Vertical profiles of bulk density in SE Asian peatlands. Left: Individual profiles (with 3 to 5 replicates at each depth) in Sumatra oil palm plantations, 18 years after drainage. Middle: Average profiles for Sumatra *Acacia* and oil palm plantations at 1, 5 and 18 years after drainage respectively; each data location represents the average of 3 to 19 profiles with 3 to 5 replicate samples at each depth. Right: average profiles in Kalimantan natural peatland forest as reported by Kool et al. (2006; average of 9 profiles) and provided by Dr Gusti Anshari (averages of 4 to 6 profiles per site). The latter data are also reported, in summary, by Anshari et al. (2010).

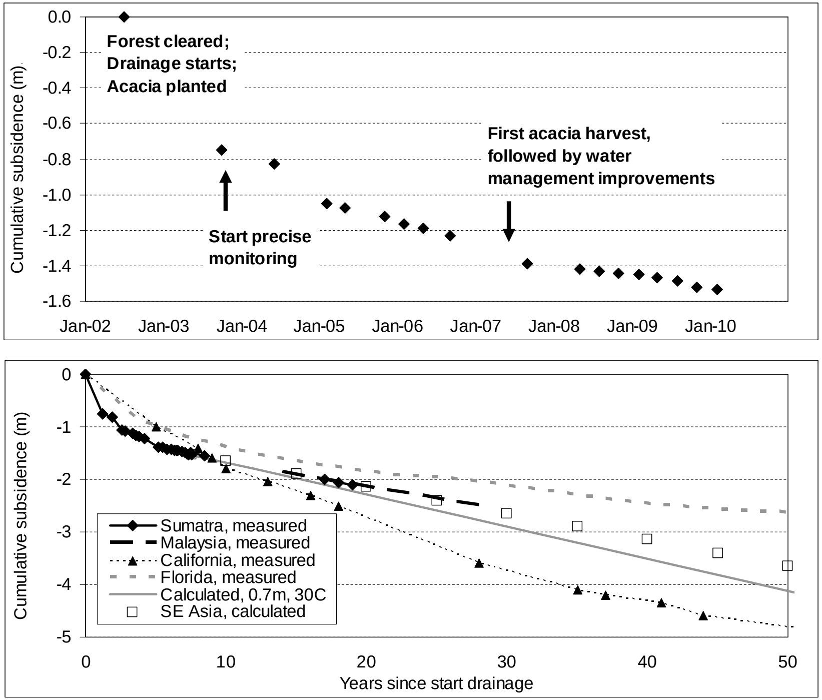


**Fig. 4.** Top: average subsidence rates as measured at 14 locations in *Acacia* plantations, over the first 9 years after drainage. Bottom: as measured at a larger number of drained peatland locations in Sumatra (this study), Malaysia (from Wösten, 1997, based on DID Malaysia, 1996), Mildred Island 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.





BGD

8, 9311–9356, 2011

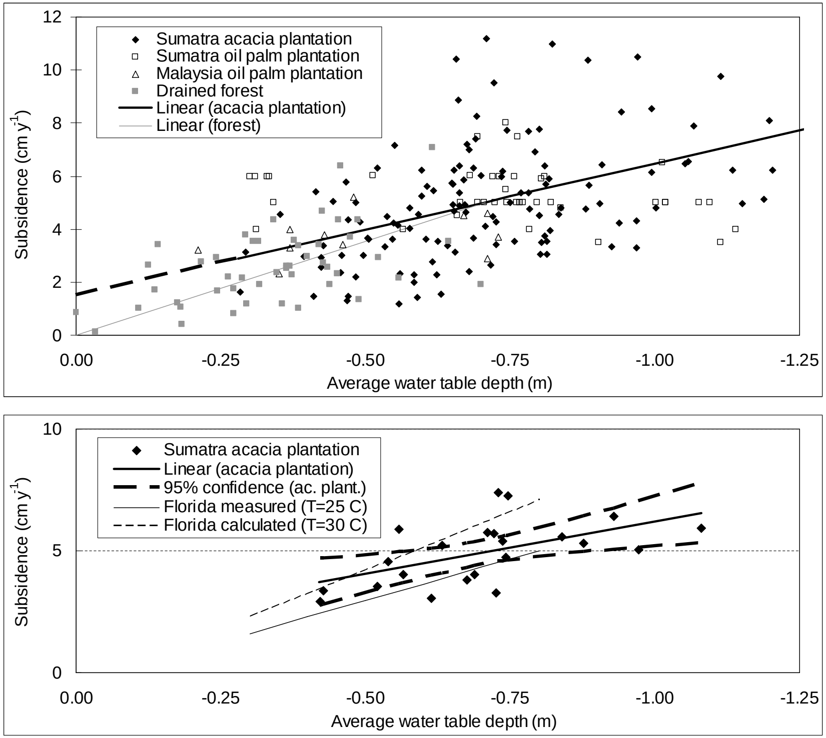


**Fig. 5.** Subsidence rates and water table depths as measured in acacia plantations, palm oil plantations and adjacent forest in Sumatra, Indonesia. Top: data for individual monitoring locations. Measurements in Malaysia palm oil plantations are shown for comparison (from DID Malaysia, 1996). The linear relations shown are for acacia plantations (excluding 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).

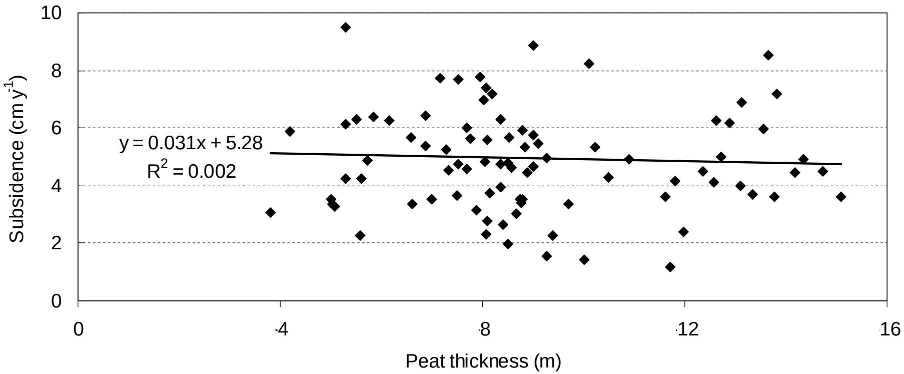


**Fig. 6.** Annual subsidence rate in *Acacia* plantations plotted against thickness of the peat layer, for selected locations with average water table depths between 0.5 and 1 m. The very low $R^2$ value of the regression line indicates that no relation exists between peat thickness and subsidence rate. Such a relation would be expected if consolidation of the peat layer as a whole would be a significant contributor to subsidence.





BGD
8, 9311–9356, 2011

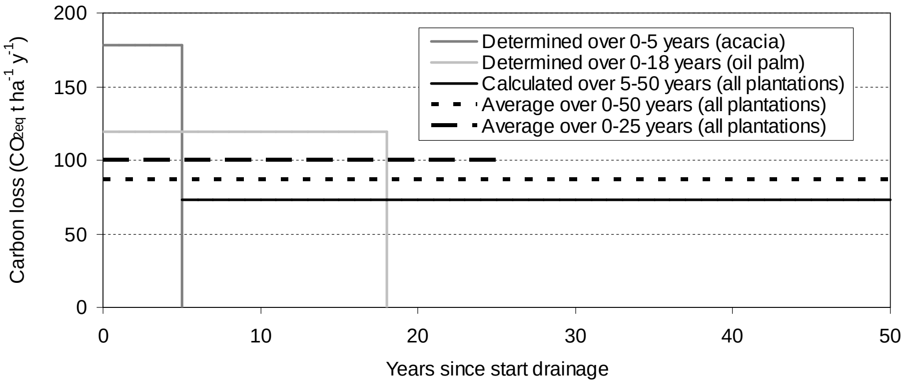


**Fig. 7.** Development in carbon loss over time in the *Acacia* and oil palm plantations studied.





BGD
8, 9311–9356, 2011

Subsidence and carbon loss in drained tropical peatlands

A. Hooijer et al.

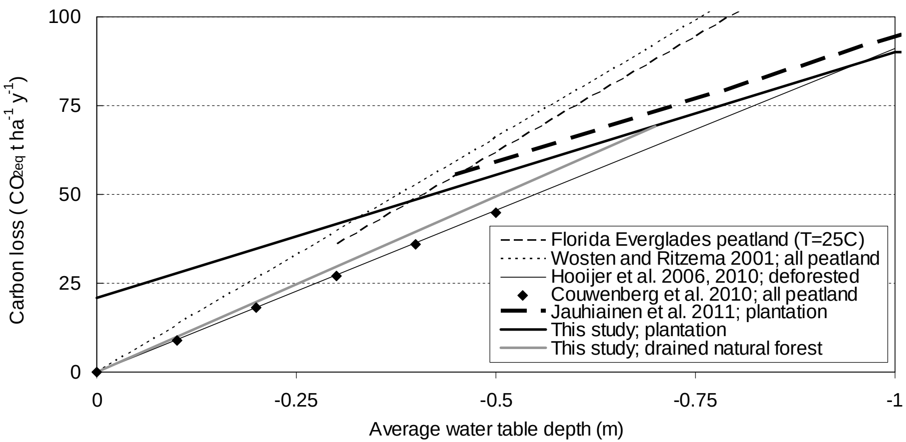


**Fig. 8.** Comparison of the relation between carbon loss ($CO_{2eq}$) and water table depth in tropical peatlands, more than 5 years after drainage, as determined in this and other studies. The Florida Everglades relation is calculated from data in Stephens and Speir (1969), that may also have been 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. (2011) 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.





BGD
8, 9311–9356, 2011

**Fig. 9.** Conditions at a mature oil palm plantation site, 18 years after conversion: open canopy (causing increased soil temperatures), limited ground cover (causing lowered soil moisture content), intensive fertilization (white patches around palm trunks), and a loose top soil structure (leaning oil palms, footprints).

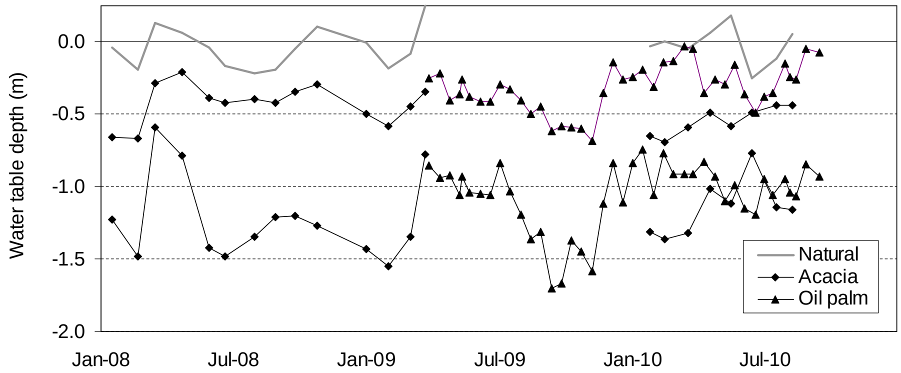


**Fig. 10.** Time series of water table depth as measured at individual locations in the studied *Acacia* and oil palm plantations, and in nearby natural forest at 2 km from the acacia plantation, over a 3-year period. In plantations, the records nearest the lower and upper 10-percentile average water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





BGD
8, 9311–9356, 2011