Emission factors for managed peat soils

An analysis of IPCC default values

Wetlands International

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(organic soils, histosols)

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Summary

Peatland drainage leads to peat oxidation, resulting in large losses of carbon and nitrogen to the atmosphere with an estimated global magnitude of 2-3 Gt/CO_2-eq per year. The conservation and restoration of peatlands can provide a major contribution to the mitigation of climate change. Improving guidance and capacity for reporting of peatland emissions will prove valuable to the current negotiations towards a post-2012 climate agreement. This paper evaluates IPCC approaches to greenhouse gas emissions from managed organic (peat) soils and notices that the IPCC Guidelines 2006:

- use an organic soil definition that is not fully compatible with FAO definitions,
- use climate zones that are not fully comprehensible,
- present default CO_2 values for peat mining and for tropical and boreal forestry that are substantially (often an order of magnitude) too low,
- present a default N_2O value for tropical cropland that is an order of magnitude too low, and
- present default CO_2 values for grasslands and for tropical cropland that are 100% too high.

The paper concludes with a summary table comparing IPCC default values with best estimates based on recent literature.

1. Organic soil (histosol)

The definition of organic soil (histosol) is complex. It not only refers to thickness of soil layers and their organic content but also to their origin, underlying material, clay content and water saturation (see Appendix A). Based on the FAO (1998) key to soil types, Annex 3A.5 of the IPCC 2006 Guidelines offers criteria for identification of organic (peat) soils.

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 upper 100 cm, containing at least 12% organic carbon (~20 % organic material) by weight. This definition departs from a slightly thicker layer and slightly lower organic matter content than most European definitions of peat (Joosten & Clarke 2002). Unfortunately, the FAO key is misrepresented by IPCC (2003, 2006) by failing to include the 40 cm criterion.

Peat soils (histosols) occur extensively in boreal, arctic and subarctic regions unattractive for agricultural use. Elsewhere, they are confined to poorly drained basins and depressions, swamp and marshlands with shallow groundwater, and highland areas with a high precipitation-evapotranspiration ratio (FAO 2006/7). In order to permit cultivation, peat soils have been drained and, normally, also limed and fertilized. Following drainage the carbon stored in organic (peat) soils will readily decompose, resulting in CO_2 and N_2O emissions to the atmosphere. Drainage of water saturated peat soils will also result in a decrease in CH_4 emissions. However, CH_4 emissions from un-drained organic soils are not addressed in the IPCC inventory guidelines unless the wetlands are managed and emissions may be deemed anthropogenic (IPCC 2003, 2006). Similarly, national inventories do not estimate the accumulation of carbon in un-drained organic soils. Rates of accumulation in undrained sites are small compared to emissions from drained organic (peat) soils.

2. Climate regions and ecological zones

IPCC (2006, Vol. 4, Ch. 3) delineates major climate zones based on rough parameters like mean annual temperature and precipitation. These climate regions are further subdivided into ecological zones (FAO 2001; see IPCC 2006, Vol. 4, Ch. 4, Fig. 4.1, Tab. 4.1). There are some stark discrepancies between the ecological zones and the reputedly higher order climate regions. In this text we refer to the FAO (2001) ecological zones as the basis for climate zones.

3. Default emission factors for organic (peat) soils

The IPCC (2006) Guidelines recognises two ways to estimate greenhouse gas fluxes in the 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 C stock estimates to be carried out for the upper 30 cm only (Tier 1 & 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. This means that a stock approach should take the entire depth of the organic soil layer into account and cannot limit itself to the upper 30 cm. Such total stock estimates are complex and the IPCC (2006) Guidelines use estimates based on flux data also for CO_2 emissions. Measuring gas fluxes from organic (peat) soils can be difficult (see Appendix B) and reliable measurements are rare.

4. Emission factors for drained organic soils in managed forests

CO_2

Whereas for the Tier 1 approach, soil C stocks of forest on *mineral soil* are assumed not to change with management, default emission factors for forestry on drained *organic soils* are as given in Table 1 below (IPCC 2003, 2006):

Table 1. CO_2 emission factors for drained organic soils in managed forests (corrected for below ground litter input

	Emission factor [t CO_2-C ha^{-1} yr^{-1}](range)	
Climate zone	IPCC (2006)[1]	Best estimate
Tropical	1.36 (0.82-3.82)	11 (8-13.5)[2,3]
Temperate	0.68 (0.41-1.91)	
Boreal	0.16 (0.08-1.09)	1.75 (1-4.3)[4,5,6]

[1]No literature references are given for these values, the rate of decomposition in tropical climate is assumed to be 2 times greater than in temperate climate; [2]Melling *et al*. 2007; [3]Couwenberg *et al*. (accepted); [4]Mäkiranta *et al*. 2007b; [5]Minkkinen *et al*. 2007; [6]Lohila *et al*. 2007

Current best estimates of CO_2 fluxes from losses in soil organic carbon are based on a limited number of measurements using trenching (see Appendix B; Melling *et al*. 2007; Mäkiranta *et al*. 2007; Minkkinen *et al*. 2007) or the eddy covariance technique (Lohila *et al*. 2007). Corrections for below ground litter input were made based on Melling *et al*. (2007) for tropical and Laiho *et al*. (2003) for boreal data (*cf*. Minkkinen *et al*. 2007a). Following the National Inventory Report of Finland for the years 1990-2007 (Statistics Finland 2009), values for below ground litter input of Laiho (2003) were halved to eliminate the input of fast-cycling material. As trenches were installed well before measurements commenced, 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*. 1997), which would result in an emission factor of 2.3 t CO_2-C ha^{-1} yr^{-1}.

While the best estimate values lie above the IPCC (2006) emission factors, often much lower emissions or considerable net uptake of carbon are cited in literature (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 likely more for tropical forests [Couwenberg *et al*. 2009]), but are small compared to direct gaseous emissions.

CH_4

Although methane emissions from ditches in forestry drained peatlands may be substantial (Minkkinen & Laine 2006; Minkkinen *et al*. 2007b), the extent of ditches will be small compared to the drained area, and even in light of the stronger radiative forcing of methane, its contribution will be small compared 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 compared to direct CO_2 fluxes from the drained area.

N_2O

With respect to N_2O emissions from (unfertilised) forestry drained peat soils, a distinction is made between nutrient rich and nutrient poor soils; the latter display near to negligible emissions (Table 2). The IPCC (2006) Guidelines provide one emission factor for the boreal and temperate climate zone together. The literature cited by IPCC (2006) to derive the emission factor covers boreal sites only. Additional data allow derivation of an emission factor for temperate drained forested peatlands (Table 2). The high value for forested nutrient rich soils is based on data from sites with Alder (*Alnus*) trees, an N-fixing plant species.
For lack of actual data, the IPCC (2006) emission factor for tropical (agro-)forestry drained peat soils was copied from the emission factor of temperate grasslands and croplands. Couwenberg *et al*. (2009) found that primary, secondary and drained tropical peatswamp forests are indiscernible from agroforestry sites on peat with respect to N_2O emissions. Emissions from forested tropical sites are lower than from forestry drained temperate European sites and more than two times smaller than assumed by IPCC (2006) (Table 1).

Table 2. N_2O emission factors for drained organic soils in managed forests

	Emission factor [kg N_2O-N ha^{-1} yr^{-1}] (range)	
Climate zone	IPCC (2006)	Best estimate
Tropical	8 (0-24)	3.4 (-0.5-13.4)[3]
Temperate, nutrient poor soils		0.6 (0.2-1.3)[4,5]
Temperate, nutrient rich soils		6.4 (0.7-17)[5,6,7,8,9,10]
Boreal[1], nutrient poor soils	0.1 (0.02-0.3)[2]	
Boreal[1], nutrient rich soils	0.6 (0.16-2.4)[2]	

[1]Reference in IPCC (2006) is to 'temperate and boreal', but the literature cited in all stems from boreal sites; [2]for references see IPCC (2006), supported by Alm *et al*. (2007); [3]Couwenberg *et al*. (2009); [4]Von Arnold *et al*. (2005a, 2005b, 2005c); [5]Ernfors (2009) ; [6]Brumme *et al*. (1999); [7]Klemedtson *et al*. (2005); [8]Augustin (2003); [9]Augustin & Merbach (1998); [10]Augustin *et al*. (1998).

5. Emission factors for cultivated organic soils (croplands and grasslands)

CO_2

The basis for much of the IPCC (2006) default emission factors for croplands on peat soil lies in subsidence data combined with generic values for the oxidative component (*cf*. Appendix B). Although these values may capture general trends, they are not precise and show large variation. The IPCC (2006) emission factors are provided for non-standard climate zones (from Ogle *et al*. 2003) that coincide with the FAO (2001) zones only to some extent.

Table 3. CO_2 emission factors for cultivated organic soils (croplands and grasslands)

	Emission factor [t CO_2-C ha^{-1} yr^{-1}] (range)	
Climate zone	IPCC (2006)	Best estimate[2]
Tropical/sub-tropical	20.0 ± 90%	
Warm temperate	10.0 ± 90%	
Boreal/cool temperate	5.0 ± 90%	
Tropical		11 (8-13.5)[3]
Temperate (grassland only)		5.5 (4.1-7.6)[4,5,6,7]
Boreal (cropland and grassland)		4.8 (-0.7-11.2)[8,9,10]
Boreal cropland[1]		6.8 (2.1-11.2)[8,9]
Boreal grassland		2.6 (-0.7-7.5)[8,9,10]

[1]Includes fallow lands; [2]Corrected for harvested biomass; [3]Couwenberg *et al.* (2009); [4]Mundel (1976); [5]Jacobs et al. (2003); [6]Veenendaal et al. (2007); [7]Beyer (2009); [8]Maljanen *et al.* (2001, 2004); [9]Lohila *et al.* (2004); [10]Shurpali *et al.* (2009).

Current best (conservative) estimates for drained tropical peat soils under cropland are derived from subsidence studies assuming 40% of height loss caused by oxidation (Couwenberg *et al*. 2009). Direct CO_2 flux measurements from temperate croplands on peat soil are not (yet) available. Estimates based on subsidence (Kasimir-Klemedtsson *et al*. 1997; Höper 2007) are highly variable and at times arrive at extreme values. Emissions from temperate croplands on peat soil may be expected to surpass those from boreal sites. Additional soil carbon losses from croplands through 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.

CH_4

See under Forestry. Methane emissions from rice paddies on peat soil (Furukawa *et al*. 2005; Hadi *et al*. 2005) are within the range of the IPCC (2007) default emission factor.

N_2O

While current best estimates for N_2O emissions from tropical grasslands (incl. abandoned lands) are much lower than the IPCC (2006) default value, emissions from fertilized croplands on tropical peat soil by far exceed this emission factor (Table 4). Nitrous oxide emissions are particularly high upon fertilizer application to wet peat soil and likely the emission factor for fertilizer-N inputs should be much higher than the default 0.01 kg N_2O-N per applied kg fertilizer N. With respect to nitrous oxide emissions from fertilized cropland on tropical peat soil, there is a need for further studies and proper land use guidelines. Emissions from boreal soils show considerably winter fluxes related to freeze-thaw cycles. These winter fluxes explain why fluxes are comparable to temperate areas.

Table 4. N_2O emission factors for cultivated organic soils (croplands and grasslands)

Climate zone	Emission factor [kg N_2O-N ha^{-1} yr^{-1}] (range) IPCC (2006)	Best estimate[2]
Tropical	16 (5-48)	52 (-1.1-252)
Cropland		107 (13-252)[3]
Grassland/abandoned[1]		4.6 (-1.1-23)[4]
Temperate	8 (2-24)	5.8 (-3.8-56)[4]
Boreal		6.8 (-0.8-37)[5,6,7]

[1]unfertilized; [2] corrected for fertilizer application using IPCC (2006) default of 0.01 kg N_2O-N per applied kg fertilizer N; [3]Takakai *et al*. (2006), [4]Couwenberg *et al*. (2009); [5]Nykänen *et al*. (1995); [6]Maljanen *et al* (2003); [7]Regina *et al*. (2004);

6. Emission factors for managed wetlands (peat extraction)

Estimating CO_2 emissions from lands undergoing peat extraction has two basic elements: on-site emissions from peat deposits during the extraction phase and off-site emissions from the use of the peat, either for energy or horticultural purposes (IPCC 2006). Off-site emissions from energy use are reported in the energy sector; those from horticultural use of peat must be accounted under the AFOLU sector. The latter 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. Recently, 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 5). Direct measurements from temperate peat extraction areas are lacking, but emissions likely surpass those from boreal sites.

Table 5. CO_2 emission factors for lands managed for peat extraction

Climate zone	Emission factor [t CO_2-C ha^{-1} yr^{-1}] (range) IPCC (2006)	Best estimate
Tropical	2.0 (0.06-7.0)[2]	8[5]
Boreal & temperate, nutrient rich	1.1 (0.03-2.9)[3]	
Boreal & temperate, nutrient poor	0.2 (0-0.6)[4]	
Boreal, mining areas		2.5 (1.0-11.2)[6,7,8]
Temperate, abandoned[1]		1.9 (0.1-4.4)[9,10,11]

[1]areas with high water levels, partly spontaneously revegetated; [2]calculated from the relative difference between nutrient poor and rich boreal & temperate; [3]default for temperate when nutrient status unknown; [4]default for boreal when nutrient status unknown; [5]Couwenberg *et al*. (2009), emissions from shallow drained bare peat; [6]Alm *et al*. (2007), [7]Sundh *et al*. 2000; [8]Shurpali *et al*. 2008; [9]Flessa *et al*. (1997); [10]Bortoluzzi *et al*. (2006); [11]Müller *et al*. (1997); [12]Drösler (2005).

The contribution of CH_4 and N_2O emissions to the global warming potential of peat extraction sites is limited (Table 6)

Table 6. Global Warming Potential for lands managed for peat extraction

Climate zone	Global Warming Potential[1] [t CO_2-C-eq. ha^{-1} yr^{-1}] (range)
Boreal, mining areas	3[2,3]
Boreal, stockpiles	43[2]
Boreal, combined	7.3 (5.2-10.1)[2]

[1]calculated using the 100 year conversion factors for CH_4 and N_2O; [2]Alm et al. (2007), combined value departs from 5-10% of the area occupied by stockpiles; [3]Sundh et al. (2000), CO_2 and CH_4 only;

The rewetting of drained peatlands (e.g. after peat extraction) entails many benefits (IPCC 2006) among which reduction of CO_2 emissions from peat decomposition. After rewetting, an increase in CH_4 emissions may be expected that (partly) offsets CO_2 emission reductions. These CH_4 emissions are considered anthropogenic and must be accounted. The overall result of rewetting is likely a reduction in global warming potential (Wilson *et al*. 2008), but generalised emission factors are not yet available.

7. Peat fires

While the IPCC (2006) Guidelines cover CO_2 and non-CO_2 emissions from fires, these only cover above-ground carbon stocks (biomass and dead organic material) and fail to address losses from burning peat. Compared to vegetation fires, the uncertainties of emission estimates of 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 type of emissions must be determined, which is only feasible in higher Tier levels.

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Appendix A: Organic soils (FAO 1998, 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 percent (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 percent 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]) percent or more organic carbon in the fine earth (by mass); ***or***
   b. 18 percent or more organic carbon in the fine earth (by mass).

From the **FAO (1998)** key to reference soil groups:
Organic soils (histosols): 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 percent (by weight) organic carbon (35 percent 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 percent or more organic carbon.

A histic horizon must have:

1. *either* - 18 percent (by weight) organic carbon (30 percent organic matter) or more if the mineral fraction comprises 60 percent or more clay;
   or - 12 percent (by weight) organic carbon (20 percent organic matter) or more if the mineral fraction has no clay;
   or - a proportional lower limit of organic carbon content between 12 and 18 percent if the clay content of the mineral fraction is between 0 and 60 percent. If present in materials characteristic for andic horizons, the organic carbon content must be more than 20 percent (35 percent 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.

FOA (2006/7):
Histosols comprise soils formed in *organic material*. These vary from soils developed in predominantly moss peat in boreal, arctic and subarctic regions, via moss peat, reeds/sedge peat (fen) and forest peat in temperate regions to mangrove peat and swamp forest peat in the humid tropics. Histosols are found at all altitudes, but the vast majority occurs in lowlands. Common names are *peat soils*, *muck soils*, *bog soils* and *organic soils*. Many Histosols belong to: *Moore*, *Felshumusböden* and *Skeletthumusböden* (Germany); *Organosols* (Australia); *Organossolos* (Brazil); *Organic order* (Canada); and *Histosols* and *Histels* (United States of America).

Summary description of Histosols
Connotation: Peat and muck soils; from Greek *histos*, tissue.
Parent material: Incompletely decomposed plant remains, with or without admixtures of sand, silt or clay.
Environment: Histosols occur extensively in boreal, arctic and subarctic regions. Elsewhere, they are confined to poorly drained basins and depressions, swamp and marshlands with shallow groundwater, and highland areas with a high precipitation–evapotranspiration ratio.
Profile development: Mineralization is slow and transformation of plant remains through biochemical disintegration, and formation of humic substances creates a surface layer of mould with or without prolonged water saturation. Translocated organic material may accumulate in deeper tiers but is more often leached from the soil.

Regional distribution of Histosols
The total extent of Histosols in the world is estimated at some 325–375 million ha, the majority located in the boreal, subarctic and low arctic regions of the Northern Hemisphere. Most of the remaining Histosols occur in temperate lowlands and cool montane areas; only one-tenth of all Histosols are found in the tropics. Extensive areas of Histosols occur in the United States of America and Canada, western Europe and northern Scandinavia, and in northern regions east of the Ural mountain range. Some 20 million ha of tropical forest peat border the Sunda shelf in Southeast Asia. Smaller areas of tropical Histosols are found in river deltas, e.g. in the Orinoco Delta and the delta of the River Mekong, and in depression areas at some altitude.

Management and use of Histosols
The properties of the organic material (botanical composition, stratification, degree of decomposition, packing density, wood content, mineral admixtures, etc.) and the type of peat bog (basin peat [fen], raised bog, etc.) determine the management requirements and use possibilities of Histosols. Histosols without prolonged water saturation are often formed in cold environments unattractive for agricultural use. Natural peats need to be drained and, normally, also limed and fertilized in order to permit cultivation of normal crops. Centrally guided reclamation projects are almost exclusive to the temperate zone, where millions of hectares have been opened. In many instances, this has initiated the gradual degradation, and ultimately the loss, of the precious peat. In the tropics, increasing numbers of landless farmers venture onto the peat lands, where they clear the forest and cause raging peat fires in the process. Many of them abandon their land again after only a few years; the few that succeed are on shallow, topogenous peat. In recent decades, increasing areas of tropical peat land have been planted to oil-palm and pulp wood tree species such as *Acacia mangium*, *Acacia crassicarpa* and *Eucalyptus* sp. This practice may be less than ideal but it is far less destructive than arable subsistence farming.
Another common problem encountered when Histosols are drained is the oxidation of sulphidic minerals, which accumulate under anaerobic conditions, especially in coastal regions. The sulphuric acid produced effectively destroys productivity unless lime is applied copiously, making the cost of reclamation prohibitive.
In summary, it is desirable to protect and conserve fragile peat lands because of their intrinsic value (especially their common function as sponges in regulating stream flow and in supporting wetlands containing unique species of animals) and because prospects for their sustained agricultural use are meagre. Where their use is imperative, sensible forms of forestry or plantation cropping are to be preferred over annual cropping, horticulture or, the worst option, harvesting of the peat material for power generation or production of horticultural growth substrate, *active carbon*, flower pots, etc. Peat that is used for arable crop production will mineralize at sharply increased rates because it must be drained, limed and fertilized in order to ensure satisfactory crop growth. Under these circumstances, the drain depth should be kept as shallow as possible and prudence exercised when applying lime and fertilizers.

Appendix B: Flux measurements

Measuring net CO_2 fluxes is a difficult task. Many published CO_2 flux data from peat soils are based on static chamber measurements where an opaque chamber is placed airtight on the soil and changes in gas concentration can be assessed. Such ‘dark chamber’ measurements cover not only heterotrophic decomposition of soil organic matter, but also autotrophic emissions from the living low vegetation as well as root respiration. Whereas living vegetation can simply be removed, excluding root respiration is much more difficult. Root respiration encompasses autotrophic activity of plant roots as well as heterotrophic activity in the rhizosphere, including decomposition of root exudates and recently dead root material. By using dark chambers also the photosynthetic capture of CO_2 by the system is ignored and dark chamber flux measurements generally result in overestimations of CO_2 emissions.

Transparent chambers that allow for accounting photosynthesis (i.e. uptake of CO_2 by the vegetation) can be used to measure the true net exchange of CO_2 with the atmosphere of the total ecosystem. After accounting for changes in standing biomass and litter, the net ecosystem CO_2 exchange can be used as a measure for emissions from the soil. With a rigorous flux measurement scheme in combination with monitoring of site conditions at a temporally higher resolution, emissions can be modelled continuously over the year, allowing for robust annual emission estimates from peat decomposition.

Similar to clear chambers, eddy covariance measurements allow for measurement of net CO_2 exchange with the atmosphere of the total ecosystem, also in case of forested ecosystems. Also here changes in biomass and litter stocks must be accounted for and these can be substantial particularly in secondary and selectively logged forests, but also in natural forests (*cf*. Luyssaert *et al*. 2008; Lewis *et al*. 2009). Whereas above ground tree biomass assessments are common and methods well developed, this much less applies to non-arboreal biomass, litter stocks and particularly below-ground biomass.

In forested ecosystems changes in soil organic carbon (CO_2 fluxes) often are assessed using dark chambers while attempting to exclude root respiration. Various methods have been developed to separate the various soil respiration components in forested ecosystems (see Kuzyakov 2006 for a review). Isotopic techniques are either only applicable under laboratory conditions, imprecise or very expensive. Non-isotopic techniques are generally destructive or change the system in such a way that it becomes difficult to make robust assessments of the relative importance of root respiration vs. peat decomposition. One often applied method to exclude root respiration is so-called ‘trenching’, where cylinders are driven into the soil to sever roots and thus exclude root respiration from future measured fluxes. As the severed fine roots may continue respiration for several months (or longer) and ultimately will be decomposed themselves, trenching must be done well before flux measurements are carried out (Mäkiranta et al. 2008). Trenching is known to affect water and temperature regimes and removes the rhizosphere priming effect, whereby the presence of roots stimulates microbial decomposition of soil organic matter. Taking all things into account, trenching likely results in an underestimation of actual CO_2 fluxes from decomposition of soil organic material. In order to calculate the CO_2 balance of the soil, the measured values must be corrected for input of slowly decomposing belowground organic material (below ground litter) (Minkkinen *et al*. 2007a).

Alternatively, CO_2 emissions from drained peat soils can be estimated by measuring subsidence of the peat (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 losses in surface height in the first years after drainage. Subsequent to consolidation there is secondary subsidence caused by shrinkage and oxidation of the peat. In addition, wind and water erosion, leaching of soluble organic matter and fire may contribute to the loss of matter and height. Only oxidation of the peat results in direct on-site CO_2 emissions to the atmosphere and other processes (particularly shrinkage) must be excluded to arrive at emission values based on secondary subsidence rates. Estimates for the oxidative component to secondary peat subsidence vary greatly and generalisation is difficult and often inappropriate. More robust assessment of the oxidative component to subsidence would be opportune considering 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 disturbances that result in ebullition (bubbling up), which is then either captured in the chamber or not. Methane emissions are highly variable in time and space. The same applies to N_2O emissions, which can be very erratic.

Summary of emission factors for CO_2 and N_2O. Values in **bold** are considerably higher than IPCC (2006); values in *underlined italics* are considerably lower than IPCC (2006).

		t CO_2-C ha^{-1} yr^{-1} (range)		kg N_2O-N ha^{-1} yr^{-1} (range)	
Climate Zone	Land use	IPCC (2006)	This study	IPCC (2006)	This study
Tropical	(Agro-)forestry	1.36 (0.82-3.82)	**11** (8-13.5)	8 (0-24)	*3.4* (-0.5-13.4)
	Cropland[1]	20 ± 90%	*11* (8-13.5)	16 (5-48)	**107** (13-252)
	Grassland				*4.6* (-1.1-23)
	Peat Mining	2.0 (0.06-7.0)	**8**	–	–
Temperate	Forestry, poor soils	0.68 (0.41-1.91)	–	–	0.6 (0.2-1.3)
	Forestry, rich soils				6.4 (0.7-17)
	Cropland	10.0 ± 90%		8 (2-24)	5.8 (-3.8-56)
	Grassland		*5.5* (4.1-7.6)		
	Peat mining, rich soils	1.1 (0.03-2.9)	**1.9**[2] (0.1-4.4)	–	–
	Peat mining, poor soils	0.2 (0-0.6)			
Boreal	Forestry, poor soils	0.16 (0.08-1.09)	**1.75** (1-4.3)	0.1 (0.02-0.3)	
	Forestry, rich soils			0.6 (0.16-2.4)	
	Cropland	5.0 ± 90%	6.8 (2.1-11.2)	–	6.8 (-0.8-37)
	Grassland		*2.6* (-0.7-7.5)		
	Peat mining, rich soils	1.1 (0.03-2.9)	**6.8**[3] (4.6-9.1)	–	2.1[3] (2.0-2.2)
	Peat mining, poor soils	0.2 (0-0.6)			

[1] CH_4 emissions from rice paddies on peat soil fall within the IPCC (2006) default range

[2] refers to abandoned peat mining areas with high water levels. Emissions from active peat mining sites are likely larger than in the boreal zone;

[3] 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}

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