First-order Draft

CHAPTER 2

CROSS-CUTTING GUIDANCE ON GREEN-HOUSE GAS EMISSIONS AND REMOVALS FROM ORGANIC SOILS IN ALL LAND-USE CATEGORIES

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2.1 INTRODUCTION

This chapter provides supplementary guidance on estimating greenhouse gas emissions and removals from drained organic soils in all land-use categories.

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 which have been, or are newly, drained. Within each land-use category water level is manipulated to varying degrees depending on land use purpose, e.g. for cereals, rice, or 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 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 Tier 1 level.

This chapter improves and extends methodologies and updates and refines emission factors by including drainage classes where possible and considering a wider geographical or temporal coverage, thus improving the regional suitability of the Tier 1 factors coverage, 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 *2006IPCC Guidelines* Volume 4, Chapter 7);
- N_2O emissions from organic soils (referring to *2006 IPCC Guidelines* Volume 4, Chapter 11).
- This chapter fills the gaps 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 indirect 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

2.2.1 Loss of carbon in organic soils due to drainage and management

This section deals with the impacts of drainage and management onCO2 emissions from organic soils, primarily by influencing carbon outputs from the soil and thus soil carbon storage, by affecting heterotrophic respiration (peat decomposition), erosion losses of particulate organic carbon (POC) and loss of dissolved organic carbon in drainage waters (DOC). There are also some changes in inputs, often associated with slash left on the ground in the case of forests and changes in root, litter and deadwood inputs in all systems. General information and guidance for estimating changes in soil C stocks are provided in the *2006 IPCC Guidelines* in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with organic soil C stocks. The main difference between mineral soils and organic soils is that in mineral soils we assume that carbon reaches a constant stock level in managed systems following changes in management and that eventually emissions become negligible. . In organic soils, once the soils are drained, we assume that emissions persist until drainage is reversed.

The total change in soil C stocks in organic soils for land remaining in a land use category is estimated using Equation 2.1, which combines the direct emissions from soil organic matter decomposition and indirect emissions from POC and DOC.

EQUATION 2.1
ANNUAL CARBON LOSS FROM DRAINED AND MANAGED ORGANIC SOILS

$$L_{Organic-CO2-C} = L_{Organic-CO2-C(on-site)} + L_{Organic-CO2-C(on-site)}$$

Where:

$L_{Organic\text{-}CO2\text{-}C}$ = Annual carbon loss from drained and managed organic soils, tonnes C yr^{-1}

$L_{organic\text{-}CO2\text{-}C(on\text{-}site0t}$ = On-site CO_2-C emissions from drained organic soils, tonnes C yr^{-1}

$L_{organic\text{-}CO2\text{-}C(off\text{-}site0t}$ = Off-site CO_2 emissions from waterborne carbon losses, tonnes C yr^{-1}

2.2.1.1 ON-SITE CO_2 EMISSIONS FROM DRAINED ORGANIC SOILS

This chapter gives supplementary guidance for CO_2 emissions from drained organic soils in all land-use categories as defined in the *2006 IPCC Guidelines* Volume 4 Chapter 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 supplementary guidance. Coastal Wetlands are considered in Chapter 4 of this Supplement. The activity re-wetting and restoration of managed peatlands and organic soils is considered in Chapter 3 of this supplement.

Guidance is given for CO_2 emissions from the soil carbon pool in drained organic soils in line with *2006 IPCC Guidelines* Volume 4 Chapter 2.3.3. 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

For Tier 1 methods, if the typical range of mean annual water table of drained organic soils for each land-use category is unknown, it is assumed that the organic soil is deeply drained because dry conditions are the most widespread and suitable for a wide range of land use types and intensities.

The magnitude of annual CO_2 emissions is roughly proportional to the distance between the mean annual water table and the soil surface in unfertilized systems, in the absence of fire. Within each land-use category, drained organic soils can experience a wide range of mean annual water tables that depend upon regional climatic characteristics and specific land-use activity or intensity. Higher Tier methods could differentiate the drainage intensity within land-use categories if there are significant areas which are wetter than the default dry conditions.

Figure 2.5 in *2006 IPCC Guidelines* Volume 4 Chapter 2.3.3 provides the decision tree for identification of the appropriate tier to estimate CO_2 emissions from drained organic soils by land-use category.

Tier 1

The basic methodology for estimating annual carbon loss from drained organic soils was presented in section 2.3.3 and equation 2.26 in Vol. 4 of the *2006 IPCC Guidelines*.:

EQUATION 2.2

ANNUAL ON-SITE CARBON LOSS FROM DRAINED ORGANIC SOILS (CO_2)

$$L_{Organic-CO2-C(on-site)} = \sum_{c,n} \left(A_{c,n} \bullet EF_{c,n} \right)$$

Where:

$L_{Organic-CO2-C(on-site)}$ = Annual on-site CO_2-C loss from drained organic soils, tonnes C yr^{-1}

A = Land area of drained organic soils in a land-use category in climate type c, and nutrient status n, ha

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

Tier 2

The Tier 2 approach for CO_2 emissions from drained 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. Potential improvements to the Tier 1 approach may include: 1) a derivation of country-specific emission factors; 2) specification of climate regions 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 in Forest Land or other land-use categories.

It is a good practice to derive country-specific emission factors is if experimental data are available. Guidance on choosing the appropriate measurement techniques is given in the Annex 2A.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 the proposed classes. Note that any derivation must be accompanied with sufficient land-use/management activity and environmental data to represent the proposed climate regions and management systems at the national scale.

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

Tier 3

CO_2 emissions from drained organic soils can be estimated with a model or measurement based approach. Dynamic, mechanistic-based models will typically be used to simulate underlying processes, while capturing the influence of land use and management, particularly the effect of variable levels of drainage on decomposition. The general considerations for mineral and organic soils in the *2006 IPCC Guidelines* Volume 4 Chapter 2.3.3 also apply here.

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

Default Tier 1 emission/removal factors for drained organic soils are found in Table 2.1.

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

Land-use category	**Climate zone**	**Emission factor (tonnes C ha^{-1} yr^{-1})**	**Uncertainty (tonnes C ha^{-1} yr^{-1})**	**References/ comments**	**Chapter in Volume 4 of *2006 IPCC Guidelines***
Forest Land					
Forest Land $EF_{CO2OrgForestBoreal}$	Boreal All organic soils	-0.609*	-0.872 , -0.346**	23 sites, Laurila *et al.* 2007; Lindroth *et al.* 2007; Lohila *et al.* 2007; Minkkinen & Laine 1998; Minkkinen *et al.* 1999; Von Arnold *et al.* 2005d	Chapter 4 Table 4.6
Forest Land $EF_{CO2OrgForestBorealPoor}$	Nutrient-poor	-1.44*	-2.77 , -0.108**	7 sites, Laurila *et al.* 2007; Lindroth *et al.* 2007; Lohila *et al.* 2007; Minkkinen & Laine 1998; Minkkinen *et al.* 1999; Von Arnold *et al.* 2005d	Chapter 4 Table 4.6
Forest Land $EF_{CO2OrgForestBorealRich}$	Nutrient-rich	-0.246*	-0.377 , -0.115**	16 sites, Laurila *et al.* 2007; Lindroth *et al.* 2007; Lohila *et al.* 2007; Minkkinen & Laine 1998; Minkkinen *et al.* 1999; Von Arnold *et al.* 2005d	Chapter 4 Table 4.6
Forest Land $EF_{CO2OrgForestTemp}$	Temperate	0.68	0.41 to 1.91****	*2006 IPCC Guidelines* Volume 4	Chapter 4 Table 4.6
Forest Land $EF_{CO2OrgForestTrop}$	Tropical/ Subtropical	2.31	2.76***		Chapter 4 Table 4.6
Plantation, e.g. Acacia $EF_{CO2OrgForest-PlantTrop}$		11.67	4.74***		Chapter 4 Table 4.6
Cropland $EF_{CO2CropBoreal}$	Boreal	6.15	2.88 , 9.43**	16 sites, Hillebrand 1993; Maljanen *et al.* 2003a, 2003b, 2004, 2007a; Nykanen *et al.* 1995	Chapter 5 Table 5.6
Cropland					
Cropland $EF_{CO2CropTemp}$	Temperate	5.88	2.95 , 8.80**	18 sites, Eggelsmann & Bartel 1975; Hoper 2002; Kasimir-Klemedtsson *et al.* 1997; Mundel 1976; Okruszko 1989; Schuch 1977	Chapter 5 Table 5.6
Cropland $EF_{CO2CropTrop}$	Tropical/ Subtropical	9.11	2.47***		Chapter 5 Table 5.6
Rice $EF_{CO2Crop-RiceTrop}$		8.56	3.32***		Chapter 5 Table 5.6
Oil palm Plantation $EF_{CO2OrgCrop-OilpalmTrop}$		5.24	2.99***		Chapter 5 Table 5.6

Grasslands					
Grassland EF$_{CO2GrassBoreal}$	Boreal	4.41	1.75 , 7.08**	13 sites, Gronlund *et al.* 2006; Krestapova & Maslov 2004; Lohila *et al.* 2004; Maljanen *et al.* 2001a, 2004; Nykanen *et al.* 1995; Shurpali *et al.* 2009	Chapter 6 Table 6.3
Grassland EF$_{CO2GrassTemp}$	Temperate	3.19	2.26 , 4.11**	48 sites, Czaplak & Dembek 2000; Hargreaves *et al.* 2003; Hoper 2002; Kasimir-Klemedtsson *et al.* 1997; Lorenz *et al.* 2002; Meyer *et al.* 2001; Okruszko 1989; Schothorst 1976; Weinzierl 1997	Chapter 6 Table 6.3
Grassland EF$_{CO2GrassTrop}$	Tropical/ Subtropical	9.11	2.47***	Same emission factor as Tropical Cropland	Chapter 6 Table 6.3
Shrubland EF$_{CO2GrassBoreal}$	Boreal	4.41	1.75 , 7.08**	Same emission factor as Boreal Grassland	Chapter 6 Table 6.3
Shrubland EF$_{CO2GrassTemp}$	Temperate	3.19	2.26 , 4.11**	Same emission factor as Temperate Grassland	Chapter 6 Table 6.3
Shrubland EF$_{CO2GrassTrop}$	Tropical/ Subtropical	9.11	2.47***	Same emission factor as Tropical Cropland	Chapter 6 Table 6.3
Wetlands					
Peatlands drained for extraction EF$_{CO2PeatBoreal}$	Boreal	1.47	0.801 , 2.14**	21 sites, Ahlholm *et al.* 1990; Alm *et al.* 2007; Glatzel *et al.* 2003; Nykanen *et al.* 1996; Shurpali *et al.* 2008; Sundh *et al.* 2000; Tuittila *et al.* 1995, 2004; Waddington *et al.* 2010	Chapter 7 Table 7.4
Peatlands drained for extraction EF$_{CO2PeatTemp}$	Temperate	0.732	-.036 , 1.50**	6 sites, Hargreaves *et al.* 2003; Sottocornola & Kiely 2005	Chapter 7 Table 7.4
Peatlands drained for extraction EF$_{CO2PeatTrop}$	Tropical/ Subtropical	2.0	0.06 to 7.0**	Same as in *2006 IPCC Guidelines*	Chapter 7 Table 7.4
Settlements	All climate zones	Same emission factor as Cropland			Chapter 8
Other Land	All climate zones	Other Land remaining Other Land: 0 Land converted to Other Land: Maintain emission factor of previous land-use category			Chapter 9

* including litter and coarse woody debris

** 95% confidence interval

*** standard error

**** range

*****Positive and negative values indicate net CO$_2$ emissions and removals respectively.

Tier 2

Tier 2 emission factors could include the following refinements:

- 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;
- stratification of boreal forestland by nutrition status (rich/poor) with use of appropriate and significantly different emission factors for organic soil CO_2 loss (See Table 2.1).
- stratification of boreal and temperate grassland categories 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.1

Tier 3

A Tier 3 approach might use process models that take into account temporal and spatial variations in water table depth on a drained wetland involving a comprehensive understanding and representation of the dynamics of CO_2 emissions and removals on managed organic soils, including the effect of site characteristics, peat type and depth, etc. Drained and managed peatlands go through a transition where subsidence is rapid in the years immediately following drainage, and continues more slowly in subsequent years. 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. No specific guidance is provided on Tier 3 methods to account for CO_2 emission factors with respect to drainage classes.

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.

Disaggregation of activity data by drainage depth should be done only if appropriate emissions factors are available. In many instances standard drainage depths are used in forestry production systems and thus, disaggregation is not useful in improving the accuracy of the inventory. Where significant variation in drainage depth exists for an activity data category, and where appropriate emissions factors exist, the accuracy of an inventory can be improved by separating out drainage classes.

Tier 1

For Tier 1 approach, requires information on managed land areas in each land use category on organic soils In general, practices that are known to increase C input to mineral soils and thus soil organic C stocks, (fertilization, liming, etc.) do not have this effect in organic 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. Classification systems for activity data that form the basis for a Tier 1 inventory are generally 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/). The Center for International Forestry Research will publish a map of carbon in wetlands for the tropics in 2012 (www.cifor.cgiar.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 under Tier 2 generally follows the methods presented for each land use in the *2006 IPCC Guidelines* and areas with organic soils should be differentiated from those with mineral soils. Activity data may further be stratified based on drainage class, nutrient status of the organic soil (poor or rich), if nationally or regionally appropriate emissions factors exist. In many instances standard drainage depths are used in forestry production systems and thus, disaggregation by drainage depth is not useful in improving the accuracy of the inventory. Where significant variations in drainage depth exist, the accuracy of an inventory can be improved by stratifying by drainage classes.

Tier 3

Tier 3 methods require activity data that are more disaggregated 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 due to biomass growth (e.g. the often occurring drop in water table due to increased evapotranspiration as grasses grow). 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 organic soils are as follows:

Step 1: Determine areas with drained organic soils under each land use category for lands remaining in that land use category, disaggregated according to climate zone and other appropriate factors as outlined above. In Forest Land areas may further be stratified by nutrient-rich and nutrient poor organic soils.

Step 2: Assign the appropriate emission factor (EF) for annual losses of CO_2 based on climatic temperature regime (from Tables 2.1, 2,2 or 2.3).

Step 3: Multiply each area with the appropriate emission factor by using Equations 2.2.

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 bias (i.e., improve accuracy) is more likely to be reduced through implementation of higher tier methods that incorporate country-specific information.

For Tier 1, A default uncertainty level of ±90% (expressed as 2x standard deviations as per cent of the mean) are assumed for emissions/removal factors for each soil-climate types. 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%). However, 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.

Bias is considered more problematic for reporting emissions because it is not necessarily captured in the uncertainty range (i.e., the true stock change may be outside of the reported uncertainty range if there is significant bias in the factors). Bias can be reduced 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 minimize bias by estimation for significant within-country differences in land-use and management impacts, such as variation among climate regions and/or soil types.

2.2.1.2 OFF-SITECO2 EMISSIONS FROM WATERBORNE CARBON LOSSES

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-}). 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 approaches for soil carbon estimation, to avoid systematic under-estimation of soil C losses.

Different forms of waterborne carbon have different sources, behaviour and ultimate fate, and different approaches are therefore required. 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; most of the CO_2 flux is emitted within the peat area (Dinsmore *et al.*, 2011), 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.*, 2011). 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 A.X 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 emission. 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 (e.g. 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 indirect carbon loss from drained organic soils was presented in section 2.3.3 and equation 2.26 in Vol. 4 of the *2006 IPCC Guidelines* as presented in Equation 2.2:

EQUATION 2.3A
ANNUAL OFF-SITE CARBON LOSS FROM DRAINED ORGANIC SOILS (CO_2)

$$L_{Organic\,CO2-C(off-site)} = \sum_{c,n} \left(A_{c,n} \bullet EF_{DOC\,c,n} \right)$$

Where:

$L_{Organic\ CO2\text{-}C\ (off\text{-}site)}$ = 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 type 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 type c and nutrient status n, tonnes C ha^{-1} yr^{-1}

EF_{DOC} can be calculated from Equation 2.3B:

EQUATION 2.3B
EMISSION FACTOR FOR ANNUAL CO_2 EMISSIONS DUE TO DOC EXPORT FROM DRAINED PEATLANDS

$$EF_{DOC} = DOC_{FLUX-NATURAL} \bullet (100 + \Delta DOC_{DRAINAGE}) / 100 \bullet F_{DOC-CO_2}$$

Where:

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

$DOC_{FLUX\_NATURAL =}$ Flux of DOC from natural (un-drained) peatland, tonnes C $ha^{-1}yr^{-1}$

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

$F_{DOC-CO2}$ = 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, waterborne 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 2.3 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. Following the Managed Land Proxy (MLP), and to ensure completeness of flux-based soil carbon reporting, the entire DOC export of drained peatlands should be included in methods developed for drained lands

CHOICE OF EMISSION FACTOR

Tier 1

A detailed description of the derivation of these values is provided in Annex 2A.1. 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 blanket bogs and tropical peatlands. Annex 2A.1 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 $F_{DOC-CO2}$ 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 raised bog/fen [b]	< 500	0.05 (0.04-0.08)	50% (17-112%)	0.07 (0.04-0.18)
	500-700	0.12 (0.08-0.15)		0.16 (0.08-0.31)
	700-900	0.18 (0.15-0.21)		0.24 (0.14-0.45)
	> 900	0.24 (0.21-0.36)		0.33 (0.20-0.76)
Blanket bog	All	0.21 (0.13-0.28)		0.28 (0.12-0.59)
Tropical	All	0.60 (0.47-0.69)		0.78 (0.44-1.46)

[a] Due to the limited number of available studies, a single value for $\Delta DOC_{DRAINAGE}$ is applied to all peatland types

[b] $DOC_{FLUX\_NATURAL}$ values for boreal/temperate raised bogs and fens are calculated from the equation $DOC_{FLUX\_NATURAL} = (0.000317 \bullet \text{Precipitation}) – 0.075$, ($r^2 = 0.67$, $p < 0.001$) in the units shown above, using representative mid-range values of 400, 600, 800 and 1000 mm for each of the classes shown. This equation may be used to calculate site-specific estimates where actual precipitation values are known.

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. Refinements 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 under different precipitation levels;
- 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. use of alternative values for $F_{DOC\text{-}CO2}$ 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.

At the present time, guidance is not presented for the effects of other 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

No specific guidance is provided on Tier 3 methods for DOC flux estimation. A Tier 3 approach might include the use of process models that describe DOC release as a function of vegetation composition, nutrient levels, water table height 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 F_{DOC_CO2} 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

Ranges are provided for DOC emission factors in Table 2.4. These ranges are calculated from literature data in Annex A.2 based on the range of observed DOC fluxes from natural peatlands used to derive values of $DOC_{FLUX\_NATURAL}$ in each of the classes used (Table 2A.2); minimum and maximum observed values for $\Delta DOC_{DRAINAGE}$ from published studies (Table 2A.3); and an uncertainty range for $F_{DOC-CO2}$ 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-CO2 emissions

In the *2006 IPCC Guidelines*, CH_4 emissions were assumed to be negligible from all drained organic soils. We provide here new estimates for soil CH_4 emissions from drained organic soils and drainage ditches (section 2.2.2.1).

2.2.2.1 CH_4 emissions from drained organic soils

Organic soils are mostly formed due to incomplete decomposition of dead organic matter in water saturated conditions and 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 emission can occur from the drained land surface, and also from the ditch networks constructed during drainage. Each of these emission pathways is considered here.

Drainage lowers the water table and exposes formerly water 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 CH_4 oxidizers (Blodau, 2002; Treat *et al.*, 2007; Murdiyarso *et al.* 2010). Drainage facilitating plant root respiration mitigates CH_4 emission dramatically (Martikainen *et al.*, 1995; 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 water table to the surface. In general, when the peatland is drained the natural production of CH_4 is reduced. 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 emission 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.*, 1999; Sundh et al, 2000; Minkkinen and Laine, 2006; Teh *et al.*, 2011; Vermaat *et al.*, 2011). This emission may approach, or even exceed, the CH_4 flux from an undrained peatland (Roulet and Moore, 1995; Schrier-Uijl *et al.*, 2011) and should therefore be included in estimation methods where possible. Emission factors for ditch CH_4 emissions were compiled from published literature (See Annex 2A.2).

CHOICE OF METHOD

Tier 1

CH_4 emission from the land surface is estimated using a simple emission factor (see Eq. 2.4). It depends on climate and type of land use. The default methodology considers boreal, temperate and tropical organic soils both under the nutrient-rich and nutrient poor peatlands. Different land uses imply drainage to different depths. The CH_4 emission factors almost entirely 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, see Chapter 3). Estimation of ditch CH_4 emissions requires information on the land-use class, and on the characteristics of the drainage ditches. At Tier 1, default values are assigned, which may be replaced by specific emission factors and data on ditch configuration at higher tiers.

EQUATION 2.4
ANNUAL CH_4 EMISSION FROM DRAINED ORGANIC SOILS

$$L_{OrganicCH4-C} = \sum_{c,n,p} \left(A_{c,n,p} \bullet \left(EF_{CH4\_land_{c,n}} + EF_{CH4\_ditch\_landscape_{c,p}} \right) \right)$$

Where:

$L_{Organic\ CH4-C}$ = 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 type c, nutrient status n and peatland type p, ha

EF_{CH4_land} = Emission factors for direct CH_4 emissions from drained organic soils, by climate type c and nutrient status n, tonnes CH_4-C ha^{-1} yr^{-1}

$EF_{CH4\_ditch\_landscape}$ = Emission factors for CH_4 emissions from drainage ditches, by climate type c and peatland type p, scaled according to the area of the landscape occupied by ditches in Equation 2.5, tonnes CH_4-C ha^{-1} yr^{-1}

EQUATION 2.5
EMISSION FACTORS FOR ANNUAL CH_4 EMISSIONS FROM DRAINAGE DITCHES

$$EF_{CH_4\_ditch\_landscape} = EFD_{CH_4\_ditch} \bullet Ditch\_width / \left(Ditch\_width + Ditch\_spacing \right)$$

Where:

$EF_{CH4\_ditch\_landscape}$ = CH_4 emission factor per unit area of peatland/organic soil which is derived from drainage ditches, tonnes CH_4 ha^{-1} yr^{-1}

EF_{CH4_ditch} = CH_4 emission factor per unit surface area of ditch, tonnes CH_4 ha^{-1} yr^{-1}

Ditch width = Width of ditch (including open water and any surrounding saturated area), m

Ditch spacing = Average distance between drainage ditches, m

Tier 2

Under Tier 2, the emission factors for CH_4 from the surface of drained organic soils are differentiated by drainage depth and time since the peat land is cleared as this relates to the input of energy for methanogens. The corresponding emission factors are country specific and take into account the management systems such as the level of fertilization.

Countries wishing to apply Tier 2 methods for CH_4 from drainage ditches should follow the Tier 1 approach described above, with country-specific measurements of annual mean ditch CH_4 emissions, and national or regional estimates of ditch width and spacing 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 peatlands and 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 maturity and depth, land use intensity, drainage depth the management systems and the level and kinds of fresh organic matter inputs. For CH_4 from drainage ditches the 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 CH4 emission associated with land-use change, and of the legacy effects of past land-use (e.g. nutrient-enriched soils).

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, grassland, cropland and wetland used for peat extraction) in boreal and temperate regions (Table 2.4). For grassland and cropland categories, separate EFs are given for low- and high-intensity land use sub-categories. For tropical peats, 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 on this peat type. Higher tier reporting for drained tropical peats would be improved by additional measurement data from these areas.

Tiers 2 and 3

Countries applying Tier 2 methods develop country-specific emission factors, which may be able to differentiate land-surface CH_4 emission rates under the natural peat vegetation and managed systems. Tiers 2 and 3 require country-specific emission data that account for site characteristics, peat type and depth, management system, peat extraction technology, the phases of peat extraction or other relevant factor. Currently, the literature is sparse, perhaps because of the low CH_4 emission of managed peatlands. Countries are encouraged to share comparable data, when environmental conditions and extraction practices are similar.

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). Tier 2 Emission factors (i.e. values for EF_{CH4_ditch}) should therefore be developed for all significant combinations of these factors at a country level, wherever possible.

A Tier 3 approach to estimating ditch CH_4 emission 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 zone**	**Emission factor (t C ha^{-1} yr^{-1})**	**Uncertainty (t C ha^{-1} yr^{-1})**	**References/ comments**
Forest Land				
Forest Land EF$_{CH4OrgForestBoreal}$	Boreal All organic soils	3.57	2.73 , 4.40**	73 sites, Huttunen *et al.* 2003a; Komulainen *et al.* 1998, 1999; Laine *et al.* 1996; Makiranta *et al.* 2007; Maljanen *et al.* 2001b, 2003a, 2003b, 2006a, 2010; Martikainen *et al.* 1992, 1995a, 1995b; Minkkinen & Laine 2006; Minkkinen *et al.* 2007a; Nykanen *et al.* 1998; Saari *et al.* 2009; Silvola *et al.* 1996; Von Arnold *et al.* 2005d
Forest Land EF$_{CH4OrgForestBorealPoor}$	Boreal Nutrient-poor	12.4	6.41 , 18.3**	19 sites, Huttunen *et al.* 2003a; Komulainen *et al.* 1998, 1999; Laine *et al.* 1996; Makiranta *et al.* 2007; Maljanen *et al.* 2001b, 2003a, 2003b, 2006a, 2010; Martikainen *et al.* 1992, 1995a, 1995b; Minkkinen & Laine 2006; Minkkinen *et al.* 2007a; Nykanen *et al.* 1998; Saari *et al.* 2009; Silvola *et al.* 1996; Von Arnold *et al.* 2005d
Forest Land EF$_{CH4OrgForestBorealRich}$	Boreal Nutrient-rich	0.471	0.342 , 0.600**	54 sites, Huttunen *et al.* 2003a; Komulainen *et al.* 1998, 1999; Laine *et al.* 1996; Makiranta *et al.* 2007; Maljanen *et al.* 2001b, 2003a, 2003b, 2006a, 2010; Martikainen *et al.* 1992, 1995a, 1995b; Minkkinen & Laine 2006; Minkkinen *et al.* 2007a; Nykanen *et al.* 1998; Saari *et al.* 2009; Silvola *et al.* 1996; Von Arnold *et al.* 2005d
Forest Land EF$_{CH4OrgForestTemp}$	Temperate	1.69	0.791 , 2.60**	16 sites, Glenn *et al.* 1993; Moore & Knowles 1990; Sikstrom *et al.* 2009; Von Arnold *et al.* 2005b, 2005c; Weslien *et al.* 2009
Forest - drained EF$_{CH4OrgForestTrop}$	Tropical/ Subtropical	0.004	0.002***	Jauhiainen *et al.* 2008; Hirano *et al.* 2009; Furukawa *et al.* 2005
Forest - burned EF$_{CH4OrgForestTrop}$		0.002	0.000***	Jauhiainen *et al.* 2008
Cropland				
Cropland EF$_{CH4CropBoreal}$	Boreal	-1.09	-2.00 , -0.178**	8 sites, Lohila *et al.* 2004; Maljanen *et al.* 2001a, 2003a, 2003b, 2004; Regina *et al.* 2007
Cropland EF$_{CH4CropTemp}$	Temperate	2.68	1.55 , 3.81**	24 sites, Flessa *et al.* 1998; Glenn *et al.* 1993; Kasimir *et al.* 2009
Cropland EF$_{CH4CropTrop}$	Tropical/ Subtropical	0.005	0.005***	Furukawa *et al.* (2005); Hirano *et al.* 2009
Rice EF$_{CH4Crop-RiceTrop}$		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 $EF_{CH4Crop-OilpalmTrop}$		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
Grasslands				
Grassland $EF_{CH4GrassBoreal}$	Boreal	1.38	0.582 , 2.17**	14 sites, Gronlund *et al.* 2006; Hyvonen *et al.* 2009; Maljanen *et al.* 2003a, 2003b, 2004, 2009a, 2009b; Nykanen *et al.* 1995; Regina et al 2007
Grassland $EF_{CH4GrassTemp}$	Temperate	0		
Grassland $EF_{CH4GrassTrop}$	Tropical/ Subtropical	0.005	0.005***	Same emission factor as Tropical Cropland
Shrubland $EF_{CH4ShrubBoreal}$	Boreal	1.38	0.582 , 2.17**	Same emission factor as Boreal Grassland
Shrubland $EF_{CH4ShrubTemp}$	Temperate	0		Same emission factor as Temperate Grassland
Shrubland $EF_{CH4ShrubTrop}$	Tropical/ Subtropical	0.005	0.005***	Same emission factor as Tropical Cropland
Wetlands				
Peatlands drained for extraction $EF_{CH4PeatBoreal}$	Boreal	3.19	1.05 , 5.34**	11 sites, Hyvonen *et al.* 2009; Nykanen *et al.* 1996; Tuittila *et al.* 2000; Waddington & Day 2007
Peatlands drained for extraction $EF_{CH4PeatTemp}$	Temperate	382	-92.2 , 856**	5 sites, BMBF Report 2006-10; Clymo & Reddaway 1971
Peatlands drained for extraction $EF_{CH4PeatTrop}$	Tropical /Subtropical			
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		

** 95% confidence interval

*** standard error

*** * Positive and negative values indicate net CH_4 emissions and removals respectively.

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 and peatlands. 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 expert judgment.

Activity data required to estimate ditch CH_4 emissions at Tier 1 consists of areas of managed organic soils disaggregated by peat type and land-use category (forest, grassland, cropland, wetlands used for peat extraction) as shown in Table 2.4.

To estimate ditch CH_4 emissions, additional activity data are required on ditch width and ditch spacing within each land category. Default estimates are provided in Table 2.4, however it is good practice to replace these values with country-specific values wherever possible, to reflect local land-use practices. Higher tier methods could incorporate additional information on water depth, 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.

Tiers 2 and 3

Activity data for Tier 2 and 3 methods may consist of areas of organic soils managed for peat extraction, paddy systems, horticulture and plantation disaggregated according to nutrient status if relevant, and annual peat production data. More sophisticated estimation methodologies will require the determination of areas in each of the three phases of the peat extraction cycle, including abandoned areas on which drainage or the effects of former peat extraction are still present; and if warranted, areas characterized by different peat extraction technology, peat types and extraction depths. Land-use intensity, particularly fertilizer and organic matter addition, may be used to refine CH4 emission estimates for grassland and cropland, as higher emissions are likely under more intensive management systems with high substrate supply for methanogenesis.

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.

A Tier 3 approach to ditch emission estimation would require activity data on the nature and timing of agricultural activities (such as organic matter additions) and on hydrological parameters such as ditch depth.

UNCERTAINTY ASSESSMENT

Ranges are provided in Table 2.4 for values of EF_{CH4_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. As the number of studies is insufficient to estimate 2.5th and 97.5th percentile values, maximum and minimum reported values have been used. These upper and lower estimates should be used, along with country-level information on ditch widths and spacings (again with ranges where available) to calculate upper and lower ranges on $EF_{CH4\_ditch\_landscape}$..

TABLE 2.4
DEFAULT CH_4 EMISSION FACTORS FOR DRAINAGE DITCHES

Land-use	Land-use sub-category	Temperature regime	Peat type	EF_{CH4_ditch} (t CH_4-C ha^{-1} yr^{-1})	Ditch width (m)[a]	Ditch spacing (m)[a]	$EF_{CH4\_ditch\_landscape}$ (t CH_4–C ha^{-1} yr^{-1})
Forest	Commercial forestry	Boreal /temperate	Raised bog/fen	0.173 (0.015-0.353)	0.5	30	0.003
			Blanket bog	0.053[c] (0.015-0.105)	0.5	15	0.002
Grassland	Low intensity	Boreal /temperate	Raised bog/fen	0.345[b] (0.180-0.503)	0.5	30	0.006
			Blanket bog	0.053 (0.015-0.105)	0.5	15	0.002
	High intensity	Boreal /temperate	Raised bog/fen	0.833 (0.293-1.815)	2	30	0.041
Cropland	Low intensity	Boreal /temperate	Raised bog/fen	0.345 [e] (0.180-0.503)	0.5	30	0.006
	High intensity	Boreal /temperate	Raised bog/fen	0.833 [d] (0.293-1.815)	2	30	0.041
Wetland	Peat extraction	Boreal /temperate	Raised bog/fen	0.488 (0.120-0.930)	1	20	0.019
Drained tropical peat (all land-use classes)				214 (62-366)	7	500	1.605 (0.465-2.745)

[a] Ditch widths and spacings shown are indicative, based on published studies. Country-specific estimates should be used in preference wherever possible.

[b] Low-intensity grazing on semi-natural vegetation

[c] Assumed equal to drained blanket bog under extensive grazing

[d] Assumed equal to high-intensity grassland.

[e] Assumed equal to low-intensity grassland.

2.2.2.2 N_2O EMISSIONS FROM DRAINED ORGANIC SOILS

Nitrous oxide (N_2O) is one of the most important radiatively active trace gases in the atmosphere. Over the last two decades there has been a nearly linear increase of 0.26% in the concentration of N_2O due to anthropogenic emissions. 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.*1984; 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).

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 emissions 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 wetland under peat extraction in boreal and temperate zones in order to update Table 7.6 in 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 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 $F_{OS,\ F\ Bor\ NP}$ and their respective emissions factors.

Direct N_2O emissions from managed soils are estimated using Equation 11.1 in 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, we provide updates for the second segment that focuses on organic soils as follows:

EQUATION 2.6

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 $N_2O–N$ 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 N_2O emissions from drained/managed organic soils, kg $N_2O–N\ ha^{-1}\ yr^{-1}$; (Table 11.1, 2006 GL) 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 determined by drainage class, amount of N fertilizer applied, and land use. The corresponding emission factors are country or region specific and take into account the land management systems.

Tier 3

Tier 3 methods are based on modeling 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. 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.

CHOICE OF EMISSION FACTORS

Tier 1

Emission factors for boreal and temperate organic soils

The 2*006 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 (poor bogs) and minerotrophic (rich 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 zone**	**Emission factor (kg N ha^{-1} yr^{-1})**	**Uncertainty (kg N ha^{-1} yr^{-1})**	**References, comments**	**Chapter in Volume 4 of *2006 IPCC Guidelines***
Forestland					
Forest Land $EF_{N2O-OrgForestBoreal}$	Boreal All organic soils	4.26	3.07 , 5.44**	52 sites, Huttunen *et al.* 2003a; Laurila *et al.* 2007; Makiranta *et al.* 2007; Maljanen *et al.* 2001b, 2003a, 2003b, 2006a, 2010; Martikainen *et al.* 1992, 1993, 1995a; Minkkinen *et al.* 2007a; Pihlatie *et al.* 2004; Regina *et al.* 1996, 1998; Saari *et al.* 2009; Von Arnold et al 2005d	Chapter 11
Forest Land $EF_{N2O-OrgForestBorealPoor}$	Boreal Nutrient-poor	0.069	-0.003 , 0.141**	6 sites, Huttunen *et al.* 2003a; Laurila *et al.* 2007; Makiranta *et al.* 2007; Maljanen *et al.* 2001b, 2003a, 2003b, 2006a, 2010; Martikainen *et al.* 1992, 1993, 1995a; Minkkinen *et al.* 2007a; Pihlatie *et al.* 2004; Regina *et al.* 1996, 1998; Saari *et al.* 2009; Von Arnold et al 2005d	Chapter 11
Forest Land $EF_{N2O-OrgForestBorealRich}$	Boreal Nutrient-rich	4.80	3.38 , 6.23**	46 sites, Huttunen *et al.* 2003a; Laurila *et al.* 2007; Makiranta *et al.* 2007; Maljanen *et al.* 2001b, 2003a, 2003b, 2006a, 2010; Martikainen *et al.* 1992, 1993, 1995a; Minkkinen *et al.* 2007a; Pihlatie *et al.* 2004; Regina *et al.* 1996, 1998; Saari *et al.* 2009; Von Arnold et al 2005d *et al.* 2005d	Chapter 11
Forest Land $EF_{N2O-OrgForestTemp}$	Temperate	3.03	1.35 , 4.72**	15 sites, Sikstrom *et al.* 2009; Struwe & Kjoller 1994; Von Arnold *et al.* 2005b, 2005c; Weslien *et al.* 2009	Chapter 11
Forest Land $EF_{N2O-OrgForestTrop}$	Tropical/ Subtropical	1.9	0.3***	Furukawa *et al.* 2005; Takakai *et al.* 2006	Chapter 11
Cropland					
Cropland $EF_{N2OCropBoreal}$	Boreal	6.16	3.91 , 9.13**	19 sites, Jaakola 1985; Maljanen *et al.* 2003a, 2003b, 2004; Regina *et al.* 2004	Chapter 11

Cropland $EF_{N2OCropTemp}$	Temperate	10.5	5.58 , 15.4**	20 sites, Flessa *et al.* 1998; Kasimir *et al.* 2009	Chapter 11
Cropland except rice $EF_{N2OOrgCropTrop}$	Tropical/ Subtropical	2.0	1.2***	Furukawa *et al.* 2005	Chapter 11
Rice $EF_{N2OOrgCrop-RiceTrop}$		0.4	0.5***	Furukawa *et al.* 2005; Hadi *et al.* 2005; Inubushi *et al.* 2003	Chapter 11
Plantation: Oil palm $EF_{N2OOrgCrop-OilpalmTrop}$		1.2		Melling *et al.* 2007	Chapter 11
Plantation: Sago palm $EF_{N2OOrgCrop-SagopalmTrop}$		3.3		Melling *et al.* 2007	Chapter 11
Grasslands					
Grassland $EF_{N2OGrassBoreal}$	Boreal	9.44	4.59 , 14.3**	17 sites, Gronlund et al. 2006; Hyvonen et al. 2009; Jaakola 1985; Maljanen et al. 2003a, 2003b, 2004, 2009a, 2009b; Nykanen et al. 1995; Regina et al 1996, 2004	Chapter 11
Grassland $EF_{N2OGrassTemp}$	Temperate	5.47	3.93 , 7.01**	51 sites, Flessa et al. 1998; Kasimir et al. 2009; Langeveld et al. 1997; Meyer et al. 2001; Van Beek et al. 2010	Chapter 11
Grassland $EF_{N2OGrassTrop}$	Tropical/ Subtropical	2.0	1.2***	Same emission factor as Tropical Cropland	Chapter 11
Shrubland $EF_{N2OGrassBoreal}$	Boreal	9.44	4.59 , 14.3**	Same emission factor as Boreal Grassland	Chapter 11
Shrubland $EF_{N2OGrassTrop}$	Temperate	5.47	3.93 , 7.01*	Same emission factor as Temperate Grassland	Chapter 11
Shrubland $EF_{N2OGrassTrop}$	Tropical/ Subtropical	2.0	1.2***	Same emission factor as Tropical Cropland	Chapter 11
Wetlands					
Peatlands drained for extraction $EF_{N2OPeatBoreal}$	Boreal	1.38	0.104 , 2.65**	7 sites, Alm *et al.* 2007; Hyvonen *et al.* 2009; Nykanen *et al.* 1996; Regina *et al.* 1996	Chapter 7 Table 7.6
Peatlands drained for extraction $EF_{N2OPeatTemp}$	Temperate	1.75	-2.60 , 6.11**	3 sites, BMBF Report 2006-10	Chapter 7 Table 7.6
Peatlands drained for extraction $EF_{N2OPeatTrop}$	Tropical/Subtropical	3.6	0.2 to 5.0****	Same as in *2006 IPCC Guidelines*	Chapter 7 Table 7.6
Settlements	All climate zones	Same emission factor as Cropland			Chapter 8

Other Lands	All climate zones	Other Land remaining Other Land: 0 Land converted to Other Land: Maintain emission factor of previous land-use category	Chapter 9

** 95% confidence interval

*** standard error

**** range

*****Positive and negative values indicate net N_2O emissions and removals respectively.

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). With the current dataset, it is impossible to disaggregate the effects of drainage depth and fertilizer application. It also needs to be highlighted that all measurements on of N_2O emissions on tropical organic soils to date are from Southeast Asia.

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. There is increasing evidence that N_2O emissions are very low in drained nutrient poor peatlands where C:Nratio in boreal soils is high (e.g. Klemetdsson *et al.* 2005), but both low and high emissions can occur with low (< 25) C:Nratios.

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 *2006 IPCC Guidelines* Chapter 11.

CHOICE OF ACTIVITY DATA

Tier 1

Activity data for non-CO_2 GHGs 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 e.g. forests affected by drainage and secondary forests. 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, which maintains conditions that promote denitrification (Melling *et al.*, 2007). Rice is also cultivated with a high water table 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.

TIER 3

See *2006 IPCC Guidelines* Chapter 11.

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*.

Calculation steps

See *2006 IPCC Guidelines* Chapter 11.

2.2.2.3 NON-CO2 EMISSIONS FROM BURNING ON ORGANIC SOILS

(NOT FINISHED.TO BE COMPLETED IN THE SECOND ORDER DRAFT.)

2.3 LAND CONVERTED TO A NEW LAND-USE CATEGORY

2.3.1 CO2 emissions in organic soils

This section deals with the impacts of land use change, drainage and management onCO2 emissions in organic soils, by influencing C inputs and outputs from the soil and thus soil C storage. Changes in losses include heterotrophic respiration (peat decomposition) erosion losses of particulate organic carbon (POC) and loss of dissolved organic carbon in drainage waters (DOC). Changes in inputs are associated with slash left on the ground in the case of forests and changes in root, litter and deadwood inputs in all systems. General information and guidance for estimating changes in soil C stocks are provided in the *2006 IPCC Guidelines* in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with organic soil C stocks. The main difference between mineral soils and organic soils is that in mineral soils we assume that carbon reaches a constant stock level in managed systems following changes in management and that eventually emissions become negligible. At Tier 1 in mineral soils, we assume that emissions persist for up to 20 years after which carbon stocks attain a new equilibrium and do not produce any further emissions. In organic soils, once the soils are managed and drained, we assume that emissions persist until drainage is reversed.

The total change in soil C stocks in organic soils for land converted to a new land use category is estimated using Equation 2.1, which combines the on-site emissions from soil organic matter decomposition and off-site emissions from POC and DOC.

2.3.1.1 ON-SITE CO_2 EMISSIONS FROM DRAINED ORGANIC SOILS

TIER 1 & 2

CO_2 emissions and removals in organic soils are dominated by water table and current land use and management. The legacy effect of land-use changes cannot be separated from the effect of the new land use at Tier 1 and Tier 2 level.

On land converted to a new land- use category (e.g. Forest land converted to Cropland) the emissions and removals of CO_2 in organic soils are calculated as in land remaining in the new land-use category (e.g. Cropland remaining Cropland). Guidance is given in Section 2.2.1.1.

TIER 3

Tier 3 methods could further differentiate transition effects of increased or reduced CO_2 emissions or removals after land use change.

2.3.1.2 OFF-SITE CO_2 EMISSIONS FROM WATERBORNE CARBON LOSSES

TIER 1 & 2

Waterborne carbon losses in organic soils are dominated by water table and current land use and management. The legacy effect of land-use changes cannot be separated from the effect of the new land use at Tier 1 and Tier 2 level.

On land converted to a new land- use category (e.g. Forest land converted to Cropland) the emissions and removals of CO_2 in organic soils are immediately calculated as in land remaining in the new land-use category (e.g. Cropland remaining Cropland). Guidance is given in Section 2.2.1.2.

TIER 3

Tier 3 methods could further differentiate transition effects of increased or reduced waterborne carbon losses after land use change.

2.3.2 Non-CO2 emissions

2.3.2.1 CH_4 EMISSIONS FROM DRAINED ORGANIC SOILS

On land converted to a new land- use category (e.g. Forest land converted to Cropland) the CH_4 emissions from organic soils are calculated as in land remaining in the new land-use category (e.g. Cropland remaining Cropland). Guidance is given in Section 2.2.2.1.

On land converted to a new land- use category (e.g. Forest land converted to Cropland) CH_4 emissions from organic soils are calculated as in land remaining in the new land-use category (e.g. Cropland remaining Cropland). Guidance is given in Section 2.2.2.2.

2.3.2.2 N_2O EMISSIONS FROM DRAINED ORGANIC SOILS

On land converted to a new land- use category (e.g. Forest land converted to Cropland) N2O emissions from organic soils are calculated as in land remaining in the new land-use category (e.g. Cropland remaining Cropland). Guidance is given in Section 2.2.2.3.

2.3.2.3 NON-CO2 EMISSIONS FROM BURNING ON ORGANIC SOILS

(NOT FINISHED.TO BE COMPLETED IN THE SECOND ORDER DRAFT.)

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 in Table 2A.1. 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 intensive and extensive 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	Ditch flux (g CH_4 m^{-2} yr^{-1})	Ditch proportion of landscape (%)	Ditch flux scaled to total area (g CH_4 m^{-2} yr^{-1})
Intensive grassland	Netherlands	Schrier-Uijl *et al.* (2009, 2011)	58	21%	12.3
Intensive grassland	Netherlands	Vermaat et al (2011)	79	25%	19.3
Intensive grassland	Netherlands	Best & Jacobs (1997)	10	6%	0.6
Intensive grassland	UK	McNamara et al (2012)	77	4%	3.1
Intensive grassland	Russia	Sirin et al (2012)	60	4%	2.2
Intensive grassland	Russia	Chistotin et al (2006)	265	4%	9.6
Intensive grassland	USA	Teh et al (2011)	227	5%	11.4
Extensive grassland	Netherlands	Vermaat et al (2011)	79	25%	19.3
Extensive grassland (restored)	Netherlands	Best & Jacobs (1997)	46	6%	2.7
Extensive grassland (restored)	Netherlands	Van den Pol-Van Dasselaar *et al.* (1999)	11	25%	2.8
Extensive grassland (restored)	Netherlands	Hendricks et al (2007, 2010)	50	10%	5.0
Conservation-managed	Netherlands	Vermaat et al (2011)	44	25%	10.7
Drained treed bog	Canada	Roulet & Moore (1995)	15	3%	0.5
Drained treed fen	Finland	Minkinnen & Laine (2006)	104	3%	2.9
Drained afforested fen	Russia	Sirin et al (2012)	19	2%	0.4
Drained afforested fen	Russia	Glagolev et al (2008)	12	4%	0.4
Drained treed bog	Canada	Roulet & Moore (1995)	4	3%	0.1
Drained afforested bog	Russia	Sirin et al (2012)	40	1%	0.4

Drained afforested bog	Russia	Sirin et al (2012)	1	1%	0.02
Drained afforested bog	Canada	Roulet & Moore (1995)	26	3%	0.8
Drained afforested bog	Sweden	Von Arnold et al (2005)	2	2%	0.04
Drained afforested bog	Finland	Minkinnen & Laine (2006)	7	3%	0.2
Peat-mining site	Finland	Nykanen et al (1995)	18	2%	0.3
Peat-mining site	Sweden	Sundh et al (2000)	48	3%	1.2
Peat-mining site	Russia	Sirin *et al.* (2012)	136	4%	4.9
Peat-mining site	Russia	Chistotin *et al.* (2006)	106	4%	3.8
Cutover bog	Canada	Waddington & Day (2007)	15	5%	0.7
Restored cutover bog	Canada	Waddington & Day (2007)	26	5%	1.3
Drained blanket bog	UK	Cooper et al (2012)	7	3%	0.2
Re-wetted blanket bog	UK	Cooper et al (2012)	83	6%	5.2
Drained tropical peat (abandoned)	Indonesia	Jauhiainen et al (2012)	62	2%	0.9
Drained tropical peat (pulpwood plantation)	Indonesia	Jauhiainen et al (2012)	366	2%	5.5

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 be sufficient to determine whether the site is a new carbon sink or carbon source (e.g. Billett *et al.*, 2004; Rowson *et al.*, 2010). 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 on 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 2.3B.

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, 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 within the ditch network. 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) which was used to calculate default values for different precipitation regimes. Blanket bogs and tropical peat swamps are generally characterised by higher precipitation, and few data were available, so single default values were assigned for each class. Note that by far the highest DOC losses are observed from tropical peat swamps. The data used in this assessment are listed in Table 2A.2.

TABLE 2A.2
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 (g c m^{-2} yr^{-1})
Subarctic fen	Canada	Koprivnjak & Moore (1992)	302	5
Boreal fen	Finland	Juutinen et al (in prep)	395	4
Boreal fen	Finland	Jager et al (2009)	476	8
Boreal fen	Canada	Moore (2003)	536	4
Boreal bog	Canada	Moore (2003)	536	6
Boreal fen	Canada	Strack et al (2008)	590	5
Boreal mire	Sweden	Agren et al (2007)	600	10
Boreal mire	Finland	Kortelainen et al (2006)[a]	620	16
Boreal mire	Finland	Kortelainen et al (2006)	620	6
Boreal bog/fen	Finland	Rantakari et al (2010)	640	12
Boreal bog	Canada	Moore et al (2003)	678	29
Boreal fen	Sweden	Nilsson et al (2008)	680	13
Boreal bog	USA	Urban et al (1989)	780	21
Boreal bog/fen	USA	Kolka et al (1999)	780	24
Boreal bog	Canada	Roulet et al (2007)	943	16
Temperate bog	Canada	Clair et al (2002)	1400	36
Blanket bog	UK	Dawson et al (2004)	1130	19
Blanket bog	UK	Dinsmore et al (2011)	1155	26
Blanket bog	UK	Billett et al (2010)	1980	23
Blanket bog	UK	Billett et al (2010)	2200	19
Blanket bog	Ireland	Koehler et al (2009,2011)	2570	14
Blanket bog	Australia	Di Folco & Kirkpatrick (2011)	2900	13
Tropical swamp forest	Indonesia	Baum et al (2008) [a]	2316	47
Tropical swamp forest	Indonesia	Alkhatib et al (2007)	2500	55
Tropical swamp forest	Malaysia	Yule et al (2009), Zulkifli (2002)	2300	63
Tropical swamp forest	Indonesia	Moore et al (2011)	2700	67

[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 ten 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 2A2.3). These included some 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. The use of concentration data to estimate

$\Delta DOC_{DRAINAGE}$ assumes no corresponding change in total water flux from this site. This assumption adds some uncertainty, although this should be relatively small for high-precipitation boreal/temperate sites, as a large change in water flux could only occur if there is a correspondingly large change in evapotranspiration. For dryer sites, drainage might be expected to increase water fluxes, therefore amplifying the observed concentration differences between drained and undrained sites.

Despite these uncertainties, 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 median (across all studies) of 53%, and there was no clear evidence to support the use of different $\Delta DOC_{DRAINAGE}$ values for different peat types, climate regimes, drainage type or drainage intensity. Therefore, an initial Tier 1 default $\Delta DOC_{DRAINAGE}$ is proposed for all forms of peatland drainage.

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 (mg/l)**		**$\Delta DOC_{DRAINAGE}$**
				Undrained	**Drained**	**(%)**
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 (peat extraction)	New Zealand	Moore et al (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%
Peat type	Land-use	Country	Study	DOC (g C m^{-2} y^{r-1})		$\Delta DOC_{DRAINAGE}$
				Undrained	Drained	(%)
Tropical peat	Drainage (sago palm)	Malaysia	Inubushi et al (1998)	33	63	91%
Tropical peat	Drainage (agriculture)	Indonesia	Moore et al (2012)	67	93	39%

Estimation of $F_{DOC-CO2}$

The significance of DOC export in terms of GHG 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 estimation. The parameter $F_{DOC-CO2}$ sets the proportion of DOC exported from peats which 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) observed measured 6-15% conversion of pore-water DOC to $CO_{2,}$ and 10-90% conversion of the vegetation-derived DOC, during one-month dark incubations, while Worrall *et al.* (2012) observed much higher (80 to near-100%) degradation of peat-derived DOC in light-exposed samples within 48 hours, which 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 $F_{DOC-CO2}$ 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 90% is proposed, with an uncertainty range of 80-100%.

There is some evidence that controlled burning (for moorland management) also increases DOC losses (e.g. Yallop *et al.*, 2010; Di Falco *et al.*, 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 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, 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 following burning. 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 POC exports can be reasonably well predicted based on a value of $POC_{FLUX\_BAREPEAT}$ of around 4 g C m^{-2} yr^{-1} per 1% bare peat (Evans *et al.*, 2012). 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).

Finally, there is little information current available from which to derive a value for $F_{POC\text{-}CO2.}$ Unlike DOC, a substantial proportion of POC is mobilized from peats through physical erosion processes, and may not be reactive in fluvial systems; a significant proportion 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. However, it does appear that at least a proportion of POC transported in aquatic systems may be actively biologically cycled, whilst material re-deposited on floodplains may be subject to rapid mineralization (Pawson *et al.*, 2008). Further research is needed to establish realistic ranges for $F_{POC\text{-}CO2}$ in different systems.

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

$$EF_{POC} = POC_{FLUX\_BAREPEAT} \bullet PEAT_{BARE} / 100 \bullet F_{POC-CO_2}$$

Where:

EF_{POC} = POC Emission factor, g C m^{-2} yr^{-1}

$POC_{FLUX\_BAREPEAT}$ = Flux of POC per 1% of the total peat area comprising bare peat, g C m^{-2} yr^{-1}

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

$F_{POC\text{-}CO2}$ = Conversion factor for amount of DOC converted to CO_2 following export from site

Developing emissions factors from the scientific literature

The IPCC Guidelines provide two methods for assessing emissions from a given carbon pool. Stock-Difference Method requires carbon stock inventories for a given land area, at two points in time (*2006 IPCC Guidelines* Equation 2.5). Annual stock change is calculated as the difference between the stock at time t_2 and time t_1, divided by the number of years between the inventories. Estimating emissions from wetland soils was not included in the *2006 IPCC Guidelines*, but a method was presented for mineral soils. To calculate the stocks for Tier 1, a reference SOC value was given for a geographic region and soil type based on the presence or absence of high activity clays. This value was then modified by different factors estimation for land use, management regime and organic matter inputs. This approach is the basis for the Tier 1 and Tier 2 methods for mineral soils, and default values for calculation of increment and losses were provided in the *2006 IPCC Guidelines*.

The second approach is the Gain-Loss Method requires carbon losses to be subtracted from carbon gains (*2006 IPCC Guidelines* Equation 2.4). Gains can be attributed to transfers of carbon from live biomass pools and decomposition of dead wood and litter. Losses can be attributed to transfers out of the SOC pools through heterotrophic respiration and losses to surface waters in the forms of dissolved and particulate organic C. This method has not previously been applied to soils, but makes sense in the context of organic soils for a number of reasons:

- Changes in carbon stocks in organic soils are not limited to the surface 30 cm of soil (Hergoualc'h and Verchot, 2011).
- Estimating the volume of an organic soil with any certainty is difficult because of non-systematic spatial variability of the thickness of the peat formation (Verwer and van der Meer, 2010; Kool *et al.*, 2006)
- Bulk density of organic soils varies non-systematically in three dimensions (Kool *et al.*, 2006). In addition, small errors due to compaction during sampling make for large errors when scaled up to the hectare level. Thus, this property is difficult to measure with any precision (Murdiyarso *et al.*, 2010).
- In the case of forest derived peats (e.g. pocosins, tropical peat swamps), the organic soil is heterogeneous and may contain intact wood and wood in varying stages of decomposition (Kool *et al.*, 2006).

The scientific literature rarely reports changes in carbon stocks associated with land-use change or management in peatlands. Most studies that attempt to estimate emissions combine estimates of different fluxes of inputs and outputs to the soil organic matter pool. Several studies report emission estimates based on total annual soil respiration and fail to account for either inputs (root turnover, litter fall and woody debris), dissolved or particulate outputs, or for the autotrophic component of soil respiration (e.g. Hooijer *et al.*, 2010; Hadi *et al.*, 2005). Despite the incomplete measurements in these studies there is still much useful information that can be used to calculate emissions factors for these ecosystems.

In this chapter we have adopted the Gain-Loss Method and we use different studies to calculate reasonable estimates of the net change of SOC stocks for different land management systems. We use average values from available studies to estimate all inputs and outputs to the soil organic C pool. We then combine these inputs and outputs for major land-use systems to derive emissions factors.

Data availability in the scientific literature

There are three principal approaches in the scientific literature that are useful to our efforts to estimate the effects of land use change and management on the atmosphere: eddy covariance or correlation techniques, clear chambers (also called cuvettes in the literature) and individual flux measurements. There have been a few attempts at estimating emissions from changes to peat elevations (Kool *et al.*, 2006; Couwenberg *et al.* 2010), but these methods still have high degrees of uncertainty regarding what part of this subsidence represents emissions.

Eddy covariance techniques measure the exchange of CO_2 across the boundary between the atmosphere and the plant canopy by measuring the covariance between vertical wind velocity and CO_2 mixing ratios (Baldocchi 2003). This method can be used to quantify how CO_2 exchange rates respond to environmental changes at the scale of the whole ecosystem at a variety of scales ranging from hours to years. When the method is applied to paired systems, it can be used to address management questions. However, because the eddy covariance approach provides measurements at the scale of the ecosystem, it is difficult to apply numbers derived from this technique to the IPCC methods, which focus on quantifying changes in 5 carbon pools. To do this, eddy covariance methods require additional measurements of different important components of the ecosystem carbon budget to provide estimates useful for IPCC default factors.

Eddy covariance measures net ecosystem exchange (NEE), which is the difference between gross primary production and respiration. To be useful for this exercise it is important to separate these two flux components. Two approaches are generally used in ecological studies: (1) Night-time respiration measurements can be extrapolated to estimate daytime rates; or (2) light–response curves can be derived from daytime NEE measurements and respiration can then be estimated from the intercept of the ordinate (Lasslop *et al.*, 2010). Additional measurements will often be required to segregate ecosystem respiration into its heterotrophic (R_h) and autotrophic (R_a) components. These measurements include trenched plots and isotopic techniques (Hanson et al 2000).

A second method involves the use of whole-plant transparent chambers (often referred to as cuvettes in the literature) that measure the diurnal variations of carbon fluxes (Baldocchi, 2003), which can be used to calculate NEE. These methods are appropriate for short stature vegetation and allow for replication of small area measurements. Experimental artefacts introduced by the chambers can be held to reasonable levels by controlling temperature and light. Similarly to eddy flux measurements, this approach does not directly separate GPP and R. These studies often involve making sequential measurements after darkening chambers to estimate stop photosynthesis and measure ecosystem R, which allows for the calculation of GPP (see for example Welker *et al.*, 2004). Further measurements are required to segregate total R into R_h and R_a.

The final method involves measuring the major fluxes into and out of the SOM pool and calculating a mass balance based on the difference between inputs and outputs (Hergoualc'h and Verchot 2011). Litterfall and deadwood inputs are measured and assigned decomposition coefficients or turnover times. At very large scales, models based on temperature and precipitation do a good job of estimating litter decomposition rates (Tuomi *et al.*, 2009), but other more complicated models based on C:N ratios are also useful. For soil respiration, dark chambers are used and partitioning or total R into R_a and R_h is done either through trenched plots or isotopic techniques (Hanson et al 2000).

Tier 1 simplifications

The Introductory chapter of the *2006 IPCC Guidelines* state that Tier 1 methods are designed to be the simplest to use, for which equations and default parameter values are provided. Country-specific activity data are needed, but for Tier 1 there are often globally available sources of activity data estimates (e.g., deforestation rates, agricultural production statistics, global land cover maps, fertilizer use, livestock population data, etc.), although these data are usually spatially coarse. Tier 2 can use the same methodological approach as Tier 1 but applies emission and stock change factors that are based on country- or region-specific data, for the most important land-use or livestock categories. Country-defined emission factors are more appropriate for the climatic regions, land-use systems and livestock categories in that country. Higher temporal and spatial resolution and more disaggregated activity data are typically used in Tier 2 to correspond with country-defined coefficients for specific regions and specialized land-use or livestock categories.

In this volume we use combinations of the approaches outlined above to generate globally applicable default factors for Tier 1 inventories. We focus on developing best estimates of the emission factor (EF) in equation 2.26 of the *2006 IPCC Guidelines*. Countries can develop studies using these methods to develop Tier 2 default factors for the same equation.

To generate Tier 1 factors we make a few simplifications. Because it is difficult to separate anthropogenic emissions from natural ones in managed lands, the authors of the *2006 IPCC Guidelines* used emissions and removals from "managed land" as a proxy for anthropogenic emissions and removals (implicitly in the *Revised 1996 Guidelines* and explicitly in later documents). This means that all emissions/removals from managed lands are assumed to be anthropogenic, while emissions/removals from unmanaged land are not included in the inventory. In most instances natural wetlands are sinks of atmospheric C and accumulation rates on the order of 0.1 to 0.2 MgC ha^{-1} y^{-1} in tundra systems (Robinson and Moore, 1999) and 0.3 to 0.7 MgC ha^{-1} y^{-1} in tropical peat systems are reported in the literature (Dommain *et al.*, 2011; Page *et al.*, 2004). Because we use managed land as a proxy for anthropogenic emissions, we do not account for this lost sink associated with conversion and we account only for emissions in the managed system. This is consistent with how the IPCC guidelines calculate emissions from other types of land use change, like deforestation.

The second simplification is that we assume inputs and outputs from the dead organic matter pools are in steady state. This means that inputs to the SOC pool from dead wood and litter are assumed to equal dead wood and litter fall.

A third simplification is that emissions are assumed to remain constant over the life of the land use. In mineral soil systems, the default for land remaining in a category is that there are no net emissions because soil organic matter is in steady state. For land conversion to another land-use category the Tier 1 assumption is that SOC pools reach a new equilibrium after 20 years and so they emit or sequester only during this period. Drainage of organic soils results in continuous emissions and so there is no new equilibrium achieved. This means that no distinction is made in emissions factors between land converted to a new land use and land converted to a new land use.

EF for tropical wetlands

Data from a variety of published sources including journal articles, theses and reports were collected and compiled. This analysis updates the work presented in Hergoualc'h and Verchot (2011). Carbon inputs to the soil were derived from litterfall and root mortality data in the literature. The main soil C outputs were mineralization (heterotrophic respiration), methanogenesis, leaching, runoff, erosion and land-clearing fires. Carbon losses from land-clearing fires were not included in the current calculation, given that they are already taken into account. Table 2a.1 presents the methods and the reference of the data sources used for calculating several of these fluxes. Soluble and physical C loss included dissolved organic carbon (DOC) and particulate organic carbon (POC). We assumed a loss from soluble and physical removal of 1.0 ± 0.5 Mg C ha^{-1} yr^{-1} for all LUs, using the combined maxima of what was observed in northern peatlands for POC and DOC (Holden, 2005). This estimate is in agreement with recent measurements by Moore *et al.* (2011) of a fluvial TOC (DOC + POC) loss flux per unit area over the entire Sebangau catchment in Indonesia of 0.88 Mg C ha^{-1} yr^{-1}. Total soil respiration rates are available in Table 2a.4 of the auxiliary material of the paper Hergoualc'h and Verchot (2011).

In all land-use (LU) treatments total C inputs to the peat were calculated as the sum of the average C inputs from litterfall and root mortality. Total C outputs from the peat were calculated as the sum of the average C outputs from heterotrophic soil respiration, physical and soluble removals and CH_4 emissions.

TABLE 2A.1

METHOD AND DATA SOURCES FOR CALCULATION OF C FLUXES INTO AND OUT OF THE SOIL FOR DIFFERENT LAND-USE CATEGORIES ON TROPICAL PEATLANDS.

Land Use	**Soil C inputs**				**Soil C outputs**			
	Litterfall		**Root Mortality**		**Heterotrophic Respiration**		**CH_4**	
	Method	**Sources**	**Method**	**Sources**	**Method**	**Sources**	**Method**	**Sources**
Intact Forest	Average (a) corrected in order to include large-branch fall	1, 2, 3, 4, 5, 6 corrected using 4	Average (a)	1, 7, 5	Proportion of total soil respiration (b)	8	Average (a)	22, 23, 24, 25, 26, 28
Degraded forest (burned/ logged)	Proportion C inputs in Intact Forest (c)	9	Proportion C inputs in Intact Forest (d)	9	Proportion of total soil respiration (b)		Average (a)	27
Cropland and Shrubland	Average (a)	10, 7	Average (a)	10, 11	Proportion of total soil respiration (b)		Average (a)	22, 24, 25, 26, 28
Rice	Average (a)	12, 13	Average (a)	12, 13	Proportion of total soil respiration (b)		Average (a)	22, 23
Oil palm plantation	Review (e)	14	Average (a)	15, 14	(Total respiration - root respiration) (f)	15	Average (a)	28
Acacia plantation	Average (a)	16, 17, 18, 19, 20, 21	Estimate (g)	21	Average (a)	29		

Method: (a) Average value calculated from data available in literature, (b) Proportion of total soil respiration that can be allocated to heterotrophic respiration, applied to mean total soil respiration assessed in Hergoualc'h and Verchot (2011), (c) Proportion of C inputs from litterfall in the virgin peat swamp forest, (d) Proportion of C inputs from root mortality in the virgin peat swamp forest (Figure 2), (e) Data from literature review, (f) Difference between total respiration assessed in Hergoualc'h and Verchot (2011) and mean root respiration from data available in the literature, (g) Estimate found in the literature.

Sources: 1, Brady (1997); 2, Rahajoe *et al.* (2000); 3, Sulistiyanto (2004); 4, Chimner and Ewel (2005); 5, Shimamura and Momose (2005); 6, Harrison *et al.* (2007); 7, Chimner and Ewel (2004); 8, Ishida *et al.* (2001); 9, Hertel *et al.* (2009); 10, Hairiah *et al.* (2000); 11, database of Gill and Jackson (2000); 12, Hairiah *et al.* (1999); 13, Matthews *et al.* (2000); 14, Lamade and Bouillet (2005); 15, Henson and Dolmat (2003); 16, Tsai (1988); 17, Bernhard-Reversat *et al.* (1993); 18, Ihwanudin (1994); 19, Pudjiharta (1995); 20, Mindawati (2000); 21, Laclau *et al.* (2008); 22, Furukawa *et al.* (2005); 23, Hadi *et al.* (2005); 24, Hirano *et al.* (2008); 25, Inubushi *et al.* (1998); 26, Inubushi *et al.*(2003); 27, Jauhiainen *et al.* (2008); 28, Melling *et al.* (2005)

Inputs

In virgin peat swamp forests, annual root mortality was assumed to equal annual root production, which is a reasonable assumption for understanding short-term soil C dynamics (*Hertel et al.*, 2009). The average C input from fine root production was calculated using the values obtained in the literature (Table 2). This table also includes the litterfall rates and total inputs to the peat.

Because there are no published litterfall and root mortality rates in logged and fire-damaged peat swamp forests, we used relationships obtained from measurements in mineral soils. From the results of Hertel *et al.* (2009), we established relationships between the remaining biomass in the forest after disturbance and C inputs from: 1) litterfall; and 2) root mortality in logged and fire-damaged forests, expressed as a percentage of C inputs from litterfall and root mortality, respectively, in the virgin peat swamp forest. We applied to these relationships the percentage of remaining phytomass after logging and fire.

TABLE 2A.2
INPUTS TO THE SOC POOL IN TROPICAL PEAT SOILS FOR DIFFERENT LAND-USE CATEGORIES (MG HA^{-1} Y^{-1}).

Land Use	Litterfall	SE	Roots	SE	Total C inputs	SE
Intact forest	7.4	0.7	1.5	0.8	8.9	1.1
Degraded forest (burned/logged)	4.3	2.2	0.8	0.7	5.1	2.3
Cropland & shrubland	2.4	0.6	1.9	0.8	4.2	1.0
Rice field	1.0	0.3	1.5	0.2	2.5	0.3
Oil palm plantation	1.5	0.1	3.6	1.1	5.0	1.1
Acacia plantation	5.1	0.3	6	n.d.	11.1	0.3

n.d. = no data available from which to make an estimate.

Outputs

Mean soil respiration rates and CH_4 fluxes were calculated for the different land use treatments from static or dynamic dark chamber measurements. There are very few data that separate the autotrophic soil respiration (R_a) from the heterotrophic soil respiration (R_h), but the few studies that exist suggest that R_h values in plantation crops are on the order of 70 ± 10% of total soil respiration (Jauainen *et al.*, 2011; Melling, 2007). For agricultural systems where only total soil respiration was measured, we calculated R_h using this coefficient (Table 2a.3). There are no measurements of R_h in intact swamp forest systems, but measurements in humid tropical forest systems suggest that 50% of total soil respiration would be a reasonable approximation for R_h for intact forest systems. (Mahli and Grace, 2000; Chambers *et al.*, 2004). Because intact forest systems have much higher root biomass than plantation crop systems (Persch et al, in prep), we use this value to estimate Rh for undisturbed forest systems.

Waterborne C loss included dissolved organic carbon (DOC) and particulate organic carbon (POC). DOC export from temperate and boreal peatlands ranges between 10 and 500 kg DOC ha^{-1} y^{-1}, which represents about 10% of the C released (*Holden*, 2005). POC loss rates are similar to DOC release in northern peatlands and range from 20 to 400 kg ha^{-1} y^{-1}. There are no estimates in the tropics; however, some recent studies (*Yoshioka et al.*, 2002; *Yule and Gomez*, 2009) measured DOC concentrations in tropical virgin peat swamp forests (50-124 mg C l^{-1}) that were about twice those in northern peatlands (20-60 mg C L^{-1}, (*Holden*, 2005)). DOC concentrations in the rivers draining tropical virgin peat swamp forests were also high (6-31 mg C L^{-1}) (*Yoshioka et al.*, 2002; *Baum et al.*, 2007). Therefore, we assumed a loss from soluble and physical removal of 1 ± 0.5 Mg C ha^{-1} y^{-1} for all land uses, using the combined maxima of what was observed in northern peatlands for POC and DOC. We do not account for the fate of this carbon, and while we know that there is some downstream sequestration of DOC and POC. This assumption is consistent with assumptions elsewhere in Tier 1 methods (e.g. HWP).

TABLE 2A.3
OUTPUTS FROM THE SOC POOL IN TROPICAL PEAT SOILS FOR DIFFERENT LAND-USE CATEGORIES ($Mg\ ha^{-1}\ y^{-1}$)

Land use	R_h	SE	POC & DOC	SE	CH4	SE	Total C outputs	SE
Forest	6.9	2.2	1.0	0.5	0.03	0.01	7.9	1.4
Degraded forest (burned/logged)	6.4	1.4	1.0	0.5	0.00	0.00	7.4	1.5
Cropland & shrubland	12.3	2.2	1.0	0.5	0.02	0.01	13.3	2.3
Rice field	9.9	3.3	1.0	0.5	0.16	0.08	11.1	3.3
Oil palm plantation	9.3	2.7	1.0	0.5	0.00	0.00	10.3	2.8
Acacia plantation	21.8	4.7	1.0	0.5	n.d.	n.d.	22.8	4.7

n.d. = no data available from which to make an estimate.

Calculation of $EF_{\Delta SOM}$

The $EF_{\Delta SOM}$ was simply taken as the difference between annual inputs and outputs to the SOC pool. Negative values indicate net losses from the SOC pool; positive values signify net sequestration. Uncertainty estimates are reported as standard errors. In all calculations, the Gaussian error propagation method was used for propagating uncertainties. This method is adequate for step-by-step calculations that are intended to compute ecological quantities that can be expressed as an analytical equation using addition, subtraction, multiplication and division, such as C stocks or fluxes (Lo, 2005). The method assumes that uncertainties can be considered to be independent and normally distributed (Malhi *et al.*, 2009). For addition and subtraction, uncertainties are propagated by quadrature of absolute errors; for multiplication and division, propagation is by quadrature of relative error (Malhi *et al.*, 2009).

Tier 1 emission factors for tropical wetlands that are to be used in Equation 2.26 of the 2006 IPCC GL are presented in Table 2a.4 along with indications of which sections of the GL that they update. These factors may also be used in the application of Equation 2.26 in other sections of these guidelines where new methods for freshwater wetland systems have been developed.

TABLE 2A.4
TIER 1 EMISSION FACTORS AND UNCERTAINTY ESTIMATES

Land Use	$EF_{\Delta SOC}$ ($Mg\ C\ ha^{-1}\ y^{-1}$)	SE
Intact forest	1.00	2.52
Degraded forest (burned/logged)	-2.31	2.76
Cropland & shrubland	-9.11	2.47
Rice field	-8.56	3.32
Oil Palm	-5.24	2.99
Acacia plantation	-11.67	4.74

Negative values indicate net losses from the SOC pool; positive values signify net sequestration.

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