Greenhouse gas emissions from managed peat soils: is the IPCC reporting guidance realistic?

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SUMMARY

Drainage of peatlands leads to the decomposition of peat, resulting in substantial losses of carbon and nitrogen to the atmosphere. The conservation and restoration of peatlands can provide a major contribution to the mitigation of climate change. Improvements to guidance and capacity for reporting of greenhouse gas emissions from peatlands will be valuable in the context of the current negotiations towards a post-2012 climate agreement. This article evaluates IPCC approaches to greenhouse gas emissions from managed organic (peat) soils and presents a summary table comparing IPCC default values with best estimates based on recent literature. Inconsistencies are pointed out with regard to the IPCC definitions of organic soils and climate zones. The 2006 IPCC Guidelines use a definition of organic soil that is not totally consistent with FAO definitions, use climate zones that are not fully compatible, present default CO_2 values that are substantially (often an order of magnitude) too low, and present a default N_2O value for tropical cropland that is also an order of magnitude too low. An update of IPCC default values is desirable. The IPCC Emission Factor Database offers a platform for establishing more accurate emission factors, but so far contains little information about emissions from peat soils.

KEY WORDS: AFOLU, global warming potential, Histosols, Kyoto Protocol, organic soils, peatland.

INTRODUCTION

Peat consists of incompletely decomposed plant remains with or without admixed sand, silt or clay. Its formation usually reflects the curtailment of decomposition due to waterlogging, such that some of the carbon originally fixed from the atmosphere by plants is placed in long-term (millennial) storage in a water-saturated peat layer beneath the vegetation. Peat layers have developed in boreal, subarctic and Arctic regions mainly from mosses; in temperate regions from mosses, reeds and sedges and beneath forests; and in the humid tropics from sedges (papyrus) and beneath mangrove and peat swamp forests. Peatlands are found at all altitudes, but occur mostly in lowlands. In order to permit the cultivation of many arable and tree crops, peatlands must be drained and are often also limed and fertilised. Peat thus becomes the parent material for productive organic soils. However, drainage leads to aeration and consequent decomposition of the peat, resulting in substantial losses of greenhouse gases (GHGs) to the atmosphere. Because they are attributed to human activities, these GHG emissions are reported to the UNFCCC in national greenhouse gas inventories. The purpose of this literature-based review is to critically evaluate the approach of the current IPCC (2006) Guidelines to reporting GHG emissions from peat soils.

THE NATURE OF ORGANIC SOILS

Common names for organic soils include *peat soils*, *muck soils* and *bog soils*. They appear in national soil classifications as e.g. *Moore* (Germany); *Organosols* (Australia); *Organossolos* (Brazil); *Organic order* (Canada); and *Histosols* and *Histels* (from the Greek *histos*, which means tissue) (United States of America). The last of these is the effective international standard (FAO 2006/7).

The definition of Histosol is complex. It refers not only to the thicknesses of soil layers and their organic content but also to their origin, underlying material, clay content and annual period of water saturation (Table 1). Annex 3A.5 of the IPCC 2006 Guidelines offers criteria for the identification of organic (peat) soils which are based on the FAO (1998) key to soil types. Basically, apart from shallow (≥10 cm) organic-rich soils overlying ice or rock, organic soils (Histosols) are identical with peat and peaty soils of at least 40 cm total thickness within the uppermost 100 cm, containing at least 12 % organic carbon (~20 % organic material) by weight. This definition deviates from most European definitions of peat in that it stipulates a slightly thicker organic layer and a slightly lower organic matter content (Joosten & Clarke 2002). IPCC (2003, 2006) omits the 40 cm criterion from the FAO definition.

The properties of the organic material (such as botanical composition, stratification, degree of decomposition, packing density, wood content, mineral admixtures *etc*.) and the type of peatland (fen, raised bog *etc*.) determine the management requirements and potential uses of Histosols (FAO 2006/7) and are reflected, ultimately, in GHG emissions.

Table 1. Definitions of organic soils, according to FAO (1998) and FAO (2006/7).

FAO (2006/7) defines organic soils (Histosols) as:

Soils having organic material, either:

1. 10 cm or more thick starting at the soil surface and immediately overlying ice, continuous rock, or fragmental materials, the interstices of which are filled with organic material; or
2. cumulatively within 100 cm of the soil surface either 60 cm or more thick if 75% (by volume) or more of the material consists of moss fibres or 40 cm or more thick in other materials and starting within 40 cm of the soil surface.

Organic material has one or both of the following:

1. 20% or more organic carbon in the fine earth (by mass); or
2. if saturated with water for 30 consecutive days or more in most years (unless drained), one or both of the following:
    a. (12 + [clay percentage of the mineral fraction × 0.1])% or more organic carbon in the fine earth (by mass); or
    b. 18% or more organic carbon in the fine earth (by mass).

From the FAO (1998) key to reference soil groups, organic soils (Histosols) are:

Soils having a histic or folic horizon,

1. either: a. 10 cm or more thick from the soil surface to a lithic or paralithic contact; or
    b. 40 cm or more thick and starting within 30 cm from the soil surface; and
2. lacking an andic or vitric horizon starting within 30 cm from the soil surface.

A folic horizon must have:

1. more than 20% (by weight) organic carbon (35% organic matter); and
2. water saturation for less than one month in most years; and
3. thickness of more than 10 cm. If a folic horizon is less than 20 cm thick, the upper 20 cm of the soil after mixing must contain 20% or more organic carbon.

A histic horizon must have:

1. either: a. 18% (by weight) organic carbon (30% organic matter) or more if the mineral fraction comprises 60% or more clay, or
    b. 12% (by weight) organic carbon (20% organic matter) or more if the mineral fraction has no clay, or
    c. a proportional lower limit of organic carbon content between 12% and 18% if the clay content of the mineral fraction is between 0% and 60%. If present in materials characteristic for andic horizons, the organic carbon content must be more than 20% (35% organic matter); and
2. saturation with water for at least one month in most years (unless artificially drained); and
3. thickness of 10 cm or more. A histic horizon less than 20 cm thick must have 12 percent or more organic carbon when mixed to a depth of 20 cm.

CLIMATE ZONES

Climatic setting is a major determinant of land use options and the resulting GHG fluxes from peat soils. IPCC (2006, Vol. 4, Ch. 3) delineates major climate regions on the basis of averaged statistics such as mean annual temperature and/or precipitation. These climate regions are subdivided into ecological zones (FAO 2001; see IPCC 2006, Vol. 4, Ch. 4, Fig. 4.1,Tab. 4.1), but there are some stark discrepancies between the ecological zones and the supposedly higher-order climate regions. In the present review the FAO (2001) ecological zones are used to distinguish three climate types, namely boreal, temperate and tropical.

Histosols without prolonged water saturation are often formed in cold boreal and subarctic environments which are unattractive for agricultural use. In the warm boreal and temperate zones, peatlands have been extensively drained in order to permit the cultivation of conventional arable crops as well as forestry and grazing and, moreover, to allow the extraction of peat for fuel or for use in horticultural growing media. In the tropics, traditional subsistence farming and pisciculture had only low impacts on peatland, but human pressure on tropical wetlands (including peatlands) has generally increased in recent decades. In south-east Asia, increasingly extensive areas of peatland have been converted to oil palm and pulp wood plantations, and widespread peat fires have become common in association with the large-scale deforestation and reclamation of peat swamp forest.

EMISSION FACTORS FOR ORGANIC (PEAT) SOILS: METHODS AND BEST ESTIMATES

Drainage of water-saturated peat soils will increase CO_2 emissions and reduce CH_4 emissions, but CH_4 emissions from undrained organic soils are not addressed in the IPCC inventory guidelines unless the wetlands are managed and the emissions consequently deemed anthropogenic (IPCC 2003, 2006). Similarly, national inventories do not estimate the accumulation of carbon in undrained organic soils. In any case, if expressed per unit area, rates of accumulation in undrained sites are small compared to emissions from drained organic (peat) soils. The IPCC (2006) Guidelines do cover CO_2 and non-CO_2 emissions from fires, but they take into account only above-ground carbon stocks (biomass and dead organic material). At Tier 1 (default) level, the Guidelines fail to address emissions from burning peat; although countries may account for these emissions using the more detailed Tier 2 and/or Tier 3 methodologies. Compared with vegetation fires, the uncertainties involved in estimating emissions from peat fires are high because peat can burn repeatedly and to different depths. Furthermore, various compounds and gases can be emitted depending on the type and density of the peat. Thus, not only the area but also the depth of the fires and the types of emissions must be determined, and this is feasible only at the higher Tier levels.

The re-wetting of drained peatlands (e.g. after peat extraction) has many benefits including the reduction of CO_2 emissions arising from peat decomposition (IPCC 2006). After re-wetting, an increase in CH_4 emissions may be expected, which (partly) offsets the reduction in CO_2 emissions. These CH_4 emissions are considered to be anthropogenic and must be accounted. The overall result of re-wetting is likely to be a reduction in global warming potential (Wilson *et al*. 2008), but generalised methane emission factors are not yet available (Couwenberg 2009a).

The IPCC (2006) Guidelines provide two methods for estimating greenhouse gas fluxes in the Agriculture, Forestry and Other Land Uses (AFOLU) sector: (1) as net changes in C stocks over time (used for most CO_2 fluxes) and (2) directly as gas flux rates to and from the atmosphere (used for estimating non-CO_2 emissions and some CO_2 emissions and removals).

For non-organic (mineral) soils the IPCC (2006) Guidelines suggest that C stock estimates should be carried out for the upper 30 cm only (Tiers 1 and 2). In organic (peat) soils, the soil layer becomes thinner when degrading, because organic material constitutes a major and often dominant component of the soil. A stock approach should, therefore, take into account the entire thickness of the organic soil layer rather than being limited to the uppermost 30 cm. Such total stock estimates are complex and the IPCC (2006) Guidelines use estimates based on flux data also for CO_2 emissions[1].

Measuring CO_2 fluxes from organic (peat) soils can be difficult, and reliable measurements are rare. Many of the published CO_2 flux data from peat soils are based on static chamber measurements, which involve measuring changes in gas concentration within an airtight opaque chamber placed on the soil. Such 'dark chamber' measurements assess not only heterotrophic decomposition of soil organic

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[1] Considering that IPCC distinguishes only mineral and organic soils, the 30 cm criterion used in the Tier 1 and Tier 2 stock change approaches for mineral soils effectively defines organic soils as soils having an organic layer more than 30 cm thick.

matter, but also autotrophic emissions from any living short vegetation as well as rhizosphere respiration. Rhizosphere respiration encompasses autotrophic activity of plant roots and heterotrophic activity in the rhizosphere, including decomposition of root exudates and recently dead root material. Whilst the living vegetation can simply be removed, excluding rhizosphere respiration is much more difficult. Dark chambers also prevent the photosynthetic capture of CO_2 by vegetation, so that CO_2 emissions are usually over-estimated. Transparent chambers which allow photosynthesis to continue can be used to measure fluxes approaching the true net exchange of CO_2 between atmosphere and ecosystem, although the results may be affected by headspace heating and high humidity within the chambers. Nonetheless, after accounting for any natural or anthropogenic changes in standing biomass and litter, the net ecosystem CO_2 exchange measured in this way gives a best-possible indication of emissions from the soil. A rigorous flux measurement scheme combined with monitoring of site conditions at a temporally higher resolution so that emissions can be modelled continuously over the year forms a robust basis for estimating annual emissions caused by peat decomposition.

Like data from transparent chambers, eddy covariance measurements reflect the net CO_2 exchange between ecosystem and atmosphere, and are effective even amongst tall vegetation including forests. Biomass and litter stocks must also be monitored, as they can change substantially even in natural forests (*cf*. Luyssaert *et al*. 2008, Lewis *et al*. 2009) and especially in secondary and selectively logged forests. Whereas assessment methods for above-ground tree biomass are well developed, this is much less true for non-arboreal biomass, litter stocks, and particularly for below-ground biomass.

In forested ecosystems changes in soil organic carbon (CO_2 fluxes) are often assessed using dark chambers whilst attempting to exclude rhizosphere respiration, and various methods have been developed to separate the different contributions to soil respiration (see Kuzyakov 2006 for a review). Isotopic techniques are imprecise, very expensive, or applicable only under laboratory conditions. Non-isotopic techniques are generally destructive or change the system in such a way that it becomes difficult to make robust assessments of the importance of rhizosphere respiration relative to peat decomposition. One method that is often applied to exclude rhizosphere respiration is so-called ‘trenching’, which involves driving cylinders into the soil to sever roots and thus prevent them from respiring during future flux measurements. As severed fine roots may continue to respire for several months (or longer), and will ultimately decompose, trenching must be done well in advance of the flux measurements (Mäkiranta *et al*. 2008). Trenching is known to affect water and temperature regimes and to remove the rhizosphere priming effect, whereby the presence of roots stimulates microbial decomposition of soil organic matter. Taking all things into account, trenching is likely to lead to under-estimation of actual CO_2 fluxes arising from the decomposition of soil organic material. In order to calculate the CO_2 balance of the soil, the measured values must be corrected for inputs of slowly decomposing buried organic material (below-ground litter) (Minkkinen *et al*. 2007a).

CO_2 emissions from drained peat soils can, alternatively, be estimated by measuring peat subsidence (lowering of the soil surface). Peat subsidence is caused by several processes. In the initial stage after drainage, settling or compaction occurs due to loss of supporting pore water pressure. This initial consolidation can result in drastic reductions in surface height during the first years after drainage. Subsequent to consolidation there is secondary subsidence, which is caused by shrinkage and oxidation of the peat. In addition, wind and water erosion, leaching of soluble organic matter and fire may all contribute to the loss of matter and surface altitude. Only oxidation of the peat results in direct on-site CO_2 emissions to the atmosphere and other processes (particularly shrinkage) must be excluded in order to derive emission values based on secondary subsidence rates. Estimates for the oxidative component of secondary peat subsidence vary greatly, and generalisation is difficult and often inappropriate. More robust assessment is desirable, considering that subsidence can be measured by remote sensing and would offer good spatially diverse data on CO_2 emissions from peatland degradation.

Measuring CH_4 and N_2O fluxes is more straightforward and can be done using either (dark) chamber or eddy covariance techniques. With respect to methane, the use of chambers may lead to disturbance that results in ebullition (bubbling up) of soil gases which may or may not be captured in the chamber. Methane emissions are highly variable in time and space. The same applies to N_2O emissions, which can be very erratic.

Applying these considerations, best estimates of emission factors for different land uses have been extracted from published literature, and these are compared with IPCC default values in Table 2. In the sections which follow, the derivation of the values is explained for each greenhouse gas and for each IPCC Land Use Sector in turn.

Table 2. Summary of emission factors for CO_2 and N_2O. Values in **bold (red)** are considerably higher, and those in underlined (blue) are considerably lower, than those given by IPCC (2006). Numbers in [square brackets] refer to the notes at the foot of this page.

Climate zone	Land use	t CO_2-C ha^{-1} yr^{-1} (range)		kg N_2O-N ha^{-1} yr^{-1} (range)	
		IPCC (2006)	Best estimate	IPCC (2006)	Best estimate
Tropical	(Agro-)forestry	1.36 (0.82–3.82) [1]	**11** (8–13.5) [2]	8 (0–24) [3]	3.4 (-0.5–3.4) [4]
	Cropland [5]	20.0 (± 90%) [6]	11 (8–13.5) [4]	16 (5–48) [8]	**107** (13–252) [9,10]
	Grassland	5 (± 90%) [7]			4.6 (-1.1–23) [10,11]
	Peat extraction	2.0 (0.06–7.0) [12]	**8** [11]	-	-
Temperate	Forestry, poor soils	0.68 (0.41–1.91) [1]	-	-	0.6 (0.2–1.3) [13,14]
	Forestry, rich soils				6.4 (0.7–17) [14,15]
	Cropland	10.0 (± 90%) [6]	-	8 (2–24) [8]	5.8 (-3.8–56) [10,11]
	Grassland	2.5 (± 90%) [7]	**5.5** (4.1–7.6) [16]		
	Peat extraction, rich soils	1.1 (0.03–2.9) [17]	**1.9** (0.1–4.4) [19]	-	-
	Peat extraction, poor soils	0.2 (0–0.6) [18]			
Boreal	Forestry, poor soils	0.16 (0.08–1.09) [1]	**1.75** (1–4.3) [20,21,22]	0.1 (0.02–0.3) [23]	
	Forestry, rich soils			0.6 (0.16–2.4) [23]	
	Cropland	5.0 (± 90%) [6]	6.8 (2.1–11.2) [22,24]	-	6.8 (-0.8–37) [26]
	Grassland	1.25 (± 90%) [7]	**2.6** (-0.7–7.5) [22,24,25]		
	Peat extraction, rich soils	1.1 (0.03–2.9) [17]	**2.5** (1.0–11.2) [27] **6.8** (4.6–9.1) [28]	-	2.1 (2.0–2.2) [28]
	Peat extraction, poor soils	0.2 (0–0.6) [18]			

Notes and literature sources: [1]no literature references are given for these values, which are based on an assumption that the rate of decomposition in tropical climate is twice that in temperate climate; [2]Melling *et al.* (2007), Couwenberg *et al.* (2010); [3]due to lack of data, IPCC adopts the emission factor for temperate grasslands and croplands; [4]Couwenberg *et al.* (2010); [5]CH_4 emissions from rice paddies on peat soil fall within the IPCC (2006) default range; [6]includes fallow land; [7]25% of the value for drained croplands; IPCC (2006) misrepresents the value for boreal grasslands as 0.25; [8]unfertilised; [9]Takakai *et al.* (2006); [10]corrected for fertiliser application using the IPCC (2006) default factor of 0.01kg N_2O-N per kg N fertiliser applied; [11]emissions from shallow drained bare peat, Couwenberg *et al.* (2010); [12]calculated from relative difference between nutrient-poor and nutrient-rich boreal and temperate peat extraction sites; [13]Von Arnold *et al.* (2005a, 2005b, 2005c); [14]Ernfors (2009); [15]Augustin *et al.* (1998), Augustin & Merbach (1998), Brumme *et al.* (1999), Augustin (2003), Klemedtson *et al.* (2005); [16]Mundel (1976), Jacobs *et al.* (2003), Veenendaal *et al.* (2007), Beyer (2009), Augustin (unpubl.); [17]default for temperate peatland when nutrient status unknown; [18]default for boreal peatland when nutrient status unknown; [19]Flessa *et al.* (1997), Müller *et al.* (1997), Bortoluzzi *et al.* (2006), abandoned areas with high water levels and partial spontaneous revegetation; [20]Mäkiranta *et al.* (2007); [21]Minkkinen *et al.* (2007a); [22]Lohila *et al.* (2007); [23]IPCC (2006) supported by Alm *et al.* (2007); [24]Maljanen *et al.* (2001, 2004); [25]Shurpali *et al.* (2009); [26]Nykänen *et al.* (1995), Maljanen *et al* (2003), Regina *et al.* (2004); [27]Sundh *et al.* 2000, Alm *et al.* (2007), Shurpali *et al.* 2008; [28] includes emissions from stockpiles, CH_4 emissions (including stockpiles) amount to 68.8 (54.4–83.2) kg CH_4 ha^{-1} yr^{-1}, total global warming potential (using 100-year conversion factors) equals 7.3 (5.2–10.1) t CO_2-C-eq ha^{-1} yr^{-1}.

CO_2 emission factors

Drained organic soils in managed forests

For the IPCC Tier 1 approach, soil C stocks for forest on mineral soil are assumed not to change with management, but default soil CO_2 emission factors for forestry on drained organic soils are given (IPCC 2003, 2006). Current best estimates of these fluxes are based on a limited number of measurements using trenching (Melling *et al*. 2007, Mäkiranta *et al*. 2007, Minkkinen *et al*. 2007a) or the eddy covariance technique (Lohila *et al*. 2007). Corrections for below-ground litter input in tropical peatlands are based on Melling *et al*. (2007), and for the boreal zone on Laiho *et al*. (2003) (*cf*. Minkkinen *et al*. 2007a). The boreal-zone litter input values have been halved in order to eliminate fast-cycling material, as in the Finnish National Inventory Report for 1990–2007 (Statistics Finland 2009, see http://www.stat.fi/index_en.html). The trenches were installed well before measurements commenced, so that fluxes resulting from the decomposition of this material will be negligible. The input of slower-cycling below-ground litter may be as small as 25% of total litter input (Domisch *et al*. 1998), which would result in an emission factor of 2.3 t CO_2-C ha^{-1} yr^{-1} for managed boreal forests.

While the best-estimate values exceed the IPCC (2006) default emission factors, much lower emissions or considerable net uptake of carbon are often cited (e.g. Byrne *et al*. 2004, Minkkinen *et al*. 2008). Such numbers include changes in (above- and below-ground) biomass stocks and do not refer to net heterotrophic soil fluxes alone. Indirect emissions from off-site decomposition of organic material and from dissolved CO_2 leached through drainage ditches can be substantial (up to ~200 kg C ha^{-1} yr^{-1}) (Roulet *et al*. 2007, Nilsson *et al*. 2008) and are likely to be higher for tropical peat swamp forests (Couwenberg *et al*. 2010), although still small compared to direct gaseous emissions.

Cultivated organic soils (croplands and grasslands)

The IPCC (2006) default emission factors for croplands on peat soil are based largely on subsidence data combined with generic values for the oxidative component. Although these values may capture general trends, they are not precise and show wide variation. The IPCC (2006) emission factor for grassland in each climate zone is taken to be one-quarter of the corresponding value for drained cropland, this being the approximate proportion according to the data presented by Armentano & Menges (1986). The IPCC (2006) emission factors for croplands and grasslands are provided for non-standard climate zones (from Ogle *et al*. 2003) which coincide only partly with the FAO (2001) zones.

Current (conservative) best estimates for drained tropical peat soils under crops are derived from subsidence studies assuming that 40 % of surface height loss is due to oxidation (Couwenberg *et al*. 2010). Direct CO_2 flux measurements from temperate croplands on peat soil are not yet available. Preliminary results suggest an emission factor between 9.2 and 11.2 t CO_2-C ha^{-1} yr^{-1} (Drösler 2008, 2010). Estimates based on subsidence (Kasimir Klemedtsson *et al*. 1997, Höper 2007) are highly variable and at times extreme. Additional losses of soil carbon from croplands due to wind and water erosion can be substantial. Emissions from boreal grasslands on peat soil are lower than from cropland, although there is a large overlap in the values.

Managed wetlands (peat extraction)

CO_2 emissions from land undergoing peat extraction comprise two basic elements, namely on-site emissions from peat deposits during the extraction phase and off-site emissions arising from the use of peat, either for energy or for horticultural purposes (IPCC 2006). Off-site emissions arising from energy use are reported in the energy sector whereas those from horticultural use of peat must be accounted under the AFOLU sector, with the assumption that all C contained in peat used in horticulture is released within one year. Off-site emissions are not analysed here. On-site emissions comprise emissions from the area under extraction itself as well as from peat decomposition in stockpiles. The IPCC (2006) Guidelines provide estimated emission factors derived from flux measurements in boreal peatlands not necessarily under extraction. Alm *et al*. (2007) derived emission factors for peat mining areas as well as for stockpiles, covering not only CO_2 but also CH_4 and N_2O emissions. Best estimates for CO_2 emissions related to peat extraction lie far above the IPCC (2006) default values (Table 2). Direct measurements from temperate peat extraction areas are lacking, but emissions are likely to exceed those from boreal sites.

Nitrous oxide emission factors

Drained organic soils in managed forests

With respect to N_2O emissions from (unfertilised) peat soils drained for forestry, a distinction is made between nutrient-rich and nutrient-poor soils; emissions from the latter are almost negligible (Table 2). The IPCC (2006) Guidelines provide emission factors for the boreal and temperate climate zones together, although the supporting literature cited covers boreal sites only. Additional data allow the derivation of emission factors for temperate drained forested peatlands. The high value for nutrient-rich soils is based on data from sites with the nitrogen-fixing genus *Alnus* (alder).

Due to lack of actual data, IPCC (2006) used the N_2O emission factor for temperate grasslands and croplands to represent tropical peat soils drained for (agro-)forestry. Couwenberg *et al*. (2010) found that primary, secondary and drained tropical peat swamp forests are indistinguishable from agroforestry sites on peat with respect to N_2O emissions. Emissions from forested tropical sites are lower than from temperate European sites which have been drained for forestry, and less than half the value assumed by IPCC (2006) (Table 2).

Cultivated organic soils (croplands and grasslands)

While current best estimates for N_2O emissions from tropical grassland (including abandoned land) are much lower than the IPCC (2006) default value, emissions from fertilised tropical peat cropland by far exceed this emission factor (Table 2). Nitrous oxide emissions are particularly high upon fertiliser application to wet peat soil, and the emission factor for fertiliser-N inputs should probably be much higher than the default 0.01 kg N_2O-N per applied kilogram of fertiliser N. With respect to nitrous oxide emissions from fertilised cropland on tropical peat soil, there is a need for further studies and improved land use guidelines. Emissions from boreal soils show considerable winter fluxes related to freeze-thaw cycles. These winter fluxes explain why the annual fluxes are comparable to those from temperate areas.

Managed wetlands (peat extraction)

On the basis of data from boreal sites only, the contribution of N_2O emissions to the global warming potential of peat extraction sites appears to be limited (Alm *et al*. 2007).

Methane emission factors

Although methane emissions from ditches in peatlands drained for forestry may be substantial (Minkkinen & Laine 2006, Minkkinen *et al*. 2007b), the extent of ditches will be small compared to the drained area so that, even allowing for the stronger radiative forcing of methane, the effect will be small relative to CO_2 emissions from the drained area. Drained organic (peat) soils have negligible methane emissions or display small net uptake. Reported methane emissions from drained peat sites amount to ~30 kg CH_4 ha^{-1} yr^{-1} (~180 kg CO_2-C equivalents ha^{-1} yr^{-1}) based on area-weighted emissions from ditches (Sundh *et al*. 2000, Minkkinen *et al*. 2007b). Closer spacing of ditches will result in higher emissions. Indirect methane emissions that occur when organic material leached from peat sites is anaerobically decomposed off-site are also likely to be small relative to the direct CO_2 fluxes from drained areas.

For croplands and grasslands, methane emissions from rice paddies on peat soil (Furukawa *et al*. 2005, Hadi *et al*. 2005) are within the uncertainty range of the IPCC (2007) default emission factor. The contribution of CH_4 emissions to the global warming potential of peat extraction sites is limited (Sundh *et al*. 2000, Alm *et al*. 2007).

CONCLUSIONS

The IPCC Guidelines 2006:

- use a definition of organic soil that is not fully compatible with FAO definitions;
- use climate zones that are not fully consistent;
- present default CO_2 values that are substantially (often an order of magnitude) too low; and
- present a default N_2O value for tropical cropland that is also an order of magnitude too low.

These conclusions underline the inadequacy of IPCC (2006) default values alone for estimating GHG emissions from peatlands. Especially where order of magnitude discrepancies have been identified, it would seem imperative that the current IPCC Guidelines are improved; and that, meanwhile, users should seek more accurate emission factors from elsewhere. The IPCC offers an additional resource in the form of the Emission Factor Database, which is a dynamically updated web-based tool intended to serve as both a library of well documented and evaluated GHG emission factors and a communication platform for those generating and using them. As yet, however, it contains few data for emissions from peat soils. The IPCC Emission Factor Database is available at: http://www.ipcc-nggip.iges.or.jp/EFDB/main.php.

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REFERENCES

Alm, J., Shurpali, N.J., Minkkinen, K., *et al.* (2007) Emission factors and their uncertainty for the exchange of CO_2, CH_4 and N_2O in Finnish managed peatlands. *Boreal Environment Research*, 12, 191–209.

Augustin, J. (2003) Gaseous emissions from constructed wetlands and (re)flooded meadows. *Publicationes Instituti Geographici Universitatis Tartuensis*, 1, 94, 3–8.

Augustin, J. & Merbach, W. (1998) Greenhouse gas emissions from fen mires in Northern Germany: quantification and regulation. In: Merbach, W. & Wittenmayer, L. (eds.) *Beiträge aus der Hallenser Pflanzenernährungsforschung*, Grauer, Beuren, 97–110.

Augustin, J., Merbach, W., Steffens, L. & Snelinski, B. (1998) Nitrous oxide fluxes of disturbed minerotrophic peatlands. *Agribiological Research*, 51, 47–57.

Beyer, M. (2009) Einfluss der Landnutzung auf den Austausch klimarelevanter Spurengase (Kohlendioxid, Lachgas, Methan) bei entwässerten Niedermooren Nordostdeutschlands (*Influence of Land Use on Emissions of Greenhouse Gases (Carbon Dioxide, Nitrous Oxide, Methane) in Re-wetted Fens in North-east Germany*). M.Sc. Thesis TUM/ZALF, x+71 pp. (in German).

Bortoluzzi, E., Epron, D., Siegenthaler, A., Gilbert, A. & Buttler, A. (2006) Carbon balance of a European mountain bog at contrasting stages of regeneration. *New Phytologist*, 172, 708–718.

Brumme, R., Borker, W. & Finke, S. (1999) Hierarchical control on nitrous oxide emissions in forest ecosystems. *Global Biogeochemical Cycles*, 13, 1137–1148.

Byrne, K.A., Chojnicki, B. & Christensen, T.R. (2004) EU peatlands: Current carbon stocks and trace gas fluxes. Carbo-Europe-GHG Concerted Action - Synthesis of the European Greenhouse Gas Budget. Report 4/2004, 58 pp.

Couwenberg, J. (2009a) *Methane Emissions From Peat Soils (Organic Soils, Histosols)*. Wetlands International, Ede, The Netherlands, 14 pp.

Couwenberg, J. (2009b) *Emission Factors for Managed Peat Soils. An Analysis of IPCC Default Values*. Wetlands International, Ede, The Netherlands, 16 pp.

Couwenberg, J., Dommain, R. & Joosten, H. (2010) Greenhouse gas fluxes from tropical peatswamps in Southeast Asia. *Global Change Biology*, 16(6), 1715–1732.

Domisch, T., Finér, L., Karsisto, M., Laiho, R. & Laine, J. (1998) Relocation of carbon from decaying litter in drained peat soils. *Soil Biology and Biochemistry*, 30(12), 1529–1536.

Drösler, M. (2008) Von der Spurengasmessung zur Politikberatung - interdisziplinärer Ansatz und erste Ergebnisse des Verbundprojekts “Klimaschutz – Moornutzungsstrategien” (From trace gas measurement to policy advice - interdisciplinary basis and first results of the joint project “climate protection - peatland use strategies”). Presentation given at the BfN workshop *Biodiversität und Klimawandel* (in German), http://www.bfn.de/4399.html, accessed March 2010).

Drösler, M. (2010) *Beitrag ausgewählter Schutzgebiete zum Klimaschutz und ihre Monetäre Bewertung* (*Contribution of Selected Protected Areas to Climate Protection and their Monetary Evaluation*). BfN Interim Report, 43+4 pp. (in German).

Ernfors, M. (2009) *Greenhouse Gas Fluxes Between Drained Forested Peatlands and the Atmosphere - Influence of Nutrient Status and Wood Ash Fertilization*. PhD Thesis, University of Gothenburg, 31 pp.

FAO (1998) *World Reference Base for Soil Resources*. World Soil Resources Reports, 84, 88 pp.

FAO (2001) Global ecological zoning for the global forest resources assessment 2000. Forest Resources Assessment Programme Working Paper 56, FAO, Rome, 211 pp.

FAO (2006/7) *World Reference Base for Soil Resources 2006, First Update 2007*. World Soil Resources Reports, 103, ix+116 pp.

Flessa, H., Wild, U., Klemisch, M. & Pfadenhauer, J. (1997) C- und N-Stoffflüsse auf Torfstichsimulationsflächen im Donaumoos (C- and N-emissions from simulated peat surfaces in the Donau Mire). *Zeitschrift für Kulturtechnik und Landentwicklung*, 38, 11–17 (in German).

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 Agroecosystems*, 71, 81–91.

Hadi, A., Inubushi, K., Furukawa, Y., Purnomo, E., Rasmadi, M. & Tsuruta, H. (2005) Greenhouse gas emissions from tropical peatlands of Kalimantan, Indonesia. *Nutrient Cycling in Agroecosystems*, 71, 73–80.

Höper, H. (2007) Freisetzung klimarelevanter Gase aus deutschen Mooren (Evolution of greenhouse gases from German peatlands). *Telma*, 37, 85–116 (in German)

IPCC (2003) Good Practice Guidance for Land Use, Land-Use Change and Forestry (eds. Penman J, Gytarsky M, Hiraishi T, et al.). IGES, Japan.

IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme (eds. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K). IGES, Japan.

Jacobs, C.M.J., Moors, E.J. & van der Bolt, F.J.E. (2003) *Invloed van waterbeheer op gekoppelde broeikasgasemissies in het veenweidegebied by ROC Zegveld* (*Influence of Water Management on Coupled Greenhouse Gas Emissions in the Peatland Area by ROC Zegveld*). Alterra Report 840, Alterra, Wageningen, 93 pp. (in Dutch).

Joosten, H. & Clarke, D. (2002) Wise use of mires and peatlands – Background and principles including a framework for decision-making. International Mire Conservation Group / International Peat Society, 304 pp.

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

Klemedtsson, L., von Arnold, K., Weslien, P. & Gundersen, P. (2005) Soil CN ratio as a scalar parameter to predict nitrous oxide emissions. *Global Change Biology*, 11, 1142–1147.

Kuzyakov, Y. (2006) Sources of CO_2 efflux from soil and review of partitioning methods. *Soil Biology and Biochemistry*, 38, 425–448.

Laiho, R., Vasander, H., Penttilä, T. & Laine, J. (2003) Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. *Global Biogeochemical Cycles*, 17, 1053, doi:10.1029/2002GB002015, 2003.

Lewis, S.L., Lopez-Gonzalez, G., Sonké, B. *et al*. (2009) Increasing carbon storage in intact African tropical forests. *Nature*, 457, 1003–1007.

Lohila, A., Aurela, M., Regina, K., Tuovinen, J-P. & Laurila, T. (2007) Wintertime CO_2 exchange in a boreal agricultural peat soil. *Tellus*, 59(5), 860–873.

Luyssaert, S., Schulze, E-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P. & Grace, J. (2008) Oldgrowth forests as global carbon sinks. *Nature*, 455, 213–215.

Mäkiranta, P., Hytönen, J., Aro, L., *et al*. (2007) Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. *Boreal Environment Research*, 12, 159–175.

Mäkiranta, P., Minkkinen, K., Hytönen, J. & Laine, J. (2008) Factors causing temporal and spatial variation in heterotrophic and rhizospheric components of soil respiration in afforested organic soil croplands in Finland. *Soil Biology and Biochemistry*, 40, 1592–1600.

Maljanen, M., Martikainen, P., Walden, J. & Silvola, J. (2001) CO_2 exchange in an organic field growing barley or grass in eastern Finland. *Global Change Biology*, 7, 679–692.

Maljanen, M., Liikanen, A., Silvola, J. & Martikainen, P.J. (2003) Nitrous oxide emissions from boreal organic soil under different land use. *Soil Biology & Biochemistry*, 35, 689–700.

Maljanen, M., Komulainen, V-M., Hytönen, J., Martikainen, P.J. & Laine, J. (2004) Carbon dioxide, nitrous oxide and methane dynamics in boreal organic agricultural soils with different soil characteristics. *Soil Biology & Biochemistry*, 36, 1801–1808.

Melling, L., Goh, K.J., Beauvais, C. & Hatano, R. (2007) Carbon flow and budget in a young mature oil palm agroecosystem on deep tropical peat. In: Rieley, J.O., Banks, C.J. & Radjagukguk, B. (eds.) *Carbon-Climate-Human Interaction on Tropical Peatland*. Proceedings of the International Symposium and Workshop on Tropical Peatland, Yogyakarta, 27–29 August 2007, 5 pp. Available online at: http://www.geog.le.ac.uk/carbopeat/yogyacontents.html (retrieved 05/2009).

Minkkinen, K., Byrne, K.A. & Trettin, C. (2008) Climate impacts of peatland forestry. In: Strack, M. (ed.) *Peatlands and Climate Change*, International Peat Society, Jyväskylä, 98–122.

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

Minkkinen, K., Laine, J., Nykänen, H., & Martikainen, P.J. (1997) Importance of drainage ditches in emissions of methane from mires drained for forestry. *Canadian Journal of Forest Research*, 27, 949–952.

Minkkinen, K., Laine, J. & Penttilä, T. (2007a) Greenhouse gas emissions from forestry drained peatlands and contributing environmental factors. In: Sarkkola, S. (ed.) *Greenhouse Impacts of the Use of Peat and Peatlands in Finland*, Report 11a/2007, Ministry of Agriculture and Forestry, ISBN 987-952-453-349-2, 22–26.

Minkkinen, K., Laine, J., Shurpali, N., Mäkiranta, P., Alm, J. & Penttilä, T. (2007b) Heterotrophic soil respiration in forestry-drained peatlands. *Boreal Environment Research*, 12, 115–126.

Müller, N., Bauche, M. & Lamersdorf, N. (1997) Zeitliche und räumliche Variabilität der CO_2-C-Emissionen in einem ombrotrophen Hochmoor des Hochharzes (Temporal and spatial variability of CO_2-C emissions in an ombrotrophic bog in the Hochharzes). *Telma*, 27, 131–146 (in German).

Mundel, G. (1976) Untersuchungen zur Torfmineralisation in Niedermooren (Studies of peat mineralisation in fens). *Archiv für Acker- und Pflanzenbau und Bodenkunde*, 20, 669–679 (in German).

Nilsson, M.B., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P. & Lindroth, A. (2008) Contemporary carbon accumulation in an oligotrophic minerogenic peatland - a significant sink after accounting for all C-fluxes. *Global Change Biology*, 14, 2317–2332.

Nykänen, H., Alm, J., Lång, K., Silvola, J. & Martikainen, P.J. (1995) Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland. *Journal of Biogeography*, 22, 351–357.

Ogle, S.M., Breidt, F.J., Eve, M.D., & Paustian, K. (2003) Uncertainty in estimating land use and management impacts on soil organic storage for US agricultural lands between 1982 and 1997. *Global Change Biology*, 9, 1521–1542.

Regina, K., Syväsalo, E., Hannukkala, A. & Esala, M. (2004) Fluxes of N_2O from farmed peat soils in Finland. *European Journal of Soil Science*, 55, 591–599.

Roulet, N., Lafleur, P., Richard, P., Moore, T., Humphreys, E. & Bubier, J. (2007) Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, 13, 397–411.

Shurpali, N.J., Hyvönen, N.P., Huttunen, J.T., Biasi, C., Nykänen, H., Pekkarinen N. & Martikainen, P.J. (2008) Bare soil and reed canary grass ecosystem respiration in peat extraction sites in Eastern Finland. *Tellus* B, 60(2), 200–209.

Shurpali, N.J., Hyvönen, N.P., Huttunen, J.T., Clement, R.J., Reichstein, M., Nykänen, H., Biasi, C. & Martikainen, P.J. (2009) Cultivation of a perennial grass for bioenergy on a boreal organic soil - carbon sink or source? *GCB Bioenergy*, 1, 35–50.

Sundh, I., Börjesson, G. & Tunlid, A. (2000) Methane oxidation and phospholipid fatty acid composition in a podzolic soil profile. *Soil Biology & Biochemistry*, 32, 1025–1028.

Takakai, F., Morishita, T., Hashidoko, Y., Darung, U., Kuramochi, K., Dohong, S., Limin, S.H. & Hatano, R. (2006) Effects of agricultural land-use change and forest fire on N_2O emission from tropical peatlands, Central Kalimantan, Indonesia. *Soil Science and Plant Nutrition*, 52, 662–674.

Veenendaal, E.M., Kolle, O., Leffelaar, P.A., Schrier-Uijl, A.P., van Huissteden, J., van Walsem, J., Möller, F. & Berendse, F. (2007) CO_2 exchange and carbon balance in two grassland sites on eutrophic drained peat soils. *Biogeosciences*, 4, 1027–1040.

Von Arnold, K., Hanell, B., Stendahl, J. & Klemedtsson, L. (2005a) Greenhouse gas fluxes from drained organic forestland in Sweden. *Scandinavian Journal of Forest Research*, 20, 400–411.

Von Arnold, K., Nilsson, M., Hanell, B., Weslien, P. & Klemedtsson, L. (2005b) Fluxes of CO_2, CH_4 and N_2O from drained organic soils in deciduous forests. *Soil Biology and Biochemistry*, 37, 1059–1071.

Von Arnold, K., Weslien, P., Nilsson, M., Svensson, B.H. & Klemedtsson, L. (2005c) Fluxes of CO_2, CH_4 and N_2O from drained coniferous forests on organic soils. *Forest Ecology and Management*, 210, 239–254.

Wilson, D., Alm, J., Laine, J., Byrne, K.A., Farrell, E.P. & Tuitila, E-S. (2008) Rewetting of cutaway peatlands: are we re-creating hot spots of methane emissions? *Restoration Ecology*, doi: 10.1111/j.1526- 100X.2008.00416.x.

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