CHAPTER 2

DRAINED INLAND ORGANIC SOILS

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2.1 INTRODUCTION

This Chapter provides supplementary guidance on estimating greenhouse gas emissions and removals from drained inland organic soils for the following land-use categories as defined in the *2006 IPCC Guidelines* Volume 4: Chapter 4 (Forest Land), Chapter 5 (Cropland), Chapter 6 (Grassland), Chapter 7 (Wetlands), Chapter 8 (Settlements) and Chapter 9 (Other Land). Managed coastal organic soils are covered in Chapter 4. The re-wetting and restoration of managed peatlands and organic soils is considered in Chapter 3 of this Supplement.

Organic soils are defined in Chapter 3 Annex 3A.5 of the *2006 IPCC Guidelines*. The guidance in this Chapter applies to all organic soils that are in the state of being drained or are newly drained. Anthropogenic greenhouse gas emissions persist as long as the drainage persists. This means that the water table level is below natural levels. Within each land-use category water table level is manipulated to varying degrees depending on land-use purpose, e.g. for cultivating cereals, rice, or for aquaculture, which can be reflected by different drainage classes.

This Chapter clarifies the *2006 IPCC Guidelines* Volume 4 by summarizing all emission factors and harmonizing the methods for organic soils in all land-use types. On the basis of recent advances in scientific information, this Chapter also updates, improves, and completes methodologies and emission factors for greenhouse gas emissions and removals of the *2006 IPCC Guidelines* and fills gaps where new scientific knowledge now allows implementation of robust methodologies and emission factors at the Tier 1 level.

This Chapter updates the *2006 IPCC Guidelines* for:

- CO_2 emissions and removals from organic soils (referring to *2006 IPCC Guidelines* Volume 4, Chapters 4 to 9);
- CH_4 emissions from organic soils (referring to *2006 IPCC Guidelines* Volume 4, Chapter 7);
- N_2O emissions from organic soils (referring to *2006 IPCC Guidelines* Volume 4, Chapter 11).

This Chapter gives new guidance not contained in the *2006 IPCC Guidelines* by:

- providing methodologies and emission factors for CH_4 emissions from drainage ditches (referring to *2006 IPCC Guidelines* Volume 4, Chapters 4 to 9);
- providing methodologies and emission factors for off-site CO_2 emissions associated with dissolved organic carbon (DOC) release from organic soils to drainage waters (referring to *2006 IPCC Guidelines* Volume 4, Chapters 4 to 9);
- providing generic guidance for higher Tier methods to estimate these fluxes, as well as CO_2 emissions associated with other forms of waterborne carbon loss, specifically particulate organic carbon (POC) (referring to *2006 IPCC Guidelines* Volume 4, Chapters 4 to 9).

2.2 LAND REMAINING IN A LAND-USE CATEGORY

The *2006 IPCC Guidelines* provide guidance for carbon stock changes in the carbon pools above-ground and below-ground biomass, dead wood and litter for managed land on organic soils. This Chapter updates the *2006 IPCC Guidelines* for the combined soil organic carbon and belowground litter pool in organic soils. The nature of organic soils makes separation of the two pools difficult, so inventory compilers can integrate these two pools.

2.2.1 CO_2 emissions and removals from drained inland organic soils

This section deals with the impacts of drainage and management on CO_2 emissions from organic soils due to peat decomposition and loss of dissolved organic carbon (DOC) in drainage waters. DOC losses lead to off-site CO_2 emissions. There are also erosion losses of particulate organic carbon (POC; see Appendix 2a.1) and dissolved inorganic carbon (DIC) losses in drainage waters. At present the science is not advanced enough to separate the DIC sources from autotrophic and heterotrophic respiration, or sources within the peat from adjacent or underlying weathering sources, but only DIC from heterotrophic respiration of the peat is a potential anthropogenic CO_2 source. Therefore, no guidance on DIC is provided here. General information and guidance for estimating changes in soil C stocks are provided in the *2006 IPCC Guidelines* in Volume 4, Chapter 2, Section 2.3.3 (including Equations), and this section needs to be read before proceeding with a consideration of specific guidance dealing with organic soil C stocks. This guidance is based on the observation that in drained inland organic soils, emissions persist as long as the soil remains drained or as long as peat remains (Wösten *et al.,* 1997; Grønlund Grønlund *et al.,* 2008; Deverel and Leighton, 2010).

Equation 2.3 in the *2006 IPCC Guidelines*, Volume 4, Chapter 2 refers to annual carbon stock changes for a stratum of a land-use category as a sum of changes in all pools. This section addresses the stratum of a land-use category on drained inland organic soils. The Equation is repeated here as Equation 2.1 to demonstrate how the guidance in this *Wetlands Supplement* links to the *2006 IPCC Guidelines*.

EQUATION 2.1

ANNUAL CARBON STOCK CHANGES FOR A STRATUM OF A LAND-USE CATEGORY AS A SUM OF CHANGES IN ALL POOLS

(EQUATION 2.3 IN THE *2006 IPCC GUIDELINES*, VOLUME 4, CHAPTER 2)

$$\Delta C_{LU_i} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

Where:

ΔC_{LUi} = carbon stock changes for a stratum of a land-use category

Subscripts denote the following carbon pools:

AB = above-ground biomass

BB = below-ground biomass

DW = deadwood

LI = litter

SO = soils

HWP = harvested wood products

The guidance for the carbon pools above-ground biomass, below-ground biomass, deadwood, litter and harvested wood products in the *2006 IPCC Guidelines* remains unchanged. This section of the *Wetlands Supplement* updates and complements the guidance for the soils pool on drained inland organic soils (ΔCso in Equation 2.1) as shown in Equation 2.2. For all practical purposes, the belowground litter pool is indistinguishable from soil organic matter pool in peatlands and the two pools are treated as one. Change in soil organic carbon consists of on-site CO_2 emissions/removals of the organic soil from mineralization and sequestration processes (CO_2-$C_{soil-onsite}$), off-site CO_2 emissions from leached carbon from the organic soil (CO_2-C_{DOC}) and anthropogenic peat fires. Countries are encouraged to consider CO_2-C_{POC} when using higher tier methodologies (see Appendix 2a.1). CO_2 emissions from peat fires have not been explicitly addressed in Equation 2.3 of the *2006 IPCC Guidelines*, vol. 4, chapter 2, but can be important on drained inland organic soils. To maintain consistency with the *2006 IPCC Guidelines*, CO_2 emissions from peat fires are not included in Equation 2.2 either, but will have to be reported separately as L_{fire} (Section 2.2.2.3).

EQUATION 2.2

ANNUAL CARBON EMISSIONS AND REMOVALS (EXCEPT FIRE) IN THE SOILS POOL FOR THE STRATA OF A LAND-USE CATEGORY ON DRAINED INLAND ORGANIC SOILS

$$\Delta C_{SO} = -\lfloor CO_2 - C_{soil-onsite} + CO_2 - C_{DOC} \rfloor$$

ΔC_{SO} = carbon stock changes expressed as annual carbon emissions and removals in the soils pool on drained inland organic soils, tonnes C yr^{-1}

CO_2-$C_{soil-onsite}$ = on-site CO_2-C emissions/removals by drained inland organic soils, tonnes C yr^{-1}

CO_2-C_{DOC} = off-site CO_2-C emissions from dissolved organic carbon, tonnes C yr^{-1}

2.2.1.1 ON-SITE CO_2 EMISSIONS/REMOVALS FROM DRAINED INLAND ORGANIC SOILS (CO_2-$C_{SOIL-ONSITE}$)

This section gives supplementary guidance for CO_2 emissions from drained inland organic soils in all land-use categories as defined in the *2006 IPCC Guidelines* Volume 4, Chapter2, Section 2.3.3. The IPCC land-use categories are discussed in Chapter 4 (Forest Land), Chapter 5 (Cropland), Chapter 6 (Grasslands), Chapter 7 (Wetlands), Chapter 8 (Settlements) and Chapter 9 (Other Land). Flooded Lands (Chapter 7) are not included in this *Wetlands Supplement*.

Guidance is given for CO_2 emissions from the soil carbon pool in drained organic soils in line with the *2006 IPCC Guidelines* Volume 4, Chapter 2, Section 3.3. Guidance for changes in the carbon pools in aboveground and belowground biomass, dead organic matter, and litter on these lands is provided in the *2006 IPCC Guidelines* and remains unchanged.

CHOICE OF METHOD

The most important factors that affect on-site CO_2 emissions/removals from drained inland organic soils are land-use and climate. Other factors such as nutrient status of the soil and drainage level affect emissions and can be factored in where appropriate. It is *good practice* to stratify land-use categories by climate domain (Table 4.1 of the *2006 IPCC Guidelines* Volume 4 Chapter 4), nutrient status (*2003 GPG LULUCF* and *2006 IPCC Guidelines* Volume 4, Chapter 7, Section7.2.1.1) and drainage class (shallow or deep) according to the stratification in Table 2.1.

Drainage class is defined as the mean annual water table averaged over a period of at least three to five years; the shallow-drained class is defined as the mean annual water table depth of less than 30 cm below the surface; the well-drained class is defined as the mean annual water table depth of 30 cm and deeper below the surface.

For Tier 1 methods, if the typical range of mean annual water table levels of drained inland organic soils for each land-use category is unknown, the default is that the organic soil is deeply drained (water-table depth is specific for land-use categories and climate domains) because deeply drained conditions are the most widespread and suitable for a wide range of management intensities. Higher Tier methods could further differentiate the drainage intensity within land-use categories if there are significant areas which differ from the default deeply drained conditions.
Figure 2.5 in *2006 IPCC Guidelines* Volume 4, Chapter 2, Section 2.3.3 provides the decision tree for identification of the appropriate Tier to estimate CO_2 emissions from drained inland organic soils by land-use category.

Tier 1

The basic methodology for estimating annual carbon loss from drained inland organic soils was presented in Section 2.3.3 and Equation 2.26 in Volume 4 of the *2006 IPCC Guidelines*. Equation 2.3 here derives from Equation 2.26 in *2006 IPCC Guidelines* Volume 4 with stratification of land-use categories by climate domain and nutrient status. Nutrient status and drainage classes only need to be differentiated for those land-use categories and climate domains for which emission factors are differentiated in Table 2.1.

EQUATION 2.3
ANNUAL ON-SITE CO_2-C EMISSIONS/REMOVALS FROM DRAINED INLAND ORGANIC SOILS

$$CO_2 - C_{soil-onsite} = \sum_{c,n,d} (A \bullet EF)_{c,n,d}$$

Where:

CO_2-$C_{soil-onsite}$ = Annual on-site CO_2-C emissions/removals from drained inland organic soils, tonnes C yr^{-1}

A = Land area of drained inland organic soils in a land-use category in climate domain c, nutrient status n, and drainage class d, ha

EF = Emission factors for drained inland organic soils, by climate domain c, nutrient status n, and drainage class d, tonnes C ha^{-1} yr^{-1}

Tier 2

The Tier 2 approach for CO_2 emissions/removals from drained inland organic soils incorporates country-specific information in Equations 2.2 and 2.3 to estimate the emissions/removals. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Improvements to the Tier 1 approach may include: 1) a derivation of country-specific emission factors; 2) specification of climate sub-domains considered more suitable for the country; 3) a finer, more detailed classification of management systems with a differentiation of land-use intensity classes; 4) a differentiation by drainage classes; or 5) a finer, more detailed classification of nutrient status.

It is *good practice* to derive country-specific emission factors if representative experimental data are available. Methodologies and measurement techniques shall be compatible with the scientific background for the Tier 1 emission factors in Box 2.1. Moreover, it is *good practice* to use a finer classification for climate and management systems, in particular drainage classes, if there are significant differences in measured carbon loss rates among these classes. Note that any country-specific emission factor must be accompanied by sufficient national or regional land-use/management activity and environmental data to represent the appropriate climate sub-domains and management systems, since 1990, for the spatial domain for which the country-specific emission factor is applied.

The general considerations of the *2006 IPCC Guidelines,* Volume 4, Chapter 2, Section 2.3.3 also apply here.

Tier 3

CO_2 emissions from drained inland organic soils can be estimated with either model or measurement approaches. Dynamic, mechanistic models will typically be used to simulate underlying processes while capturing the influence of land-use and management, particularly the effect of seasonally variable levels of drainage on decomposition (van Huissteden *et al.,* 2006). The general considerations for mineral and organic soils in the *2006 IPCC Guidelines* Volume 4, Chapter 2, Section 2.3.3 also apply here. It is *good practice* to transparently describe the methodologies and models, document the considerations for choosing and applying the model in the inventory and provide evidence that it represents the national circumstances according to the guidance in the *2006 IPCC Guidelines* Volume 4, Chapter 2, Section 5 and Chapter 7 of this *Wetlands Supplement*.

BOX 2.1

SCIENTIFIC BACKGROUND FOR DEVELOPING CO_2 EMISSION/REMOVAL FACTORS FOR PEAT CARBON FROM THE SCIENTIFIC LITERATURE IN TABLE 2.1

CO_2 emissions were obtained by two well-established methods: (1) gain-loss or flux method: fluxes have been studied extensively using gas exchange methods at frequencies of seconds to weeks over measurement periods of up to few years or (2) stock difference method: observed subsidence of the peat layer at frequencies of months to years over a year or longer periods of time.

Gain-loss or flux method

The gain-loss method either used chamber based techniques or eddy covariance in combination with data about partial carbon fluxes in pools. CO_2 emission measurement techniques based on dark chambers can only determine total respiration (autotrophic plus heterotrophic) from the peat surface over relatively small time periods, and small surface area. The balance of net emission or net removal depends on the conditions for growth and decomposition, typical for nutrient poor and nutrient rich peatlands (Ojanen et al 2012). The role of fine root litter and turnover rate is decisive for the peat net C loss or gain, but is hard to measure directly (Finér *et al.,* 2011; Gaudinski *et al.* 2010; Sah *et al.,* 2010). Root autotrophic respiration has been separated in chamber gas exchange studies and the measurements made at least one year after the trenching. In fertile sites, heterotrophic respiration rate has been found higher than in nutrient poor sites (von Arnold *et al.,* 2005c; Minkkinen *et al.,* 2007; Silvola *et al.,* 1996). Reported CO_2 emissions based on respiration chambers which included autotrophic respiration were converted to CO_2-$C_{soil\text{-}onsite}$ by applying site-specific ratios of heterotrophic respiration to total respiration and deducing aboveground litter input or also fine root litter when reported in the study. Dark chamber techniques have been applied in all land-use types in boreal and temperate climate zones.

CO_2 emission measurement techniques based on transparent chambers determine total net ecosystem exchange similar to eddy covariance techniques, but over relatively small time periods, and small surface area. Measured flux rates are aggregated to annual carbon balance by light and temperature response models (e.g. Bellisario, 1998; Alm *et al.,* 1999; Drösler 2005). Transparent chamber techniques have been applied in croplands, grasslands and peat extraction sites in boreal and temperate climate zones.

Eddy covariance studies can only determine total net ecosystem exchange, which includes autotrophic plus heterotrophic carbon fluxes from biomass and the peat surface. The observed flux needs to be converted to soil fluxes by deducing biomass growth and harvest. Reported CO_2 emissions-based eddy covariance which included changes in biomass carbon stocks were converted to CO_2-$C_{soil\text{-}onsite}$ fluxes (Equation 2.2) by applying ecosystem- and site-specific values of biomass growth and harvest. Eddy covariance techniques have been applied in all land-use types in boreal and temperate climate zones.

Subsidence method

The subsidence method measures the height loss of the peat surface using a network of subsidence markers. Peat oxidation/decomposition are obtained by converting the volume loss to carbon via bulk density, carbon content and the oxidized fraction of the volume lost as compared to compaction or consolidation (Grønlund *et al.,* 2008; Leifeld *et al.,* 2011).

Quality criteria for measurements used for emission factors

For the derivation of CO_2 emission factors, the following quality criteria were applied: Winter emissions can account for 10-30% of net annual emissions in boreal and northern temperate regions (Alm *et al.,* 1999). Therefore data were used which covered at least one full year of data, or at minimum in data-scarce climate zones, were representative for all seasons (e.g. rainy and dry season in the tropics). Measurement frequency adequately addressed seasonal variability of CO_2 fluxes. Study conditions were representative of regional management practices. Study sites were treated as independent data if they were in different peat complexes or under different hydrological management on the same peat complex, or under different land-use, or any combination of these three criteria. Studies experiencing fire in the measurement period were omitted so that the observed CO_2 emissions/removals could be fully attributed to CO_2-$C_{soil\text{-}onsite}$ (Equation 2.1).

Only observational studies were accepted for the derivation of emission factors, which have reported CO_2-$C_{soil\text{-}onsite}$ flux, so that the reported CO_2-$C_{soil\text{-}onsite}$ flux could be directly taken. Studies with artificial disturbance by root or litter removal or additions were accepted for deriving parameters, such as heterotrophic/autotrophic ratios. Studies were checked for methodological correctness and transparent documentation of methodology. Many studies do not report uncertainty associated with methodology, assumptions, measurement gaps and errors, aggregation in space and time, etc. This uncertainty could not be assessed from the literature so that there may be considerable uncertainty around individual data used in the derivation of emission factors. The confidence interval given in Table 2.1 mainly reflects the spatial and temporal variation in reported CO_2 emissions/removals.

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

All Tier 1 emission factors have been updated from the *2006 IPCC Guidelines* based on a large number of new measurement data in all land-use categories and climate zones. The new evidence allows for stratification of more land-use categories and climate domains by nutrient status than in the *2006 IPCC Guidelines*. In addition, temperate, nutrient-rich Grasslands are further stratified into shallow-drained (less than approximately 30 cm below surface) and well-drained. Within each land-use category, drained inland organic soils can experience a wide range of mean annual water table levels that depend upon regional climatic characteristics and specific land-use activity or intensity. For temperate Grasslands EF are given for shallow-drained (mean annual water table depth of less than 30 cm below the surface) and well-drained (mean annual water table depth of 30 cm or deeper below the surface). The shallow-drained and well-drained Grassland emission factors differ significantly. Without additional national information about mean annual water table and/or land-use intensity as proxy, countries should choose well-drained as default.

The *2003 GPG LULUCF* and *2006 IPCC Guidelines* (Volume 4, Chapter 7, Section 7.2.1.1) distinguish between nutrient-rich and nutrient-poor organic soils in some land-use categories and climate zones. This approach is maintained here, in line with guidance in the *2006 IPCC Guidelines*.

Default Tier 1 emission/removal factors for drained inland organic soils (Table 2.1) were generated using combination of subsidence and gain-loss data found in the literature as described in Box 2.1. The fluxes emerge predominantly from the drained, oxidized soil layer and thus reflect human-induced CO_2-C fluxes from the part of the soil profile affected by drainage, which can be deeper or shallower than the default 0 to 30 cm layer considered in the Tier 1 default methodology for mineral soils.

The CO_2 emission factors presented in Table 2.1 have been calculated as annual net change of the peat carbon plus belowground litter carbon in the different land-uses. In peat extraction sites, no vegetation is present so that the net change in peat carbon equals heterotrophic respiration. In drained Croplands or Grasslands where the annual biomass production stays at equilibrium the net change in peat carbon is assumed to equal heterotrophic respiration. Countries can refine these factors if appropriate data exist to factor out these inputs. In ecosystems where above-ground and below-ground biomass accumulates annually for several decades, such as peatlands drained for forestry, the annual production rate of above-ground litter (mosses, ground vegetation, leaves) can exceed the annual rate of decomposition in peat at least during the major part of the tree rotation cycle. In such cases the integrated C stocks of soil and below-ground litter may increase, and is displayed as net removal of CO_2 from the atmosphere (see e.g. Minkkinen *et al.*, 1999; Ojanen *et al.*, 2010, Ojanen *et al.*, 2012, Ojanen *et al.*, 2013).

Table 2.1 presents the CO_2 emission factors for Boreal and Temperate climate zones. The authors could not reach complete consensus on CO_2 emission factors for drained tropical peatlands. There has been some convergence of views between the author groups, but there still are a few outstanding issues and the group could not finalize them for the Second Order Draft. Appendix 2a.2 provides a summary of the issues involved and the progress made so far in the derivation of emission factors for drained tropical peatlands.

TABLE 2.1
TIER 1 CO_2 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES***

Land-Use Category		Climate / Vegetation Zone	Soil Emission Factor** (tonnes CO_2-C ha^{-1} yr^{-1})	95% Confidence Interval (centred on mean)		No. of sites	Citations
Forest Land, Drained	Nutrient-rich	# Boreal	0.390	-0.078	0.857	64	Komulainen *et al.*,1999; Lohila *et al.*, 2011; Minkkinen & Laine, 1998; Minkkinen *et al.*, 1999; Ojanen *et al*,. 2010, 2011, 2013; Simola *et al.*, 2012
	Nutrient-poor	# Boreal	0.947	0.555	1.338	65	Komulainen *et al.*, 1999; Laurila *et al.*, 2007; Lohila *et al.*, 2007; Minkkinen & Laine, 1998; Minkkinen *et al.*, 1999, 2007b; Ojanen *et al.*, 2010, 2013; Simola *et al.*, 2012
Forest Land, Drained		# Temperate	4.65	2.56	6.73	8	Glenn *et al.*, 1993; Minkkinen *et al.*, 2007b; Von Arnold *et al.*, 2005b, c
Grassland, Drained		# Boreal	5.73	2.89	8.57	8	Grønlund *et al.*, 2006; Krestapova & Maslo, 2004; Lohila *et al.*, 2004; Maljanen *et al.*, 2001a, 2004; Nykanen *et al.*, 1995; Shurpali *et al.*, 2009 ; Shurpali *et al.*, 2009
Grassland, Deep Drained < -30 cm, Poor		* Temperate	6.12	4.42	7.82	5	Kuntze, 1992, Hargreaves *et al.*, 2003, Drösler *et al.*, 2013
Grassland, Shallow Drained ≥ -30 cm, Poor		* Temperate	1.68	-0.364	3.72	6	Drösler *et al.*, 2013
Grassland, Deep Drained < -30 cm, Rich		* Temperate	5.90	4.84	6.97	35	Czaplak & Dembek, 2000; Drösler, *et al.*, 2013; Elsgaard *et al.*, 2012; Hoper, 2002; Kasimir-Klemedtsson *et al.*, 1997, Leifeld *et al.*, 2011; Lorenz *et al.*, 2002; Meyer *et al.*, 2001; Nieveen *et al.* 2005; Okruszko, 1989; Schothorst, 1976, Schrier-Uijl *et al*,. 2010, Weinzierl, 1997
Grassland, Shallow Drained ≥ -30 cm, Rich		* Temperate	3.21	1.22	5.20	13	Drösler *et al.*, 2013; Lloyd, 2006; Morrison *et al.*, 2013a
Cropland, Drained		* Boreal & Temperate	7.87	6.31	9.42	37	Drösler *et al.*,2013; Elsgaard *et al.*, 2012, Gronlund *et al.*, 2008, Kasimir-

						Klemedtsson *et al.,* 1997; Leifeld *et al.,* 2011; Maljanen *et al.,* 2001a, 2003a, b, 2004, 2007a,; Morrison *et al.,* 2013b
Wetland in Peat Production	* Boreal & Temperate	2.37	1.116	3.62	23	Ahlholm *et al.,* 1990; Drösler *et al.* 2013; Glatzel *et al.,* 2003; Hargreaves *et al,* 2003; Makiranta *et al.* 2007; McNeil & Waddington, 2003, Nykanen *et al.,* 1996; Shurpali *et al.,* 2008; Sundh *et al.,* 2000; Tuittila *et al.,* 1995; 2000, 2004; Waddington *et al.,* 2010

Using FAO Climate/Vegetation Zones from 2006 Guidelines, Vol 4, Ch 4, Fig 4.1, Tab 4.1

* Using IPCC Climate Zones from 2006 Guidelines, Vol 4, Ch 3, Fig 3A.5.1

** Mean

*** Table 2.1 presents the CO_2 emission factors for Boreal and Temperate climate zones only. Authors could not reach complete consensus on CO_2 emission factors for drained tropical peatlands. Appendix 2a.2 provides a brief summary of the issues involved and the progress made so far in derivation of CO_2 emission factors for drained tropical peatlands.

Common tropical plantations include oil palm, sago and Acacia. Plantations for food and oil crops like sago and oil palm should be classified under agriculture, while fibre plantations like Acacia may be classified as Forest Land. It is *good practice* to report plantations in the appropriate national land-use category according to the national forest definition.

Tier 2

The Tier 2 approach for C loss from drained inland organic soils incorporates country-specific information in Equation 2.2 to estimate the emissions. Also, Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Tier 2 emission factors by land-use category can, in general, be developed depending on a) climate, b) drainage lay-out and intensity, c) nutrient status and d) land-use intensity and practises.

Tier 2 emission factors could include the following refinements:

- Integration of belowground C inputs from root mortality;
- Use of country specific emission factors measured or calculated locally taking into account climatic factors that provide for wetter or drier drainage classes than those defined here;
- Use of adjusted emission factors measured or calculated locally taking into account slope factors (e.g. blanket bogs) that may promote wetter or drier drainage classes than those defined here;
- Derivation of EFs for boreal Forest Land by nutrition status (rich/poor) with use of appropriate and significantly different emission factors for organic soil CO_2 loss (See Table 2.1);
- Development of boreal and temperate Grassland EFs according to land-use intensity, for example to distinguish high-intensity (fertilized, ploughed and reseeded) Grassland from low-intensity permanent Grassland, or moorland rough grazing on drained blanket bogs.

CO_2 flux data, disaggregated by activity type should be used to develop more precise, locally appropriate emission factors, correcting for carbon losses through leaching of waterborne carbon. Additional guidance on how to derive these stock change factors is given in the Annex 2A.

Tier 3

A Tier 3 approach might use measurements or process-based models or other more elaborate approaches, adequately validated using observation data that take into account temporal and spatial variations. This approach involves a comprehensive understanding and representation of the dynamics of CO_2 emissions and removals on managed organic soils, including the effect of management practices, site characteristics, peat type and depth, etc. Tier 3 approaches could start by developing robust relationships between drainage or nutrient status and peat heterotrophic CO_2 emissions, which can be further refined by land- use category and fertilization. Establishing relationships between land-use category and litter above- and belowground C inputs will allow the mass balance calculation applied in the gain-loss method. Drained and managed peatlands go through a transition where carbon loss is rapid in the years immediately following drainage, and continues more slowly in subsequent years. Furthermore, forested peatlands undergo a cycle repeated after one or several decades, related to rotation of the tree cohorts. Models should describe the rotational variation in water tables.

At harvesting the peat surface is disturbed by machinery and may be amended for regeneration. Drainage systems may be renewed. These manipulations may affect the moisture, nutrient and temperature conditions and thereby the heterotrophic peat decomposition and emissions. Time-dependent rates capture more accurately land-use and management effects on emissions. Such models may calculate refined and stratified emission factors for CO_2.

In all cases, rigorous criteria must be applied so that any CO_2 emission/removal is neither under- nor overestimated.

CHOICE OF ACTIVITY DATA

Activity data consist of areas of land remaining in a land-use category on organic soils stratified by climate domains, soil nutrient status, drainage class or additional criteria such as management practices, and disturbance regimes. Total areas should be determined according to approaches laid out in Chapter 3 of the *2006 IPCC Guidelines* and should be consistent with those reported under other sections of the inventory. The estimation of CO_2 emissions/removals from drained inland organic soils will be greatly facilitated if this information can be used in conjunction with national soils and climate data, vegetation inventories, and other biophysical data. Stratification of land-use categories according to climate domains, based on default or country-specific classifications can be accomplished with overlays of land-use on suitable climate and soil maps.

It is *good practice* that the area of organic soils is constant over time unless it is demonstrated that the area of organic soils change (e.g. as organic soil disappears).

Tier 1

The Tier 1 approach requires area data of managed land with organic soils for each land-use category, for boreal, temperate and tropical climate domains. Classification systems for activity data that form the basis for a Tier 1 inventory are provided in the respective land-use Chapters of the *2006 IPCC Guidelines*.

Several institutions, including ISRIC and FAO have country-specific and global maps that include organic soils (http://www.fao.org/geonetwork/srv/en/main.home or http://www.isric.org/). A global consortium has been formed to make a new digital soil map of the world at fine resolution (http://www.globalsoilmap.net/).

The *2003 GPG LULUCF* and *2006 IPCC Guidelines* (Volume 4, Chapter 7, Section 7.2.1.1) distinguish between nutrient-rich and nutrient-poor organic soils in some land-use categories and climate zones. This approach is maintained here, in line with guidance in the *2006 IPCC Guidelines*. Nutrient-poor bogs predominate in boreal regions, while in temperate regions, nutrient-rich fens and mires are more common. Types of peatlands can be inferred from the end-use of peat: sphagnum peat, dominant in oligotrophic (nutrient-poor) bogs, is preferred for horticultural uses, while sedge peat, more common in minerotrophic (nutrient rich) fens, is more suitable for energy generation. Boreal countries that do not have information on areas of nutrient-rich and nutrient-poor peatlands should use the emission factor for nutrient-poor peatlands. Temperate countries that do not have such data should use the emission factor for nutrient-rich peatlands. Only one default factor is provided for tropical regions, so disaggregating peatland area by soil fertility is not necessary in the tropical climate zone using the Tier 1 method. Due to lack of data, rice fields on tropical organic soils are not disaggregated by water management regimes.

The areas of shallow-drained and well-drained inland organic soils with Grasslands need to be derived from national data. Data from water management plans, such as target water table levels can serve as source of information. Land-use intensity, e.g. the time of the first cut of Grassland, grazing intensity or animal production levels can serve as a proxy as well as restrictions imposed by water management or biodiversity management (e.g. riparian zones, buffer zones, nature conservation for species or habitats with typical water regime).

Without additional national information about mean annual water table and/or land-use intensity as proxy, countries should choose well-drained as default.

Tier 2

Activity data under Tier 2 are generally derived following the methods presented in Chapter 3 of the *2006 IPCC Guidelines* and areas with organic soils have to be differentiated from those with mineral soils. All management practices for land remaining in a land-use category are assumed to result in persistent emissions from soils as long as the management system remains in place or as long as the land falls under the definition of organic soils. Activity data should be disaggregated by drainage depth and/or nutrient status to improve the accuracy of the inventory if different land management systems use different drainage depths and/or nutrient levels, and if appropriate emissions factors are available. In general, practices that increase C stocks in mineral soils by increased organic material input (fertilization, liming, etc.) do not have a sequestration effect in drained organic soils.

The combination of land-use databases and soil maps or spatially explicit data allow to delineate the combinations of land-use categories, climate domains, drainage classes and management systems and their changes over time on organic soils.

Stratification that allows consistent reporting under the UNFCCC and the Kyoto Protocol, in case the activity Wetland Drainage and Rewetting is elected, separates drained, undrained, and rewetted organic soils over the time series. Data and their documentation could combine information from a land-use matrix specifically made for organic soils. Stratification needs to be consistently applied across the entire time series.

Information sources about drainage with adequate disaggregation may include:

- National land-use statistics, land-use maps and soil maps, maps of water and nature conservation zones with restrictions for water management, wetlands
- National water management statistics: in most countries, the agricultural land base including Croplands is usually surveyed regularly, providing data on distribution of different land-uses, crops, tillage practice and other aspects of management, often at sub-national regional level. These statistics may originate, in part,

from remote sensing methods, from which additional information about wetness or periods with seasonal flooding could be extracted.

- Inventory data from a statistically based, plot-sampling system of water table wells, ditches and surface waters on organic soils: water table is monitored at specific permanent sample plots either continuously or on plots that are revisited on a regular basis. It has to be documented that the water data represent the water table in the organic soil and for what land-use and drainage stratum and that the data cover a representative period, which represents a multi-year mean annual water table.
- Water management plans and documentation from water management installations
- Drainage maps
- Maps of rewetting projects including remote sensing

Tier 3

The Tier 3 method requires more disaggregated activity data than lower Tiers. This includes disaggregation according to drainage classes or typology, and may take into account such variables as seasonal norms and modifications in water table level. Seasonal variations in emissions are then aggregated to annual CO_2 emissions. Approaches outlined in the *2006 IPCC Guidelines* need to be taken into account and modified according to the specific characteristics of management on organic soils.

CALCULATION STEPS FOR TIER 1

The steps for estimating the direct loss of soil C from drained inland organic soils are as follows:

Step 1: Determine areas with drained inland organic soils under each land-use category for *lands remaining in a land-use category*, disaggregated by climate domain and other appropriate factors as outlined above. Where needed for Tier 1 emission factors, land area are further stratified by nutrient-rich and nutrient-poor organic soils. Temperate nutrient-rich Grasslands are further stratified into shallow-drained and well-drained classes.

Step 2: Assign the appropriate emission factor (EF) from Table 2.1 for annual losses of CO_2 to each land-use category, climate domain, nutrient status and drainage class stratum.

Step 3: Multiply each area with the appropriate emission factor by using Equations 2.3.

UNCERTAINTY ASSESSMENT

Three broad sources of uncertainty exist in soil carbon inventories in organic soils: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in the emission/removal factors for Tier 1 or 2 approaches; and 3) model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. In general, precision of an inventory is increased and confidence ranges are smaller with more sampling to estimate values for these categories, while accuracy is more likely to be increased through implementation of higher Tier methods that incorporate country-specific information.

For Tier 1, the default uncertainty level of emissions/removal factors is 95% confidence interval in Table 2.1. Countries developing specific emission factors for their inventories at higher tiers should assess the uncertainty of these factors.

If using aggregate land-use area statistics for activity data (e.g., FAO data), the inventory agency may have to apply a default level of uncertainty for the land area estimates (±50%). It is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level of uncertainty. Uncertainties in activity data may be reduced through a better national system, such as developing or extending a ground-based survey with additional sample locations and/or incorporating remote sensing to provide additional coverage. It is *good practice* to design a classification that captures the majority of land-use and management activities with a sufficient sample size to minimize uncertainty at the national scale.

Uncertainties in activity data and emission/removal factors need to be combined using an appropriate method, such as simple error propagation Equations. Details are given in the *2006 IPCC Guidelines Volume 1, Chapter 3* and *2003 IPCC Good practice Guidance.*

Accuracy can be increased by deriving country-specific factors using a Tier 2 method or by developing a Tier 3 country-specific estimation system. The underlying basis for higher Tier approaches will be measurements in the country or neighbouring regions that address the effect of land-use and management on soil carbon. In addition, it is *good practice* to further stratify by significant within-country differences in land-use and management impacts, such as variation among climate domains and/or organic soil types.

2.2.1.2 OFF-SITE CO_2 EMISSIONS VIA WATERBORNE CARBON LOSSES FROM DRAINED ORGANIC SOILS

Waterborne carbon comprises dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (DIC) (including the dissolved gases CO_2 and CH_4, and the dissolved carbonate species HCO_3^- and CO_3^{2-}). Particulate inorganic carbon (PIC) losses are negligible from organic soils. Collectively, waterborne carbon export can represent a major part of the overall carbon budget of an organic soil, and in some cases can exceed the net land-atmosphere CO_2 exchange (e.g. Billett *et al.,* 2004; Rowson *et al.,* 2010). It is therefore important that waterborne carbon is included in flux-based (i.e. gain-loss) approaches for soil carbon estimation, to avoid systematic under-estimation of soil C losses. Airborne (erosional) POC loss may also be significant where land-use leads to bare peat exposure, but few data exist to quantify this (see Appendix 2a.1)

Different forms of waterborne carbon have different sources, behaviour and ultimate fate, and different approaches are therefore required to quantify the off-site CO_2 emissions associated with each form. Gaseous CO_2 and CH_4 dissolved in water transported laterally from the peat matrix represent indirectly emitted components of the total emission of these gases from the land surface. Dissolved CO_2 in excess of atmospheric pressure will also be degassed from drainage waters. At present, a separate methodology is not presented to account for CO_2 emissions from drainage waters, as specific data on CO_2 degassing fluxes in relation to land-use are not currently available. It appears that these emissions form a relatively small component of total land-atmosphere CO_2 exchange; data from an undisturbed blanket bog suggest that most of the CO_2 flux is emitted within the peat area (Dinsmore *et al.,* 2010), and may therefore already be captured in total fluxes measured using eddy covariance methods, and thus be included in existing CO_2 emission factors if this technique is used.

In most peatlands and organic soils, DOC forms the largest component of waterborne carbon export (e.g. Urban *et al.,* 1989; Dawson *et al.,* 2004; Jonsson *et al.,* 2007; Dinsmore *et al.,* 2010). DOC export can be affected by land-use, in particular drainage. It is reactive within aquatic ecosystems and most or all DOC is thought to be ultimately converted to CO_2 and emitted to the atmosphere (see Appendix 2A.2 for supporting discussion). Therefore, DOC should be accounted for in flux-based carbon estimation methods, and a Tier 1 methodology is described below.

Of the other forms of waterborne carbon, POC fluxes are typically very low from vegetated peatlands and organic soils, but can become very large where bare peat becomes exposed, e.g. due to erosion, peat extraction, and conversion to Cropland. Although it may be possible to estimate POC loss fluxes as a function of bare peat exposure, high uncertainty remains regarding the reactivity and fate of POC exported from peatlands. Some POC is likely to be converted to CO_2, but POC that is simply translocated from peatlands to other stable carbon stores, such as freshwater or marine sediments, may not lead to CO_2 emissions. Due to the uncertain fate of POC export, an estimation method is not presented at this time; current knowledge and data needs to support POC estimation in future are described in Appendix 2a.1.

Finally, no method is presented for DIC flux estimation. DIC fluxes from bogs (other than degassed CO_2, as discussed above) comprise only a minor part of the total waterborne carbon export. DIC fluxes from fens are greater, but a large (and uncertain) proportion of this flux derives from mineral weathering processes in the groundwater supplying the fen, rather than from carbon produced within the fen itself (Fiedler *et al.,* 2008). Therefore, it is not currently possible to account for the DIC flux specifically associated with peat carbon loss.

CHOICE OF METHOD

The basic methodology for estimating annual off-site carbon loss from drained organic soils was presented in section 2.3.3 and adapted from Equation 2.26 in Volume 4 of the *2006 IPCC Guidelines* as presented in Equation 2.3:

EQUATION 2.4
ANNUAL OFF-SITE CARBON LOSS FROM DRAINED ORGANIC SOILS (CO_2)

$$CO_2 - C_{DOC} = \sum_{c,n} \left(A \bullet EF_{DOC} \right)_{c,n}$$

Where:

CO_2-C_{DOC}= Annual off-site CO_2-C loss from drained organic soils, tonnes C yr^{-1}

$A_{c,n}$ = Land area of drained organic soils in a land-use category in climate zone c and nutrient status n, ha

$EF_{DOCc,n}$ = Emission factors for annual CO_2 emissions due to DOC export from drained organic soils, by climate zone c and nutrient status n, tonnes C ha^{-1} yr^{-1}

EF_{DOC} can be calculated from Equation 2.5:

EQUATION 2.5
EMISSION FACTOR FOR ANNUAL CO_2 EMISSIONS DUE TO DOC EXPORT FROM DRAINED PEATLANDS

$$EF_{DOC} = DOC_{FLUX-NATURAL} \bullet \left(1 + \Delta DOC_{DRAINAGE}\right) \bullet Frac_{DOC-CO_2}$$

Where:

EF_{DOC} = Emission factor for DOC from a drained site, tonnes C ha^{-1} yr^{-1}

$DO_{CFLUX\_NATURAL}$ = Flux of DOC from natural (undrained) peatland, tonnes C ha^{-1} yr^{-1}

$\Delta DOC_{DRAINAGE}$ = Percentage increase in DOC flux from drained sites relative to un-drained sites

$Frac_{DOC-CO_2}$ = Conversion factor for proportion of DOC converted to CO_2 following export from site

Because of the lack of data for other components of off-site carbon losses and uncertainty about their sources and fate, off-site carbon losses are only represented by DOC losses at this stage. However, if in the future adequate data become available or if adequate data are available for higher Tiers, inventory compilers can expand Equation 2.4 to include POC and/or DIC (See section on methodological requirements for off-site emission estimation associated with POC in Appendix 2a.1).

All peatlands export some DOC in their natural, un-drained state. However, most published studies indicate that DOC fluxes are likely to increase following drainage (see Annex 2A.2). Following the Managed Land Proxy (MLP), and to ensure completeness of flux-based soil carbon reporting, the entire DOC export of drained peatlands and organic soils should be included. The method presented in Equation 2.5 reflects the relative availability of robust data suitable for the calculation of emission factors for DOC, which largely comprise accurate DOC flux estimates for natural peatlands and paired assessments of relative DOC change in drained versus undrained sites, whereas comparatively few reliable direct measurements of DOC fluxes from drained sites are available (see Annex 2A.2).

CHOICE OF EMISSION FACTOR

Tier 1

A detailed description of the derivation of default values for Tier 1 is provided in Annex 2A.2. In summary, data indicate that the rate of DOC export from temperate and boreal raised bogs and fens is positively correlated with water fluxes, and a simple schema for deriving values of $DOC_{FLUX\_NATURAL}$ as a function of rainfall is provided in Table 2.2. Single representative mean values are given for tropical peatlands. Annex 2A.2 provides details of the derivation of parameter values. Note that a single default value for $\Delta DOC_{DRAINAGE}$ is currently proposed for all peat/land-use types, and a default $Frac_{DOC-CO_2}$ value of 0.9 (± 0.1), implying near-complete conversion of DOC to CO_2 following export from the peat.

TABLE 2.2
DEFAULT DOC EMISSION FACTORS FOR DRAINED PEATLANDS AND ORGANIC SOILS

Peat type	Precipitation regime (mm yr^{-1})	$DOC_{FLUX\_NATURAL}$ (t C ha-1 yr-1)	$\Delta DOC_{DRAINAGE}$ [a]	$EF_{DOC\_DRAINED}$ (t C ha^{-1}yr^{-1})
Temperate/boreal bog/fen [b]	Dry (< 600)	0.05 (0.04-0.07)	0.60 (0.43-0.78)	0.08 (0.05-0.12)
	Intermediate (600-1000)	0.16 (0.12-0.21)		0.25(0.13-0.37)
	Wet (> 1000)	0.23 (0.17-0.29)		0.33 (0.19-0.51)
Tropical	All	0.57 (0.49-0.64)		0.82 (0.56-1.14)

Values shown in parentheses represent 95% confidence intervals. For data sources see Tables 2A.2 and 2A.3

[a] Due to the limited number of available studies, a single Tier 1 value for $\Delta DOC_{DRAINAGE}$ has been assigned to all peat types based on all available comparisons of drained and undrained sites. For fens, there is more uncertainty associated with the estimation of DOC flux changes after drainage, therefore countries may choose to apply values of $DOC_{FLUX\_NATURAL}$ given above (multiplied by $Frac_{DOC-CO_2}$ but assumed $\Delta DOC_{DRAINAGE} = 0$) or to obtain direct measurements of the DOC flux from drained sites.

[b] Where precipitation measurements are available, $DOC_{FLUX\_NATURAL}$ values for boreal/temperate raised bogs and fens may also be calculated from the empirical Equation $DOC_{FLUX\_NATURAL} = (0.000317 \bullet \text{Precipitation}) - 0.075$, ($R^2 = 0.67$, $p < 0.001$ for the studies listed in Table 2A.2), in the units shown above. Note that this Equation is not applicable to blanket bogs.

Tier 2

A Tier 2 approach for estimation of DOC may follow the Tier 1 methodology provided above, but should use country–specific information where possible to refine the emission factors used. Possible refinements where supporting data are available could include:

- Use of the Equation shown at the bottom of Table 2.2 to assign more accurate values for $DOC_{FLUX\_NATURAL}$ from temperate/boreal raised bogs and fens;
- Use of country-level measurements from natural peatlands to obtain accurate values of $DOC_{FLUX\_NATURAL}$ for that country, for example by developing specific values for raised bogs versus fens, or for blanket bogs;
- Use of country-level data on the impacts of peatland drainage on DOC flux to derive specific values of $\Delta DOC_{DRAINAGE}$ that reflect local peatland types, and the nature of drainage practices and subsequent land-use. If sufficient, robust direct measurements are available from representative drained sites, these may be used to estimate DOC fluxes from drained sites, replacing $DOC_{FLUX-NATURAL} \bullet (1 + \Delta DOC_{DRAINAGE})$ in Equation 2.4. Specific DOC flux estimates from drained organic soils in different land-use categories could also be considered where data support this level of stratification;
- Use of alternative values for $Frac_{DOC-CO_2}$ where evidence is available to estimate the proportion of DOC exported from drained organic soils that is transferred to stable long-term carbon stores, such as lake or marine sediments.

Guidance is not currently presented for the effects of land-use impacts other than drainage on DOC loss from peatlands and organic soils, for example the effects of managed burning or intensity of agricultural use. However, these may be included in Tier 2 methods if sufficient evidence can be obtained to develop the associated emission factors.

Tier 3

A Tier 3 approach might include the use of more detailed data to develop and apply process models that describe DOC release as a function of vegetation composition, nutrient levels, land-use category, water table level and hydrology, as well as temporal variability in DOC release in the years following land-use change (e.g. initial drainage) and on-going management activity (e.g. drain maintenance, forest management) (see Annex 3A.2, Chapter 3).

CHOICE OF ACTIVITY DATA

Tier 1

Activity data consist of areas of *land remaining in a land-use category* on drained organic soils summarised by peatland type and land-use type (specifically occurrence of drainage). Total areas should be determined according to approaches laid out in Chapter 3 of the *2006 IPCC Guidelines* and should be consistent with those reported under other sections of the inventory. They also need to be consistent with activity data for on-site CO_2

emissions. For boreal and temperate raised bogs and fens, additional data on annual mean rainfall may be used to refine flux estimates, as shown in Table 2.2.

Tier 2 & 3

For higher Tier approaches, additional activity data requirements may include specific information on the land-use type associated with drained organic soils, and intensity of drainage. Use of a variable $Frac_{DOC-CO_2}$ value at a country level, or within a country, would require information on the characteristics of downstream river networks (e.g. water residence time, extent of lakes and reservoirs, lake sedimentation rates). A Tier 3 modelling approach would require additional information on the timing of drainage, drain maintenance and land-management (e.g. forest management, fertiliser application rates).

UNCERTAINTY ASSESSMENT

Uncertainties in estimates of off-site CO_2 emissions from DOC are associated with the measurement of DOC fluxes from natural peatlands; estimates of the increase in DOC flux associated with drainage based on measurements from paired studies (including measurements or assumptions about changes in water flux from drained versus natural sites); and estimates of the proportion of DOC which is ultimately converted to CO_2 within water bodies. Additional uncertainty is introduced by the aggregation of data into broad peat categories, particularly at Tier 1 where default values are applied to different peat types, and drainage impacts are assumed to be the same for different peat and land-use categories.

Uncertainty ranges (95% confidence intervals) are provided for DOC emission factors in Table 2.2. These ranges are calculated from literature data in Annex 2A.2 based on observations from natural peatlands used to derive values of $DOC_{FLUX\_NATURAL}$ in each of the peat classes used (Table 2A.2); observations of $\Delta DOC_{DRAINAGE}$ from published studies (Table 2A.3); and an uncertainty range for $Frac_{DOC-CO_2}$ value of 0.8 to 1.0 as described above. These uncertainty ranges may be adapted or refined under Tier 2 if further sub-classification according to land-use type or intensity is undertaken, based on additional measurement data.

2.2.2 Non-CO_2 emissions and removals from drained inland organic soils

In the *2006 IPCC Guidelines*, CH_4 emissions were assumed to be negligible from all drained organic soils. Here new methodologies and emission factors are provided for soil CH_4 emissions from drained organic soils and drainage ditches (section 2.2.2.1).

2.2.2.1 CH_4 emissions and removals from drained organic soils

Organic soils are mostly formed due to incomplete decomposition of dead organic matter in water saturated conditions. Management of organic soils, especially peatlands, involves drainage by ditching. In the *2006 IPCC Guidelines*, CH_4 emissions were assumed to be negligible from all drained organic soils. However, recent evidence suggests that some CH_4 emissions can occur from the drained land surface, and also from the ditch networks constructed during drainage. Each of these emission pathways is considered here (Best and Jacobs, 1997; Minkkinen and Laine 2006; Schrier-Uijl *et al.,* 2011; Hyvönen *et al.,* 2012).

Drainage lowers the water table and exposes formerly saturated peat layers to oxidation and, as described above, increases CO_2 emissions from the land surface. Drainage alters environmental factors such as temperature, reduction–oxidation potential, and the amount of easily decomposable organic matter. This also affects the activity of methanogens and methanotrophs (Verchot *et al.,* 2000; Blodau, 2002; Treat *et al.,* 2007). Drainage facilitating plant root respiration mitigates CH_4 emission dramatically (Martikainen *et al.,* 1995a; Strack *et al.,* 2004) as the methanogenic bacteria thrive only in anaerobic conditions. Shifts in vegetation from aerenchymous (methane transporting) wetland species to other vegetation types will also reduce the transfer of methane from the soil profile to the atmosphere. In general, when the peatland is drained the natural production of CH_4 is reduced or even can convert to limited consumption for CH_4, once methanotrophs dominate the CH_4 cycle. As natural CH_4 emissions are not included in the inventory, this emission reduction is not considered when natural un-drained organic soils are being drained. However, for completeness any remaining CH_4 emission from the land surface of drained organic soils needs to be included in inventories.

Ditch networks provide a further source of CH_4 emissions from drained organic soils. This occurs due to a combination of lateral CH_4 transfer from the peat matrix, and in-situ CH_4 production within the ditches themselves (e.g. Roulet and Moore, 1995; Van den Pol – Van Dasselaar *et al.,* 1999a; Sundh *et al.,* 2000; Minkkinen and Laine, 2006; Teh *et al.,* 2011; Vermaat *et al.,* 2011). These emissions may approach, or even exceed, the CH_4 flux from an undrained peatland when averaged over the land surface (Roulet and Moore, 1995; Schrier-Uijl *et al.,* 2011) and should therefore be included in estimates where possible. Emission/removal factors for ditch CH_4 emissions were compiled from available published literature (See Annex 2A.1). We present only general factors for ditches because of limited data. Effects of ditch maintenance, deepening etc. should be dealt with at higher Tiers.

CHOICE OF METHOD

Tier 1

CH_4 emissions from the land surface are estimated using a simple emission factor approach (see Eq. 2.6), depending on climate and type of land-use. The default methodology considers boreal, temperate and tropical climate zones and nutrient-rich and nutrient-poor peatlands. Different land-uses imply drainage to different depths. The CH_4 emission factors depend on gas flux measurements, either from closed chambers or from eddy covariance (Hirano *et al.,* 2007).

Ditch CH_4 emissions should be quantified for any area of drained organic soil where there are ditches or drainage canals (note that CH_4 may also be emitted from ditches within re-wetted peatlands, where ditches remain present, although at Tier 1 it is assumed that this flux equates to that from the remainder of the re-wetted site; see Chapter 3). Estimation of ditch CH_4 emissions requires information on the land-use class and on the area of the landscape occupied by the drainage ditch network, $Frac_{ditch}$.

EQUATION 2.6
ANNUAL CH_4 EMISSION FROM DRAINED ORGANIC SOILS

$$CH_4 - C_{organic} = \sum_{c,n,p} \left(A_{c,n,p} \bullet \left((1 - Frac_{ditch}) \bullet EF_{CH_4\_land_{c,n}} + Frac_{ditch} \bullet EF_{CH_4\_ditch_{c,p}} \right) \right)$$

Where:

CH_4-$C_{organic}$ = Annual CH_4-C loss from drained organic soils, tonnes CH_4-C yr^{-1}

$A_{c,n,p}$ = Land area of drained organic soils in a land-use category in climate zone c, nutrient status n and peatland type p, ha

$EF_{CH_4\_land}$ = Emission factors for direct CH_4 emissions from drained organic soils, by climate zone c and nutrient status n, tonnes CH_4-C ha^{-1} yr^{-1}

$EF_{CH_4\_ditch}$ = Emission factors for CH_4 emissions from drainage ditches, by climate zone c and peatland type p, tonnes CH_4-C ha^{-1} yr^{-1}

$Frac_{ditch}$ = Fraction of the total area of drained organic soil which is occupied by ditches

Tier 2

The Tier 2 approach for CH_4 emissions from drained organic soils incorporates country-specific information in Equation 2.5 to estimate the emissions. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Under Tier 2, the emission factors for CH_4 from the surface of drained organic soils can be further differentiated by drainage depth, land-use subcategories or vegetation type. Land-use subcategories can consider the CH_4 formation when plant residues decay in wet conditions and the role of plants as active or passive transporters of CH_4 from the soil to the atmosphere. Guidance for further stratification follows the principles given in section 2.2.1.1.

Tier 2 approaches for CH_4 from drainage ditches generally follow the Tier 1 approach described above, with country-specific measurements or estimates of annual mean ditch CH_4 emissions, and national or regional estimates of fractional ditch area that reflect local drainage practices. The land-use sub-categories in Table 2.4

may be expanded or sub-divided where appropriate to reflect the range of observed land-use on drained organic soils.

Tier 3

Tier 3 methods for estimating land-surface CH_4 emissions involve a comprehensive understanding and representation of the dynamics of CH_4 emissions and removals on managed peatlands, including the effect of site characteristics, peat type, peat degradation and depth, land-use intensity, drainage depth, management systems, and the level and kinds of fresh organic matter inputs.

For CH_4 from drainage ditches, development of a Tier 3 approach could take account of the influence of land-management activities (e.g. organic matter additions to agricultural land) on substrate supply for methane production in ditches, of possible short-term pulses of ditch CH_4 emissions associated with land-use change, and of the legacy effects of past land-use (e.g. nutrient-enriched soils). Information on drainage ditch characteristics and maintenance may be used to refine ditch CH_4 emissions estimates, for example taking account of the potential effects of plant or algal growth within ditches; water flow rates, transport length of water and oxygen status; ditch maintenance activities, and the deposition of organic material removed from ditches onto adjacent land areas.

CHOICE OF EMISSION FACTORS

Tier 1

Default emission factors for the Tier 1 method are provided in Tables 2.3 and 2.4.

At present, literature data are sufficient to provide Tier 1 default values of EF_{CH4_ditch} for each of the four major land-use classes on organic soils (Forest Land, Grassland, Cropland and wetlands-used for peat extraction) in boreal and temperate regions (Table 2.4). For Grassland and Cropland categories, separate EFs are given for high- and low-intensity land-use sub-categories. For Grassland, these typically correspond to fertilised, annually replanted Grassland and unfertilised ‘conservation managed’ permanent Grassland respectively. For Cropland, they correspond to intensive arable or horticultural use, and low-intensity ‘paludiculture’ activities such as reed production. For tropical organic soils, few data on ditch CH_4 emissions are currently available, and a single Tier 1 EF is therefore provided for all drained land-use classes.

Tier 2

Tier 2 emission factors are based on country- or region-specific emission factors for CH_4 emissions from the surface of drained organic soils. These allow a further stratification of land-use categories by drainage class, nutrient status or vegetation characteristics.

Methane emissions from ditches will vary according to peat type, land-use type, drainage intensity, and (for agriculturally managed areas) land-use intensity. For example labile organic matter and nutrient supply from terrestrial areas are likely to increase CH_4 production in ditches (Schrier-Uijl *et al.,* 2011). The Tier 1 emission factors provided are based on measurements from ditches located within the peat layer; where ditches are cut into underlying mineral soil, emissions may be lower (Hyvönen *et al.,* 2012). Tier 2 emission factors (i.e. values for) should therefore be developed for all significant combinations of these factors at a country level, wherever possible.

Currently, the literature is sparse, so countries are encouraged to share comparable data, when environmental conditions and extraction practices are similar.

Tier 3

Tier 3 emission factors or relations are based on country-specific emission data that account for site characteristics, peat type and depth, and management factors such as drainage intensity; crop, livestock or forest type; fertiliser or organic matter additions; peat extraction technology and the phases of peat extraction or other relevant factors for CH_4 emissions.

CH_4 emissions from ditches can be based on relations between drainage ditch characteristics and maintenance and CH_4 emissions, for example taking account of the potential effects of plant or algal growth within ditches; water flow rates, transport length of water and oxygen status; ditch maintenance activities, and the deposition of organic material removed from ditches onto adjacent land areas.

A Tier 3 approach to estimating ditch CH_4 emissions could take account of the temporal variability of hydrological conditions, labile substrate and nutrient supply, and controls on the composition of in-ditch vegetation that might enhance or reduce emission rates.

TABLE 2.3
TIER 1 CH_4 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES

Land-Use Category		Climate / Vegetation Zones	Soil CH_4 Emission Factor*** (tonnes CH_4-C ha^{-1} yr^{-1})	95% Confidence Interval (centred on mean)		No. of Sites	Citations/Comment
Forest Land, Drained	Nutrient-rich	# Boreal	0.0052	0.0022	0.0083	47	Komulainen *et al.*, 1998; Lohila *et al.*, 2011, Maljanen *et al.*, 2006a; Martikainen *et al.*, 1992, 1995a; Minkkinen & Laine, 2006; Minkkinen *et al.*, 2007a; Nykanen *et al.*, 1998; Ojanen *et al.*, 2010, 2011, 2013
	Nutrient-poor	# Boreal	0.0015	-0.0012	0.0041	85	Huttunen *et al.*, 2003a; Komulainen *et al*, 1998; Laine *et al.*, 1996; Makiranta *et al.*, 2007; Maljanen *et al.*, 2001b, 2003a, b, 2006a, 2010; Martikainen *et al.* 1992, 1995a, b; Minkkinen & Laine, 2006; Minkkinen *et al.*, 2007a; Nykanen *et al.*, 1998; Ojanen *et al.*, 2010, 2013; Saari *et al.*, 2009; Huttunen *et al.*, 2003a; Komulainen *et al.*, 1998; Laine *et al.*, 1996;, Makiranta *et al.*, 2007; Maljanen *et al.*, 2001b, 2003a, b, 2006a, 2010; Martikainen *et al.*, 1992, 1995a, b; Minkkinen & Laine, 2006; Minkkinen *et al.*, 2007a; Nykanen *et al.*, 1998; Ojanen *et al.*, 2010, 2013; Saari *et al.*, 2009
Forest Land, Drained		# Temperate	0.0018	-0.0009	0.0044	14	Glenn *et al.*, 1993; Moore & Knowles, 1990; Sikstrom *et al.*, 2009; Von Arnold *et al.*, 2005b, c; Weslien *et al.*, 2009
Forest. Drained		Tropical/ Subtropical	0.004	0.002**			Jauhiainen *et al.*, 2008; Hirano *et al.*, 2009; Furukawa *et al.*, 2005
Forest, Burned			0.002	0.000**			Jauhiainen *et al.*, 2008
Grassland, Drained		# Boreal	0.0014	-0.0008	0.0036	13	Grønlund *et al.*, 2006; Hyvonen *et al.*, 2009; Maljanen *et al.*, 2001a, 2003a, b, 2004, 2009a, b, Nykanen *et al.*, 1995; Regina *et al.*, 2007
Grassland, Deep		* Temperate	0.0013	0.0005	0.0021	5	Drösler *et al.*, 2013; Kasimir *et al.*, 2009

Drained < -30 cm, Poor						
Grassland, Shallow Drained ≥ -30 cm, Poor	* Temperate	0.0125	-0.0055	0.0305	6	Drösler *et al.,* 2013
Grassland, Deep Drained < -30 cm, Rich	* Temperate	0.0181	0.0041	0.0320	35	Best & Jacobs, 1997, Drösler *et al.,* 2013; Flessa *et al.,* 1998; Meyer *et al.,* 2001; Petersen *et al.,* 2012; Schrier-Uijl *et al.,* 2010; Teh *et al.,* 2011; Van den Pol-van Dasselaar, 1998; Van den Pol-van Dasselaar *et al.,* 1999c
Grassland, Shallow Drained ≥ -30 cm, Rich	* Temperate	0.1053	-0.0388	0.2494	12	Drösler *et al.* 2013,
Grassland	Tropical/ Subtropical	0.005	0.005**			Same emission factor as Tropical Cropland
Shrubland		0.005	0.005**			Same emission factor as Tropical Cropland
Cropland, Drained	* Boreal & Temperate	0.0010	-0.0007	0.0027	34	Augustin *et al.,* 1998; Drösler *et al.,* 2013; Flessa *et al.,* 1998; Glenn *et al.,* 1993; Maljanen *et al.,* 2003a, b, 2003, 2004, 2007a; Petersen *et al.,* 2012; Regina *et al.,* 2007; Taft *et al.,* 2013
Cropland	Tropical/ Subtropical	0.005	0.005**			Furukawa *et al.,* 2005; Hirano *et al.,* 2009
Rice		0.108	0.060**			Furukawa *et al.,* 2005; Hadi *et al.,* 2001; Inubushi *et al.,* 2003 (with 10 cm to -10 cm water table)
Plantation: Oil palm		0	0			Melling *et al.* 2005 (50-70 cm drainage)
Plantation: Sago Palm		0.020	0.014**			Watanabe *et al.,* 2009; Melling *et al.,* 2005; Inubushi *et al.* , 1998 (0-40 cm drainage)
Wetland in Peat Production	* Boreal & Temperate	0.0342	-0.0285	0.0968	16	Drösler *et al.,* 2013; Hyvonen *et al.,* 2009; Nykanen *et al.,* 1996; Sundh *et al.,* 2000; Tuittila *et al.,*. 1995, 2000; Waddington & Day 2007

Settlements	All climate zones	Same emission factor as Cropland
Other Land	All climate zones	*Other Land remaining Other Land*: 0 *Land Converted to Other Land*: Maintain emission factor of previous land-use category

Using FAO Climate/Vegetation Zones from *2006 IPCC Guidelines*, Volume 4, Chapter 4, Figure 4.1 and Table 4.1

* Using IPCC Climate Zones from *2006 IPCC Guidelines*, Volume 4, Chapter 3, Figure 3A.5.1

**Standard error

*** Mean

Plantations can be defined as Forest Land or Cropland, according to national definitions. The attribution to Cropland made in this table is not binding. It is *good practice* to report plantations in the appropriate national land-use category according to the national forest definition.

CHOICE OF ACTIVITY DATA

Tier 1

The same activity data should be used for estimating CO_2, N_2O and CH_4 emissions from managed organic soils. Information on obtaining these data is provided in Section 2.2.1 above. For countries in boreal and temperate regions using the Tier 1 method, if the available information does not allow stratification by peat fertility, countries may rely on guidance given in section 2.2.1.1.

Activity data required to estimate ditch CH_4 emissions at Tier 1 consist of areas of managed organic soils disaggregated by peat type and land-use category (Forest Land, Grassland, Cropland, wetlands used for peat extraction) as shown in Table 2.4. Fractional ditch areas recorded in published studies are given for individual sites in Table A2.1, however it is *good practice* to derive country-specific values wherever possible, to reflect local land-use practices. Often the fractional ditch area depends more on the topographic situation and peat properties rather than on the land-use so that at Tier 1 the same fractional ditch area is used for all land-use categories.

Fractional ditch area can be calculated from spatially explicit information about ditch and canal networks. From these the length and width of ditches can be derived, or alternatively, ditch spacing and ditch width on organic soils, which gives the ditch area on organic soils. This geometrical information is converted to fractional ditch area by dividing the ditch area on organic soils through the area of drained organic soils.

Tier 2

Activity data required for higher Tier methods are likely to include more detailed information on land-use, in particular land-use intensity within Grassland and Cropland classes. Further stratification may be necessary for other classes if sufficient data become available to estimate emission factors, e.g. for cleared peat swamp forest, oil palm or pulpwood plantation in tropical peat areas.

Activity data for Tier 2 methods may consist of areas of organic soils managed for different forest types, peat extraction, paddy systems, horticulture and plantation disaggregated according to nutrient status of the organic soil if relevant, and annual peat production data. More sophisticated estimation methodologies will require the determination of areas in different phases of land-uses with longer term rhythms such as age-classes in Forest Land or in a peat extraction cycle, where on abandoned areas drainage or the effects of former peat extraction are still present. Land-use intensity, particularly fertilizer and organic matter addition, may be used to refine CH_4 emission estimates for Grassland and Cropland, as higher emissions are likely under more intensive management systems with high substrate supply for methanogenesis.

To estimate ditch CH_4 emissions, additional activity data are required on fractional ditch area within each land category. Country-specific values of fractional ditch areas are used to reflect region-specific drainage methodologies such as typical ditch spacing, depth, width and length, maintenance and land-use practices. Fractional ditch area can be stratified by type of organic soil or topographic situation, peat properties and land-use.

Tier 3

Tier 3 activity data for ditch CH_4 emissions could incorporate additional information on water table level, flow rates, in-ditch vegetation and land-use factors affecting substrate supply for methanogenesis, such as livestock density and fertilizer application in intensive Grasslands and Croplands. Incorporating seasonal and short-term controls on emissions, would require additional activity data on the nature and timing of agricultural activities (such as organic matter additions) and on hydrological parameters.

UNCERTAINTY ASSESSMENT

Uncertainty ranges are provided in Table 2.4 for values of $EF_{CH_4\_ditch}$ for each peat/land-use category. The major source of uncertainty in these values is simply the small number of studies on which many estimates are based, and the high degree of heterogeneity in measured fluxes between different studies undertaken within some classes. 95% confidence intervals have been calculated for all classes other than the drained tropical peat class, for which only one study (Jauhianen *et al.,* 2012) is available, providing estimates of ditch CH_4 emissions from areas of drained, deforested and abandoned peatland, and pulpwood plantation. For this category, the uncertainty range is provided by the lower (abandoned) and higher (pulpwood plantation) emission values recorded. Note that the final calculation of CH_4-$C_{organic}$ is also sensitive to uncertainties in the activity data used to estimate the proportion of the land area which is occupied by drainage ditches, $Frac_{ditch}$. Uncertainty assessments should therefore also take account of this source of uncertainty in calculating total CH_4 emissions from drained organic soils.

Uncertainty ranges in Table 2.3 are expressed as 95% confidence intervals or as standard errors, depending on the number of studies available.

TABLE 2.4
DEFAULT CH_4 EMISSION FACTORS FOR DRAINAGE DITCHES

Climate zone	Land-use	EF_{CH4_ditch}(t CH_4-C ha^{-1} yr^{-1})	Uncertainty range (t CH_4-C ha^{-1} yr^{-1})	References
Boreal /temperate	Drained forest Drained wetland[a]	0.163	0.031 – 0.294	8 sites: Cooper & Evans, 2013; Glagolev *et al.,* 2008; Minkinnen & Laine, 2006 (two study areas); Roulet & Moore, 1995 (three study areas); Sirin *et al.,* 2012 (three study areas); von Arnold *et al.,* 2005.
	Low-intensity Grassland	0.345	0.187 – 0.503	5 sites: Best & Jacobs, 1997; Hendricks *et al.,* 2007, 2010; Van den Pol-Van Dasselaar *et al.,*1999; Vermaat *et al.,* 2011 (two study areas).
	High-intensity Grassland Cropland[b]	0.832	0.299 – 1.364	7 sites: Best & Jacobs, 1997; Chistotin *et al.,* 2006 ; McNamara, 2013; Schrier-Uijl *et al.* 2009, 2011; Sirin *et al.,* 2012; Teh *et al.,* 2011; Vermaat *et al.,* 2011.
	Peat extraction	0.435	0.128 – 0.743	6 sites: Chistotin *et al.,* 2006; Nykänen *et al.,* 1995; Sirin *et al.,* 2012; Sundh *et al.,* 2000; Waddington & Day, 2007 (two study areas)
Tropical	All land-use involving drainage	1.694	0.449 – 2.939c	2 sites from Jauhianen & Silvennoinen, 2012 (drained and abandoned, and pulpwood plantation)

Values shown in parentheses represent 95% confidence intervals unless otherwise stated

[a] Ditch CH_4 fluxes from wetlands subject to drainage but no other land-use modification are assumed to be equivalent to those from organic soils drained for forestry.

[b] Ditch CH4 fluxes from Croplands are assumed to be the same as those from high-intensity Grassland, for which more data exist.

[c] Due to limited data for CH4 emissions from tropical drainage channels, the range of measurements is shown, rather than 95% confidence intervals.

2.2.2.2 N_2O EMISSIONS FROM DRAINED ORGANIC SOILS

N_2O emissions from soils are biologically produced by the microbiological processes of nitrification and denitrification (to N_2O or N_2) (Davidson 1991; Firestone and Davidson 1989). These processes are controlled by several factors, including water-filled pore space (Aulakh *et al.* 1997; Davidson 1991; Dobbie *et al.* 1999; Ruser *et al.* 2001), temperature (Keeney *et al.* 1979) and concentration of mineral nitrogen (Bremner 1997; Firestone and Davidson 1989; Ryden and Lund 1980).

Drained organic soils emit significant amounts of N_2O whereas N_2O emissions from wet organic soils are close to zero (Kasimir-Klemedtsson *et al.,* 1997; Flessa *et al.,* 1998). A main reason for increased N_2O emissions is the nitrogen mineralization which goes along with carbon losses from drained organic soils (Höper, 2002). In well drained organic soils nitrogen mineralization from degrading peat or organic matter exceed by far the nitrogen uptake by vegetation. The mineralized nitrogen from organic soils is one out of several anthropogenic sources of nitrogen (nitrogen fertilizer, crop residues, organic amendments, mineralized soil nitrogen from humus loss in mineral soils) for direct N_2O emissions in Chapter 11 of Volume 4 the *2006 IPCC Guidelines* and in all earlier guidance. These nitrogen sources have been conceptually separated for the Tier 1 methodology for N_2O emissions although they cannot be readily separated by field observations. N_2O emissions from drained organic soils are entirely attributed to the mineralization of peat or organic matter. This supplement maintains this well-established IPCC concept for N_2O sources although there is a certain risk of double-counting on highly fertilized organic soils.

Most of the published data on N_2O fluxes from managed organic soils refer to boreal and temperate ecosystems and these data served as the basis for the emission factors in the *2006 IPCC Guidelines*. However, new published data are used to derive separate N_2O emission factors for Forest Land, Cropland, Grassland, and peatland under peat extraction in boreal and temperate zones in order to update Table 7.6 in Volume 4, Chapter 7 of the *2006 IPCC Guidelines*.

There are still limited data available for tropical peatlands; however the studies that have been published over the past decade allow us to estimate appropriate Tier 1 emissions factors for the first time.

CHOICE OF METHOD

Tier 1

This section presents the methods and Equation for estimating total anthropogenic emissions of N_2O (direct and indirect) from managed organic soils. The revisions presented here are applicable to Equation 11.1 presented in Volume 4, Chapter 11 of the *2006 IPCC Guidelines*. This Equation can be used to estimate N_2O within specific land-use categories; there are inadequate data available to develop coefficients to modify EFs by condition-specific variables (e.g., levels of N additions or variations of drainage depths). The Equations 11.1 and 11.2 can be modified to suit boreal conditions as well by adding terms $F_{OS,\,CG\,Bor\,NR}$, $F_{OS,\,CG,\,Bor\,NP}$, $F_{OS,\,F,\,Bor,\,NR}$, and $F_{OS,\,F\,Bor\,NP}$ (the subscripts CG, F, Bor, NR and NP refer to Cropland and Grassland, Forest Land, Boreal, Nutrient-Rich, and Nutrient-Poor, respectively) and their respective emissions factors.

Direct N_2O emissions from managed soils are estimated using Equation 11.1 in Volume 4, Chapter 11 of the *2006 IPCC Guidelines*. This Equation has three segments: one for emissions associated with N inputs, one for organic soils, and one for urine and dung inputs during grazing. In this section, update provided for the second segment focuses on organic soils as follows:

EQUATION 2.7
DIRECT N_2O EMISSIONS FROM ORGANIC SOILS

$$N2O-N_{OS}=\begin{bmatrix}\left(F_{OS,CG,Temp}\bullet EF_{2GC,Temp}\right)+\left(F_{OS,CG,Trop}\bullet EF_{2GC,Trop}\right)+\\ \left(F_{OS,F,Temp,NR}\bullet EF_{2F,Temp,NR}\right)+\\ \left(F_{OS,F,Temp,NP}\bullet EF_{2F,Temp,NP}\right)+\left(F_{OS,F,Trop}\bullet EF_{2F,Trop}\right)\end{bmatrix}$$

Where:

$N_2O–N_{OS}$ = Annual direct N2O–N emissions from managed organic soils, kg N_2O–N yr^{-1}

F_{OS} = Annual area of managed/drained organic soils, ha (Note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient Rich, and Nutrient Poor, respectively)

EF_2 = Emission factor for N2O emissions from drained/managed organic soils, kg N_2O–N ha^{-1} yr^{-1}; (Table 11.1, Volume 4, Chapter 11 of the *2006 IPCC Guidelines*) Note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient Rich, and Nutrient Poor, respectively.

Tier 2

Tier 2 estimates are to be based on the Tier 1 Equation, but should use country–or region–specific EFs. These can be further stratified by drainage class, nutrient status of organic soils or other criteria used for stratifying organic soils for on-site CO_2 emissions. The corresponding emission factors are country or region specific and take into account the land management systems. The nitrogen sources conceptually separated for the Tier 1 methodology for N_2O emissions cannot be readily separated by field observations. N_2O emissions from drained organic soils should be entirely attributed to the mineralization of peat or organic matter unless N_2O can be proven to be attributable to other nitrogen sources.

Tier 3

Tier 3 methods are based on modelling or measurement approaches. Models can simulate the relationship between the soil and environmental variables that control the variation in N_2O emissions and the size of those emissions (Stehfest & Bouwman, 2006; Dechow & Freibauer, 2011). These models can be used at larger scales where measurements are impractical. Models should only be used after validation against representative measurements that capture the variability of land-use, management practices and climate present in the inventory (IPCC, 2010). Tier 3 approaches can be used to attribute N_2O emissions from organic soils to various anthropogenic sources such as peat mineralization, nitrogen fertilization or crop residues.

Calculation steps

See Volume 4, Chapter 11 of the *2006 IPCC Guidelines*.

CHOICE OF EMISSION FACTORS

Tier 1

Emission factors for boreal and temperate organic soils

The *2006 IPCC Guidelines* provided emission factors that were partly disaggregated for land-use types or climatic zones. An increased availability of scientific data allows for an improved choice of default emission factors. Nutrient poor and rich peatlands drained for forestry have different N_2O emissions. Croplands and grasslands are established on nutrient-rich peat or are amended for better nutrient availability, and are considered here as rich. Peat extraction occurs both on ombrotrophic (bogs) and minerotrophic (fens) peatlands. In all cases the residual bottom peat layers consist of minerogenous but recalcitrant fen peat. There is not enough data available to disaggregate for the peat types in peat extraction areas.

TABLE 2.5
TIER 1 N_2O EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES

Land-Use Category		**Climate / Vegetation Zone**	**Soil N_2O Emission Factor*** (kg N_2O-N ha^{-1} yr^{-1})**	**95 % confidence interval (centred on mean)**		**No. of Sites**	**Citations/Comment**
Forest Land, Drained	Nutrient-rich	# Boreal	0.218	0.153	0.284	43	Lohila *et al.,* 2011; Maljanen *et al.*, 2006a; Martikainen *et al.*, 1993, 1995a; Ojanen *et al.*, 2010, 2011, 2013; Regina *et al.*, 1996
Forest Land, Drained	Nutrient-poor	# Boreal	3.03	1.77	4.29	76	Huttunen *et al.*, 2003a; Laurila *et al.*, 2007; Makiranta *et al.*, 2007; Maljanen *et al.*, 2001b,2003a, b, 2006a, 2010; Martikainen *et al.*, 1993, 1995a, Minkkinen *et al.*, 2007a; Ojanen *et al.*, 2010, 2013; Pihlatie *et al.*, 2004, Regina *et al.*, 1996, 1998; Saari *et al.*, 2009
Forest Land, Drained		# Temperate	3.10	0.084	6.28	13	Sikstrom *et al.*, 2009; Struwe & Kjoller, 1994; Von Arnold *et al.*, 2005b, c; Weslien *et al.* 2009
Forest Land		Tropical/ Subtropical	1.9	0.3**			Furukawa *et al.*, 2005; Takakai *et al.*, 2006
Grassland, Drained		# Boreal	9.73	4.88	14.6	16	Grønlund *et al.*, 2006; Guomundsson & Oskarsson, 2008; Hyvonen *et al.*, 2009; Jaakola, 1985; Maljanen, *et al.*, 2001a, 2004, 2009a, b; Nykanen *et al.*, 1995; Regina *et al.*, 1996, 2004
Grassland, Deep Drained < -30 cm, Poor		* Temperate	3.86	0.292	8.02	5	Drösler *et al.*, 2013; Kasimir *et al.*, 2009
Grassland, Shallow Drained ≥ -30 cm, Poor		* Temperate	2.34	0.106	4.78	6	Drösler *et al.*, 2013
Grassland, Deep Drained < -30 cm, Rich		* Temperate	8.00	3.34	12.7	29	Drösler *et al.*, 2013; Flessa *et al.*, 1998; Meyer *et al.*, 2001; Petersen *et al.*, 2012; Teh *et al,* 2011; Van Beek *et al.*, 2010
Grassland, Shallow Drained ≥ -30 cm, Rich		* Temperate	1.27	0.470	2.07	12	Drösler *et al.*, 2013

Grassland	Tropical/ Subtropical	2.0	1.2**			Same emission factor as Tropical Cropland
Shrubland	Tropical/ Subtropical	2.0	1.2**			Same emission factor as Tropical Cropland
Cropland, Drained	* Boreal & Temperate	13.0	7.77	18.2	33	Augustin *et al.*, 1998; Drösler *et al.*, 2013; Flessa *et al.*, 1998; Maljanen *et al.*, 2003a, b, 2003, 2004, 2007a; Petersen *et al,* 2012; Regina *et al.*, 2004, 2007; Taft *et al.*, 2013
Cropland except rice	Tropical/ Subtropical	2.0	1.2**			Furukawa *et al.*, 2005
Rice		0.4	0.5**			Furukawa *et al,* 2005; Hadi *et al.*, 2005; Inubushi *et al,* 2003
Plantation: Oil palm		1.2				Melling *et al.*, 2007
Plantation: Sago palm		3.3				Melling *et al.*, 2007
Wetland in Peat Production	* Boreal & Temperate	1.63	0.816	4.09	6	Drösler *et al.*, 2013; Hyvonen *et al.*, 2009; Makiranta *et al.*, 2007; Nykanen *et al.*, 1996; Regina *et al.*, 1996
Peatlands drained for extraction	Tropical/ Subtropical	3.6	0.2 to 5.0***			Same as in *2006 IPCC Guidelines*
Settlements	All climate zones	Same emission factor as Cropland				
Other Lands	All climate zones	*Other Land remaining Other Land*: 0 *Land Converted to Other Land*: Maintain emission factor of previous land-use category				

Using FAO Climate/Vegetation Zones from 2006 Guidelines, Volume 4, Chapter 4, Figure 4.1 and Table 4.1

* Using IPCC Climate Zones from 2006 Guidelines, Vol ume 4, Chapter 3, Figure 3A.5.1

** Standard error

*** Mean

Plantations can be defined as Forest Land or Cropland. The attribution to Cropland made in this table is not binding. It is *good practice* to report plantations in the appropriate national land-use category according to the national forest definition.

Emission factors for tropical organic soils

In the *2006 IPCC Guidelines*, factors were provided for $EF_{2CG, trop}$ and $EF_{2F, Trop}$, based on the expectation that net mineralization was twice as high in tropical soils compared to temperate soils. Research in tropical soils suggests that net mineralization is not a useful predictor of N_2O flux and that net nitrification or the nitrate portion of the inorganic-N pool are better predictors (Verchot *et al.,* 1999, 2005; Ishizuka *et al.,* 2005). It also needs to be highlighted that all measurements on of N_2O emissions on tropical organic soils to date are from Southeast Asia. Nonetheless these EFs should be used for all tropics until better data become available.

Tier 2

Emission factors for boreal and temperate organic soils

In the boreal zone more than 50 % of N_2O emissions from organic nutrient-rich soils can occur during the winter (Maljanen *et al.,* 2010). When national data are used, it is *good practice* to only use N_2O data measured in all seasons and representative of the seasonal average. There is increasing evidence that N_2O emissions are very low in drained nutrient-poor peatlands where C:N ratio in boreal soils is high (e.g. Klemedtsson *et al.,* 2005), but there is strong potential for high emissions with low (< 25) C:N ratios. In addition to nutrient (nitrogen) level in peat, other more dynamic factors such as drainage status (Maljanen *et al.,* 2010), may control the rates of nitrification or denitrification and suppress high N_2O emissions even at low C:N ratios. Therefore the uncertainty of annual N_2O emission rates increases in nutrient rich peatlands compared to those in nutrient poor peatlands.

Emission factors for tropical organic soils

The EFs presented for Tier 1 represent agronomic practices in the early to mid-2000s. The inventory compiler should assess whether agronomic practices have changed significantly and whether disaggregated factors are necessary in place of aggregated factors and if so use a Tier 2 approach.

Tier 3

See Volume 4, Chapter 11 of the *2006 IPCC Guidelines*.

CHOICE OF ACTIVITY DATA

Activity data consist of areas of land remaining in a land-use category on organic soils stratified by major land-use types, management practices, and disturbance regimes. Total areas should be determined according to approaches laid out in chapter 3 of the *2006 IPCC Guidelines* and should be consistent with those reported under other sections of the inventory. The assessment of changes in soil carbon will be greatly facilitated if this information can be used in conjunction with national soils and climate data, vegetation inventories, and other biophysical data. Stratification of land-use categories according to climate regions, based on default or country-specific classifications can be accomplished with overlays of land-use on suitable climate and soil maps.

Tier 1

Activity data for non-CO_2 greenhouse gas emissions should be consistent with activity data for CO2 and CH_4 emissions from soils. Guidance for activity data is given in the respective sections in this Chapter.

Tier 2

In tropical peatlands there are several significant distinctions for land-use. Inventory compilers can increase the accuracy of inventories by making distinctions between different forest types. Several countries have datasets available in national forest statistics that allow for this type of disaggregation. Further improvements to Tier 2 estimation can be made with targeted measurements to provide data for other widespread practices, like Acacia plantation forestry.

Likewise, particularly in Southeast Asia, there are large areas of organic soils that are cultivated using specific practices. Inventory compilers can also increase the accuracy by disaggregating specific Grasslands and Cropland types like oil palm cultivation, rice and sago palm. Sago palm, for example, is cultivated with a relatively high water table level, which maintains conditions that promote denitrification (Melling *et al.,* 2007). Rice is also cultivated with a high water table level in peatlands and is generally fertilized. Oil palm, on the other hand usually is produced with deep drainage >60 cm and has high fertilizer application rates near the trees during the establishment phase of the crop. All other types of agriculture have to be aggregated at the moment because of the paucity of data.

Similarly under temperate and boreal conditions, the accuracy of the inventories can be enhanced once information about different forest types and crop types as well as grassland management practices (intensities) are available and different country specific EF for these classes can be used.

Tier 3

See Volume 4, Chapter 11 of the *2006 IPCC Guidelines*.

UNCERTAINTY ASSESSMENT

Uncertainties in estimates of direct N_2O emissions from managed soils are caused by uncertainties related to the emission factors (see Table 2.5 for uncertainty ranges), inter-annual variability associated with temperature and rainfall, activity data, lack of coverage of measurements, spatial aggregation, and lack of information on specific on-farm practices.

Additional uncertainty will be introduced in an inventory when emission factors are derived from measurements that are not representative of the variation of conditions in a country. Because of very high spatial variability of N_2O emissions from soils, most estimates have large standard errors relative to the mean flux. In general, the reliability of activity data will be higher than that of the emission factors. Further uncertainties may be caused by missing information on observance of laws and regulations related to handling and application of fertiliser and manure, and changing management practices in farming. Generally, it is difficult to obtain information on the actual observance of laws and possible emission reductions achieved as well as information on farming practices. For more detailed guidance on uncertainty assessment refer to Volume 1, Chapter 3 of the *2006 IPCC Guidelines*.

2.2.2.3 CO_2 AND NON-CO_2 EMISSIONS FROM FIRES ON DRAINED ORGANIC SOILS

Peat fires can be a large and variable source of greenhouse gases and significantly affect other feedbacks within the climate system. When compared to combustion of above-ground vegetation, the emissions from both uncontrolled wildfires and managed (prescribed) fires in organic (peat) soils are high. In peatland ecosystems, fires comprise both surface fires that consume vegetation, litter and duff, and deep peat fires which burn into and below the surface consuming the peat itself as a fuel source. Deep peat fires are smouldering fires that may persist for long periods of time, burn repeatedly in response to changing soil moisture and surface hydrology, and penetrate to different depths. This section deals with deep peat fires. In any ecosystem, fire activity is strongly influenced by three factors, namely weather/climate, fuel availability, and ignition agents, including human activities (Johnson, 1992; Swetnam, 1993). In ecosystems with organic soils, site conditions such as peat moisture, vegetation composition and peat surface micro-topography (e.g. Benscoter *et al.,* 2003) along with fire characteristics, such as intensity, frequency and duration (Kasischke *et al.,* 1995) influence the quantity of organic matter consumed and hence the emissions of greenhouse gases (Kuhry 1994; Kasischke *et al.,* 1995; Kasischke and Bruhwiler, 2003).

2006 IPCC Guidelines covered emissions from burning of above-ground carbon stocks (biomass and dead organic material) but did not cover the often substantial release of emissions from combustion of organic soils. It is *good practice* to report greenhouse gas emissions from fires on all managed lands with organic soils.

This Chapter updates the *2006 IPCC Guidelines* by:

- Providing default methodologies and emission factors for CO_2, CH_4 and CO emissions from fires on organic soils
- Providing generic guidance for higher Tier methods to estimate these fluxes

Change in soil organic carbon following fire is the result of both CO_2 as well as non-CO_2 emissions (principally of CH_4 and CO). Emissions of both CO_2 and non-CO_2 greenhouse gases are dealt with in the following sections. These deal specifically with fire-driven soil (i.e. below-ground biomass) as opposed to vegetation and litter (above-ground biomass) losses (the latter are included in the estimation of C stock changes in the *2006 IPCC Guidelines*).

CHOICE OF METHOD

CO_2 and non-CO_2 emissions from burning of drained organic soils can either be directly measured or estimated using data on area burnt along with the default values for mass of fuel consumed and emission factors provided in this chapter. Previous IPCC Guidelines have noted that emissions from wildfires on managed (and unmanaged) land can exhibit large inter-annual variations that may be driven by either natural causes (e.g. climate cycles, random variation in lightning ignitions), or indirect and direct human causes (e.g. historical fire suppression and past forest harvest activities) or a combination of all three causes, the effects of which cannot be readily separated. This variability is also true for emissions from peatland fires which critically depend on the depth of the organic soils, the fuel moisture, and the resulting depth of the consumed organics, all of which are affected by ecosystem type, weather, land management, fire type, and climate. At Tier 1, differentiation by land management category and fire type is possible, but reporting at higher Tiers will enable a greater level of differentiation between ecosystem, land-use and fire types.

The parameters required to calculate the CO_2 and non-CO_2 emissions from burning organic soils are: area burned, mass of fuel available for consumption, combustion factor (this is also known as burning efficiency and can be used to characterize smouldering vs. flaming fires) and emission factor. Compared with vegetation fires, the uncertainties involved in estimating emissions from peat fires are much higher because peat can burn repeatedly and to different depths. Furthermore, the type and density of peat combined with the combustion efficiency will determine the nature of the gases and other compounds emitted.

The mass of fuel per unit area that can potentially burn in a fire event on organic soils will be determined by depth of burn, soil bulk density and carbon content; the former is controlled by soil moisture content (with position of water table a reasonable proxy) while the latter variables are ideally measured in the field. While default values can be used for Tier 1 reporting, for higher Tiers data on the depth of burn need to be determined. The combustion factor describes how much of the biomass available is actually consumed during a fire event, i.e., converted into CO_2 or non-CO_2 gases. The emission factor (G_{ef}) determines the mass of CO_2 or non-CO_2 gas emitted per mass of fuel consumed by the fire (e.g. g CO_2/kg dry fuel). The total emissions of CO_2 or non-CO_2 are calculated from the product of area burnt and the corresponding biomass loading, combustion factor, and emission factor.

EQUATION 2.8

ANNUAL CO_2 AND NON-CO_2 EMISSIONS FROM ORGANIC SOIL FIRE

$$L_{fire} = A \bullet M_B \bullet C_f \bullet G_{ef} \bullet 10^{-3}$$

Where:

L_{fire} = amount of CO_2 or non-CO_2 emissions from fire, tonnes

A = total area burned annually, ha

M_B = mass of fuel available for combustion, tonnes ha^{-1} (i.e. mass of dry peat fuel) (default values in Table 1)

C_f = combustion factor, dimensionless

G_{ef} = emission factor for each gas, g kg^{-1} dry matter burnt (default values in Table 2.7)

Note: Where data for M_B and C_f are not available, a default value for the amount of fuel actually burnt (the product of M_B and C_f) can be used under Tier 1 methodology (Table 2.6). The value 10^{-3} is a conversion of the emission factor units to per tonnes.

The amount of fuel that can be burned is given by the area burned annually and the mass of fuel available in that area.

Default values for the Tier 1 method or components of a Tier 2 method are provided in Tables 2.6 and 2.7. For higher Tiers data on the variation in the mass of fuel available (based on site or region specific data, including area of organic soils burnt, depth of organic soil, depth of burn and/or depth of water table/soil moisture content values and peat bulk density) are incorporated.

Figures 1 and 2 present a decision tree that guides the selection of the appropriate Tier level to report CO2 and non-CO_2 emissions from the burning of organic soils.

Figure 2.1 Generic decision tree for identification of the appropriate tier to estimate greenhouse gas emissions from fire in a land-use for *land remaining in the same land-use category*

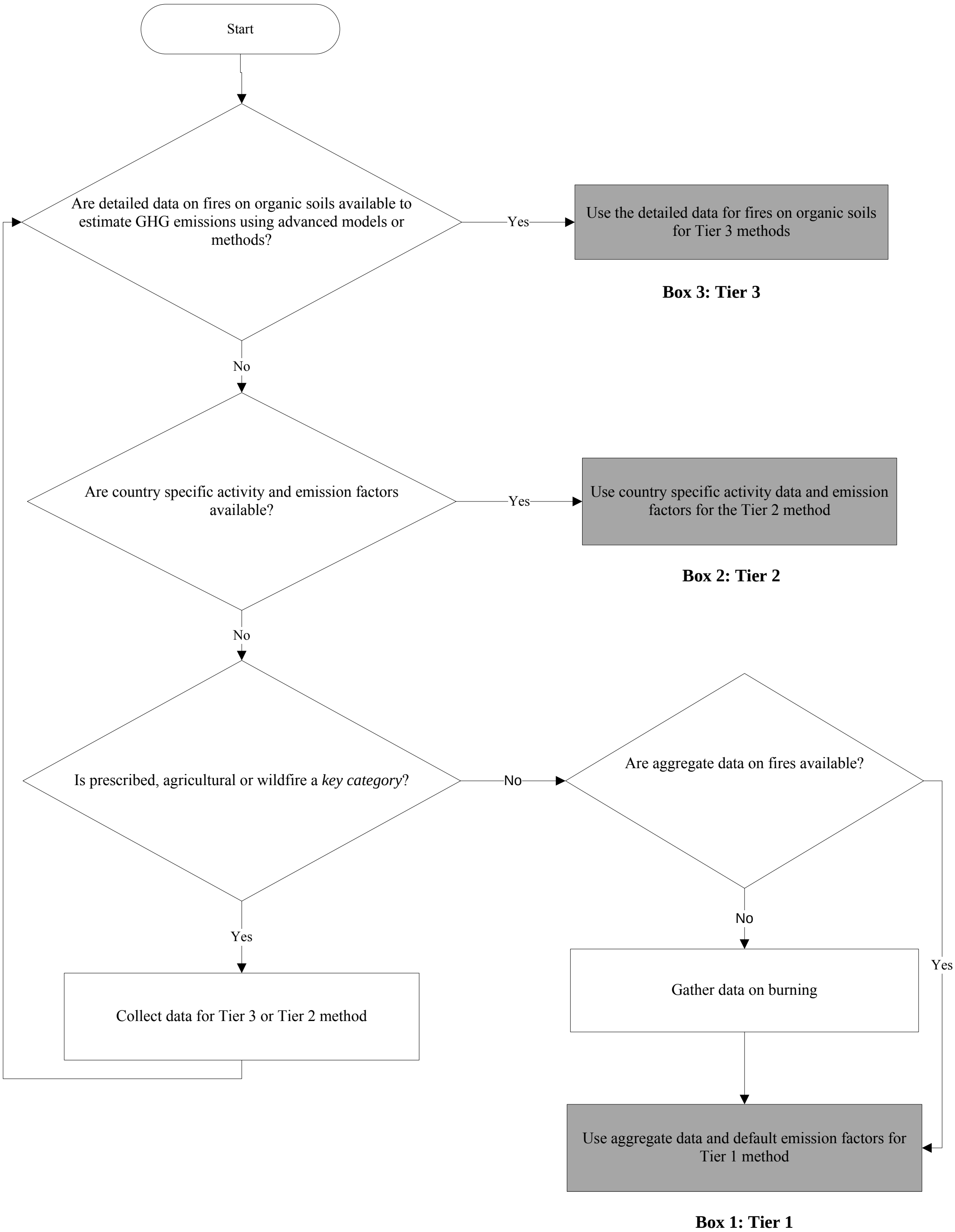
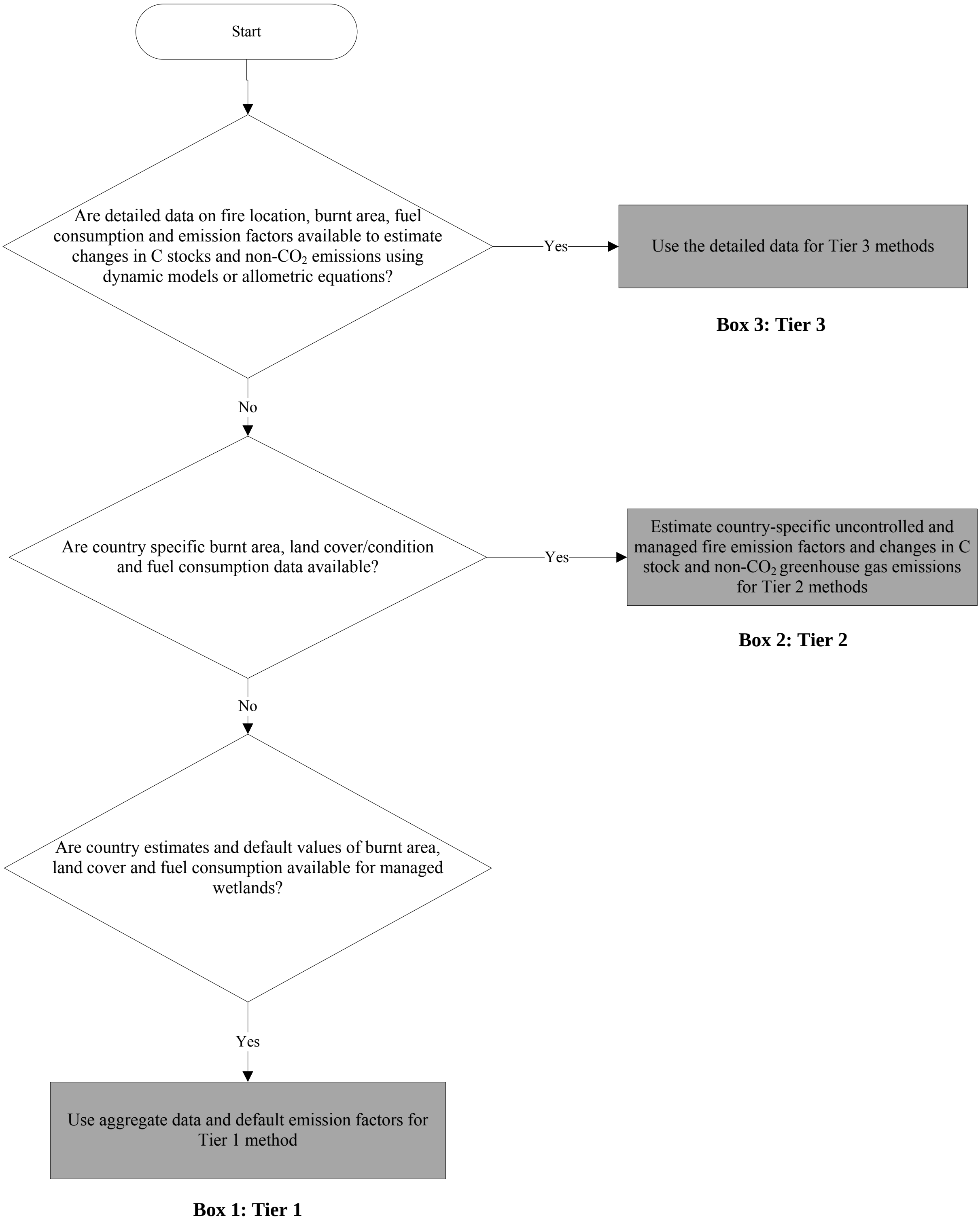


Figure 2.2 Decision tree for identification of appropriate tier to estimate carbon stocks and non-CO_2 greenhouse gas emissions for wild (uncontrolled) and managed (prescribed and agricultural) fires in managed wetlands with organic soils



BOX 2.2

SCIENTIFIC BACKGROUND FOR DEVELOPING CO_2 AND NON-CO_2 EMISSION FACTORS FOR EMISSIONS FROM BURNING OF ORGANIC SOILS FROM SCIENTIFIC LITERATURE IN TABLE 2.6 AND TABLE 2.7

CO_2 emission factors for fires on organic soils were obtained by a consideration of the available scientific literature. The data presented in Table 2.6 and Table 2.7 provide default values for mass of available fuel and emissions factors.

The data in Table 2.6 have been obtained using a variety of different approaches in order to calculate the mass of fuel combusted. It should be noted that there are only a limited number of publications providing ground- or laboratory-based data on the depth (i.e. volume) of peat consumed during peatland fires. Quantitative estimation of depth of burn as well as peat characteristics (i.e. bulk density and carbon content) are not easy to determine in the field, thus information on these key parameters is often based on theoretical assumptions or limited spatially scattered ground measurements. This knowledge gap contributes considerably to the overall uncertainties related to emissions from peatland fires (French *et al.,* 2004, Kasischke *et al.,* 2005, Soja *et al.,* 2004) because it is difficult to accurately assess the amount of fuel that is consumed. Field data of depth of burn are available from a number of studies of fires on organic soils in northern forests and peatlands in North America, Europe and Asia (e.g. Zoltai 1998; Turetsky & Wieder 2001; Benscoter & Wieder 2003; Turetsky *et al.,* 2011a, 2011b), while in other cases, data have been extrapolated from previous studies.

Obtaining accurate field data on the depth of peat combustion is problematic since there is usually a lack of reference data. Turetsky *et al.* (2001) developed a method for field assessment that considered the rooting depth of trees, while other studies have used comparison of adjacent unburned sites to quantify combustion depth (e.g. Kasischke *et al.,* 2000; Page *et al.,* 2002; Turetsky *et al.,* 2011a). The use of remote sensing (LiDAR) has also been applied in one study (Ballhorn *et al.,* 2009).

Nearly all the data presented in Table 2.6 for the boreal/temperate zones are actually for the boreal zone, with only one study in the temperate zone (Poulter *et al.*, 2006). Most studies are of wildfires (i.e. unwanted and unplanned fires ignited other than by prescription (e.g. by lightning or as a result of human activities, including escaped prescribed fires as well as those started through negligence or by arson) (US Federal Fire Management Policy 2008)) and are for fires on undrained peatlands. Only Turetsky *et al.* (2011b) provides depth of burn data for a wildfire on a drained boreal peatland. In addition, there are no data for organic soil losses associated with prescribed fires in the boreal/temperate zone. Most prescribed (i.e. managed) fires on the vegetation of organic soils probably result in either no or only minimal ignition loss of soil carbon. Fuel moisture content, depth of water table and burn history will all determine the extent of organic soil combustion during a prescribed fire but the scale of loss will often depend on the skill and experience of the fire manager. In some parts of the temperate zone, prescribed rotational burning of vegetation on organic soils is a long-established land management practice. In the UK it is carried out on about 18% of peatlands, predominantly in the uplands (Marsden & Ebmeier, 2012), with the aim of removing the older, less productive vegetation and encouraging new growth for livestock grazing and cover for game birds (Worrall *et al.* 2010). In North America, prescribed burning of vegetation on organic soils is also practiced, with a range of benefits including the reduction of wildfire hazards, improvement of wildlife habitats and restoration of ecosystem diversity and health (e.g., Christensen, 1977; US Federal Fire Management Policy, 1995, 2001). The typical timing for prescribed burning is in the spring and autumn months when fuel moisture is high enough to prevent peat combustion but low enough to carry a surface fire which reduces the risk of organic soil ignition. Shifts in climate have narrowed the window of opportunity for prescribed burning and changes in weather patterns have resulted in unexpected drying of peatlands during on-going prescription burns. Some local fire managers have recognised this shift, but unfortunately this is a minimally studied area and little information exists on the scale of emissions arising from the combustion of organic soils during prescription burns. At Tier 1, it is assumed that there is either no or very little combustive loss of soil organic matter during prescribed fires on organic soils.

For tropical organic soils, the average depth of burn has not been explored in a consistent way that representatively covers the different geographical regions nor the different fire types (i.e. wild vs. agricultural fires). There have only been a limited number of field measurements of depth of burn and estimates of peat combustion losses. These have used either direct field measurements (e.g. Page *et al.,* 2002) or a combination of field measurements and LiDAR data (e.g. Ballhorn *et al.,* 2009). There are only two studies of wildfires on drained peatlands and none in undrained peatlands, although studies have demonstrated that in an intact condition tropical peat swamp forest is at very low risk of fire (e.g. Page *et al.,* 2002). There have been a limited number of studies investigating depth of burn on drained peatlands under agricultural management (e.g. Saharjo & Munoz, 2005). Agricultural burning is undertaken in order to improve soil fertility or to remove forest or crop residues during land preparation activities. For example, traditional 'sonor' rice cultivation on shallow peat involves regular burning of crop residues along with the surface peat to enhance soil fertility. Fire is also used on both a small and large scale to dispose of forest debris and invasive vegetation during land preparation and of crop residues at the end of a planting cycle (e.g. Saharjo & Munoz, 2005).

In addition to field measurements, there have been limited laboratory-based burn tests aimed at establishing the environmental controls on depth of peat combustion (e.g. Benscoter *et al.,* 2011). While more field and laboratory experiments to determine fuel consumption during peat fires are needed (French *et al.,* 2004) there is also a need for improved remote sensing methods to aid burn severity mapping in peatlands (defined as the magnitude of ecological changes between pre- and post-fire conditions) which can provide an indication of the likely depth of burn. Burn severity is not easy to either investigate or quantify but there have been a number of studies using spectral indices to discriminate different levels of burn severity in boreal and temperate forests (e.g. van Wagtendonk *et al.,* 2004; Epting *et al.,* 2005; Hall *et al.,* 2008) but only one study to date in tropical peatland (Hoscilo *et al.,* 2013). Even regionally developed consumption models can have large uncertainties with respect to organic soils consumption (e.g. Larkin *et al.,* 2013). The development of robust methodologies to assess burn severity and total organic soil consumption peat-covered landscapes would enable more accurate quantification of carbon emissions from both above and below-ground fires for reporting at Tier 3 level.

Accurate assessment of the volume of peat combusted during a fire will only be feasible at higher Tier 2 and Tier 3 levels, while at Tier 1 level some simplifying assumptions are required.

Tier 1

Countries may choose to report CO_2 emissions using the Tier 1 method if fires on organic soils are not a *key category*. This approach is based on highly aggregated data and default factors. It does, however, require primary data on area burned.

If burning in ecosystems with organic soils is a *key category*, countries are encouraged to report emissions by applying the highest Tier possible, given national circumstances. For prescribed fires, country-specific data will be required to generate reliable estimates of emissions.

Tier 2

Tier 2 refines the Tier 1 method by incorporating more disaggregated area estimates (per peatland and fire type sub-categories) and country-specific estimates of combustion and emission factors into Equation 1. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Potential improvements to the Tier 1 approach may include:

- Knowledge of the amount of soil organic matter consumed;
- The position of the water table in a peatland relative to the surface;
- Improved information on land-use/management and their effects on peatland condition, in particular peatland hydrological status; and
- Improved data on area burnt estimated using remotely sensed data of adequate spatial and temporal resolutions analysed according to a robust sampling design at suitable periodicity to take account of the monthly variations of area burnt.

Countries may further stratify the data on area burnt by depth of burn, peatland condition (e.g., drained vs. undrained, with further detail possible through characterisation of the intensity of drainage) and fire types (wildfire vs. prescribed or agricultural).

Tier 3

The Tier 3 method is based on models with algorithms to generate regional scale maps of area burnt using satellite data of multiple sources and of moderate spatial resolution. For Tier 3, model results should be validated, for example, by using high spatial resolution data augmented by field observations, and refined based on the validation results and feedback from operational users whenever possible. A sampling approach can be designed to generate estimates of area burnt. The Tier 3 reporting method should provide estimates (fluxes) of the impact of burning on below-ground biomass, particularly including the depth of burn, and if feasible the variation of depth within the area burned. Reporting at this level should differentiate fires burning at different intensities and with different proportions of smouldering vs. flaming combustion (i.e. different Modified Combustion Efficiency (MCE) defined as $\Delta CO_2/(\Delta CO_2/\Delta CO)$ which is an index of the relative proportion of smouldering vs. flaming combustion). The development of robust methodologies to assess burn severity in peat-covered landscapes would enable more accurate quantification of greenhouse gas emissions from below-ground fires for reporting at Tier 3 level.

CHOICE OF EMISSION FACTORS

Tier 1

The Tier 1 method uses default values for M_B along with default emissions factors provided in Tables 2.6 & 2.7 respectively.

Due to the limited data available in the scientific literature peatlands have been very broadly stratified according to climate domain (boreal/temperate and tropical) and fire type (wild vs. prescribed vs. agricultural). Values are derived from the literature for all categories with the exception of prescribed fires.

For all peat fires, the default combustion factor is 1.0, since the assumption is that smouldering combustion accounts for all fuel consumption in burning organic soils (Yokelson *et al.,* 1997).

TABLE 2.6
PEAT FUEL CONSUMPTION VALUES (TONNES DRY MATTER HA^{-1}) FOR FIRES IN A RANGE OF PEATLAND TYPES
(TO BE USED IN CONJUNCTION WITH EQUATION 2.7, TO ESTIMATE THE PRODUCT OF QUANTITIES M_B AND C_F, I.E. AN ABSOLUTE AMOUNT)

Peatland type	Sub-category	Mean	SE	References
Boreal/temperate	Wildfire (undrained peat)	66.4	9.8	Zoltai *et al.,* 1998; Turetsky & Wieder, 2001; Benscoter & Wieder, 2003; Kasischke & Bruhwiler, 2003; Amiro *et al.,* 2001; Kajii *et al.,* 2002; Kasischke *et al.,* 1995; Pitkänen et al. 1999; Cahoon *et al.,* 1994; Turetsky *et al.,* 2011a; Turetsky *et al.,* 2011b; Poulter *et al.,* 2006; de Groot & Alexander, 1986; Kuhry, 1994
	Wildfire (drained peat)	336.0	4.0	Turetsky *et al.,* 2011b
	Prescribed fire (land management)	0	1.0	No literature found; informed opinion
Tropical	Wildfire (undrained peat)	66.4	9.7	No literature found; same value as boreal/temperate
	Wildfire (drained peat)	438.7	51.8	Page *et al.,* 2002; Ballhorn *et al.,* 2009
	Agricultural/land clearance fires	146.6	32.6	Saharjo & Munoz, 2005; Saharjo & Nurhayati , 2005; Usop *et al.,* 2004

Note: Where fuel consumption values have been reported as t C ha^{-1}, default values for peat bulk density (0.1 g cm^{-3})* and carbon density (50% mass dry weight)** have been applied to derive a value for mass of fuel (t ha^{-1}) (following Akagi *et al.* 2011). At higher Tier levels, country or ecosystem specific values for both these variables are used.

*The value for surface peat bulk density is an average derived from Gorham (1991) who provides a default value of 1.12 g cm^{-3} for all northern peatlands and Page *et al.* (2011) who provide a default value of 0.09 g cm^{-3} for all tropical peats.

**The value for surface peat carbon density is an average derived from the typical average for eutrophic peat of 48% and the typical average for oligotrophic peat of 52% (after Lucas (1982), Immirzi *et al.* (1992) as reported in Charman (2002)).

TABLE 2.7
EMISSION FACTORS (G KG^{-1} DRY MATTER BURNED) FOR PEAT FIRES. VALUES ARE MEANS ± SD. (TO BE USED AS QUANTITY G_{EF} IN EQUATION 2.7)

Peatland type	CO_2	CO	CH_4	References
Boreal/temperate	1328 ± 179	207 ± 97	9 ± 6	Ward & Hardy, 1984; Yokelson *et al.,*1997; Yokelson *et al.* (2013)
Tropical	1703	210	21	Christian *et al.,* 2003

1. These values have been derived from a very limited number of studies. Surface (flaming) and deep (smouldering) peat fires produce a complex mixture of gases and fine particles, the nature of which will reflect vegetation type, fire behaviour, peat physical and chemical characteristics as well as the combustion conditions (in particular combustion efficiency) (Itkonen and Jantunen, 1983; NCDENR, 1998). The combustion of organic material leads to a loss of carbon; most of this is in the form of CO_2, but quantities of CO, CH_4, long-chain hydrocarbons, and carbon particulate matter are also emitted. Other greenhouse gases along with ozone precursors (NOx), volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons are also released (Ramadan *et al.,* 2000, Gebhart *et al.,* 2001, Honrath *et al.,* 2004, Val Martin *et al.,* 2006, Lapina *et al.,* 2008, , Akagi *et al,.* 2011). There is no evidence of N_2O emissions from fires, although it can be produced in canisters during sample storage (Yokelson pers. comm.).
2. The composition of peat fire emissions differs substantially from forest fires; in part this is a function of the fact that peat fires, particularly deep peat fires, are dominated by smouldering rather than flaming combustion owing to the moist and often oxygen-limiting substrate conditions. Fire temperatures also differ: the typical peak temperature of smoldering peat fires is in the range 500-700 ^{0}C, while for flaming fires it can be 1000-1500 ^{0}C (Usop *et al.,* 2004; Rein, 2008). The lower temperatures and smoldering combustion associated with deep peat fires makes them harder to detect by satellites and leads to the emission of high amounts of CO relative to CO_2 as well as large amounts of fine particulate matter (PM2.5); tropical peat fires, for example, emit as much as 3 to 6 times more particulate matter per amount of biomass consumed than other types of biomass fires (Grassland, forest, plantation fires) (Heil *et al.,* 2006). The emission ratio of CO to CO_2 (ERCO/CO_2) can be used as an indicator of the relative amount of flaming versus smouldering combustion during biomass burning with higher ERCO/CO_2 observed in smoldering fires (Cofer *et al.,* 1989, 1990; Christian *et al.,* 2007, Yokelson *et al.,* 2007).

Tier 2

The Tier 2 approach for estimating greenhouse gas emissions from fires on organic soils incorporates country-specific information in Equation 1. When deriving Tier 2 emission factors country-specific combustion factors need to be developed. Regional factors for stratification could include:

- Stratification by drainage class. Position of the peat water table is a proxy for soil moisture which determines depth of burn.
- Depth of burn. This can be measured in the field post-fire (e.g. Page *et al.,* 2002; Turetsky & Wieder, 2003; Turetsky *et al.,* 2011a, b) or using remote sensing approaches (e.g. LiDAR) (Ballhorn *et al.,* 2009). Stratification by different fire types (wild vs. prescribed or. agricultural fires).
- Stratification by peatland type taking into account general hydrology (e.g. bog vs. fen); vegetation structure (open, shrubby, forested); and peatland condition (particularly relevant for tropical peatlands) whenever possible.
- Use of regionally-specific values for organic soil bulk density and carbon concentration.
- Stratification by different land-use and management types, including differences in drainage lay-out and intensity, land-use intensity and practices, all of which will influence the mass of fuel available for combustion.

Emission factors can be derived from measurements (field or laboratory based) or calculations validated against country-specific measurements. The literature on emissions from fires on organic soils is very sparse and countries are encouraged to share data when peat quality, environmental conditions and land-use practices are similar.

Tier 3

A Tier 3 approach might use process-based models, adequately validated using observation data that take into account temporal and spatial variations in the differences between fires on different peatland types and conditions and fuel combustion efficiencies. This approach will involve a comprehensive mechanistic understanding of combustion of organic soils, including the effects of site characteristics, drainage intensity, vegetation cover, peat type, depth, management practices, depth of water table and soil moisture among others. Tier 3 approaches could start by developing robust relationships between drainage and depth of burn which could then be further refined by land management category. Models ideally also take into account fire return interval. Fire changes peat chemical and physical characteristics (Yefremova & Yefremov, 1996; Zoltai *et al.,* 1998; Milner *et al.,* submitted) as well as the rate and nature of post-fire vegetation recovery, and thus can alter total net ecosystem productivity.

CHOICE OF ACTIVITY DATA

Activity data consist of areas of land remaining in a land-use category on organic soils stratified by major land-use types, management practices, and disturbance regimes. Total areas should be determined according to approaches laid out in Chapter 3 of the *2006 IPCC Guidelines* and be consistent with those reported under other sections of the inventory. The assessment of fire-driven changes in soil carbon will be greatly facilitated if this information can be used in conjunction with national soils and climate data, vegetation inventories, maps of burned area and other biophysical data. Stratification of land-use categories according to climate zones, based on default or country-specific classifications can be accomplished with overlays of land-use on suitable climate and soil maps.

Tier 1

Tier 1 methods require data on burned area of organic soils stratified by climate domain and fire type (wild vs. prescribed or agricultural). Data on burned area are often obtained from a time series of images from remote sensors and, in inaccessible locations, this may be the only method available to assess area burned. Box 2.3 provides more details on the remote-sensing platforms currently used for obtaining burnt area data.

BOX 2.3

RECENT ADVANCES IN SATELLITES DERIVED FIRE PRODUCTS

Recent advances in satellite-derived fire products using MODerate resolution Imaging Spectroradiometer (MODIS) data from the Terra and Aqua satellites (Roy *et al.,* 2008; Giglio *et al.,* 2009); the Advanced Very High Resolution Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration (NOAA); Polar Operation Environmental Satellite (POES); the European SPOT satellites, and the Geostationary Operational Environmental Satellite (GOES) have all enabled the derivation of burned area data in near real-time and thereby enhanced the ability to estimate the areal extent of regional and global wildland fires and hence the scale of emissions (e.g. Gregoire *et al.,* 2003; Simon *et al.,* 2004; Tansey *et al.,* 2008; Giglio *et al.,* 2009; Kasischke *et al.,* 2011). The uncertainties and particular challenges associated with commission and omission errors in remote sensing approaches to peat fire detection, however, need to be recognized and acknowledged. In particular, during their extended smouldering phases, fires in organic soils may be particularly difficult to pick up by radiance measurements.

Several institutions, including ISRIC and FAO have country-specific and global maps that include organic soils (http://www.fao.org/geonetwork/srv/en/main.home or http://www.isric.org/). A global consortium has been formed to make a new digital soil map of the world at fine resolution (http://www.globalsoilmap.net/).

Tier 2

Activity data for Tier 2 consist of areas with organic soils stratified by peat type and condition; vegetation type and condition; drainage depth; land management status; and depth of burn to improve the accuracy of the inventory. Data on depth of burn (obtained from in situ field or remote sensing (e.g. LiDAR) measurements), along with country-specific data on peat bulk density and carbon content will also greatly improve knowledge of the mass of fuel consumed and the scale of carbon emissions.

Tier 3

The Tier 3 method requires more disaggregated activity data than lower Tiers. This includes disaggregation according to drainage classes, and may take into account such variables as seasonal norms and modifications in water table level due to seasonal weather patterns etc. Seasonal variations in fire-driven emissions are then aggregated to annual emissions. Also the annual average water table level as a robust proxy for depth of burn includes seasonal water table level differences.

The accuracy of emission estimates will be further improved if information is also available on land-use and its effect on peatland condition, since fire extent and severity and hence quantity of emissions increase according to the scale of disturbance (e.g. disturbance of vegetation cover, and the presence of drainage structures associated with agriculture, forestry, peat harvesting, oil and gas extraction, roads etc. (e.g. Turetsky *et al.,* 2011)). Remote sensing techniques (e.g., Kasischke *et al.,* 2009) can also be used to provide an indication of the likely fire risk by estimating soil moisture conditions and providing an accurate proxy measure of peat surface moisture levels and hence likely depth of burn at a landscape scale.

CALCULATION STEPS FOR TIER 1

The steps for estimating the CO_2 and non-CO_2 emissions from fires on drained organic soils for *land remaining in a land-use category* are as follows:

Step 1: Using guidance in Chapter 3 of the *2006 IPCC Guidelines*, stratify areas with drained organic soils of *land remaining in that land-use category* for each land-use category according to climate domain and fire type. Obtain estimates of A (area burnt) from global database or from national sources.

Step 2: Assign the appropriate fuel load (M_B) and emission factor (G_{ef}) from Table 2.6 and 2.7 respectively for the gas and

Step 3: Estimate the CO_2 or non-CO_2 emissions by multiplying burnt area with the appropriate fuel load (M_B) and emission factor (G_{ef}) from Table 1 using Equation 1.

Step 4: Repeat steps 1-4 for each greenhouse gas.

UNCERTAINTY ASSESSMENT

There are several sources of uncertainty related to estimates of CO_2 and non-CO_2 emissions from fires on organic soils. Fire behaviour varies greatly among wetland types and hence, disaggregation of vegetative formations will lead to greater precision. The fraction of fuel that is actually combusted during burning (the combustion factor) varies, not only between ecosystems, but also between fires, between years, and as a function of land management practices. Measurements from a given fire, year, and/or region cannot be extrapolated with confidence to other locations or years, or to biome scale. Other major causes of uncertainty are the accuracy of the estimates of area burnt, proportion of the available fuel oxidized, and the biomass fuel available. Uncertainties of estimates of areas burnt can vary markedly depending on the methodology employed – for example, where very high resolution remote-sensing is used it may be of the order of 20%, whereas the use of global fire maps may result in uncertainties of up to two-fold. Uncertainties in estimates of greenhouse gas emissions over large regions from fire are likely to be at least 50%, even with good country-specific data, and at least two-fold where only default data are used. The calculation of emission errors is addressed by French *et al.* (2004).

2.3 LAND CONVERTED TO A NEW LAND-USE CATEGORY

2.3.1 CO_2 emissions and removals from drained inland organic soils

CO_2 emissions/removals from land converted to a new land-use category on organic soils within the inventory time period are calculated in the same way as CO_2 emissions/removals from *land remaining in a land-use category*. CO_2 emissions/removals for the newly converted lands are calculated using Equations 2.1 and 2.2.

On-site CO_2 emissions after land-use change on drained organic soils can occur from all five carbon pools. Land-use change can result in direct losses/gains because of biomass clearance/(re)planting. This is addressed by guidance for changes in the carbon pools in aboveground and belowground biomass and dead organic matter on lands converted to new land-use categories provided in the *2006 IPCC Guidelines.*

Land-use change can indirectly affect carbon gains and losses because of altered growth of woody biomass and altered respiration and peat oxidation through altered soil temperature. These effects are included in the guidance for lands remaining in a land-use category provided in the *2006 IPCC Guidelines* for aboveground and belowground biomass and dead organic matter and updated emission factors in Table 2.1 of section 2.2.1.1.

Additional carbon losses from biomass and soil can occur through altered fire frequency after drainage and land-use change. These CO_2 emissions from fire are addressed in section 2.3.2.3.

2.3.1.1 ON-SITE CO_2 EMISSIONS/REMOVALS FROM DRAINED INLAND ORGANIC SOILS (CO_2-$C_{SOIL\text{-}ONSITE}$)

CHOICE OF METHOD

CO_2 emissions/removals from land converted to a new land-use category on organic soils within the inventory time period are calculated in the same way as CO_2 emissions/removals from land remaining in the new land-use category. CO_2 emissions/removals for the newly converted lands are calculated using Equation 2.3 if the soils are drained. Specific guidance by new land-use categories is given in the *2006 IPCC Guidelines*, Chapters 5, 6, 8 and 9.

At Tier 1, there is no transition period for CO_2 emissions from organic soils because the land immediately switches to the methodologies of the new land-use category. Accelerated carbon loss from organic soil has been observed directly after converting tropical peat swamp forests to other land-uses (Jauhiainen *et al.,* 2008; Hooijer *et al.,* 2012). This transitional high-emission phase is likely to occur in other land-use conversions as well but is not captured by the Tier 1 methodology. The transitional high-emission phase should be addressed by higher tier methods. Additional guidance on the Tiers 1, 2 and 3 approaches is given in Section 2.2.1.1.

CHOICE OF EMISSION/REMOVAL FACTORS

CO_2 emissions/removal factors for the newly converted lands are the same as for land remaining in the new land-use category. For Tier 1 these are given in Table 2.1. Additional guidance on the Tiers 1, 2 and 3 emission/removal factors is given in Section 2.2.1.1.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category in Section 2.2.1.1.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category in Section 2.2.1.1.

2.3.1.2 OFF-SITE CO_2 EMISSIONS VIA WATERBORNE CARBON LOSSES FROM DRAINED ORGANIC SOILS

CHOICE OF METHOD

TIER 1

At Tier 1, CO_2 emissions/removals from land converted to a new land-use category on organic soils within the inventory time period are calculated in the same way as CO_2 emissions/removals from land remaining in the new land-use category. Guidance is given in Section 2.2.1.2 for DOC. CO_2 emissions/removals for the newly converted lands are calculated using Equations 2.4 and 2.5.

TIER 2

The Tier 2 approach for waterborne carbon losses from organic soils incorporates country-specific information to estimate the emissions. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Tier 2 emission factors can in general be developed following the same principles as for land remaining in the new land-use category. Guidance is found in section 2.2.1.2. Generally, the same stratification should be used for land converted to a new land-use category as is used for land remaining in the new land-use category. Tier 2 approaches for land-use changes can be further stratified according to the time since land-use change. Specific transition periods can be considered depending on the type of land-use change and the persistence of emissions or removals which differ from those on lands that have been in the new land-use category for long time. Alternatively, the default transition period applicable to the new land-use category in the *2006 IPCC Guidelines* can be applied.

TIER 3

The development of Tier 3 approaches follows the guidance given in section 2.2.1.2 including the guidance for transparent documentation of Tier 3 approaches given in section 2.2.1.1. Generally, the same approach should be used for land converted to a new land-use category as is used for land remaining in the new land-use category. Tier 3 methods should further differentiate transition effects of increased or reduced waterborne carbon losses after land-use change and the time since land-use change.

Additional guidance on the Tiers 1, 2 and 3 approaches is given in Section 2.2.1.2.

CHOICE OF EMISSION/REMOVAL FACTORS

CO_2 emissions/removal factors for the newly converted lands are the same as for land remaining in the new land-use category. For Tier 1 these are given in Table 2.2. Additional guidance on the Tiers 1, 2 and 3 emission/removal factors is given in Section 2.2.1.2.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category in Section 2.2.1.2.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category in Section 2.2.1.2.

2.3.2 Non-CO_2 emissions and removals from drained inland organic soils

2.3.2.1 CH_4 EMISSIONS FROM DRAINED INLAND ORGANIC SOILS

CHOICE OF METHOD

CH_4 emissions/removals from land converted to a new land-use category on organic soils within the inventory time period are calculated in the same way as CH_4 emissions/removals from land remaining in the new land-use category. CH_4 emissions/removals for the newly converted lands are calculated using Equation 2.5. Additional guidance on the Tiers 1, 2 and 3 approaches is given in Section 2.2.2.1.

CHOICE OF EMISSION/REMOVAL FACTORS

CH_4 emissions/removal factors for the newly converted lands are the same as for land remaining in the new land-use category. For Tier 1 these are given in Tables 2.3 and 2.4. Additional guidance on the Tiers 1, 2 and 3 emission/removal factors is given in Section 2.2.2.1.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category in Section 2.2.2.1.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category in Section 2.2.2.1.

2.3.2.2 N_2O EMISSIONS FROM DRAINED ORGANIC SOILS

CHOICE OF METHOD

N_2O emissions from land converted to a new land-use category on organic soils within the inventory time period are calculated in the same way as N_2O emissions from land remaining in the new land-use category. N_2O emissions for the newly converted lands are calculated using Equation 2.7. Additional guidance on the Tiers 1, 2 and 3 approaches is given in Section 2.2.2.2.

CHOICE OF EMISSION/REMOVAL FACTORS

N_2O emission factors for the newly converted lands are the same as for land remaining in the new land-use category. For Tier 1 these are given in Table 2.5. Additional guidance on the Tiers 1, 2 and 3 emission/removal factors is given in Section 2.2.2.2.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category in Section 2.2.2.2.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category in Section 2.2.2.2.

2.3.2.3 NON-CO_2 EMISSIONS FROM BURNING ON ORGANIC SOILS

CHOICE OF EMISSION/REMOVAL FACTORS

Non-CO_2 emission factors for the converted lands are the same as for *land remaining in a land-use category*. For Tier 1 these are given in Tables 2.6 and 2.7. Additional guidance on the Tiers 1, 2 and 3 emission/removal factors is given in Section 2.2.2.3.

CHOICE OF ACTIVITY DATA

Guidance is the same as for *land remaining in a land-use category* in Section 2.2.2.3.

UNCERTAINTY ASSESSMENT

Guidance is the same as for *land remaining in a land-use category* in Section 2.2.2.3.

Annex 2A.1 Derivation of ditch CH_4 emission factors

The Tier 1 default EFs presented in Table 2A.1 were derived from the published studies listed. The number of studies available remains relatively small, although some include a substantial number of individual measurement sites. Measured fluxes are generally quite variable within each peat/land-use type, and are not evenly distributed across different peatland types (for example, most of the data for high-intensity and low-intensity Grasslands on drained organic soils are obtained from studies in the Netherlands). There are currently few data on CH_4 emissions from ditches in tropical peats or from blanket bogs. Further published data on ditch CH_4 emissions may be used to refine the default values presented in Table 2.4, or to derive country-specific Tier 2 emission factors.

Note that the table includes all measurements that were identified, including (for completeness) a small number of values from re-wetted sites. These were not used to derive EFs for Chapter 2, but could be used to account for ditch CH_4 emissions in re-wetted peatlands (see Chapter 3), where ditches remain a feature within the peatland landscape.

TABLE 2A.1
COLLATED DATA ON DITCH CH_4 EMISSIONS FROM DRAINED AND RE-WETTED PEAT SOILS

Peat/land-use type	Country	Reference	$EF_{CH_4\_ditch}$ (t CH_4-C ha^{-1} yr^{-1})	$Frac_{ditch}$
High-intensity Grassland	Netherlands	Schrier-Uijl *et al.,* 2010, 2011	0.435	0.21
High-intensity Grassland	Netherlands	Vermaat *et al.,* 2011	0.592	0.25
High-intensity Grassland	Netherlands	Best & Jacobs, 1997	0.072	0.06
High-intensity Grassland	UK	McNamara, 2013	0.580	0.04
High-intensity Grassland	Russia	Sirin *et al., 2*012	0.450	0.04
High-intensity Grassland	Russia	Chistotin *et al.,* 2006	1.989	0.04
High-intensity Grassland	USA	Teh *et al.,* 2011	1.704	0.05
Low-intensity Grassland	Netherlands	Vermaat *et al.,* 2011	0.592	0.25
Low-intensity Grassland (restored)	Netherlands	Best & Jacobs, 1997	0.345	0.06
Low-intensity Grassland (restored)	Netherlands	Van den Pol-Van Dasselaar *et al.,* 1999	0.085	0.25
Low-intensity Grassland (restored)	Netherlands	Hendriks *et al.* (2007, 2010)	0.375	0.10
Conservation-managed	Netherlands	Vermaat *et al., 2*011	0.329	0.25
Drained treed bog	Canada	Roulet & Moore, 1995	0.114	0.03
Drained treed fen	Finland	Minkkinen & Laine, 2006	0.783	0.03
Drained afforested fen	Russia	Sirin *et al.,* 2012	0.139	0.02
Drained afforested fen	Russia	Glagolev *et al.,* 2008	0.088	0.04
Drained treed bog	Canada	Roulet & Moore, 1995	0.028	0.03
Drained afforested bog	Russia	Sirin *et al.,* 2012	0.301	0.01

Drained afforested bog	Russia	Sirin *et al.*, 2012	0.011	0.01
Drained afforested bog	Canada	Roulet & Moore, 1995	0.192	0.03
Drained afforested bog	Sweden	Von Arnold *et al.*, 2005	0.013	0.02
Drained afforested bog	Finland	Minkinnen & Laine, 2006	0.053	0.03
Peat-mining site	Finland	Nykanen *et al.*, 1995	0.133	0.02
Peat-mining site	Sweden	Sundh *et al.*, 2000	0.356	0.03
Peat-mining site	Russia	Sirin *et al.*, 2012	1.022	0.04
Peat-mining site	Russia	Chistotin *et al.*, 2006	0.797	0.04
Cutover bog	Canada	Waddington & Day, 2007	0.110	0.05
Restored cutover bog	Canada	Waddington & Day, 2007	0.195	0.05
Drained blanket bog	UK	Cooper & Evans, 2013	0.070	0.03
Re-wetted blanket bog	UK	Cooper & Evans, 2013	0.619	0.06
Drained tropical peat (abandoned)	Indonesia	Jauhiainen & Silvennoinen, 2012	0.449	0.02
Drained tropical peat (pulpwood plantation)	Indonesia	Jauhiainen & Silvennoinen, 2012	2.939	0.02

Annex 2A.2 Derivation of DOC emission factors

Dissolved organic carbon (DOC) is commonly the largest component of waterborne carbon loss from peatlands and organic soils, with measured fluxes from natural peatlands ranging from around 5 to 90 g C m^{-2} yr^{-1}. In many peatlands, this flux is of comparable magnitude to the rate of long-term carbon accumulation (e.g. Gorham, 1991; Turunen *et al.,* 2004), and the size of waterborne carbon flux can therefore determine whether the site is a carbon sink or carbon source (e.g. Billett *et al.,* 2004; Rowson *et al.,* 2010). If this DOC is subsequently converted to CO_2 via photochemical or biological breakdown processes, this flux will also contribute to overall CO_2 emissions from the peatland (as an 'off-site' emission). This section describes the methodology that has been used to derive emission factors for DOC losses from drained peatlands and organic soils. At present, it is not considered possible to set reliable emission factor estimates for other forms of waterborne carbon loss, or for the effects of specific land-use and land-use changes (other than drainage) on DOC loss. Methodological requirements to develop these emission factors in future are described in Appendix 2a.1. The approach is based on Equation 2.3B.

Estimation of $DOC_{FLUX\_NATURAL}$

Most of the available published studies of drainage impacts on DOC loss report concentration changes relative to undrained comparison sites, rather than direct (robust) flux measurements. On the other hand, a larger number of studies provide reliable DOC flux estimates from natural, or near-natural, peatland systems. These two data sources (DOC fluxes from natural sites, and DOC changes from drained-natural comparisons) were therefore combined to derive best estimates of the DOC flux from drained sites, following Equation 2.4.

Default values for $DOC_{FLUX\_NATURAL}$ were derived from 26 published studies reporting DOC fluxes from natural boreal and temperate raised bogs and fens, temperate blanket bogs, and tropical peat swamp forests. Most data were derived from catchment-scale studies with natural drainage channels, for which accurate hydrological flux data are available, and to avoid double-counting of reactive DOC exports from peatlands that are rapidly converted to CH_4 or CO_2 within the ditch network (i.e. on-site emissions). For boreal and temperate raised bogs and fens, a significant (R^2 = 0.67, p < 0.001) linear relationship was observed between $DOC_{FLUX\_NATURAL}$ and annual mean precipitation (see Table 2A.2). Tier 1 default fluxes were therefore assigned based on three borad rainfall classes, with blanket bogs (for which few flux data are available) included in the calculation of fluxes from the high-rainfall class. A single default value was assigned for tropical peat swamps, had by far the highest DOC losses. The data used in this assessment are listed in Table 2A.2.

TABLE 2A.2
ANNUAL DOC FLUX ESTIMATES FROM NATURAL OR SEMINATURAL PEATLANDS USED TO DERIVE DEFAULT VALUES FOR $DOC_{FLUX\_NATURAL}$

Peat type	Country	Study	Rainfall (mm yr^{-1})	DOC flux (t C ha^{-1} yr^{-1})
Subarctic fen	Canada	Koprivnjak & Moore, 1992	302	0.05
Boreal fen	Finland	Juutinen *et al.* (in prep)	395	0.04
Boreal fen	Finland	Jager *et al.*, 2009	476	0.08
Boreal fen	Canada	Moore, 2003	536	0.04
Boreal bog	Canada	Moore, 2003	536	0.06
Boreal fen	Canada	Strack *et al.*, 2008	590	0.05
Boreal mire	Sweden	Agren *et al.*, 2007	600	0.10
Boreal mire	Finland	Kortelainen *et al.*, 2006[a]	620	0.16
Boreal mire	Finland	Kortelainen *et al.*, 2006	620	0.06
Boreal bog/fen	Finland	Rantakari *et al.*, 2010	640	0.12
Boreal bog	Canada	Moore *et al.*, 2003	678	0.29
Boreal fen	Sweden	Nilsson *et al.*, 2008	680	0.13
Boreal bog	USA	Urban *et al.*,1989	780	0.21
Boreal bog/fen	USA	Kolka *et al.*, 1999	780	0.24
Boreal bog	Canada	Roulet *et al.*, 2007	943	0.16
Temperate bog	Canada	Clair *et al.*, 2002	1400	0.36
Blanket bog	UK	Dawson *et al.*, 2004	1130	0.19
Blanket bog	UK	Dinsmore *et al.*, 2010	1155	0.26
Blanket bog	UK	Billett *et al.*, 2010	1980	0.23
Blanket bog	UK	Billett *et al.*, 2010	2200	0.19
Blanket bog	Ireland	Koehler *et al.*, 2009,2011	2570	0.14
Blanket bog	Australia	di Folco & Kirkpatrick, 2011	2900	0.13
Tropical swamp forest	Indonesia	Baum *et al.*, 2008 [a]	2316	0.47
Tropical swamp forest	Indonesia	Alkhatib *et al.*, 2007	2500	0.55
Tropical swamp forest	Malaysia	Yule & Gomez, 2009, Zulkifli, 2002	2300	0.63
Tropical swamp forest	Indonesia	Moore *et al.*, 2013	2800	0.62

[a] DOC flux for natural peatland derived by linear regression of DOC flux vs % peat area for mixed subcatchments

Estimation of $\Delta DOC_{DRAINAGE}$

A total of eleven published studies were identified which provided sufficient data to calculate ratios of either DOC concentration or DOC flux between comparable drained and un-drained peat sites (Table 2A.3). These included data from boreal and temperate raised bogs and fens, blanket bogs, and tropical peats, and drainage for both peat extraction and land-use change to agriculture. There is a reasonable degree of consistency among the studies included; all show an increase in DOC following drainage, with an overall range of 15% to 118%. Most of the published studies suggest a DOC increase close to the mean (across all studies) of 60%, and there was insufficient evidence to support the use of different Tier 1 $\Delta DOC_{DRAINAGE}$ values for different peat types, climate zones, drainage type or drainage intensity. The use of concentration data to estimate $\Delta DOC_{DRAINAGE}$ does however assume no corresponding change in total water flux from as a result of drainage, which adds uncertainty to the calculated flux changes. This uncertainty should be relatively small for high-precipitation boreal/temperate bogs, as a large change in water flux could only occur if there is a correspondingly large change in evapotranspiration. For drier bog sites, drainage might be expected to increase water fluxes, therefore amplifying the observed concentration differences between drained and undrained sites. However for fens, which are fed by external groundwater or surface water inputs rather than solely by rainfall, there is greater potential for drainage to lead to fundamental changes in hydrological functioning (e.g. by routing lateral water inputs around the fen rather than through it), thus altering the water flux. Consequently, although observed DOC concentration changes in drained fens are similar to those from drained bogs (Table 2A.3), the appropriate default value of $\Delta DOC_{DRAINAGE}$ for fens is more uncertain. At Tier 1, it could therefore be assumed that the DOC flux from a drained fen is unchanged from the natural flux (i.e. that $\Delta DOC_{DRAINAGE}$ is equal to zero, and the the DOC export is thus equal to $DOC_{FLUX\_NATURAL}$). At Tier 2 it may be possible to develop specific estimates of $\Delta DOC_{DRAINAGE}$ based on paired comparisons between reliable DOC flux measurements for undrained and drained fens, either on a country-specific basis or by pooling studies in different countries. Alternatively, direct measurements of DOC export flux could be used to derive Tier 2 EFs for DOC emissions from drained fens.

Overall, the available data support a Tier 1 default $\Delta DOC_{DRAINAGE}$ value of 0.60 for all bogs and tropical peats. Given difficulties of quantifying the water budget of drained fens, there is greater uncertainty about the applicable value for $\Delta DOC_{DRAINAGE}$ for this peat type. Therefore, countries may choose to apply the same Tier 1 default value as in other peat types, or to make the assumption that DOC export does not increase with drainage from fens, i.e. to apply the natural DOC flux value to calculate EF_{DOC}.

TABLE 2A.3
DOC CONCENTRATION (ABOVE) OR FLUX (BELOW) COMPARISONS BETWEEN DRAINED AND UNDRAINED PEATS, USED TO DERIVE DEFAULT VALUE FOR $\Delta DOC_{DRAINAGE}$

Peat type	Land-use	Country	Study	DOC		$\Delta DOC_{DRAINAGE}$ (%)
				Undrained	Drained	
Concentration-based studies (DOC mg l^{-1})						
Boreal bog	Drainage (peat extraction)	Canada	Glatzel *et al.*, 2003	60	110	83%
Boreal fen	Drainage	Canada	Strack *et al.*, 2008	16	24.29	53%
Boreal fen	Drainage	USA	Kane *et al.*, 2010	56	71.7	29%
Boreal fen	Drainage (peat extraction)	Finland	Heikkinen, 1990	17	20	15%
Temperate bog	Drainage	Poland	Banaś & Gos, 2004	48	71	49%
Temperate bog	Drainage (peat extraction)	New Zealand	Moore & Clarkson, 2007	70	108	54%
Temperate bog	Drainage	Czech Republic	Urbanova *et al.*, 2011	36	53.9	51%
Temperate fen	Drainage	Czech Republic	Urbanova *et al.*, 2011	17	37.5	118%
Blanket bog	Drainage	UK	Wallage *et al.*, 2006	28	42.9	55%
Flux-based studies (DOC g m^{-2} yr^{-1})						
Tropical peat	Drainage (sago palm)	Malaysia	Inubushi *et al.*, 1998	33	63	91%
Tropical peat	Drainage (agriculture)	Indonesia	Moore *et al.*, 2013	62	97	54%

Estimation of $Frac_{DOC-CO_2}$

The significance of DOC export in terms of greenhouse gas estimation depends on its ultimate fate, i.e. whether it is returned to the atmosphere as CO_2 (or even CH_4), or deposited in stable forms such as lake or marine sediments. The latter simply represents a translocation of carbon between stable stores, and should not therefore be included in the estimation. The parameter $Frac_{DOC-CO_2}$ sets the proportion of DOC exported from peats that is ultimately converted to CO_2.While considerable uncertainty remains in the estimation of this parameter, there is growing evidence that fluvial systems process a high proportion of incoming terrestrial carbon, and that much of this is converted to CO_2 (e.g. Cole *et al.,* 2007; Wickland *et al.,* 2007; Battin *et al.,* 2009). The highly coloured DOC typically exported by peatlands is susceptible to photo-degradation, which may lead to rapid conversion rates in water exposed to sunlight in rivers, lakes or coastal waters (e.g. Opsahl and Benner, 1998). Dawson *et al.* (2001) estimated that 12-18% of DOC was removed within a 2 km peat stream reach, and Jonsson *et al.* (2007) estimated that around 50% of all terrestrially-derived organic carbon was mineralised within a lake catchment (not including subsequent mineralization downstream or in the sea). Wickland *et al.* (2007) measured 6% to 15% conversion of pore-water DOC to CO_2, and 10% to 90% conversion of the vegetation-derived DOC, during one-month dark incubations. Experiments undertaken on light-exposed samples (Köhler *et al.,* 2002; Worrall *et al.,* 2013; Jones *et al.* , 2013) show far more rapid and extensive DOC loss, with averages ranging from 33% to 75% over periods of up to 10 days. Since much of this degradation occurs within the first 48 hours; this would be sufficient to convert most peat-derived DOC to CO_2 before it enters the sea. Terrestrially-derived DOC which does reach the sea largely appears to be microbially processed in the marine system, mostly within years to decades (Bianchi, 2011; Opsahl and Benner, 1997).

On the basis that a high proportion of peat-derived DOC may be mineralized rapidly in headwaters; that this processing continues at a relatively high rate through rivers and lakes; and that any peat-derived DOC that does reach the sea will nevertheless largely be mineralized in the marine ecosystem, a $Frac_{DOC-CO_2}$ is likely to be high. Given the remaining uncertainty regarding DOC fate, and the possibility that some may be precipitated out in lake or marine sediments, a Tier 1 default value of 0.9 is proposed, with an uncertainty range of 0.8-1.0%.

There is some evidence that controlled burning (for moorland management) also increases DOC losses (e.g. Yallop *et al.,* 2010; Di Falco *et al.* and Kirkpatrick, 2011), although other experimental studies have shown no effect (e.g. Ward *et al.,* 2007; Worrall *et al.,* 2007b). A precautionary estimate is that managed burning may increase mean DOC loss by 20-50%. Grazing levels on semi-natural vegetation have not been shown to affect DOC loss (Ward *et al.,* 2007; Worrall *et al.,* 2007b), and data on the effects of more intensive agricultural

(Grassland and Cropland) management on DOC loss are currently insufficient to estimate an emissions factor. Therefore, generic values for the effects of drainage may be used.

Appendix 2a.1 Estimation for Particulate Organic Carbon (POC) loss from peatlands and drained organic soils: Basis for future methodological development

This Appendix provides a basis for future methodological development rather than complete guidance.

Particulate organic carbon (POC) is generally a negligible component of the carbon balance of natural peatlands. However, disturbance of peatlands through land-use change, including drainage (which can include the dredging of peat from drains and canals), burning (managed burning and wildfire), conversion to arable and peat extraction, can all result in high rates of POC loss via waterborne erosion and also wind erosion. In actively eroding blanket bogs, POC losses in excess of 100 g C m^{-2} yr^{-1} may represent the dominant form of soil carbon loss (e.g. Pawson *et al.,* 2008; Worrall *et al.,* 2011).

Available data suggest that the key determinant of POC loss is the proportion of the total area occupied by exposed (bare) peat, according to Equation 2A.1. The bare peat area, $PEAT_{BARE}$, would include unvegetated drainage ditches, erosion gullies, peat extraction surfaces, and areas of the soil surface exposed by burning, intensive grazing or the deposition of peat dredged from drainage channels onto the land surface. For Croplands, some estimation of the annual average proportion of the organic soil surface exposed over the full crop rotation would be required. Data from eroding UK blanket bogs suggest that waterborne POC exports can be reasonably well predicted based on a POC flux from bare peat surfaces ($POC_{FLUX\_BAREPEAT}$) of around 4 t C ha^{-1} yr^{-1} (Goulsbra *et al.,* 2013). Further work is required to establish whether different values would be applicable to other peat types, land-use types and climate regimes (in particular whether it is dependent on rainfall amount or intensity). At present there are few data on which to base an estimate of airborne POC loss, and further work is required to quantify this loss term, which may be large in peat extraction and Cropland sites.

Finally, there is limited information currently available from which to derive a value for the proportion of POC ultimately converted to CO_2, $Frac_{POC-CO_2}$. Unlike DOC, a substantial proportion of POC is mobilized from peats through physical erosion processes, and its reactivity in fluvial systems is uncertain. Some studies have shown fairly high rates of POC turnover in river and estuarine systems (e.g. Sinsabaugh and Findlay, 1995), and POC redeposited on floodplains may be subject to moderate rates of oxidation (Goulsbra *et al.,* 2013). However, it is likely that a significant proportion of waterborne POC loss from organic soils may simply be transferred to lake or coastal sediments, re-deposited on floodplains, or transported to other land areas via aeolian transport, rather than converted to CO_2. Further research is therefore needed to establish realistic ranges for $Frac_{POC-CO_2}$ in different systems.

EQUATION 2A.1
CALCULATION OF POC EXPORT FROM DRAINED PEATLANDS

$$EF_{POC} = POC_{FLUX\_BAREPEAT} \bullet PEAT_{BARE} \bullet Frac_{POC}$$

Where:

EF_{POC} = POC Emission factor, t C ha^{-1} yr^{-1}

$POC_{FLUX\_BAREPEAT}$ = Flux of POC from a bare peat surface, t C ha^{-1} yr^{-1}

$PEAT_{BARE}$ = Proportion of the ground surface occupied by exposed peat

$Frac_{POC-CO_2}$ = Conversion factor for the fraction of POC converted to CO_2 following export from site

Appendix 2a.2 CO_2 emission factors for drained tropical peatlands: Basis for future methodological development

This appendix is provisionally proposed due to the lack of complete consensus among the authors on CO_2 emission factors for drained tropical peatlands. There has been convergence of views between the author groups, but that there are still a few outstanding issues and the group ran out of time for the second order draft.

There is consensus among the authors that drained tropical peatlands are a source of CO_2. However, the available scientific basis is smaller than for the temperate and boreal climate zones. While the authors agree that the same measurement methods can be applied to drained tropical peatlands as in drained boreal and temperate peatlands, authors have not reached consensus on some methodological issues in deriving CO_2 emissions from the literature and the procedure to derive the IPCC emission factors.

Gain-loss method

The gain-loss method uses chamber techniques in combination with measurements of carbon fluxes in other pools to determine net emissions and removals. Total soil respiration (R_t) measurements in tropical studies are based on dark chambers that determine the total CO_2 flux from the peat surface. None of the studies on drained tropical peatlands has fully measured soil on-site C gains and losses and calculated a balance. There is no consensus among authors in the method for calculating the emission factors. These can be computed using either an aggregated approach taking into account the average C components of the gain-loss balance per land use category or a disaggregated one averaging site-by-site estimated balances. Measured total respiration (R_t) data have to be combined with data for the ratio of heterotrophic to total respiration and litter input from literature to derive CO_2 emissions. Few studies have directly measured soil heterotrophic respiration (R_h) and there is also no complete consensus on the ratios of R_h:R_t to be applied to land-use categories for which no R_h:R_t ratios are available in the literature. Furthermore, aboveground litter and fine root turnover can significantly contribute to the measured R_h. There is a lack of complete agreement on the magnitude of the contribution of aboveground litter input and root mortality to the observed R_t in the measurement chambers and whether these chambers are representative of mean ecosystem level litter and fine root input. If the chambers are representative, mean ecosystem level litterfall and root mortality data must be subtracted from the R_h flux to give CO_2 emissions. Otherwise, subtracting mean ecosystem level litterfall and root mortality from the R_h flux would produce an underestimate of CO_2 emissions. As none of the studies on drained tropical peatlands has measured litter and root mortality, these data have to be derived from literature. There is no consensus whether root mortality data from mineral soils can be transferred to organic soils.

Subsidence method

The subsidence method is unique to peatland ecosystems and measures the height loss of the peat surface using a network of subsidence markers inserted firmly into the mineral substrate beneath the peat deposit. Peat oxidation/decomposition CO_2 emission estimates are obtained by converting the volume loss to carbon via bulk density, carbon content and estimates of the oxidized fraction of the volume lost as compared to compaction. DOC and erosion losses need to be subtracted from the C loss estimates. Measured data have to be combined with data from the literature to derive site-based CO_2 emissions. Measured data comprise subsidence rates and final bulk density. Each study had calculated a site-specific oxidation fraction, which accounts for compaction above the water table. None of the studies on drained tropical peatlands have directly measured soil carbon content or change in bulk density. Authors agreed to use the equation of Warren *et al.* (2012) for calculating peat carbon content from peat bulk density. Authors agreed to use final bulk density and assume no change over the measurement period. Authors could not reach a consensus on some of the underlying methodological assumptions involved in the subsidence method, e.g. whether or not consolidation below the water table played a role in the studied sites. If peat consolidation below the water table had a significant influence on the results, the measured subsidence rates give overestimated site based CO_2 emissions from soil. While peat consolidation below the water table was ruled out by some authors based on soil mechanical principles and models, other authors argue that the process persisted beyond a period of initial consolidation.

Deriving IPCC emission factors

Study sites were treated as independent observations if they were in different peat complexes; or under different hydrological management on the same peat complex; or under different land-use; or any combination of these three criteria. Authors have not achieved complete consensus about what constitutes a study site in subsidence studies, which partly cover many km² and catchments on a peat complex. While one author group favours to group the observations by catchment and/or peat depth and drainage level, the other author group favours to treat the entire study area as one study site with replicated observations. There is disagreement whether a site-by-site aggregation of CO_2 emission values or a generic calculation of a mean typical land-use category is to be pursued for deriving the IPCC emission factor.

Table 2a.1 shows the second order draft status of discussions among authors and presents two alternative preliminary values for emission factors as orientation.

TABLE 2A.1
TWO PRELIMINARY ALTERNATIVES FOR EMISSION FACTORS FOR DRAINED TROPICAL PEATLANDS, BASED ON TWO ALTERNATIVE PREFERRED WAYS OF AUTHOR GROUPS TO CALCULATE AND INTEGRATE THE UNDERLYING DATA.

Land-Use Category	**Climate / Vegetation Zone**	**Soil Emission Factor (tonnes CO_2-C ha^{-1} a^{-1}) (Mean)**	**95% Confidence Interval (centred on mean)**		**Citations**
Forestland, Drained	Tropical	Alternative 1: 6 or Alternative 2: 4	4 or 1	8 or 7	Ali *et al.,* 2006; Brady 1997; Chimner and Ewel 2005; Chimner and Ewel 2004; Comeau *et al.,* 2013; Darung *et al.,* 2005; Furukawa *et al.,* 2005; Hadi *et al.,* 2005; Harisson *et al.,* 2007; Hatano et al., 2010; Hergoualc'h and Verchot 2011; Hirano *et al.,* 2009; Hirano *et al.,* 2012; Inubushi *et al.,* 2003; Ishida *et al.,* 2001; Jauhiainen *et al.,* 2008; Melling *et al.,* 2005; Rahaoje *et al.,* 2000; Shimamura and Momose 2005; Sundari *et al.,* 2012; Warren *et al.,* 2012
Acacia Plantation	Tropical	Alternative 1: 22 or Alternative 2: 19	20 or 15	25 or 23	Basuki *et al.,* 2012; Hooijer *et al.,* 2012; Jauhiainen *et al.,* 2012; Nouvellon *et al.,* 2012; Warren *et al.,* 2012
Oil palm Plantation	Tropical	Alternative 1: 14 or Alternative 2: 11	11 or 5	17 or 17	Comeau *et al.,* 2013; Dariah et al. submitted; DID and LAWOO 1996; Hooijer and Couwenberg submitted; Lamade et al. 2005; Marwanto and Agus submitted; Melling *et al.,* 2005; Melling *et al.,* 2007; Warren *et al.,* 2012; Wösten *et al.,* 1997
Sago Plantation	Tropical	Alternative 1: 3 or Alternative 2: -2	0 or -5	5 or 1	Melling *et al.,* 2005; Watanabe *et al.,* 2009
Cropland, Drained	Tropical	Alternative 1: 21 or Alternative 2: 16	16 or 5	26 or 27	Ali *et al.,* 2006; Darung *et al.,* 2005; Furukawa et al., 2005; Hairiah *et al.,* 1999; Hatano *et al.,* 2010; Hirano *et al.,* 2009; Matthews *et al.,* 2000; Stephens *et al.,* 1984; Stephens and Speir 1969; Warren *et al.,* 2012

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