Methods for determining greenhouse gas emissions and carbon stocks from oil palm plantations and their surroundings in tropical peatlands

Report

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Abstract

2011. This report discusses the available options for measuring, reporting and verifying carbon stocks and greenhouse gas emissions in oil palm plantations and their surroundings in tropical peatlands.

This report was commissioned by the Peatland Working Group of the RSPO and provides an independent review of available scientific information on measuring, reporting and verifying carbon stocks in tropical peatlands. It describes methodologies currently used for the measuring fluxes and for analysis of the data gathered. The report also presents gaps in knowledge, uncertainties and recommendations.

Keywords: sampling design, carbon stock, system boundaries, biomass, peat soil.

Chapter 1. Introduction

1.1. *Background and outline of the document*

The objective of the Roundtable on Sustainable Palm Oil (RSPO) is to promote the growth and use of sustainable oil palm products through credible global standards and engagement of stakeholders. Part of the RSPO is the Peatland Working Group (PLWG), which is envisaged as a short-term, multi-stakeholder expert panel established to conduct specific tasks on issues related to the use of tropical peat for palm oil production. One of the objectives of the PLWG is to summarize options for measuring, reporting and verifying greenhouse gas emissions and carbon stocks related to the conversion of tropical forest into plantations and also from the oil palm plantations themselves and their surroundings.

This document describes the currently used methodologies for measuring and analysis. The document is intended to be a user friendly tool to support stakeholders in tracking their carbon gains and GHG emission reductions. This can be through either avoidance of emissions by not draining peat for cultivation and no clearance of forest, or through more sustainable practices on existing plantations on peat such as improved water management to decrease drainage depth and also fire control. Measures that can be taken to decrease carbon and greenhouse gas losses have been described in more detail in the RSPO Best Management Practices Guide and in the RSPO Scientific Review on the Impacts of Development of Oil Palm Plantations on Peat.

The first chapter of this document comprises background information on the greenhouse gases of concern and the carbon pools that are important in tropical peat swamp forests. The second chapter deals with the methodologies that are currently available for measuring and estimating fluxes and changes in fluxes of greenhouse gases. Chapter three comprises methods for determining carbon stocks and carbon stock changes and Chapter four is the reference list. The Annexes in the back of the document are practical tools for measuring variables that are needed to calculate carbon stocks and/or greenhouse gas emission (changes).

1.2. *Importance of Peatlands*

Peatland ecosystems contain a large amount of carbon. They cover approximately 3% of the global land mass, but contain 550 Gt of carbon in their soils. Tropical peat soils are estimated to contain around 90 Gt of carbon, more than 20% of global peat carbon, with 70 Gt of that located in Southeast Asia (Page *et al*, 2011; Jauhiainen *et al*., 2011). The peat soils in Southeast Asia contribute considerably to the global terrestrial carbon stock through their underlying thick peat soil, but also through the above ground biomass, the peat swamp forests. Indonesian peat currently stores 50-60 Gt of carbon (132 Gt of CO_2 equivalent) below ground (Page et al., 2011; Jeanicke et al., 2008). In addition, peat forests store 4.2 Gt of carbon (15 Gt CO_2e) above ground. As a comparison, the world's largest rainforest, the Amazon, stores 46 Gt of carbon (168 Gt of CO_2equivalents).

The main carbon stocks in tropical forest ecosystems are conceptually divided into:

1. Above ground living biomass (AGB)
2. Below ground living biomass (BGB)
3. Necromass or wood debris
4. Litter
5. Soil organic matter (SOM)

Global awareness of the important role of tropical peatlands in terms of carbon storage has increased, but much uncertainty still exists on the magnitude of this role (Malhi, 2010). As a result of economic development over the past decades, peat swamp forests have been subject to intensive logging, drainage, fires and conversion to plantation estates (Rieley *et al*., 1996, Rieley and Page, 2002). Half of the peat swamp forests in Southeast Asia have been cleared and drained for agricultural use (Hooijer *et al*., 2010). The remaining half of the peat swamp forests are for a large part degraded through timber extraction and drainage (Joosten, 2009). These activities cause loss of carbon due to drainage and subsequent fires (Wosten *et al*., 2006). Drainage of peatlands (as the peatlands are opened for cultivation) leads to oxidation of the peat material and a resulting release of CO_2 into the atmosphere (as 50% to 60% of the peat dry matter is carbon). Fires in degraded peatland result in further CO_2 emissions; fire is extremely rare in non-degraded and non-drained peatlands because of their naturally high moisture content.

1.3. *Greenhouse gas emissions*

The enormous growth of the human population and industrialization have led to rapid increases in biomass burning, agricultural activities and land use change, resulting in enhanced emissions of aerosols and greenhouse gases into the atmosphere. Changes in the biogeochemical cycles of terrestrial ecosystems, such as the carbon and nitrogen cycles and their influence on the dynamics of the atmosphere, influence the climate in terms of temperature and precipitation, resulting in an increased number of droughts, an increase in extreme rainfall events and shifting seasons.

Greenhouse gasses act to reduce heat from escaping from the Earth's surface and thus, changes in greenhouse gas concentrations in the atmosphere will have a strong impact on climate. Without greenhouse gases, scientists estimate that the average temperature on Earth would be approximately 30 degrees Celsius cooler. But as their concentrations increase, so does absorption of thermal radiation, followed by rising tropospheric and soil surface temperatures. The key greenhouse gases of concern are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2007). The global warming potentials (GWP) of CO_2 and CH_4 over a 100-year time frame relative to CO_2 are 25 for CH_4 and 298 for N_2O, respectively (IPCC 2006, 2007).

Carbon dioxide

Carbon dioxide (CO_2) fluxes between the atmosphere and ecosystems are primarily controlled by the photosynthesis and respiration of vegetation, animals and soil and by decomposition processes. The balance between the production and decomposition of organic compounds determines whether a system is a sink (resulting in uptake) or a source (resulting in release) of CO_2 (Valentini *et al*., 2000). Ecosystems generally act as sources of CO_2 during the night (respiration only) and as sinks for CO_2 during the daytime (when photosynthesis exceeds respiration). In wetland soils, the decomposition of organic material is slow because shallow water tables prevent O_2 from penetrating deeply into the soil. Consequently, the degradation of the peat is slow and net peat formation can take place (Alm, 1997). Areas of peat are commonly seen worldwide to act as sinks for CO_2, in temperate, boreal and tropical zones. When the peat areas are drained, however, the situation is different. The peat will oxidize and carbon will be released to the atmosphere.

Previous research

For *tropical peat soils* data on CO_2 emissions is still sparse and estimates of emissions are contradictory. Changes in CO_2 emission result from land use (change), drainage (and therefore the oxidation of peat) and from peat and forest fires. CO_2 emissions following drainage of peat soils are the main CO_2 source and are dependent on water level and on temperature, despite the small temperature range of the tropics (e.g. Hirano *et al*., 2007; Melling *et al*., 2005; Couwenberg *et al*., 2010; Furukawa *et al*., 2005; Hooijer et al., 2011). Fires cause significant peak CO_2 emissions over relatively short periods of time (Page *et al*., 2002; Couwenberg *et al*., 2010).

In *temperate peat soils*, CO_2 net ecosystem exchange (NEE) usually correlates positively with temperature and negatively with depth of the water table. Managed, drained sites are usually CO_2 sources, while unmanaged, natural sites are CO_2 sinks (e.g. Hendriks *et al*., 2007; Veenendaal *et al*., 2007).

In *boreal zones*, organic agricultural soils emit CO_2 (Nykänen *et al*., 2002; Maljanen *et al*., 2004) while pristine water-saturated peat soils serve as sinks for CO_2 (Gorham *et al*., 2003; Alm *et al*., 1997). Photosynthesis is strongly dependent on the leaf area index (LAI) and irradiation (*I*) during the growing season (e.g. Maljanen *et al*., 2004). It is highest in summer and decreases in autumn with the changes in the phenology of the vegetation and temperature. Total CO_2 emitted in winter averages 22% of the annual NEE (Maljanen et al., 2004).

Methane

Methane (CH_4) is emitted to the atmosphere as a net result of it's production, consumption and transport through soil or water. It is produced under anaerobic conditions in soil and water bodies. Methane production is a microbiological process, which can occur when organic matter is degraded anaerobically and when other terminal electron acceptors (O_2, NO_3^-, FE_3^+, SO_4^-) are depleted by the microbial community (Zehnder & Sturm, 1988). The factors that affect how much of the CH_4 produced is consumed by oxidation on its way through an oxygen rich medium before it reaches the atmosphere include the residence time of CH_4 within an environment, the oxygen status of the transport route and the biological activity of that environment. Wetlands, including peatlands, are considered the largest single source of atmospheric CH_4 and water bodies are large emitters (Bastviken *et al*., 2004; Walter *et al*., 2006; St. Louis *et al*., 2000; Schrier-Uijl *et al*., 2010c). Methane emissions from wetlands show large spatial and temporal variability. The main factors in temperate regions determining this variability are management, land use history, moisture conditions and environmental conditions such as temperature (Moore and Knowles, 1989; Bridgeham and Richardson, 1992; Roulet, 1993; Dise, 1993; Segers, 1998; Schrier-Uijl *et al*., 2010abc).

Previous research
A few studies have focused on CH_4 fluxes in *tropical peat soils* (e.g. Ueda et al., 2000; Hadi et al., 2005; Couwenberg et al., 2010; Melling et al., 2005; Furukawa et al., 2005). In tropical peat soils usually CH_4 emissions show a clear positive relationship with water level. However, spatial and temporal variability of the published data is large (Smemo and Yavitt, 2006; Melling *et al*., 2006).
Lowering the water table from a depth of 20 cm to a depth of 30 cm led to the CH_4 emissions decreasing by 25% (Furukawa, 2005). The combination of high temperature, wet conditions,

sufficiently available organic substrates and an active microbial community creates optimum conditions for CH_4 production.

In *temperate regions*, peat soils were initially considered to be a substantial CH_4 source. However, it was discovered that CH_4 emissions from drained peat soils in Europe (with the water table 30 cm below field level) are low or even negative (Mosier *et al.*, 1991; van den Pol-van Dasselaar *et al.*, 1998; Martikainen *et al.*, 1992; 1993; Roulet *et al.*, 1993; Glenn *et al.*, 1993). In more natural fens, not used for agriculture, however, CH_4 emissions may be in the order of 1.7 mg CH_4 m^{-2} yr^{-1}. The effects of fertilizer inputs on CH_4 emissions from peat lands are not yet well known. In situ studies have shown that the incorporation of organic matter markedly increases CH_4 emissions (Le Mer, 2001). In water bodies, the transport and magnitude of CH_4 fluxes are dependent on the trophic status of the water, it's depth and the turbulence (Schrier-Uijl *et al.*, 2010c).

Nitrous dioxide

Nitrous oxide (N_2O) is primarily emitted from agricultural and natural ecosystems as a by-product of nitrification and denitrification (e.g. Hansen et al., 1993). Nitrous oxide is a natural gas in the Earth's atmosphere. However, the atmospheric concentration has increased in recent decades. The increase in N_2O is of concern because N_2O is a long-lived greenhouse gas with a large global warming potential (298 times that of CO_2, IPCC, 2007). N_2O is emitted by natural, anthropogenic, and interrelated sources. Natural wetlands with high water tables do not necessarily produce N_2O (Nykänen *et al.*, 2002) but may consume small amounts of N_2O in denitrifation, a process through which atmospheric N_2O is reduced to N_2 (e.g. Regina *et al.*, 1996). However, agricultural soils are significant sources of N_2O (Mosier, 1991; Kroeze *et al.*, 1999), and direct N_2O emissions from agricultural soils contribute considerably to the greenhouse gas balance (Kroon *et al.*, 2010) and account for up to one third of the global emissions (Mosier *et al*, 1991). N_2O fluxes also have a high spatial temporal variability, and are therefore difficult to predict (Denmead, 1979; Groffmann *et al.*, 2000; Velthof *et al.*, 1996).

Previous research

A few studies on N_2O fluxes on *tropical peat soils* under different management are available (e.g. Melling et al., 2007; Furukawa et al., 2005; Hadi et al., 2005). In tropical peat soils, application of nitrogen fertilizers in cultivated systems could accelerate the release of N_2O. Fungi may also play an important role in N_2O production from tropical peat soils (Yanai *et al.*, 2007). The extent of N_2O release from the system and the processes that cause N_2O emissions in tropical peatland ecosystems are poorly understood.

In *temperate regions* research on N_2O suggests that 90% of all N_2O emitted originates from biological processes in soils (e.g. Bouwman, 1990). The factors controlling N_2O emission are soil conditions such as soil moisture, soil temperature and the availability of ammonium and nitrate. Natural wetlands do not usually produce emissions. Drained agricultural wetlands are, however, known to be N_2O emitters when fields are fertilized (Schothorst, 1977; Langeveld *et al*., 1997; Oenema *et al*., 1997). Pennock *et al* (2004) observed three basic annual patterns for N_2O emissions from Canadian peatlands: background emissions, seasonal emissions (dependent on soil temperature and moisture conditions) and event emissions (after application of fertilizer). Kroon *et al* (2010) found similar patterns for a managed temperate peatland in Europe. Event emissions (or *peak* emissions) were caused by the combination of application of fertilizer and rainfall (Melling et al., 2007; Melling et al., 2005b). In the study of Kroon *et al* (2010), N_2O emissions accounted for 45% of the total greenhouse gas balance.

1.4. *Above ground biomass*

According to the IPCC definition, above ground biomass (AGB) comprises all the living above ground vegetation, including stems, branches, twigs and leaves (Verwer and van der Meer, 2010). AGB in tropical forests and in oil palm plantations may vary considerably depending on, for example, climate, soil parameters, forest age, forest type, type of undergrowth, etc. Undisturbed primary forests that generally have the highest biomass are rare, while the AGB in remaining forests varies with disturbance history and natural variation. For example, in peat domes six different forest types have been distinguished (Anderson, 1961). These depend on differences in the hydrology, chemistry and organic matter content in the dome (Page *et al*., 1999). Studies show that in general AGB estimates range from 111-432 t C ha^{-1} in natural or primary peat swamp forest, 73-245 t C ha^{-1} in logged forest and 25-84.6 t C ha^{-1} in oil palm plantation (Waldes and Page, 2002; Agus *et al*., 2009; Lasco 2002; Gibbs *et al* 2008; Morel, 2009; Verwer and van der Meer, 2010).

1.5. *Below ground biomass*

Below ground biomass (BGB) comprises all living biomass of roots (Verwer and van der Meer, 2010) and varies from 26.5 t ha^{-1} for mixed swamp forest to 14.4 t ha^{-1} for low pole forest (Sulistiyanto, 2004). In peat swamp forests roots may be the most important contributors to peat formation (Chimner and Ewel, 2005; Joosten, 2008). Data on root biomass in tropical peat swamp forests is very limited due to difficulties in directly measuring the BGB (Cairns *et al*., 1997; Jackson *et al*., 1996). For other ecosystems root-shoot ratios have often been used to calculate the BGB. For tropical peat swamp forests the only studies that publish root-shoot ratios are those of Jackson *et al* (1996), Cairns *et al* (1997) and Sulistiyanto (2004). The latter study suggests a ratio of 1:12 (root:shoot) for mixed peat swamp forest and 1:18 for low pole forest.

1.6. *Necromass or wood debris*

Necromass or dead wood debris (WD) includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country and can be a large contributor to the total C balance in a tropical peat swamp (Verwer and van der Meer, 2010; UNFCCC 2010). Research has shown that in tropical moist forests the contribution to the C-balance can range between 17 and 58 t C ha-1 (e.g. Clark et al., 2002; Chambers et al., 2004; Pyle et al., 2008; Palace et al., 2008 in Verwer and van der Meer, 2010), equalling 9.5% - 33.5% of the live AGB (Verwer and van der Meer, 2010). In these studies the carbon content of the WD varied between 46.4% in fully decomposed material to 48.3% in sound material. A study in Borneo (*Dipterocarp* forests) revealed a total average mass of 12.4 t ha^{-1} standing dead biomass and 27.2 t C fallen dead trees (Gale, 2000). Values of 61 t C ha^{-1} have been recorded in Borneo for coarse wood debris (Bruenig, 1996). To measure the biomass and carbon content of the necromass is not easy, especially in mixed stands. It requires considerable labour and it is difficult to obtain an accurate measurement. Destructive sampling is often used to estimate the biomass of individual trees and relate it to easily measured variables such as stem diameter.

1.7. *Litter*

Litter includes all non-living biomass with a diameter less than a minimum diameter chosen by the country (usually diameter < 100 mm). It is the biomass pool that comprises lying dead organic matter, in various states of decomposition above the mineral or organic soil, such as leaves, small branches, flowers, fruits and seeds (Verwer and van der Meer, 2010; Sayer et al., 2007; UNFCCC 2010). Quantitative data tropical peat litter is scarce. However, because the rate of decomposition in tropical peat soils is slow, the litter biomass pool may be relatively larger compared to other forest types in the tropics, but often not significantly contributing to the total balance. Estimates of the litter carbon pools range from 2.4 t C ha^{-1} (Denlaney et al., 1997) to 15 t C ha^{-1} (Chiti et al., 2010). In carbon accounting methodologies the litter pool is often not taken into account because of the minor contribution to the total carbon stock.

1.8. *Soil organic matter*

Accumulation of organic matter originates from remains of plants or dead leaves, twigs, branches, flowers and fruits. Accumulation occurs because the rate of decomposition of organic matter in wet or water-logged conditions is lower than the rate of build-up of dead vegetation. Vast tropical peat deposits containing wood are the result of long-term ecosystem carbon sequestration from the atmosphere. In Indonesia alone, the estimated current peat carbon (C) store is 50 – 60 Gt (Page *et al*., 2011; Jeanicke et al., 2008), and carbon density values between 1500 and 2000 t C ha^{-1} (Anshari et al., 2010). Some peatlands, even in natural conditions, are in a steady-state and are no longer accumulating peat. Others, especially drained peatlands, are undergoing degradation as in the form of gaseous carbon loss and peat subsidence. The balance between the rates of net C sequestration by photosynthesis and C-release by organic matter decay determines whether the C-reservoir decreases, is in equilibrium, or increases. It has been shown that a high leaf area index (LAI) and high water levels are essential for net C sequestration in peat swamp forest ecosystem (Suzuki *et al*., 1999; Hirano *et al*., 2007).

1.9. *Total balances*

Integrated carbon balance

Estimates of above and below ground carbon stocks can be used to estimate the carbon balance and carbon balance changes if, for example, land use changes. To determine biomass carbon stocks it is necessary to determine the average carbon stock density based on permanent sampling plots on forest classes of land and non-permanent sampling plots on non-forest land use classes. The number of plots and their location must be best determined in a stratified sampling design (VCS, VM0004, 2010), taking into account the following steps:

- Identify the land use classes and (forest) strata for which carbon stocks are to be quantified;
- Review existing biomass and biomass increment data for comparison with field measurements;
- Determine the sample size per land use class or forest stratum;
- Calculate fluxes from each land use transition category.

The total carbon stock in tropical peat consists of C stored in above and below ground biomass plus C stored in the peat. The C inputs comprise the C sequestered from the atmosphere by photosynthesis (Net Primary Production) resulting in biomass increment and accumulated peat. The C outputs are the C emissions to the atmosphere as a result of autotrophic and heterotrophic respiration (decomposition), vegetation/crop removal, fire and C released (as dissolved organic carbon) in water. Destructive sampling, that involves felling, drying and weighing all components of the living biomass, is the most direct and accurate method for quantifying biomass within a small unit area, but is labour intensive, expensive and damaging to the environment when applied at larger scales. Currently, biomass monitoring more and more depends primarily on in situ inventory information supported by remote sensing data. In the field, allometric (regression) equations are commonly used to estimate AGB and are usually based on tree diameter at breast height. It may be necessary to gather additional field data in order to validate biomass estimates at larger spatial scales.

Integrated greenhouse gas balance

The total greenhouse gas balance of an ecosystem consists of 1) natural, terrestrial sinks and sources (including fluxes from fields, waterlogged land and water bodies) and 2) sinks and sources related to land use (change) and management practices. The total greenhouse gas balance is quantified by using the global warming potential of each gas of concern:

$$NEE_{GHG} = NEE_{CO2} + 25NEE_{CH4} + 298NEE_{N2O}.$$

Where NEE is the net ecosystem exchange and 25 and 298 are the GWP's of CH_4 and N_2O for a 100-year time horizon.

Changes in balances

If biomass is removed and peat is drained, the carbon and greenhouse gas balances will change directly and carbon will be lost. Drainage allows O_2 to penetrate deeper into the soil, causing respiration rates to increase, with release of carbon as CO_2. Inversely, if drainage depth is shallower, less carbon will be lost as CO_2. Because methanogenenis is a product of anaerobic respiration, the emission of CH_4 will decrease when water tables fall. Nitrous oxide emissions, which are mainly dependent on the application of nitrogen in the system, will decrease if management becomes less intensive. Land use changes or activities, for example, restoration of drained peatlands, decreases in water table depth, reduction of fires, deforestation or oil palm plantation development, will cause a change in the total carbon and greenhouse gas balance. To investigate the total GHG balance and the underlying processes of ecosystems, different measurements are needed. The carbon stocks and greenhouse gas emissions before and after change have to be investigated for each area of interest and each source or sink. The most obvious and most commonly used method is to directly measure all carbon and greenhouse gas fluxes in the proposed ecosystem. Examples of direct measurement methods for greenhouse gas emissions are 1) the often used small scale enclosure or chamber method and 2) continuous measurements at a landscape scale, using eddy covariance methodology. For carbon flux estimates allometric equations are often used based on inputs such as tree height and stem diameter. Examples of indirect measures to estimate emissions and/or carbon losses from peat are measuring soil subsidence and/or water level.

1.10. *System boundaries and sampling designs*

Monitoring carbon and greenhouse gas fluxes from an ecosystem involves taking measurements over time and over space. To be effective in the monitoring strategy it is important to:

- Define the 'project-area' or 'research-area' in terms of latitude, longitude and record changes if they exist during the monitoring period.
- Describe land use before plantation development, land use changes, management activities etc. during the monitoring period. Changes in the surroundings should also be included.
- Include all possible sources and sinks within the proposed ecosystem and include a range of relevant situations (e.g. management activities, meteorological differences, etc.) of soil-C changes, CO_2, CH_4 and N_2O emissions.
- Stratify the area in strata that differ significantly in source/sinks strength or pool size (see Fig. 1 for an example). This can be based on hydrology, land use, management, vegetation type, etc. or a combination of factors that control emissions and carbon fluxes in a certain area. Be sure that the sample plots within a certain strata do not all fall in the area with the densest or least vegetation or potentially highest or lowest emissions. For oil palm plantations these strata should be based on the ages of oil palm tree blocks. A suggestion would be to classify 5 yr., 10 yr., 15 yr., 20 yr. and 25 yr. old palms.
- For estimating above ground biomass often a 'nested' sampling approach is followed, assessing large diameter trees (with a stem diameter > 30 cm) in rectangular plots of 20x2000 m, smaller trees (stem diameter 5-30 cm) in subplots of 5m x 40m = 200 m^2 within these, and understorey vegetation and litter in smaller sub-subplots. Plot location is randomized if there are marked discontinuities in the vegetation (International Center for Research in Agroforestry).

- Include monitoring of possible explanatory variables (hydrological and others) such as water table, soil moisture conditions, soil and air temperature, inputs of fertilizer, stem diameter, age of tree, peat depth.
- Insert a subsidence pole in each strata to monitor soil subsidence and to estimated carbon losses and greenhouse gas emissions from these measurements (see Annex B).
- Include, if needed, additional measurements in the surrounding area of factors that could increase or decrease carbon and greenhouse gas emissions within that area.

The key principle underlying the definition of the area and the duration of the study is that the spatial extent (or area) of the study and the temporal extent (or duration) of the sampling must match the scale of the process under study (Pennock *et al*., 2004). There will always be an interaction between the costs of sampling and the resources available.

The *spatial sampling design* should specify the procedures to be used to summarize data, the number of samples to be taken and the specific sampling design to be used. The choice of the appropriate spatial sampling design involves two major decisions: the number of sites to be sampled and the sampling design to be used at each site. Ideally, a number of land use/management combinations should be defined in each situation. Then several replicates of each combination should be selected for sampling and, if appropriate, stratified into wetness classes (Pennock *et al*., 2004). In this document the focus will be on the monitoring of land based fluxes.

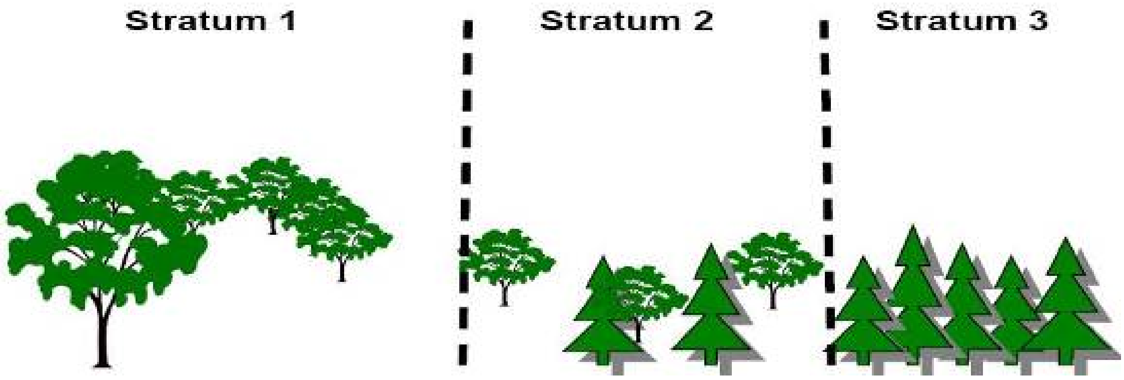


Fig 1. An example of stratification of an area based on forest type.

In the *temporal sampling design* the spacing and effective data interpolation requires an understanding of temporal patterns of emissions and carbon fluxes. This temporal behaviour is different for different peat land uses and is dependent on, for example, climatic conditions, fertilizer inputs and soil moisture. For N_2O and CH_4 high emission peaks have been observed (e.g. Denmead, 1979; Groffmann *et al*., 2000; Dobbie *et al*., 2003; Kroon *et al*., 2010) and the ability to capture these patterns depends on the temporal spacing of measurements and on the estimator selected to describe the central tendency of the sample distribution. The inclusion or exclusion of major flux events (e.g. after fertilizer application, after rainfall, etc.) can lead to over or underestimation of the annual mean depending on whether or not the events are captured during sampling.

Chapter 2. Estimation of Greenhouse gas emissions

2.1. *Greenhouse gas emission measurements*

Continuous field scale measurements are preferred for deriving direct and indirect site emission values such as from oil palm plantations. On the other hand, the main drivers behind the fluxes can be better investigated by measurements at the plot scale. Because of the large spatial and temporal variability of the emission of the three greenhouse gases of concern it is difficult to predict emissions at a larger scale (e.g. site scale, landscape scale or regional scale) from up-scaled point measurements. If driving processes are not fully known, model-based predictions are still uncertain. In order to obtain full greenhouse gas balances over larger areas, multiple year measurements of all three gases are needed to cover the variability. There are three major challenges when upscaling fluxes from small-scale measurements to larger scales: 1) selecting the correct ecosystem variables, 2) developing robust predictive relationships (Grofmann *et al.*, 2000), and 3) using long-term datasets.

Various measurement techniques and flux estimation methodologies have been developed in recent decades to provide accurate long-term datasets. Strengths and weaknesses are given in table 1. Combining methods and also coupling the measured emissions with driving variables is useful for upscaling emissions to large scales and for gaining insights into the details of the processes. A sufficiently dense network of observations is necessary to cover fine scaled spatial patterns that are typical for (managed) peatlands and degraded peatlands. On the scale of an oil palm plantation, the number of chamber based samples would, depending on the homogeneity of the area and the number of strata, range between 10 and 20 sample plots and at least four samples per strata. If the sampling performed is representative, it can be used to upscale data to larger areas.

Table 1. General comparative characteristics of greenhouse gas measurement techniques given by Drösler *et al*., 2008. Capacity/properties ranges from large/positive (++) to small/negative (--).

Characteristics	Methods		
	Eddy covariance	Automatic chamber	Manual chamber
Undisturbed gas exchange	++	+/-	+/-

Integration over spatial variability	++	-	-
Direct measurements of small-scale spatial variability and management	--	+	++
Tracking temporal variability	++	++	-
Costs	--	--	++
Workload	++	+	
Performance under all climatic conditions	+/-	+/-	++

In the last two decades numerous papers have been published on greenhouse gas emission estimates covering a broad range of ecosystems. In addition, detailed studies have been performed on methodological aspects related to missing data or gap-filling and energy balance closure. However, there are large uncertainties in emissions estimates, while CH_4 and N_2O eddy covariance data are sparse because this method is still being developed. Instrumentation that meets the requirements to measure CH_4 and N_2O fluxes continuously is just becoming available (Kroon *et al*., 2007; 2009; 2010). These methods use lead salt tuneable diode laser (TDL) spectrometers (e.g. Smith *et al*., 1994; Wienhold *et al*., 1994; Laville *et al*., 1999; Kroon *et al*., 2010). CH_4 and N_2O estimates in tropical regions are currently based on chamber measurements. These estimates have large uncertainties due to the temporal and spatial variation of emissions. Both chamber-methods and eddy covariance methods are expensive for standard monitoring. Chamber-based methods cannot be performed remotely, while eddy covariance equipment is expensive. For both methods, the data processing takes a considerable amount of time. The methods are feasible for selected sites, for a certain period, depending on the available budget. Long term datasets are needed to develop, calibrate and verify allometric models to arrive at reliable annual emission estimates. Estimates from other sites can then be obtained based on existing regression or allometric models. Also indirect methods are used to estimate emissions, like for example, the use of soil subsidence and the oxidation component or the use of water level as a proxy.

Input parameters for models that predict emissions have to be easy to measure in the field (such as water table, soil temperature, soil subsidence). Parameters that drive emissions (proxies) will be different for the three greenhouse gases and will differ for each stratum in the area (strata can be based on hydrology, land use, management, vegetation type, topography, soil type, etc.). Methodologies used for emission estimates can in general be classified as 1) direct measurements of greenhouse gases and 2) estimates based on variables such as soil subsidence, the indirect approach.

2.2. *Estimating emissions, the direct approach*

If properly used, and upscaling is performed in a reliable way, direct greenhouse gas measurements are the best option to determine fluxes from an ecosystem and to understand the processes that underlie greenhouse gas emissions. All possible sources and sinks of CO_2, CH_4 and N_2O must be captured, including photosynthesis, plant- and root respiration, soil respiration, management related fluxes, emission from open water, land etc.

The static chamber method (automatic or manual, see Fig. 2 for pictures of possible applications of the chamber- or enclosure method) (e.g. Melling *et al*., 2005; Schrier-Uijl *et al*., 2010ab) and the Eddy covariance method (e.g. Veenendaal *et al*., 2007; Kroon *et al*., 2010; Hirano *et al*., 2007) have been used successfully for CO_2 for many years. The physical structure of an ecosystem restricts the methods available for studies on ecosystems-atmosphere gas exchange. A low or missing vegetation layer, as in the case of degraded peat soils or open agricultural lands (Saarnio *et al*., 2007; Maljanen *et al*., 2007), allows for the use of portable chambers. Chambers can also be used to determine respiration at the soil surface below canopies, however, then the 'tree canopy exchange' part is excluded from the balance. The eddy covariance method, with towers reaching above the highest canopy, is useful to capture the total greenhouse gas balance in sites with trees (Lohila *et al*., 2007), but is burdened with high costs, low portability and low spatial resolution.

Fig 2. Example of a portable enclosure, connected to a gas analyser and a computer (a). The enclosure is equipped with a water lock to avoid pressure differences and a filter for water vapour to avoid cross-interferences (b). The system can be used to measure CO_2, CH_4 and N_2O on land or on water (a and c) (Images A. Schrier-Uijl)

Chamber based methods

Chamber methods are often used to determine source and sink distributions in non-uniform landscapes and are used to quantify small-scale spatial differences in CO_2, N_2O and CH_4 fluxes (e.g. Christensen *et al*., 1995; Hutchinson and Livingston, 2002; Hendriks *et al*., 2007; Schrier-Uijl *et al*., 2010b).

System set up

In the case of a static chamber method, a closed chamber is placed on the surface to investigate emissions for a certain time (t) (see Fig. 3 for an example of an enclosure). The enclosures function by restricting the volume of available air for exchange across the covered surface, so that any net emissions or uptake of the enclosed gases can be measured as a concentration change. Closed chambers may be transparent of dark (opaque). The use transparent chambers includes the photosynthesis component of the plants that are captured by the enclosure, and thus measured the net ecosystem exchange of CO_2 with the atmosphere. Dark chambers exclude photosynthesis and account for respiration only. Almost all CO_2 measurements from peat in SE Asia have been determined by using dark chamber, and most studies do not differentiate between autotrophic (root respiration) and heterotrophic (decomposition of peat and litter) respiration. One way to differentiate between autotrophic and heterotrophic respiration is the use of so called ‘ trenching approaches’ (e.g. Melling et al., 2007). The principle is that measures are taken including and excluding roots. The trenching approach is not well established yet, and the most recent literature in this is from Jauhiainen et al., 2012. They combined the trenching approach with measurements made along transect within and beyond the tree rooting zone on oil palm plantations.

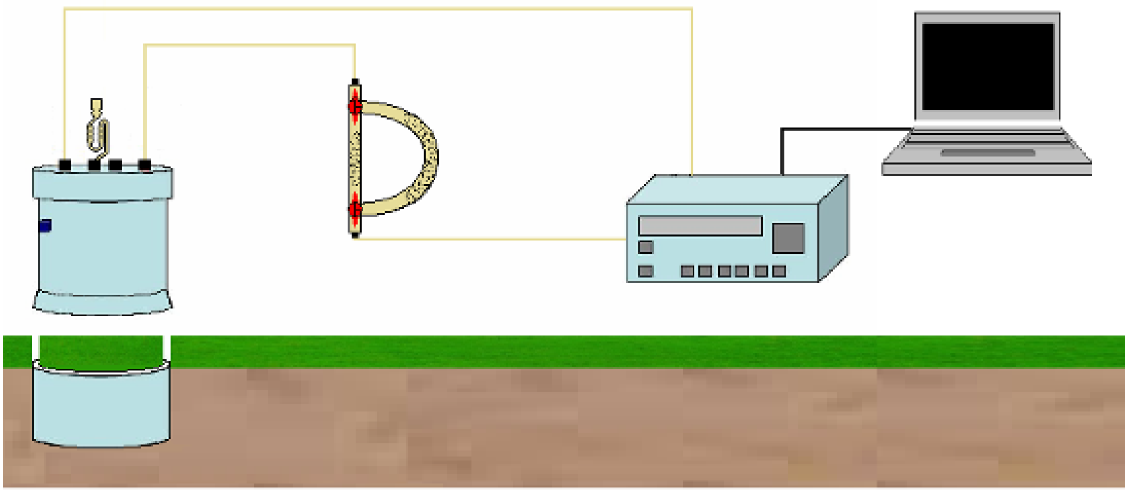


Fig. 3. An example of a chamber set-up as used in field experiments. The enclosure for flux chamber measurements, place air tight on a basis that is inserted in the soil, is connected to a gas analyser. The enclosure is equipped with a temperature sensor to correct for temperature, a pressure lock to maintain air pressure inside the chamber and a moisture filter to prevent for interference with water.

The flux dC/dt is not constant over the enclosure time if long measurement times are used (Kroon *et al*., 2010; Kutzbach *et al*., 2007). However, when short measurement times are used (4 – 6 minutes) linear regression can be used to estimate the slope dC/dt at time t = 0 s (Schrier-Uijl *et al*., 2010ab). The possible underestimation of fluxes using long closure times has been discussed in several studies (e.g. Hutchinson and Mosier, 1981; Pederson *et al*., 2001).

Constraints

Usually, multiple gas concentration measurements are performed at fixed time intervals of, for example, one or two minutes, using a linear regression. Flux determinations might be seriously biased by inappropriate use of linear regression (e.g. Kutzbach *et al*., 2007). Chamber-based methods are highly accurate when used properly (Alm *et al*., 2007; Denmead, 2008; Schrier-Uijl *et al*., 2010ab) and are the most widely used approach for measuring fluxes of CO_2, CH_4 and N_2O from bare soil surfaces and surfaces with short vegetation. Because the spatial integration of measurements is complicated, the chamber-based method is not often used for large-scale estimates of greenhouse gas emission (Flechard *et al*., 2007). Linear interpolation between directly measured emissions is commonly used for temporal upscaling of fluxes, however, because of the restricted temporal scale of chamber measurements and the risk of missing emission peaks, this method can over or underestimate annual fluxes considerably. Uncertainties are lower when a regression based approach is used together with explanatory variables or proxies to upscale emissions temporally. The method is sometimes criticized because of the uncertainties caused by pressure artefacts, temperature effects (e.g. Hutchinson and Livingston, 2002; Rochette and Eriksen-Hamel, 2008), and temporal discontinuity of measurements. Measurements have to be performed manually and therefore day-time measurements have usually been made, and the possibility of diurnal variability has been neglected. Although most of the chamber effects have been eliminated from recent set-ups, the problem of neglecting the influence of wind remains (Denmead, 2008). The drawback of taking only day-time measurements also remains, unless automatic logging instruments are used during the night.

Eddy Covariance Methodology

Eddy covariance (EC) techniques are used to continuously quantify landscape-scale temporal variability of CO_2 and, to a lesser extent, of CH_4 and N_2O (e.g. Baldocchi *et al*., 2003; Aubinet *et al*., 2000; Veenendaal *et al*., 2007; Hendriks *et al*., 2007; Kroon *et al*., 2007, 2010). The EC method is based on measuring turbulent ascending and descending wind fields, temperature, and gas concentrations at high frequency at a certain measurement point (e.g. Baldocchi, 2003). The advantage of this method is that it does not disturb the soil/air environment, integrates over larger areas and has a continuous time coverage. An EC output flux represents the integrated net flux from the landscape upwind from the measurement point. The footprint of the mast, the area where the signal is coming from is dependent on wind velocity and wind direction and is oval shaped (Fig. 4). The extent of the upwind area from which the flux originates, depends on atmospheric stability and surface roughness (e.g. Grelle and Lindroth, 1996; Kormann and Meixner, 2001; Neftel *et al*., 2007). EC measurements are based on assumptions such as horizontal homogeneity, flat terrain and negligible mean vertical wind velocities over the averaging period. Uncertainties arise for reasons that include one-point sampling and the lack of low and high frequency responses (e.g. Moore, 1986; Aubinet *et al*., 2000; Kroon *et al*., 2007).

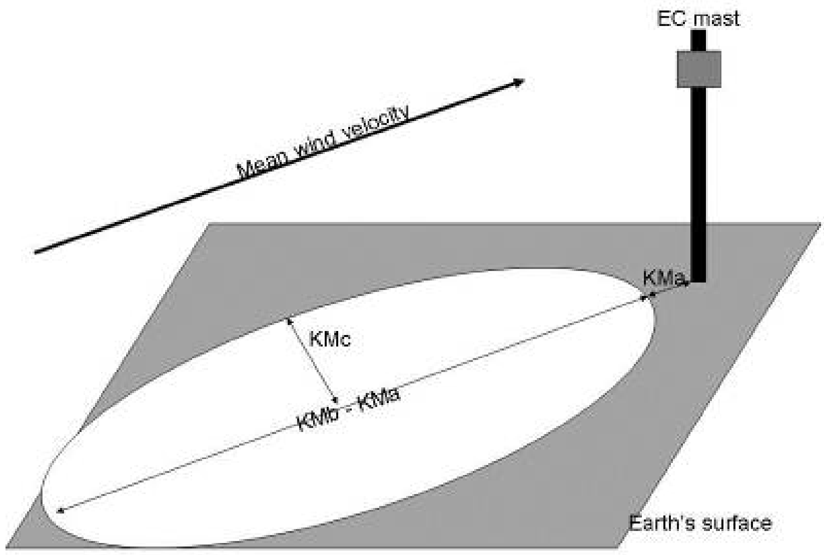


Fig. 4. Representation of the footprint area of a measurement mast by Kormann and Meixner (2001). The length of the ellipse (KMb – Kma) and half width of the ellipse (KMc) are drawn.

Net ecosystem exchange of CO_2 (NEE) is determined directly from the EC flux measurements and is considered to be the sum of the gross ecosystem production (GEP) and ecosystem respiration (Reco). The respiration is determined using nightly NEE values, when photosynthetic active radiation (PAR) = 0, and CO_2 flux is due solely to respiration. In temperate regions, the soil respiration is described as a function of the half hourly soil temperatures and parameters (R10 and E0) are estimated. The missing night and day time CO_2 respiration data (PAR>0) are estimated with this model (e.g. Veenendaal *et al*., 2007; Hendriks *et al*., 2007; Reichstein *et al*., 2005). Data gaps in CH_4 flux datasets are usually filled using linear interpolation or a regression model.

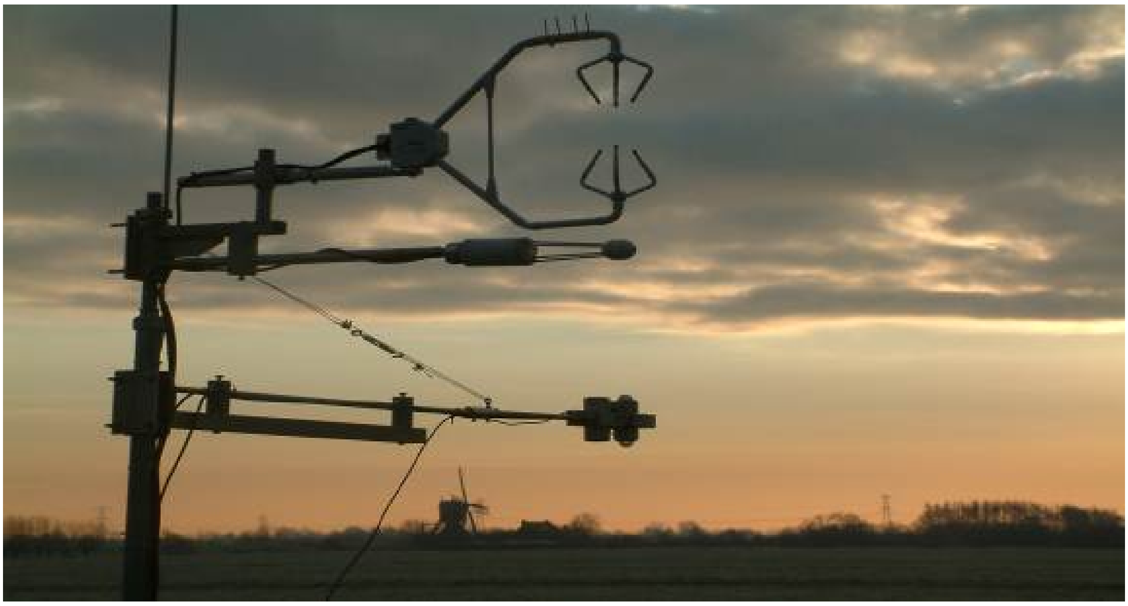


Fig. 5. An eddy covariance system, equipped with sensors for irradiation, wind, temperature, CO_2 and water vapour (Image E. Veenendaal).

After checks for diurnal cycling, dependency on friction velocity (u*) at low and high turbulence and statistical distributions, daily averages are estimated from half hourly data. From these, annual balances are estimated. A regression model can be used to fill data gaps in the CO_2 flux dataset. In temperate regions these models are usually based on temperature (Fig. 6).

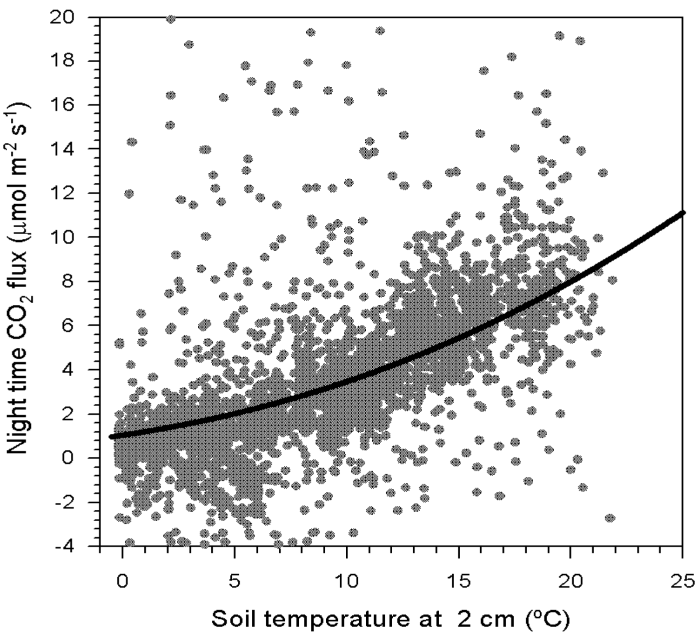


Fig. 6. An example of temperature dependency of respiration in temperate regions, adapted from Veenendaal *et al*., 2007. This model can be used to fill data gaps.

With the currently used instruments, gaps can make up more than 50% of the data set. Gap filling is usually performed by using a regression model based on explanatory variables. Eddy covariance measurements cannot be used to separate autotrophic and heterotrophic respiration (e.g. Couwenberg et al., 2010; Wetland international, 2009).

2.3. *Remote sensing approach*

Remote sensing provides information on land surface properties over large areas. It can be used e.g. to estimate, areas of forest, pasture, open water, croplands such as e.g. rice paddies (that are hotspots for CH_4) and land use changes. It is also an effective method to assess fire and logging, which do not always lead to detectable changes in forest cover. Deforestation refers to the conversion of forest land to agricultural cropland, grassland, and settlements. Degradation refers to a decrease in tree biomass, carbon stock or biodiversity of an ecosystem, however, the definition of degradation changes depending on the scientific discipline (Putz *et al*., 2010). Afforestation is the conversion of other land categories to forest. In general, the transformation of peat forest to cropland leads to emissions of CO_2 to the atmosphere. After clearing, de-forested peat land can remain an annual net source of CO_2 when drainage is permanent. In areas of afforestation a small long term CO_2 sink can develop. Degradation due to selective logging is more difficult to detect by remote sensing. In tropical forests, selective logging may leave a forest canopy that fills in within a year and does not appear to have been thinned. Anthropogenic fires in tropical peatlands contribute substantially to inter-annual variation in the rate of atmospheric CO_2 and CH_4, so fire monitoring is crucial to separate natural trends in atmospheric concentrations from the effects of human induced fires. In addition, fire is used in some parts of the world to clear forest for pasture or agriculture, and is an important source of atmospheric CH_4 (14-88 Tg CH4 yr^{-1}; Mikaloff Fletcher *et al*., 2004ab; van der Werf *et al*., 2006; Denman *et al*., 2007). A variety of remote sensing methods are being used to identify the location, area, and intensity of fire (e.g. Siegert *et al*., 2011; Souza *et al*., 2005; Matricardi *et al*., 2010; Cochrane 2003). Table 2 describes remote sensing methods that are able to estimate the events responsible for emissions caused by land use change (e.g., deforestation) and for greenhouse gas uptake by sinks.

Table 2. Current Land Remote Sensing Instruments in the Public Domain.

Instrument	**Measurement**	**Resolution and Coverage**	**Data Availability**
Land Remote Sensing Satellite (Landsat)	Provides the longest continuous record of the Earth's continental surfaces	30-60 m, global	Landsat 7: 1999-present Landsat 5: 1984-present

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)	Provides high-resolution images of the land surface, water, ice, and clouds	15-90 m, global	1999-present
Moderate Resolution Imaging Spectrometer (MODIS)	Measures biological and physical processes occurring on the surface of the Earth, in the oceans, and in the lower atmosphere	250 m-1 km, global	1999-present
Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)	Measures constituents of the Earth's surface and atmosphere	5-20 m, aircraft is tasked	1998-present

At the national scale, the most effective method for detecting areas of selective logging is to apply high spatial and temporal resolution remote sensing approaches to areas suspected of thinning, such as those determined by detection of logging companies along roads. Asner *et al*. (2005) applied an automated image analysis approach to annual Landsat data and pattern recognition techniques for detecting selective logging in the Brazilian Amazon. The analysis required initial ground-based spectroscopic characterization of surface features and tree species canopy spectra from a spaceborne hyperspectral sensor (Hyperion). The authors found an overall uncertainty of up to 14 percent in total logged area, based on seasonal Landsat data, atmospheric modeling, and detection of forest canopy openings, surface debris, and bare soil exposed by forest disturbances. A combination of seasonal Landsat-type remote sensing and LiDAR (Light Detection and Ranging) or P-band radar may be required to reduce uncertainty (Treuhaft *et al*., 2004).

2.4. *Estimating emissions, the indirect approach*

If direct measurements of greenhouse gases are logistically and practically impossible, simple and reliable approaches can be used to determine net greenhouse gas losses from an ecosystem. This can be achieved by determining the change in carbon stock directly, from measurements of e.g. surface subsidence (Hooijer et al., 2011) or water level (Couwenberg et al., 2010) and peat characteristics that are relatively straight forward to measure in the field and to interpret. The use of this approach has long been hampered by a scarcity of long term data that couples greenhouse gas emissions to variables that control the emissions. However, the study reported by Hooijer et al (2011) and Jauhiainen et al. (2011) was designed to overcome this limitation. The study has shown that CO_2 emissions measured using the subsidence method and using the direct measurement method to be very similar at long time scales. This study was modelled after the long-term Everglades study reported by Stephets et al. (1984), that reported the same close agreement in results of the two methods for subtropical conditions. It appears that, on this basis, monitoring of carbon emissions using subsidence as a proxy may be applied more widely than has been the case to date.

Soil subsidence as a proxy for CO_2 emissions

Peat subsidence is influenced by three main factors:

1. Mechanical compression
2. Shrinkage of peat after drying
3. Decomposition/oxidation of organic matter

Soil subsidence can be a very useful proxy for CO_2 emission if the decomposition/oxidation component of the total soil subsidence is known. Using soil subsidence as a proxy integrates all changes in the soil carbon store over a long time period, does not depend on instantaneous measurements and takes account of the total peat soil carbon budget, including losses with water discharge. However, uncertainties still exist mainly because of a scarcity of reliable subsidence data, in combination with scarce bulk density profile data at the same locations and scarce knowledge on the oxidation component. Because the soil subsidence data provide a time-integrated measurement of the net carbon balance of the peat, this approach might be a good alternative for the often used 'direct' chamber method. The method requires long monitoring periods and large-scale experiments across reference areas (Page et al., 2011; Hooijer et al., 2012). Monitoring periods for estimating the emission balance are dependent on the time after drainage. In a stable situation, e.g. 15 years after drainage, fewer measurements are needed compared to the situation just after drainage.

The key question is to what extent soil subsidence can be attributed to oxidation versus mechanical compaction and consolidation due to evacuation of water layers following drainage. Driessen and Soepraptohardjo (1974) and Stephens and Speir (1969) separated oxidation, compaction, accounting for changes in bulk density of the remaining peat to isolate the compaction component. Hooijer *et al* (2012) used their methods to calculate the oxidation component of soil subsidence and came up with an oxidation contribution of 90% after the first five years of drainage, in *Acacia* and oil palm plantations . This is at the high end of published values, but corresponded with the 85-90% range reported by Stephen *et al* (1984) on the basis of 76 years of measurements of subsidence rates, soil characteristics and CO_2 flux measurements. Wosten *et al* (1997) suggested that the rate of land subsidence due to decomposition is about 60%, while Couwenberg *et al*. (2010) conservatively suggested that it is at least 40%. However the 60% number is based on very limited data, while the 40% estimate is derived from a limited number of studies in temperate climates and should be considered too low for tropical climates. Even in the Netherlands, where compaction will bemore important than in the tropics as temperature is far lower, Schothorst (1977) reports a oxidation percentage of 72%; this number is widely accepted although recent studies in the Netherlands suggest that the historical oxidation component there may be around 85% (Erkens et al., in prep.). It therefore appears that estimates of the contribution of oxidation to subsidence in peatlands are being revised upwards internationally, as more data have become available in recent years and process understanding has increased. Lower estimates of oxidation contribution as discussed in Couwenberg *et al*. 2010 may be explained by 1) the use of data that apply to the entire period after drainage, including the initial years when compaction is indeed dominant, and by 2) a reliance on sources describing temperate conditions, where oxidation makes a lower relative contribution to subsidence as the biological processes involved are highly temperature dependent (Hooijer *et al*., 2012). Partitioning of net peat emissions will require additional use of closed chambers and/or detailed accounting of the different carbon stocks (Couwenberg et al., 2010; Wetlands International 2009).

Kuikman *et al* (2003) calculated the CO_2 emissions from temperate peatlands based on soil subsidence with

$$\mathbf{CO_{2,em} = S_{mv} * \rho_{so} * fr_{ox} * fr_{OS} * fr_C * (44/12) * 10^4}$$

Where:

$CO_{2,em}$ = CO_2 emission (kg CO_2 ha^{-1} yr^{-1})

S_{mv} = soil subsidence rate (m yr^{-1})

ρ_{so} = Bulk density of the peat (kg m^{-3})

fr_{ox} = Oxidation fraction of the peat (-).

fr_{OS} = Fraction organic matter in peat (-) on weight base.

fr_C = Carbon fraction in organic matter (-).

They found a clear relationship between soil subsidence and water level. Also Hooiier et al (2012) coupled water level depth to soil subsidence (in an *Acacia* plantations after 5 years of drainage) as follows:

$$\mathbf{S = 1.5 - 4.98 \times WD \ (\mathit{R}^2 = 0.21)}$$

Where S = annual subsidence of the peat surface (cm yr^{-1})

And WD = average water table depth below the peat surface (-m; negative).

The relation for drained forest, 5 years after drainage at water table depths of 0-0.7 m, was:

S = -7.06 x WD (R^2 = 0.34)

Water level and soil temperature as a proxy for CO_2 emissions

Several studies in tropical regions in Southeast Asia have estimated emissions based on water level or drainage depth. For example, Couwenberg *et al* (2009) coupled soil subsidence and water level to emissions and calculated emissions of at least 9 t CO_2 ha^{-1} yr^{-1} for each 10 cm of additional drainage depth. Going from a peat swamp forest with the water table at the soil surface to a drained peat area with a drainage depth of 60-80 cm would thus increase the emissions by 54-72 t CO_2 ha^{-1} yr^{-1} (Fig. 7).

Emission CO_2 (t CO_2 ha^{-1} yr^{-1}) = 0.9 x drainage depth (cm).

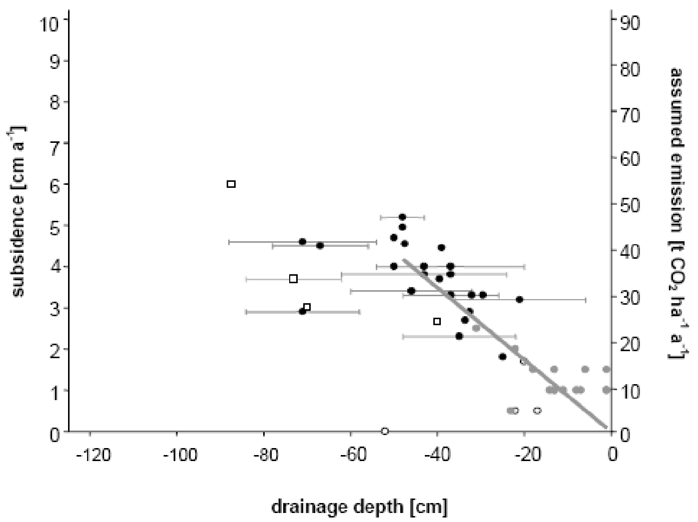


Fig. 7. The rate of subsidence and the assumed CO_2 emission in relation to mean annual water level below surface. Horizontal bars indicate standard deviation in water table. Open circles denote unused, drained forested sites. These were not taken into account in the regression that applies to water levels ≤ 50 cm below surface only. Most of the sites used for analyses are drained for over 10 years. Squares are agricultural sites and black dots are oil palm plantations, grey dots are degraded open land and open dots are drained, forested plots (Couwenberg *et al.*, 2010). The regression of water level – assumed CO_2

emission has a slope -0.086 and $r^2 = 0.75$; the regression of water level – soil subsidence has a slope -0.09 and $r^2 = 0.95$.

A summary of the results of various studies that studied the relation between carbon loss (in CO2-eq ha-1 yr-1) and the average water table depth is shown in Fig 8.

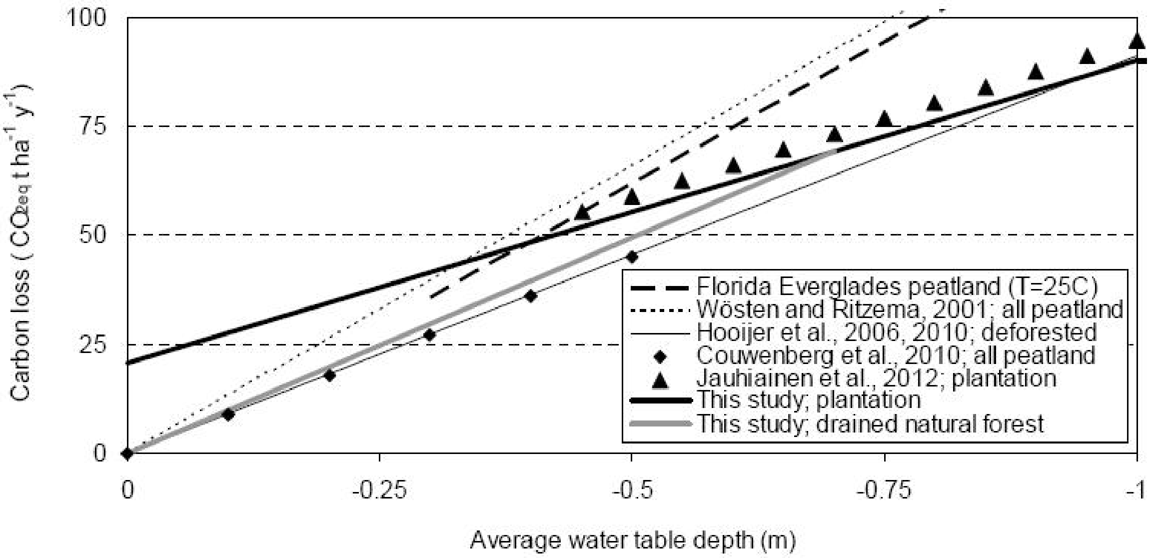


Fig 8. Comparison of the relation between carbon loss (in CO_2-eq ha^{-1} yr^{-1}) and water table depth in tropical peatlands, more than 5 years after drainage, as determined in the studies of Hooijer et al. (2012, 2010 and 2006), Stephens and Speir (1969), Wosten and Ritzema (2001), Jauhiainen et al. (2012), Couwenberg et al. (2010). The relations by Hooijer (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 CO2 flux measurements in the same Acacia plantation as Hooijer et al. (2012), excluding root respiration and corrected for diurnal temperature fluctuations. The figure is taken from Hooijer et al. (2012).

We zoom in on a study that addresses the relation between water level and CO_2 emissions in an *Acacia* plantation on fibric peat of over 4 meters depths is that of Jauhiainen *et al* (2012) (Fig. 8). They also studied the effect of temperature differences and concluded that each 1°C soil temperature difference yields a 10% difference in CO_2 emission. With a 5°C temperature difference after deforestation and drainage for clearing land, this would make temperature the main driver of emissions. This likely dominance of temperature as a cause of oxidation in tropical peatland plantations has not been given much attention. The relation between water table depth (in meters) and day time CO_2 emission (in mg m^{-2} h^{-1}) is described by the following linear regressions (95% confidence limits) where autotrophic and heterotrophic respiration have been separated using a ‘trenching’ approach:

Allometric equations for daytime oxidation emission at “furthest from trees” locations (excluding root respiration as much as possible):

$$\mathbf{CO_2\ emission\ (mg\ m^{-2}\ hr^{-1}) = 953.35\ x\ drainage\ depth + 309.07\ (R^2 = 0.47, SE = 197)}$$

For daytime total emission at “nearest to trees” locations (including root respiration):

$$\mathbf{CO_2\ emission\ (mg\ m^{-2}\ hr^{-1}) = 989.46\ x\ drainage\ depth + 391.79\ (R^2 = 0.34, SE = 317)}$$

With drainage depth in meters.

Guidelines for measuring the water table depth are given in Annex A. Guidelines on measuring soil subsidence are given in Annex B.

The CH_4 emissions from tropical wetlands show a clear relationship with water level (Jungkunst and Fiedler, 2007; Huttunen et al., 2003; in Gobal Change Couwenberg). Emissions in fields were the water level is below 20 cm below surface level are negligible. An exponential relationship exists for water levels above -20 cm (Couwenberg et al., 2009).

For N_2O a constant fraction of N fertilizer is lost as N_2O to the atmosphere. IPCC (2006) suggests that 1% of N fertilizer is lost as N_2O from agricultural systems. In the literature also values of 4% are suggested. The N_2O is then converted to CO_2-equivalents based on their global warming potential (GWP), which is 296.

Knowledge on CH_4 and N_2O from tropical peat ecosystems is sparse, and underlying processes are very uncertain. Measurements of CH_4 and N_2O fluxes are until now performed by the so called chamber measurements. Soil subsidence cannot (yet) been coupled to emissions and also water level as a proxy is to uncertain to can be widely used.

Chapter 3. Estimation of Carbon Stocks

3.1. *Estimation of carbon stocks in above ground biomass*

Different steps need to be taken to estimate the total above ground biomass (AGB) in a forest, a plantation or other area. Estimates are usually based on different variables: diameter of the trees at breast height (DBH) and/or tree height and crown area of individual trees of varying diameters. Tree species can differ within a project area, and on peat often a stratified pattern can be found (*Fig. 9*). The sample size should be large enough to capture the spatial variability in DBH and crown areas of trees within the project boundary.

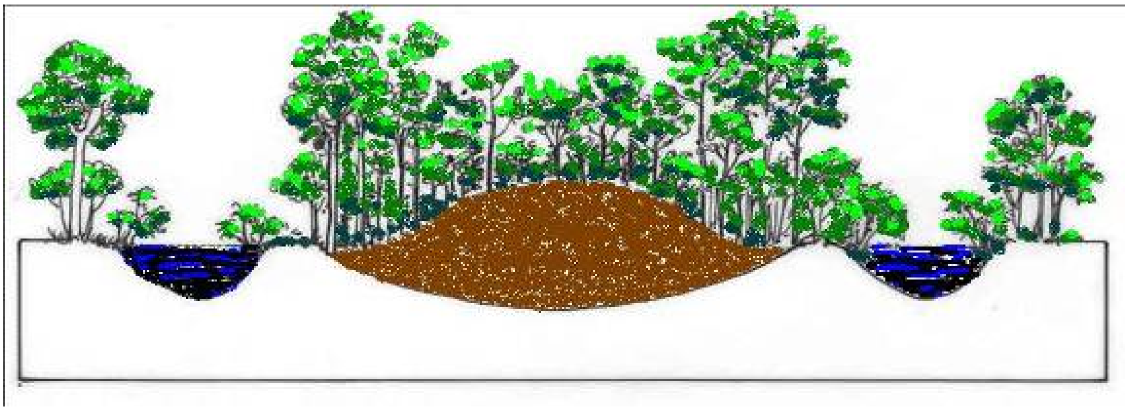


Fig. 9. Schematic cross section through a peat dome.

Allometric equations for estimating above ground biomass

Allometric models that are available are based on destructive sampling in non-peat swamp forests. In these models a relationship is constructed between, for example, a combination of the height and/or crown area and the biomass of each tree observed. Options include:

Models developed by Verwer and van der Meer (2010); Basuki *et al* (2009), i.e.:

$$\mathbf{Ln}\ (AGB) = -0.744 + 2.188 \times \ln(DBH) + 0.832 \times \ln\ (WD)$$

In which WD (g cm^{-3}) is wood density and DBH (cm) is the stem diameter at breast height and above ground biomass (AGB) is given in g cm^{-2}.

Allometric relationships between tree diameter and AGB have also been developed by Hashimoto *et al* (2004), see *table 3* for the coefficients a and b:

$$\mathbf{Ln}\ (AGB) = a \times \ln\ (DBH) + b$$

DBH is the stem diameter at breast height, and a and b are coefficients which vary between species.

Table 3. Statistical details of allometric equations for estimating above ground biomass of some tree species (Hashimoto *et al*., 2004).

Species	a	b	N samples	Min	Max	Adjusted r^2	Adjusted means of ln (Wt)
Ficus sp.	2.60	-2.59	26	3.5	9.1	0.95	1.55
Geunsia pentandra	2.62	-2.89	20	3.4	16.2	0.91	1.31
Piper aduncum	2.39	-2.42	37	3.2	8.3	0.92	1.38
Other species	2.40	-2.49	108	3.2	20.3	0.81	1.36
All species combined	2.44	-2.51	191	3.2	20.3	0.85	

Danielsen et al., (2009) estimated above ground biomass to range from 254-390 t C ha^{-1} in natural peat swamp forest to 148-254 t C ha^{-1} in logged forest.

Chave et al (2005) tested different models and concluded that the overall best model for ABG, was for wet forest if the tree height is known:

$$\mathbf{ABG = 0.0776 \times (\rho\, D^2\, H)^{0.940}}$$

And if the tree height is not known:

$$\mathbf{ABG = \rho \times \exp(-1.239 + 1.980 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln D))^3)}$$

With ABG in (kg), D = diameter (cm), ρ = oven dry wood volume over green volume (g/cm^3) and H = total tree height in (m).

Guidelines for estimating above ground biomass are given in Annex E. Guidelines for estimating the tree height are given in Annex G. Guidelines for destructive sampling for under-storey and the litter layer are given in Annex F. Carbon stock estimations for the non-tree vegetation components are usually based on destructive harvesting, drying and weighting. These methods are also described in the Sourcebook for LULUCF projects (Pearson et al., 2005).

Validation of existing allometric models

It is necessary to validate the applicability of existing allometric equations (VCS, IFM methodology, 2011). Source data from which equations were derived should be reviewed and confirmed to be representative of the forest type/species and conditions in the research area and should cover the range of potential independent variable values. Allometric equations as mentioned above can be validated either by:

1. Limited Measurements (VCS, IFM methodology, 2011)

- selecting at least 30 trees (if validating forest type-specific equation, selection should be representative of the species composition in the project area, i.e. with species being represented roughly in proportion to their relative basal area). The minimum diameter of measured trees should be 20cm and the maximum diameter should reflect the largest trees present or potentially present in the project area;
- measuring DBH, and height to a 10 cm diameter top or to the first branch;
- calculating stem volume from measurements and multiplying by species-specific density to obtain biomass of the bole;
- applying a biomass expansion factor to estimate total above ground biomass from stem biomass.
- plotting the estimated biomass of all the measured trees along with the curve of biomass against diameter as predicted by the allometric equation.

If the estimated volume of the measured trees are distributed both above and below the curve (as predicted by the allometric equation) the equation may be used. The equation may also be used if the measured individuals have a biomass consistently higher than predicted by the equation. If >75% of the measured trees have a biomass lower than the predicted curve, destructive sampling must be undertaken or another equation must be selected.

2. Destructive Sampling (VCS, IFM methodology, 2011)

- selecting at least five trees, again being representative of the species composition in the project area, but at the upper end of the range of independent variable values existing in the project area;
- measuring DBH and height and calculate volume;
- felling and weighing the above ground biomass to determine the total (wet) mass of the stem, branch, twig, leaves, etc. This may be done by extracting and immediately weigh sub samples of each of the wet stem and branch components, followed by oven drying at 70 degrees C to determine dry biomass;
- determining the total dry weight of each tree from the wet weights and the averaged ratios of wet and dry weights of the stem and branch components; and

- plotting the estimated biomass of all the measured trees along with the curve of biomass against diameter as predicted by the allometric equation.

If the estimated volume of the measured trees are distributed both above and below the curve (as predicted by the allometric equation) the equation may be used. The equation may also be used if the measured individuals have a biomass consistently higher than predicted by the equation. If >75% of the measured trees have a biomass lower than the predicted curve another equation must be selected.

Details of destructive sampling measurements are given in Brown (1997).

3.2. *Estimation of carbon stocks in oil palm plantations on peat*

For the estimation of carbon stocks in oil palm plantations, historical data or scientific data can be used. The above ground biomass of oil palms and the related carbon stock is depended on the age of the tree. Oil palms usually have a life span of 20 – 30 years. After this period trees will be replaced by new plantings. Currently no allometric models are available for the assessment of carbon stocks of oil palms on tropical peat soil. Destructive sampling could be used to estimate the carbon stock in the trees. Melling et al (2008) reported values of 19 t C ha^{-1} stored in the stems, canopy and roots of a five years old oil palm agro-ecosystem and an additional 7 t C ha^{-1} in the palm's by-products. After the palm's life time of 20-30 years, the carbon that is stored in the palm biomass will be lost by decomposition and/or burning or will be used for biomass energy. Sometimes old palms that are replaced by new plantings are pulverized and used as fertilizer or soil protection.

Once the biomass is estimated, C stocks of each pool within an oil palm plantation can be calculated by multiplying the biomass by the carbon content of each component of biomass (table 4).

Table 4. Average carbon content of the different components of living and dead biomass in oil palm plantations.

Component	C content
Living biomass	
• Palm biomass	0.47
• Understorey	0.47
• Root	0.47
Dead organic matter	
• Litter	0.4

• Dead wood	0.5

3.3. *Estimation of carbon stocks in below ground biomass*

The below ground biomass pool is smaller than the above ground biomass pool (see table 5 for an idea of the order of magnitude). Roots as carbon stock or organic inputs in tropical agriculture have often been neglected due to difficulties in measurements and have often been included in the peat carbon pool.

Table 5. Estimated biomass and carbon content of relatively undisturbed peat swamp forest based on plots measured by Anderson between 1954-1960 in Sarawak, Malaysia (Anderson 1961). Note the order of magnitude difference in carbon stock between the different biomass compartments.

	Biomass (t dry matter/ha)		Carbon content (t C/ha)	
Biomass compartment	Range	average±SD	Range	Average±SD
Aboveground biomass	264.0-397.4	338.8±52.5	132.0-198.7	169.4±26.4
Belowground biomass	57.2-89.8	74.0±15.8	28.6-44.9	37.0±7.9
Coarse woody debris	32.2-113.8	62.9±9.8	16.1-56.9	31.4±4.9
Litter	4.5-11.9	7.9±1.2	2.3-5.9	3.9±0.6

Currently, allometric models are available for estimating the below ground root biomass in peat swamp forest (Niiyama *et al*., 2005; Sierra *et al*., 2007; Kenzo *et al*., 2009; Niiyama *et al*., 2010). It has to be noted that estimates should be considered as approximations.

An example is the equation of Niiyama *et al* (2010):

$BGB = 0.02186 \times DBH^{2.487}$

In which BGB is below ground biomass and DBH = stem diameter at breast height, 1.3m).

Another method is to estimate BGB from the root:shoot ratio as described in the literature. Sulistiyanto (2007) estimated that the BGB varies from 26.5 t ha^{-1} for mixed swamp forest to 14.4 t ha^{-1} for low pole forest, suggesting a trend of decreasing root biomass with increasing peat thickness and with a root:shoot ratio of 1:12 for mixed swamp forest and 1:18 for low pole forest.

IPCC uses root:shoot ratios as shown in table 6. Brady *et al* (1997) indicated a trend in the opposite direction. In his study, marginal mixed swamp forest had the lowest root biomass (2.8 t ha^{-1}) and low pole forest vegetation on the thickest peat had the highest root biomass (9 t ha^{-1}). Usually a C content of 50 – 60 % of the biomass dry weight for the below-ground living biomass carbon stock should be used for tropical forest in Central Kalimantan.

Table 6. Root:shoot ratio's used by IPCC 2006 for the calculation of BGB.

Domain	Ecological Zone	Above-ground biomass	Root-to-shoot ratio	Range
Tropical	Tropical rain*forest*	<125 $t.ha^{-1}$	0.20	0.09-0.25
		>125 $t.ha^{-1}$	0.24	0.22-0.33
	Tropical dry *forest*	<20 $t.ha^{-1}$	0.56	0.28-0.68
		>20 $t.ha^{-1}$	0.28	0.27-0.28
Subtropical	Subtropical humid *forest*	<125 $t.ha^{-1}$	0.20	0.09-0.25
		>125 $t.ha^{-1}$	0.24	0.22-0.33
	Subtropical dry *forest*	<20 $t.ha^{-1}$	0.56	0.28-0.68
		>20 $t.ha^{-1}$	0.28	0.27-0.28

When there is no sufficient data available, below ground biomass is included in the peat component in most accounts of tropical peatland C stocks. For oil palm root biomass a root:shoot ratio of 1:4 has been used.

3.4. *Estimation of carbon stocks in necromass*

The range of wood debris (WD) biomass or necromass in peat swamp forest can be estimated roughly using the ratio between wood debris and AGB found in non-peat tropical forests and apply this ratio to the AGB calculated for peat swamp forests. Verwer and van der Meer (2010) published a table on biomass carbon stock of coarse wood debris based on different studies in tropical moist and wet forests. On average these studies revealed that the WD biomass pool may comprise 9.5 – 33.6 % of the live AGB pool. Verwer and van der Meer (2010) then calculated the average minimal and maximal WD mass and carbon content of peat swamp forest communities, based on historical inventories and the AGB:WD ratio, however, their estimates are based on studies carried out in non-peat swamp forest.

For lying dead wood the VCS approved methodology for assessing carbon gains through avoided planned deforestation of undrained peat swamp forests uses the line intersect method (Harmon and Sexton, 1996) using the equation by Warren and Olsen (1964) as modified by Van Wagener (1968).

3.5. *Estimation of carbon stocks in peat*

The carbon storage capacity of peat (C_{peat}) depends on it's bulk density, carbon content and depth. Thus:

$$\mathbf{C_{peat}\ (t\ C\text{-}org) = A\ (ha) \times D\ (m) \times BD\ (t\ m\text{-}3) \times C\ (\%)}$$

Where A is the total area of peatland in hectares, D is the average peat depth in meters, BD is bulk density in tones per m^3 and C is the carbon content in tonnes. Changes in carbon stock are determined by the differences in these parameters over time. Tropical peat is very heterogeneous and therefore the procedure of estimating BD is not straightforward. Surface BD can range from 0.05 t/m^3 to 0.25 t/m^3 for a very well compacted peat. Some of the peatlands are just floating in a peat basin. A procedure that is commonly used to estimate BD in peat soils is given in Annex C. Guidelines for estimating the peat depth and carbon content of the peat are given in Annex D.

Losses through peat fires should be calculated in the same way: determine the area of the fire scar, determine the peat depth decrease because of the fire and calculate with the bulk density and carbon content of the peat the amount of carbon that has been lost. Most of the carbon is lost as CO_2 to the atmosphere..

Annex A Sampling of water level in water bodies and in the field

To determine groundwater elevation above mean sea level, use the following equation:

EW = E - D

where:

EW = Elevation of water above mean sea level (m) or local datum

E = Elevation above sea level or local datum at point of measurement (m)

D = Depth to water (m)

The water level in canals, drains, rivers, stream and other open water bodies can be determined with a simple ruler (Fig. a).

Fig. a.

Fig. b

Fig. c.

Fig. d.

For measuring the groundwater, a piezometer can be installed. Different techniques could be used to measure the groundwater level in the field within the piezometer or well, including:

- ‘Plopper’, where a concave metal casting attached to the graduated tape makes a plopping noise when it hits the groundwater surface (Fig. c).
- Electrical sounder, where the insulated wires for a pair of electrodes are incorporated into a graduated flat tape. A circuit is completed when the electrodes come into contact with the groundwater surface, which activates a light and/or buzzer (Fig. b)
- Automatic water level recorders, similar to those used in surface water bodies such as pressure transducers, or capacitance probes. An example of a very accurate device that accurately and continuously records the groundwater levels in the field and the temperature of the water is the e+ WATER L. The measurements automatically compensate for air pressure differences. The sensor can be programmed by the user to set, for example,. the

measurement intervals. The instrument can be used to determine water level variations up to 2 m (Fig. d).

The Groundwater rule Source Water Monitoring Guidance Manual of United States Environmental Protection Agency (U.S. EPA) contains information about groundwater monitoring, how to determine the appropriate faecal indicator for monitoring and how the different analytical analyses and methods work.

Annex B Soil Subsidence

Soil subsidence can be measured by installing a (steel) pole into the peat (Fig. e). The pole has to be anchored in the mineral soil (minimum up to 50 cm) beneath the peat layer to obtain a fixed base. Every year the subsidence of the peat has to be marked on the subsidence pole or has to be recorded elsewhere.

Fig. e. Left: Example of subsidence pole installed in late 2007, 10 years after initial drainage, in PT TH Indo Plantations, Riau, Indonesia and Right: A subsidence pole inserted in deep peat at Woodman Plantations. At the time of this photograph (2011), the pole was installed 8 years prior to the photograph and about 50 cm of subsidence had occurred (Image: Marcel Silvius).

Annex C Bulk density

(the weight of undisturbed soil for a given volume of peat, expressed in g/cm3)

The bulk density measurement should be performed at the soil surface (10-60 cm) above the water table depth. To avoid compaction during sample collection, it is best to dig a hole in the soil, and collect a series of bulk density samples at a 10 cm peat layer interval in depth. So, the samples are not collected vertical, but from the horizontal side of a dug peat profile. To get a more representative bulk density measurement of the area, additional samples may be taken.

Materials needed to measure bulk density:

- 3-inch or 7.6 cm diameter ring
- hand sledge
- wood block
- garden trowel
- flat-bladed knife
- sealable bags and marker pen
- scale (0.1 g precision)
- 1/8 cup (or 30 ml) measuring scoop
- paper (or ceramic) cups
- 18-inch or 46 cm metal rod
- access to a microwave oven

Drive Ring into Soil:

- Using the hand sledge and block of wood, drive the 3-inch or 7.6 cm diameter ring, sharp edge down, to a depth of 3 inches or 7.6 cm (Fig. f).
- The exact depth of the ring must be determined for accurate measurement of soil volume. To do this, the height of the ring above the soil should be measured. Take four measurements (evenly spaced) of the height from the soil surface to the top of the ring and calculate the average.
- Record the average.

Fig. f. Driving ring into soil.

NOTE: Use the metal rod to probe the soil for depth to a compacted zone. If one is found, dig down to the top of this zone and make a level surface.

Remove 3-inch or 7.6 cm Ring:

Dig around the ring and with the trowel underneath it, carefully lift it out to prevent any loss of soil.

Remove Excess Soil:

- Remove excess soil from the sample with a flat bladed knife. The bottom of the sample should be flat and even with the edges of the ring (see Fig. g).
- Place Sample in Bag and Label; Touch the sample as little as possible.
- Using the flat bladed knife, push out the sample into a plastic sealable bag. Make sure the entire sample is placed in the plastic bag.
- Seal and label the bag.

Fig. g. Remove soil with a sharp knife.

Weigh and Record Sample (either in a lab or in the field):

- Weigh the soil sample in its bag. If the sample is too heavy for the scale, transfer about half of the sample to another plastic bag. The weights of the two sample bags will need to be added together.
- Weigh an empty plastic bag to account for the weight of the bag, subtract this from the sample+bag weight.
- Extract a sub sample to determine water content and dry soil weight.
- Mix the sample thoroughly in the bag by kneading it with your fingers.
- Take a 1/8-cup level scoop sub-sample of loose soil (not packed down) from the plastic bag and place it in a paper cup (a glass or ceramic cup may be used).
- Weigh the soil subsample in its paper or ceramic cup and record the weight
- Weigh an empty cup to account for its weight, subtract its weight from the weight of the cup + soil subsample.

Dry Sub sample:

Place samples in an oven set to 100^{o} C for about 72 hours. After drying, record the weight of the cup + dry soil.

or

Place the paper cup containing the sub-sample in a microwave and dry for two or more four minute cycles at full power. Open the microwave door for one minute between cycles to allow venting. Weigh the dry sub sample in its paper cup and record the weight.

NOTE: To determine if the soil is dry, weigh the sample and record its weight after each 4-minute cycle. When its weight does not change after a drying cycle, then it is dry.

Calculations:

Soil water content (g/g) = (weight of moist soil - weight of oven dry soil) / weight of oven dry soil.

Soil bulk density (g/cm^3) = oven dry weight of soil / volume of soil.

Volumetric water content (g/cm^3) = soil water content (g/g) x bulk density (g/cm^3).

Annex D Carbon content and peat depth

To determine the carbon content of the peat, samples have to be taken. Samples can be obtained by using a peat sampler auger (Fig. e) which can also be used to determine the peat depth.

Fig. e. Peat sampler set. Source; www.eijkelkamp.com

The carbon content of the peat depends on the peat type. Generally in tropical peat three peat types can be distinguished: (A) Sapric, low fiber content and high BD; (B) Hemic, and (C) Fibric, high fiber content and low BD.

Samples usually are taken with 50 cm increments, to get an average C content for the whole peat profile, over the total depth.

Samples have to be transported in, for example, half-round PVC pipes and have to be carefully wrapped to avoid damage and loss of moisture and brought into the lab (Anshari, 2010; Anshari et al. 2010). To measure the total amount of carbon (TOC) the samples have to be homogenized and dried in the oven for 24 hours at 40^o C and then completely oxidized at 1000-1200^{o}C and converted into CO_2. Then the concentrations of CO_2 can be measured following Schumacher (2002).

To measure the carbon that is available, carbon content can also be accurately measured by burning the dry matter and determining the weight of ash left after burning.

Average peat depth in tropical Southeast Asia can vary between 0.5 and 15 meters. Average peat depth can be determined by drilling with the Dutch auger until the mineral subsoil is reached. The number of samples should be such that it gives a representative overview for the area of interest.

Carbon density (t/ha) = (BD (g/cm^3) x peat depth (cm) x %C x 100

Annex E Living tree biomass

(Int. Centre for Research in Agroforestry)

Equipment:

- Line for center of transect, 40 m long for standard plot and 100 m for large-tree plot
- Sticks to measure width, 2.5 m long for standard plot
- Wooden sticks of 1.3 m length
- Measurement tape (linear or special ones for tree diameter, which include the factor p)
- Knife
- Tree height measurement device

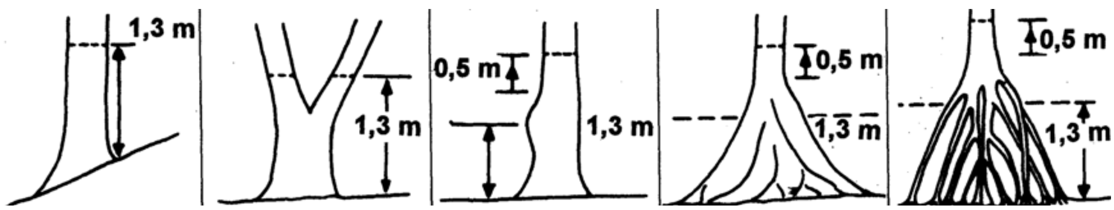


Fig. f. Measurement of tree diameter at 1.3 m ('breast height'), or the equivalent on odd-shaped trees

Procedure:

Set out two 200 m^2 quadrats (5m x 40 m), by running a 40 m line through the area and then sampling the trees 5 cm < diameter < 30 cm that are within 2.5 meter of each side of the tape, by checking their distance to the central line. For each tree the diameter is measured at 1.3 m above the soil surface, except where trunk irregularities at that height occur (plank woods, tapping or other wounds; Fig. f) and necessitate measurement at a greater height. Further tree information, e.g. from the literature, or from destructive sampling can help in getting improved estimates of wood density.

If trees > 30 cm diameter are present in the sampling plot, whether or not they are included in the transect, an additional larger sample of 20 * 100 m^2 is needed, including all trees with a diameter > 30 cm. Knowing the tree height is optional, but can be helpful in establishing parameters for a allometric relationship.

Calculation: http://www.edb.ups-tlse.fr/equipe1/chave/chave-jte08.pdfs:

Calculate the tree biomass in kg/tree for each tree using an appropriate allometric equation.

Cave et al (2005) advices to use the following allometric equations for ABG for wet forest if the tree height is known:

$$\mathbf{ABG = 0.0776 \times (\rho\, D^2\, H)^{0.940}}$$

And if the tree height is not known:

$$\mathbf{ABG = \rho \times \exp(-1.239 + 1.980\ ln\ (D) + 0.207\ (ln\ (D))^2 - 0.0281\ (ln\ (D))^3)}$$

With ABG in (kg), D = diameter ate breast height (cm), ρ = oven dry wood volume over green volume (g/cm^3) and H = total tree height in (m).

Palms need a separately established equation, however, for peat soils no allometric equation is established yet.

Sum the tree biomass for each quadrat and divide by the sampling area in m^2.

Annex F Destructive sampling for non-tree biomass and litter layer

(Int. Centre for Research in Agroforestry; VCS, VM0015))

Equipment:

- Quadrat of 1 x 1 m and 0.5 x 0.5 m
- Knives and/or scissors
- Scales: one allowing weights up to 10 kg (with a precision of 10 g) for fresh samples and one with a 0.1 g precision for subsamples
- Marker pens, plastic & paper bags
- Sieves with a 2 mm mesh size
- Trays

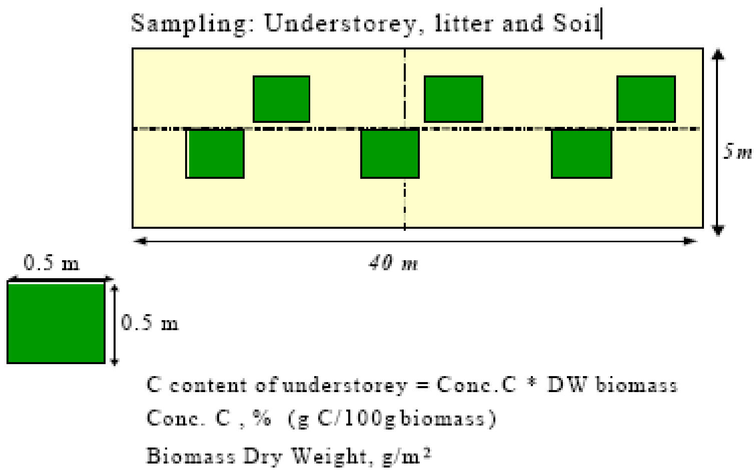


*Fig. h. Position of non-tree biomass sampling within a 40 * 5 m vegetation transect*

a. Place the sampling frame at the sample site within the 40 * 5 m2 transect, as indicated in Fig. h, placing it once (randomly) in each quarter of the length of the central rope.

b. Collect all the litter inside the frame. Pieces of twigs or wood that cross the border of the frame should be cut using a knife or pruning scissors. Place all the litter on a tarpaulin beside the frame or inside a weighting bag. Weigh the sample on-site, then oven-dry to a constant weight.

c. Where sample bulk is excessive, the fresh weight of the total sample should be recorded in the field and a sub-sample of manageable size (approximately 80-100 g) taken for moisture content determination, from which the total dry mass can be calculated.

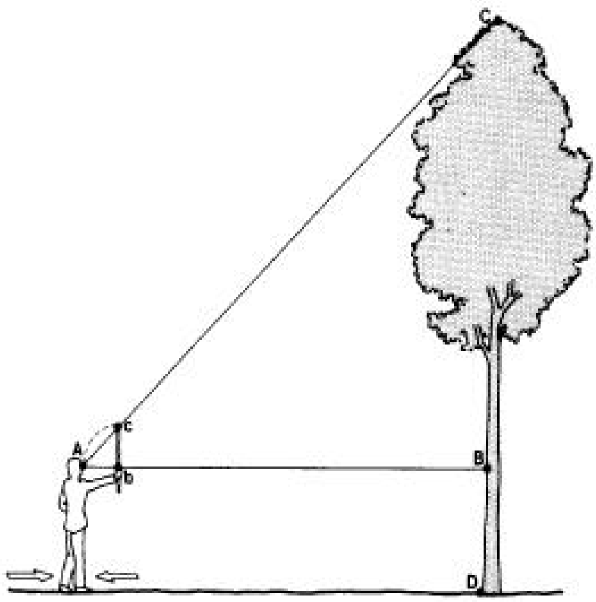
d. Calculate the dry mass of the sample.

e. The carbon stock per hectare in the litter carbon pool is calculated by multiplying the dry mass by an expansion factor calculated from the sample-frame or plot size and then by multiplying by the carbon fraction and CO_2/C ratio.

Annex G Tree height measurement

(Weyerhauser and Tennigkeit, 2000)

The best method to measure tree height is based on the geometric relationship between triangles as long as there is enough space. The operator holds a stick in his stretched arm the same length as the distance between his hand and his eye. Then he moves forwards and backwards until the tip of the tree and the top of the stick are in one line. The distance Ab and Ac is the same as the AB and AC. Accordingly, the tree height is the sum of the distance between AB and the measured DB.



References

Agus F, Runtunuwu E, June T, Susanti E, Komara H, Syahbuddin H, Las I, Noordwijk M (2009). Carbon dioxide emissions in land use transitions to plantation. Jurnal Libtang Pertanian 28 (4), 2009.

Alm, J., Talanov A., Saarnio, S., Silvola, J., Ikkonen, E., Aaltonen, H., Nykanen, H. & Martikainen, P. J. (1997): Reconstruction of the carbon balance for microsites in a boreal oligotrophic pine fen, Finland. Oecologia 110: 423-431.

Anderson JAR (1961). The ecology and Forest types of the Peat Swamp Forests of Sarawak and Brunei in Relation to their Silviculture. M.C., B.Sc thesis.

Anshari, G.2010. Carbon content of the freshwater peatland forests of Danau Sentarum. Borneo Research Bulletin 41: 62-73

Anshari, G., Afifudin, M., Nuriman, M., Gusmayanti, E., Arianie, L., Susana, R., Nusantara, R.W., Sugardjito, J., and Rafiastanto, A., 2010. Drainage and land use impacts on changes in selected peat properties and peat degradation in West Kalimantan Province, Indonesia. Biogeosciences 7 (11): 3403-3419

Asner, GP, Knapp DE, Cooper AN, Bustamante MCC, and Olander LO (2005). Ecosystem structure throughout the Brazilian Amazon from Landsat Observations and Automated Spectral Unmixing. Earth Interactions 9(7):1-31.

Aubinet M, Grelle A, Ibrom A, Rannik U, Moncrieff J, Foken T, Kowalski AS, Martin PH, Berbigier P, Bernhofer C, Clement R, Elbers J, Granier A, Grunwald T, Morgenstern K, Pilegaard K, Rebmann C, Snijders W, Valentini R and Vesala T, 2000. Estimates for the annual net carbon and water exchange of forests. The EUROFLUX methodology. Adv. in Ecol. Res.: 30, 113-175.

Baldocchi D (2003). Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Glob. change Biol.: 9, 479-492.

Baldocchi DD, Hicks BB, and Meyers TP (1988). Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology: 69, 1331-1340.

Bastviken D, Cole J, Pace M et al (2004) Methane emissions from lakes: Dependence of lake characteristics two regional assessments and a global estimate. Glob Biogeochem Cycles 18 GB4009 doi: 10.1029/2004GB002238.

Basuki TM, van Laake PE, Skidsmore AK, Hussin YA (2009). Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. Forest Ecology and Management, 257, 1684-1694.

Boelter, D.H (196). Physical properties of peats as related to degree of decomposition. Soil Science Society America 33, 606-609.

Bouwman, A.F., 1990. In: Bouwman AF (Ed.) Soils and the Greenhouse effect (pp. 61-127) Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. John Wiley and Sons. Chichester, UK.

Brady MA (1997). Organic matter dynamics of coastal peat deposits in Sumatra, Indonesia. PhD thesis, Department of forestry, University of British Columbia.

Bridgham, S. D. & Richardson, C. J. (1992): Mechanisms Controlling Soil Respiration (Co2 and Ch4) in Southern Peatlands. Soil Biology & Biochemistry 24: 1089-1099.

Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer.

FAO Forestry Paper 134, Italy. http://www.fao.org/docrep/W4095E/W4095E00.htm

Bruenig EF (1996). Conservation and management of tropical rainforest. CAB International, Wallingford, U.K.

Businger JA (1986). Evaluation of the accuracy with which dry deposition can be measured with current micrometeorological techniques. Journal of Climate and Applied Meteorology, 25, pp1100-1124.

Cairns MA, Brown S, Helmer EH, Baumgardner GA (1997). Root biomass allocation in the world's upland forests. Oecologica, 111, 1-11.

Chambers, F.M., D.W. Beilman & Z. Yu. 2011. Methods for determining peat humification and for quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics. Mires and Peat 7, 1-10.

Chambers JQ, Higuchi N, Teixeira LM, dos Santos J, Laurance SG, Trumbore SE (2004). Response of tree biomass and wood litter to disturbance in a Central Amazon forest. Oecologica, 141, 596-611

Chimner RA, Ewel KC (2005). A tropical freshwater wetlands: Production, decomposition, and peat formation. Wetlands Ecology and Management, 13, 671-684.

Chiti T, Certini G, Grieco E, Valentini R (2010). The role of soil in storing carbon in tropical rainforests: the case of Ankasa Park, Ghana. Plan and Soil, 331, 453-461.

Christensen, T.R., Jonasson, S., Callaghan, T.V., Havström, M., 1995. Spatial variation in high-latitude methane flux along a transect across Siberian and Eurasian tundra environments. J. of Geoph. Res.: 100, 21035-21045.

Christensen TR, Ekberg A, Strom L, Mastepanov M (2003). Factors controlling large scale variations in methane emissions from wetlands. Geophysical Research Letters, Vol 30, 7, doi: 10 . 1029/2002GL06848, 2003.

Clarck DE, Clarck DA, Brown S, Oberbauer SF, Veldkamp E (2002). Stocks and flows of coarse woody debris across a tropical rain forest nutrient and topography gradient. Forest Ecology and Management, 164, 237-248.

.Couwenberg J (2007). Biomass energy crops on peatlands: on emissions and perversions. IMCG Newsletter 2007/3:12-14.

Couwenberg J (2009). Emission factors for managed peat soils – an analysis of IPCC default values. Wetlands International, Ede. 14pp.

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

Danielsen, F., Beukema, H., Burgess, N. D., Parish, F., Bruhl, C. A., Donald, P. F., … Fitzherbert, E.B. (2009). Biofuel Plantations on Forested Lands: Double Jeopardy for Biodiversity and Climate. Conservation Biology, 23(2), 348-358.

Delaney M, Brown S, Lugo AE, Torreslezama A, Quintero NB (1997). The distribution of organic carbon in major components of forests located in five zones of Venezuela. Journal of Tropical Ecology, 13, 697-708

Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Da Silva Dias, P. L., Wofsy S. C., and Zhang, X.: Couplings between changes in the climate system and biogeochemistry in: Climate Change 2007: The Physical Science Basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K. B., Tignor M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Denmead O. T., Freney J. R. & Simpson J. R. (1979) Nitrous-Oxide Emission During Denitrification in a Flooded Field. Soil Science Society of America Journal 43: 716-718.

Denmead O.T., 2008. Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere, Plant Soil: 309, 5-24.

Dise, N. B. (1993): Methane Emission from Minnesota Peatlands - Spatial and Seasonal Variability. Global Biogeochemical Cycles 7: 123-142.

Dobbie KE, Smith KA (2003). Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. Global Change Biology (: 204-218.

Flechard CR, Ambus P, Skiba U, Rees RM, Hensen A, van Amstel A, van den Pol-van Dasselaar A, et al. (2007a). Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe, Agric. Ecosyst. And Environm.: 121, 135-152.

Flechard CR, Neftel A, Jochner M, Ammann C, Leifeld J, Fuhgrer J (2007b). Temporal changes in soil pore space CO2 concentration and storage under permanent grassland. Agric. For Meteorology, 142, pp 66-84.

Furukawa, Y., Inubushi, K., Ali, M., Itang, A.M., Tsuruta, H. (2005): Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands, Nutrient Cycling in Agro ecosystems 71, 81-91.

Gale N (2000). The aftermath of tree death: Coarse woody debris and the topography in four tropical rain forests. Canadian Journal of Forest Research, 30, 1489-1493.

Gibbs HK, Johnston M, Foley JA, Holloway T, Monfreda C, Ramankutty N, Zaks D (2008): Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. Environ. Res. Lett. 3 034001 doi:10.1088/1748-9326/3/3/034001.

Glenn S., Heyes A. & Moore T. (1993) Carbon-Dioxide and Methane Fluxes from Drained Peat Soils, Southern Quebec. Global Biogeochemical Cycles 7: 247-257.

Gorham E, Janssens JA, Glaser PH (2003). Rates of peat accumulation during the postglacial period in 32 sites from Alaska to Newfoundland, with special emphasis on northern Minnesota. Canadian Journal of Botany, 81, 429-438.

Grelle A, Lindrothy A (1996). Eddy-correlation systems for long-term monitoring of fluxes of heat, water vapour and CO2, Glob. Change Biol.: 2, 297-307.

Groffman, P.M., Brumme, R., Butterbach-Bahl, K., Dobbie, K.E., Mosier, A.K., Ojima, D., Papen, H., Parton, W.J., Smith, K.A. and Wagner-Riddle, C. (2000) Evaluating annual nitrous oxide emissions at the ecosystem scale, Global Biogeochemical Cycles, 14, 1061-1070.

Hadi A, Inubushi K, Furukawa Y, Purnomo E, Rasmadi M, Tsurati H (2005). Greenhouse gas emissions from tropical peatlands of Kalimantan, Indonesia, Nutrient Cycling in Agro ecosystems, 71, 73-80.

Hansen S, Maehlum JE, Bakken LR (1993). N2O and CH4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biol. Biochem.. 25, pp. 1495-1510.

Hargreaves KJ, Fowler D (1998). Quantifying the effects of water table and soil temperature on the emission of methane from peat wetland at the field scale. Atm. Env. Vol 32, 19, pp 3275-3282.

Hargreaves KJ, Fowler D, Pitcairn CER, Aurela M., 2001. Annual methane emission from Finnish mires estimated from eddy covariance campaign measurements. Theoretical and Applied Climatology: 70, 203-213.

Harmon and Sexton, 1996

Hashimoto et al 2004

Hendriks DMD, Dolman AJ Van der Molen JK & Van HuisstedenJ (2008). A compact and stable eddy covariance set-up for methane measurements using off-axis integrated cavity output spectroscopy. Atmos. Chem. Phys., 8: 431-443.

Hendriks DMD, van Huissteden J, Dolman AJ, van der Molen MK (2007). The full greenhouse gas balance of an abandoned peat meadow, Biogeosciences 4, 411-424.

Hirano T, Segah H, Harada T, Limin S, June T, Hirata R, Osaki M (2007). Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. Global Change Biology 13: 412-425.

Hirano T, Segah H, Harada T, Limin S, June T, Hirata R, Osaki M (2007). Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. Global Change Biology 13: 412-425.

Hooijer A, Page S, Canadell JG, Silvius M, Kwadijk J, Wosten H and Jauhiainen J (2010). Current and future CO2 emissions from drained peat lands in Southeast Asia, BiogeoSciences, 7, 1505-1514, doi:10.5194/bg-7-1505-2010.

Hooijer A, Page S, Jauhainen J, Lee WA, Lu X (2011). Recent findings on subsidence and carbon loss in tropical peatlands: reducing uncertainties. Workshop on ‘ Tropical Ecosystems of Indonesia: Science Needs to Address Climate Change Adaptation and Mitigation’ . Bali, 11-14 April 2011.

Hooijer A., M. Silvius, H. Wosten & S. Page. 2006. Peat CO2: Assessment CO2 emission from drained peatlands in SE Asia. Delft Hydraulics report Q3943. Wetlands International – Alterra.

Hutchinson GL and Mosier AR (1981). Improved soil cover method for field measurements of nitrous-oxide fluxes. Soil Sci Soc Am J, 45 (2), pp 311-316.

Hutchinson GL, Livingston GP (2002). Soil-atmosphere gas exchange. In : J.H. Dane and G.C. Topp, Editors, Methods of soil analysis. Part 4. Physical methods, SSSA Book Series, no. 5, Soil science Society of America, Madison, WI, 1159-1182.

Huttunen JT, Nykänen H, Turunen J, Martikainen PJ (2003). Methane emissions from natural peatlands in the northern boreal zone in Finland, Fennoscandia. Atmospheric Environment, 37: 147-151.

IPCC 2007. Climate Change 2007: The Physical Science Basis. Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC 2006. IPCC guidelines for national greenhouse gas inventories. Geneva, Switzerland.

Jackson RB, Canadell J, Ehleringer JR, Mooney HA Sala OE, Schulze ED (1996). A global analysis of root distributions for terrestrial biomes. Oecologia, 108, 389-411.

Jackson CR, Liew KC, Yule CM (2008). Structural and functional changes with depth in microbial communities in tropical peat swamp forest sediments. Microbial Ecology, 57, 402-412.

Jauhiainen J, Takahashi H, Heikkinen JEP, Martikkainen PJ, Vasanders H (2005). Carbon fluxes from a tropical peat swamp forest Floor. Global Change Biology 11, 1788-1797.

Jauhiainen, J., Hooijer, A., & Page, S. E. (2011). Carbon Dioxide Fluxes in an Acacia Plantation on Tropical Peatland. Biogeosciences Discussions, 8, 8269-8302.

Joosten H, Couwenberg J (2009). Are emission reductions from peatlands MRV-able? Produced for the UN-FCCC meetings in Bonn, June 2009. www.wetlands.org.

Joosten H (2008). The challenge of being domed: hydrological self-regulation, conservation, and restoration of south-east Asian peatswamp forests. Institute of Botany and Landscape Ecology, Ernst Moritz Arndt University, Greifswald, Germany.

Jungkunst HF, Fiedler S (2007). Latitudinal differentiated water table control of carbon dioxide, methane and nitrous oxide fluxes from hydromorphic soils: feedbacks to climate change. Global Change Biology, 13:1-16.

Kenzo T, Ichei T, Hattori D, Itioka T, Handa C, Ohkubo T, Kendawang JJ, Nakamura M, Sakaguchi M, Takahashi T, Okamoto M, Tanaka-Oda A, Sakurai K,, Ninomiya I (2009). Development of allometric relationships for accurate estimation of above- and below-ground biomass in tropical secondary forests in Sarawak, Malaysia. Journal of Tropical Ecology, 25, 371-386.

Koh, L.P., R.A. Butler & C.J.A. Bradshaw. 2009. Conversion of Indonesia's peatlands. Frontiers in Ecology and the Environment 7 (5), 238-238.

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

Kormann R, Meixner FX (2001). An analytical footprint model for neutral stratification. Boundary-Layer Meteorology: 99, 207-224.

Kroeze C., Mosier A. & Bouwman L. (1999) Closing the global N2O budget: A retrospective analysis 1500-1994. Global Biogeochemical Cycles 13: 1-8.

Kroon PS, Hensen A, Jonker HJJ, Ouwersloot HG, Vermeulen AT, Bosveld FC (2009). Uncertainties in eddy covariance flux measurements assessed from CH4 and N2O observations. Agric. For. Meteorol., doi:10.1016/j.agrformet. 2009.08.008.

Kroon PS, Hensen A, Jonker HJJ, Zahniser MS, Van het Veen WH, Vermeulen AT (2007). Suitability of quantum cascade laser spectroscopy for CH4 and N2O eddy covariance flux measurements. Biogeosciences, 4, 715-728.

Kroon PS, Schrier-Uijl AP, Hensen A, Veenendaal, EM, Jonker HJJ (2010). Annual balances of CH4 and N2O from a managed fen meadow using eddy covariance flux measurements. Eur. J. Soil Sci. Vol 61.

Kuikman P, de Groot W, Hendriks R, Verhagen J, de Vries F (2003). Stocks of C in soils and emissions of CO2 from agricultural soils in the Netherlands. Alterra report 561, Green World Research.

Kutzbach L, Schneider J, Sachs T, Giebels M, Hykanen H, Shurpali NJ, Martikainen PJ, Alm J, Wilmking M (2007). CO2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression. Biogeosciences, 4, 1005-1025.

Lambert, K. 1995. Physico-Chemical Characterisation of Lowland Tropical Peat Soil. PhD report. Universiteit Gent.

Langeveld, C.A., Segers, R., Dirks, B.O.M., van den Polvan Dasselaar, A., Velthof, G.L., Hensen, A (1997): Emissions of CO2, CH4 and N2O from pasture on drained peat soils in the Netherlands, European journal of agronomy, Vol 7, Issue 1-3, 35-42.

Lasco RD (2002). Forest carbon budgets in Southeast Asia following harvesting and land cover change. Science in China (Series C): Vol. 45 Supp. 55-64.

Laville P, Jambert C, Cellier P, Delmas R (1999). Nitrous oxide fluxes from a fertilized maize crop using micrometeorological and chamber methods. Agric. For. Meteor. 96, pp. 19-38.

Le Mer J. & Roger P. (2001) Production, oxidation, emission and consumption of methane by soils: A review. European Journal of Soil Biology 37: 25-50

Livingston GP, Hutchinson GL, Spartallian K (2006). Trace gas emission in chambers: a non-steady state diffusion model. Soil Sci. Soc. Am. J., 70, pp. 1459-1469.

Lohila A, Laurila T, Aro L, Aurela M, Tuovinen J-P, Laine J, Kolari P, Minkkinen K (2007). Carbon dioxide exchange above a 30-years old Sots pine plantation established on organic soil cropland. Boreal Env. Res. 12: 141-157.

Lloyd, J., Taylor, J.A., 1994. On the temperature dependency of soils. Functional Ecology: 8, 315-323.

Malhi, Y (2010). The carbon balance of tropical forest regions, 1990-2005. In: Science Direct, current opinion in environmental sustainability 2010, 2:237-244.

Maljanen M, Komulainen V-M, Hytonen J, Martikainen PJ, Laine J (2004). Carbon dioxide, nitrous oxide and methane dynamics in boreal organic agricultural soils with different soil management. Soil Biology and Biochemistry 36: 1801-1808.

Maljanen M, Hytonen J, Makiranta P, Alm J, Minkkinen K, Laine J, Martikainen PJ (2007). Greenhouse gas emissions from cultivated and abandoned organic croplands in Finland. Boreal Env. Res. 12: 133-140.

Martikainen, P.J., H. Nykänen., P. Crill., J. Silvola,1992. The effect of changing water table on methane fluxes at two Finnish mire sites. Suo 43: 237-240.

Martikainen P. J., Nykanen H., Crill P. & Silvola J. (1993) Effect of a Lowered Water-Table on Nitrous-Oxide Fluxes from Northern Peatlands. Nature 366: 51-53.

Melling L, Hatano R, Goh KJ (2005) Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. In: Soil Biology and Chemistry 37 (2005) 1445-1453.

Melling L, Hatano R, Goh KJ (2005) Soil CO2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. In: Tellus (2005) 57B, 1-11.

Melling L, Hatano R, Goh KJ, 2005: Global warming potential from soils in tropical peatland of Sarawak, Malaysia. Phyton. 45, 275-284.

Melling L, Goh JK, Hatano R, 2006. Short term effect of urea on CH4 flux under oil palm on tropical peatland in Sarawak, Malaysia. Soil Science and Plant Nutrition. 52, 788-792.

Melling L, Hatano R, Goh KJ (2007). Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia. In: Soil Science and Plant Nutrition (2007) 53, 729-805.

Melling L, Goh KJ, Beauvais C, Hatano R (2008). Carbon flow and budget in a young mature oil palm agro-ecosystem on deep tropical peat. The Planter, Volume 84 No. 982.

Mikaloff Fletcher SE, Tans PP, Bruhwiler LM, Miller JB, Heimann M (2004a): CH4 sources estimated from atmospheric observations of CH4 and its 13C/12C isotope rations: 1. Inverse modeling of source processes. Global Biogeochem. Cycles, 18(4), doi:10.1029/2004GB002223.

Mikaloff Fletcher SE, Tans PP, Bruhwiler LM, Miller JB, Heimann M (2004b): CH4 sources estimated from atmospheric observations of CH4 and its 13C/12C isotope rations: 2. Inverse modeling of CH4 emissions from geographical regions. Global Biogeochem., 18, doi:10.1029/2004GB0022223.

Minkkinen K, Laine J (2006). Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. Plant Soil 285:289-304.

Moore CJ (1986). Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology: 37, 17-35.

Moore, T.R and R. Knowles. 1989. The influence of water table levels on methane and carbon dioxide emission from peatland soils. Can J. Soil Sci. 69:33-38.

Mosier A., Schimel D., Valentine D., Bronson K. & Parton W. (1991) Methane and Nitrous-Oxide Fluxes in Native, Fertilized and Cultivated Grasslands. Nature 350: 330-332.

Murdiyarso, D., N. Suryadiputra, S. Dewi & F. Agus. 2008. How can REDD scheme support the management of vulnerable carbon pools of Indonesia peatlands?. Proceeding of the 13th International Peat Congress, Tullamore, Ireland, 10th June 2008. (Eds. C. Farrell and J. Feehan). Peat Society, Finland, 230-232.

Neftel A, Flechard C, Ammann C, Conen F, Emmenegger L, Zeyer K (2007). Experimental assessment of N2O background fluxes in grassland systems. Tellus B: 59, 470-482.

Neue HU, Roger PA (1993). Rice agriculture: factors controlling emissions. In: Khalil MSK (Eds.), Atmospheric Methane: Sources, Sinks, and Role in Global Change. Springer-Verlag, New York, pp. 254-298.

Niiyama K, Kajimoto T, Matsuura Y, Yamashita T, Kassim AR, Ripin A, Noor N (2005). Allometric relationship between stem diameter, tree height, leaf, stem and root biomass in Pasoh Forest Reserve. In: annual report of NIES/FRIM/UPM joint project tropical ecology and biodiversity 2005 (ed. T.K. Okuda), pp 22-36.

Niiyama K, Kajimoto T, Matsuura Y, Yamashita T, Kassim AR, Ripin A, Noor N (2010). Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. Journal of Tropical Ecology, 26, 271-284.

Nykanen H., Vasander H., Huttunen J. T. & Martikainen P. J. (2002) Effect of experimental nitrogen load on methane and nitrous oxide fluxes on ombrotrophic boreal peatland. Plant and Soil 242: 147-155.

Oenema O., Velthof G. L., Yamulki S. & Jarvis S. C. (1997) Nitrous oxide emissions from grazed grassland. Soil Use and Management 13: 288-295.

Page SE, Morrison S, Malins R, Hooijer A, Rieley JO, Jauhiainen J (2011). Review of peat surface greenhouse gas emissions from oil palm plantations in SE Asia. ICCT (International Council on Clean Transportation).

Page, S., J.O. Rieley & C.J. Banks. 2011. Global and regional importance of the tropical peatland carbon stock. Global Change Biology 17, 798-818.

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S (2002). The amount of carbon released form peat and forest fires in Indonesia during 1997. Nature 420:61-65.

Page SE, Rieley JO, Shotyk OW, Weiss D (1999). Interdependence of peat and vegetation in a tropical peat swamp forest. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, 354, 1885-1897.

Page SE, Morrison R, Malins C, Hooijer A, Rieley JO & Jauhiainen J. (2011). Review of peat surface greenhouse gas emissions from oil palm plantations in Southeast Asia (ICCT White Paper 15). Washington: International Council on Clean Transportation.

Page SE, Rieley JO & Banks CJ (2011). Global and regional importance of the tropical peatland carbon pool. Global Change Biology 17, 798-818.

Palace M, Keller M, Silva H (2008). Necromass production: studies in undisturbed and logged Amazon Forests. Ecological applications, 18, 873-884.

Pederson AR, Peterson SO, Vinther F (2001). Stochastic diffusion model for estimating trace gas emissions with static chambers. Soil. Sci. Soc. Am. J., 65, pp 49-58.

Pennock DJ, Yates TT, Braidek JT (2004). Towards optimum sampling for regional-scale N2O emission monitoring in Canada. Canadian Journal of Soil Science 86: 441-450.

Pyle EH, Santoni GW, Nascimento HEM, Hutyra LR, Vieira S, Curran DJ, van Haren J, Saleska SR, Chow VY, Carmago PB, Laurance WF, Wofsy SC (2008). Dynamics of carbon, biomass, and structure in two Amazonian forests. Journal of Biophysical Research-Biogeosciences, 133.

Regina K., Nykanen H., Silvola J. & Martikainen P. J. (1996) Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. Biogeochemistry 35: 401-418.

Reichstein M, Falge E, Baldocchi D, Papale D , Aubinet M , Berbigier P, Bernhofer C, Buchmann N, Gilmanov T, Granier A, Grunwald T, Havrankova K, Ilvesniemi H, Janous D, Knohl A, Laurila T, Lohila A, Loustau D, Matteucci G, Meyers T, Miglietta F, Ourcival JM, Pumpanen J, Rambal S, Rotenberg E, Sanz M, Tenhunen J, Seufert G, Vaccari F, Vesala T, Yakir D, Valentini R, 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Glob. Change Biol.,11, 1424–1439.

Rieley JO, Ahmad-Shah AA, Brady MA (1996), The extent and nature of tropical peat swamps. Maltby E, Tropical Lowland Peatlands of Southeast Asia, Proceedings of a Workshop on Integrated Planning and Management of Tropical Lowland Peatlands held at Cisarua, Indonesia, 3-8 July 1992.

Rieley J and Page S (2002). Peatlands for people: natural resources function and sustainable management. Proceedings of the international symposium on tropical peatland. BPPT and Indonesian Peat Association, Jakarta, 272 pp, 22-23 Aug 2001

Rinne J, Riutta T, Pihlatie M, Aurela M, Haapanala S, Tuovinen JP, Tuittila ES, Vesala T (2007). Annual cycle of methane emission form a boreal fen measured by the eddy covariance technique. Tellus 59B, 449-457.

Rochette P, Eriksen-Hamel NS (2008). Chamber Measurements of Soil Nitrous Oxide Flux: Are Absolute Values Reliable? Soil Sci. Soc. Am. J.: 72, 331-342.

Roulet, N. T., Ash, R., Quinton, W. & Moore, T. (1993): Methane Flux from Drained Northern Peatlands - Effect of a Persistent Water-Table Lowering on Flux. Global Biogeochemical Cycles 7: 749-769.

Saarnio S, Morero M, Shurpali NJ, Tuittila ES, Makila M, Alm J (2007). Annual CO2 and CH4 fluxes of pristine boreal mires as a background for the lifecycle analyses of peat energy. Boreal Env. Res. 12: 101-113.

Sachs T, Wille C, Boike J, Kutzbach L (2008). Environmental controls on ecosystem-scale CH4 emission from polygonal tundra in the Lena River Delta, Siberia. Journ. of Geoph. Res. Vol 113, G00A03, doi: 10.1029/2007JG000505.

Sayer EJ, Powers JS, Tanner EVJ (2007) Increased Litter fall in Tropical Forests Boosts the Transfer of Soil CO2 to the Atmosphere. PLoS ONE 2(12): e1299. doi:10.1371/journal.pone.0001299.

Schothorst et al., 1977. Schothorst, C.J., 1977: Subsidence of low moor peat in the Western Netherlands, Geoderma, 17, 265-271.

Schrier-Uijl AP, Veenendaal EM, Leffelaar PA, van Huissteden JC, Berendse F (2010a). Methane emissions in two drained peat agro-ecosystems with high and low agricultural intensity. Plant Soil, doi:10.1007/s11104-009-0180-1.

Schrier-Uijl AP, Kroon PS, Hensen A, Leffelaar PA, Berendse F & Veenendaal EM (2010b). Comparison of chamber and eddy covariance based CO2 and CH4 emission estimates in a heterogeneous grass ecosystem on peat, Agric. For. Meteorol., doi:10.1016/j.agrformet.2009.11.007.

Schrier-Uijl AP, Veraart AJ, Leffelaar PA, Berendse F, Veenendaal E.M (2010c): Release of CO2 and CH4 from lakes and drainage ditches in temperate wetlands. Biogeochemistry, doi:10.1007/s10533-010-9440-7.

Segers, R. , 1998: Methane production and methane consumption; a review of processes underlying wetland methane fluxes, Biochemistry, 41 23-51.

Siegert, F. & J. Jaenicke. 2008. Estimation of carbon storage in Indonesia peatlands. Proceeding of the 13th International Peat Congress, Tullamore, Ireland, 10th June 2008. (Eds. C. Farrell and J. Feehan). Peat Society, Finland, 254-256.

Sierra CA, del Valle JI, Orrego SA, Moreno FH, Harmon ME, Zapata M, Colorado GJ, Herrara MA, Lara W, Resptrepo DE, Berrout LM, Loaiza LM, Benjumea JF (2007). Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. Forest Ecology and Management, 243, 299-309.

Smemo, K.A., Yavitt, J.B. (2006): A multi-year perspective on methane cycling in a shallow peat fen in central New York State, USA, Wetlands 26(1) 20-29.

Smith KA, Clayton H, Arah JRM, Christensen S, Ambus P, Fowler D, Hargreaves KJ, Skiba U et al. (1994). Micrometeorological and chamber methods for measurements of nitrous oxide fluxes between soils and the atmosphere: Overview and conclusions. J. Geophys. Res., 99, pp. 16541-16548.

St. Louis VL, Duchemin CAE, Rudd JWM et al (2000) Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. Bioscience 50 766 – 775 doi: 10.1641/0006-3568(2000)050[0766: RSASOG.

Sulistiyanto Y, Rieley JO, Page SE, Limin SH (2007). Nutrient inputs, cycling and retention in the upper Sebangau peatland. Proceedings of the International symposium and workshop on tropical peatland. (ed. J.O. Rieley), pp. 168-178. Palanka Raya.

Suzuki E (1999). Diversity in specific gravity and water content of wood among Bornean tropical rainforest trees. Ecological Research, 14, 211-224.

Treuhaft RN, Law BE, and Asner GP (2004). Forest attributes from radar interferometric profiling and its fusion with optical data. BioScience 54(6):561-571.

Ueda S, Go C-Su, Yoshioka T et al. (2000). Dynamics of dissolved O2, CO2, CH4, and N2O in a tropical coastal swamp in southern Thailand. Biogeochemistry, 49, 191-215.

UNFCCC (2010). Clean Development Mechanism Booklet. https://cdm.unfccc.int/methodologies/

Valentini R., Dore S., Marchi G., Mollicone D., Panfyorov M., Rebmann C., Kolle O. & Schulze E. D. (2000) Carbon and water exchanges of two contrasting central Siberia landscape types: regenerating forest and bog. Functional Ecology 14: 87-96.

Van Der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano Jr AF (2006). Interannual variability of global biomass burning emissions from 1997 to 2004. Atmospheric Chemistry and Physics Discussions, 6, 3175-3226.

VCS, VM0004, methodology for Conservation Projects that Avoid Planned Landuse Conversion in Peat Swamp Forests. http://www.v-c-s.org/methodologies/find.

VCS, VM0011, methodology for Improved Forest Management. http://www.v-c-s.org/methodologies/find.

Veenendaal EM, Kolle O, Leffelaar PS, Schrier-Uijl AP, Van Huissteden J, Van Walsem J, Möller F & Berendse F (2007). CO2 exchange and carbon balance in two grassland sites on eutrophic drained peat soils. Biogeosciences, 4, 1027-1040.

Velthof G. L., Oenema O., Postma R. & Van Beusichem M. L. (1996) Effects of type and amount of applied nitrogen fertilizer on nitrous oxide fluxes from intensively managed grassland. Nutrient Cycling in Agroecosystems 46: 257-267.

Velthof, G.L. and Oenema, O., (1997): Nitrous oxide emission from dairy farming systems in the Netherlands. Netherlands Journal of Agricultural Science, 45, pp. 347-360.

Verwer C and Meer Pvd (2010). Carbon pools in tropical peat forest. Towards a reference value for forest biomass carbon in relatively undisturbed peat swamp forests in Southeast Asia. Alterra report 2108, ISSN 1566-7197.

Waldes and Page SE (2002). Forest structure and tree diversity of a peat swamp forest in Central Kalimantan, Indonesia. In: Peatlands for people, natural resources function and sustainable management, Proceedings of the international symposium on tropical peatland, 22-23 August 2001. BPPT and Indonesian Peat Association, Jakarta, Indonesia.

Walter KM, Zimov SA, Chanton JP (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature 443 71– 75 doi:10.1038/nature05040.

Wetlands International-Indonesia Programme. 2003. Maps of Area of Peatland Distribution and Carbon Content in Sumatra. Book 1.

Wetlands International (2009). The Global peatland CO2 picture – Peatland status and drainage related emissions in all countries of the world. Ede, Author: H. Joosten. Produced for the UN-FCCC meetings in Barcelona, November 2009.

White JWC, Ferretti DF, Baughn BH, France RJ, Allison CE (2002). Stable isotope measurements of atmospheric CO2. In: Stable isotope measurement techniques for atmospheric

Whiting GJ, Chaton JP (1993). Primary production control of methane emission from wetlands. Nature 364, 26 august 1993.

Wienhold FG, Welling M, Harris GW (1994). Measurements of N2O fluxes from fertilized grassland using a fast response tunable diode laser spectrometer. J. Geophus. Res., 99, pp. 16557-16567.

Wosten JHM, Ismail AB, van Wijk ALM (1997). Peat subsidence and its practical implications: a case study in Malaysia. Geoderma 78, 25-36.

Wosten JHM, van der Berg J, van Eijk P, Gevers W, Giesen W, Hooijer A, Idris A, Leenman PH, Rais DS, Siderius C, Silvius MJ, Suryadiputra N, Wibisono IT (2006). Interrelationships between hydrology and ecology in fire degraded tropical peat swamp forests. International Journal of Water Resources Development, 22, 157-174.

Yanai Y, Toyota K, Morishita T, Takakai F, Hatano R, Limin SH, Darung U, Dohong S (2007). Fungal N2O production in an arable peat soil in Central Kalimantan, Indonesia. DOI: 10.1111/j.1747-0765.2007.00201.x

Zehnder AJB, and W Stumm, Geochemistry and biogeochemistry of anaerobic habitats, in Anaerobic Microbiology, edited by A.J.B. Zehnder, pp 1-38, Wiley, New York, 1988.