CHAPTER 3

CROSS-CUTTING GUIDANCE ON REWETTED ORGANIC SOILS AND RESTORED PEATLANDS

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3.1 INTRODUCTION

What is rewetting, restoration, rehabilitation and how they affect GHG

For the purpose of this chapter, rewetting, restoration and rehabilitation are understood as follows:

Wetlands are lands characterised by water saturation of the soil dominating hydrological and biogeochemical processes. Rewetting is the deliberate action of raising the water table on drained land to re-establish such saturated conditions, e.g. by blocking drainage ditches or disabling pumping facilities.

Rewetting may be accompanied by restoration, which is the permanent re-establishment of hydrological and biogeochemical processes characteristics of saturated soils, as well as of the vegetation cover that pre-dated the disturbance of these areas (FAO 2005, Nellemann & Corcoran 2010). Re-establishing the vegetation cover on rewetted soils is necessary to reinstate the ecosystem sink functions that ultimately lead to soil C sequestration. Although restoration, e.g. of vegetation cover, may take place on undrained sites, in the majority of cases restoration is accompanied by rewetting.

While the focus of this chapter is on rewetted peatlands and organic soils, restoration and wet management practices on undrained organic soils are also considered but no default guidance is provided.

Rehabilitation or reclamation is the re-establishment, on formerly drained sites, of some of – but not necessarily all - the hydrological, biogeochemical and ecological processes and functions that characterized pre-drainage conditions. As such, rehabilitation can involve a large variety of practices on formerly drained peatlands or organic soils, which may or may not include rewetting. Rehabilitation as an activity separate from rewetting (with or without restoration) is not covered by this chapter (FAO 2005, Nellemann & Corcoran 2010).

The biogeochemical processes responsible for GHG fluxes from wetlands are controlled by water level position (Reddy & DeLaune 2008, pages 162-163); therefore rewetting leads to changes in GHG fluxes from peatlands and organic soils. Generally rewetting decreases CO_2 emissions compared to the drained state, and under certain conditions leads to the recovery of a CO_2 sink function (Komulainen et al., 1999, Tuittila et al., 1999, Waddington et al., 2010). After a vegetation succession promoted by rewetting, CO_2 sink may reach the level typical of undrained wetlands. However, during the first years after restoration the ecosystem sink can be significantly larger (Soini et al., 2010, Wilson et al., 2012).

Rewetting generally increases CH_4 emissions (e.g. Augustin & Chojnicki 2008, Waddington & Day 2007), although in some cases lower emissions have been measured (Tuittila et al., 2000, Juottonen et al., 2012) compared to the drained state. Everything else (vegetation composition, site fertility) being equal, generally CH_4 emissions from rewetted sites are comparable to undrained sites. N_2O emissions in turn rapidly decrease close to zero after rewetting (Augustin et al., 1998; Wilson et al., in press).

Scope of this guidance: wetland types covered, gases, pools, relevant classifiers

The guidance provided in this chapter will include rewetting and restoration of wetlands on peat or organic soils, with a focus on the soil pool. Peatlands and organic soils can also support perennial woody vegetation. To avoid repeating guidance already provided, wherever appropriate the reader will be referred to existing guidance in the *2006 IPCC Guidelines*, especially on C stock changes in the woody biomass and dead wood pools.

Contrary to most ecosystems, the distinction between C pools in some peatlands can be difficult, especially between the herbaceous biomass (mosses, sedges, grasses), the dead organic matter derived from this biomass and soil pools. For example, the dead portion of mosses characteristic of many peatlands could be included in the dead organic matter or soil pool. This ecosystem component cannot be ignored as it is essential in the restoration of the ecosystem sink function that in turn results in the sequestration over time of very large quantities of carbon. Because the default emission factors in this chapter were all derived from flux measurements over peatlands or organic soils with moss and/or herbaceous vegetation, these default EFs integrate all C fluxes from the soil and these non-woody vegetation components. In all cases the guidance in this chapter will clarify which C pools are included in default EFs.

In this chapter boreal and temperate peatlands are divided into nutrient poor and nutrient rich peatlands (Rydin & Jeglum 2006). Most nutrient poor peatlands, whether undrained or rewetted, receive water and nutrients mainly from precipitation, while nutrient rich peatlands are generally also fed by water from the surrounding or underlying mineral soil.

Tropical peatlands include a great variety of different peatland ecosystems, from papyrus dominated sites in Africa to peat swamp forests in South East Asia. In general much less information is available for tropical peatlands than for temperate or boreal ones.

Rewetting activities in (sub-)tropical regions have been reported from the USA, South Africa and Indonesia (Schumann & Joosten 2008). Southeast Asia harbours the largest extent of tropical peatlands (Page et al., 2011) and several attempts at large scale rewetting have been undertaken here. Although successful rewetting of peatlands or organic soils in (sub-)tropical regions has been demonstrated, flux data from such sites are lacking. Tropical peatland restoration is still in its infancy, and basic information is lacking on restoration practices and outcome. Therefore, a default EF for rewetted tropical organic soils or peatlands was developed based on a conceptual approach. No default EF could be developed for restored tropical peatlands; flux values from undrained (pristine) peatlands were compiled for limited sites in Southeast Asia and Latin America and are provided in Appendix 3.1. It is *good practice*, where significant areas of tropical or sub-tropical peatlands or organic soils have been rewetted or restored, to develop science-based, documented, country-specific emission factors for CO_2, CH_4 and N_2O emissions.

Generally the likelihood of fire occurrence in rewetted ecosystems is low. There continues to be insufficient scientific evidence to support the development of default factors for the emission of any greenhouse gas specifically due to soil burning. The conceptual approach provided in this chapter identifies soil burning as an emission source for all greenhouse gases. Guidance recommends developing domestic emission factors where soil burning is a non-negligible source of emissions.

In keeping with its focus, this chapter will provide generic guidance for higher tiered methodology on undrained inland organic soils, peatlands undergoing wet management or restoration not necessitating rewetting.

How to use guidance in this chapter and relationship to reporting categories

Depending on circumstances and practices, rewetting and restoration may or may not involve a change in land use. Hence pre- and post-rewetting land use of peatlands and organic soils can vary according to national circumstances, and be reported under forest land, cropland, grassland or wetlands. It is recommended to consider this guidance as common to all reporting categories. In particular, the guidance in this chapter does not recommend or involve specific transition periods; countries can apply the existing transition period of appropriate land use categories to rewetted peatlands or organic soils. Because the functioning of these ecosystems has already been deeply altered, reporting rewetted peatlands or organic soils as unmanaged land is not consistent with *good practice*.

In this chapter, unlike in drained peatlands of Chapter 2, former ditches are included as a part of rewetted sites and not treated separately. High spatial variation in microtopography, water level and consequently in GHG fluxes is typical to pristine peatlands (Strack et al., 2006, Laine et al., 2007, Riutta et al., 2007, Maanavilja et al., 2011). In rewetting this heterogeneity is recreated; in rewetted sites blocked ditches form the wetter end of the variation (Strack & Zuback 2012, Maanavilja et al., submitted).

3.2 GREENHOUSE GAS EMISSIONS AND REMOVALS FROM REWETTED PEATLANDS AND ORGANIC SOILS

Equation 2.3 in Chapter 2, Volume 4 of the *2006 IPCC Guidelines* illustrates how emissions and removals of carbon-containing GHGs from an ecosystem can be calculated from the sum of C stock changes in each of the ecosystem carbon pools. This chapter provides additional guidance specifically on the soil pool – term ΔC_{so} of equation 2.3 - in particular for organic soils or peat soils. When rewetting of organic soils or peatland restoration practices also involve C stock changes in woody biomass or DOM pools, the appropriate default assumptions will be provided along with references to existing equations in the *2006 IPCC Guidelines* for the Tier 1 estimation of C stock changes for these pools.

With respect to the soil pool, this chapter elaborates on the estimations of CO_2 emissions or removals and CH_4 emissions from organic or peat soils, which can occur simultaneously on rewetted organic soils or restored peatlands, and be of comparable magnitude.

In the context of this chapter, equation 3.1 below replaces equations 2.24 and 2.26 in Chapter 2, Volume 4 of the *2006 IPCC Guidelines*; equations 2.24 and 2.26 implicitly assumed that organic soils can only lose carbon, while in fact restored peatlands can accumulate soil organic carbon, as exemplified with the very large C stocks in existing organic or peat soils. Equation 3.1 reflects the fact that the net C stock change of rewetted organic (or peat) soils results from net gains (or losses) of C resulting from the balance between CO_2 and CH_4 emissions and removals.

In large carbon pools such as organic or peat soils, net CO_2 emissions or removals are more accurately measured directly as a CO_2 flux (an emission is a positive flux, a removal a negative flux), as opposed to being derived from a change in C stocks. Likewise, CH_4 emissions are generally measured as fluxes. In this chapter these fluxes are denoted CO_2-C and CH_4-C, for the net C flux as CO_2 and as CH_4 respectively. This notation is consistent with that used in Chapter 7, Volume 4 of the *2006 IPCC Guidelines*. From here on equations will generally use the form flux = activity data x emission factor.

EQUATION 3.1

NET C FLUX FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$\Delta C_{\text{rewetted org soil}} = CO_2\text{-}C_{\text{rewetted org soil}} + CH_4\text{-}C_{\text{rewetted org soil}}$$

Where:

$\Delta C_{\text{rewetted org soil}}$ = net C flux to or from rewetted organic or peat soils (tonnes C yr^{-1})

CO2-$C_{\text{rewetted org soil}}$ = net flux of CO_2 -C (emissions or removals) from the rewetted organic or peat soil (tonnes C yr^{-1})

CH_4-$C_{\text{rewetted org soil}}$ = net flux of CH_4 -C (commonly emissions) from the rewetted organic or peat soil (tonnes C yr^{-1})

3.2.1 CO_2 Emissions and Removals by Rewetted Peatlands and Organic Soils

CO_2-C emissions/removals by rewetted peatlands and organic soils have the following components:

EQUATION 3.2

CO_2-C EMISSIONS/REMOVALS BY REWETTED PEATLANDS AND ORGANIC SOILS

$$CO_2\text{-}C_{\text{rewetted org soil}} = CO_2\text{-}C_{\text{composite}} + CO_2\text{-}C_{\text{DOC}} + CO_2\text{-}C_{\text{soil burn}}$$

Where:

CO_2-$C_{\text{rewetted org soil}}$ = CO_2-C emissions/removals by rewetted peatlands and organic soils, tonnes C yr^{-1}

CO_2- $C_{\text{composite}}$ = CO_2-C emissions/removals from the soil and non-woody vegetation tonnes C yr^{-1}

CO_2-C_{DOC} = CO_2-C emissions from dissolved organic carbon exported from rewetted peatlands or organic soils, tonnes C yr^{-1}

CO_2-C_{soilburn} = CO_2-C emissions from soil or peat burning on rewetted peatlands or organic soils, tonnes C yr^{-1}

On-site CO_2 emissions/removals

Since the default CO_2-C EFs in this chapter are all derived from flux measurements (see Annex 3A.1), the CO_2-$C_{\text{composite}}$ results from the net flux, emissions or removals, from the soil and non-woody vegetation taken together . CO_2 emissions are produced during the decomposition of the peat/soil by heterotrophic organisms and are strongly controlled by oxygen availability within the soil and by soil temperature. The contribution from non-woody vegetation occurs via the two processes of photosynthesis (CO_2 uptake) and autotrophic respiration (CO_2 emissions).

Consistent with the *2006 IPCC Guidelines*, the Tier 1 or default approaches assume that the woody biomass and DOM stocks and fluxes are zero on all lands except on forest land and on cropland with perennial woody biomass. But for these exceptions, rewetting organic soils or peatlands with no land-use change do not involve changes in woody biomass and DOM C. For rewetting or restoration on forest land or on cropland with woody crops, the woody biomass and DOM pools pool are potentially significant and should be estimated in a way consistent with the guidance provided in Chapters 2 (generic methods), 4 (Forest Land) and 5 (Cropland) in Volume 4 of the *2006 IPCC Guidelines*. Inventory compilers are directed to equations 2.7 and 2.8 and the subsequent equations in that chapter which decompose C stock changes in the biomass pool or ΔC_B into the various gains and losses components, including harvest and fires.

If re-wetting is accompanied by a change in land use that involves forests or cropland with perennial woody biomass, changes in C stocks in biomass and dead wood and litter pools are equal to the difference in C stocks in the old and new land-use categories (see Eq. 2.19, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*). These changes occur in the year of the conversion (carbon losses), or are uniformly distributed over the length of the transition period (carbon gains). Default values for C stocks in forest litter can be found in Chapter 4 (Forest biomass), Chapter 5 (Cropland) and Chapter 2 (Table 2.2 for forest litter) in Volume 4, of the *2006 IPCC Guidelines*.

Emissions from burning

While the likelihood of fires on rewetted peatlands and organic soils is considered low (particularly in comparison to drained peatlands and organic soils), fire risk may still be considerable. Any emissions from the burning of biomass, dead organic matter as well as soil or peat ($CO2\text{-}C_{soilburn}$) should be included. Generic methodologies for estimating CO2 emissions from the burning of vegetation and dead organic matter are provided in Chapter 2, Volume 4 of the *2006 IPCC Guidelines*, while methodologies specific to vegetation and DOM burning in Forest Land, Cropland, Grassland and Wetlands are provided in Chapters 3-6 in Volume 4 of the *2006 IPCC Guidelines*. Emissions from the burning of soil or peat should be estimated using country-specific emission factors.

Off-site CO_2 emissions: $CO_2\text{-}C_{DOC}$

$CO_2\text{-}C_{DOC}$ is produced from the decomposition of dissolved organic carbon (DOC) lost from the peatland via aquatic pathways. In all types of peatlands and organic soils, including rewetted ones, DOC has been shown to be the largest component of waterborne carbon loss, that will be processed and almost entirely returned eventually to the atmosphere. There is some evidence to suggest that rewetting will return DOC fluxes to natural levels (e.g. Glatzel *et al.,* 2003, Wallage *et al.,* 2006, Waddington *et al.,* 2008). The importance of fluvial C export as a pathway linking the peatland C pool to the atmosphere is described in Chapter 2 and the various sources, behaviour and ultimate fate of the different forms of fluvial C following rewetting can be found in Annex 3.A2.

CHOICE OF METHOD

The decision tree in Figure 3.1 presents guidance in the selection of the appropriate Tier for the estimation of greenhouse gas emissions/removals from rewetted peatlands and organic soils.

Tier 1

Under Tier 1, the basic methodology for estimating annual C emissions/removals from rewetted peatlands and organic soils was presented in Equation 3.2 and can be compiled using Equations 3.3 and 3.4 where the nationally derived area of rewetted peatlands and organic soils is multiplied by an emission factor, which is disaggregated by climate region and where applicable by peatland nutrient status.

For temperate and boreal organic soils or peatlands, the basic approach makes no distinction between rewetted and restored sites and therefore the term ‘rewetted peatlands and organic soils’ is used throughout the default methodology to encompass both activities.

In addition, the basic methodology is based on the assumption of no transient period for rewetted peatlands and organic soils.

EQUATION 3.3

ANNUAL ON-SITE CO_2-C EMISSIONS/REMOVALS FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$CO_2\text{-}C_{composite} = \sum_{c,p} \left[A \cdot EF_{CO_2} \right]_{c,p}$$

Where:

$CO_2\text{-}C_{composite}$ = CO_2-C emissions/removals from rewetted peatlands and organic soils, tonnes C yr^{-1}

A= land area of rewetted peatlands and organic soils in climate region *c*, peatland nutrient status *p*, ha

EF_{CO2} = CO_2-C emission factor for rewetted peatlands and organic soils in climate region *c*, peatland nutrient status *p,* tonnes C ha^{-1} yr^{-1}

EQUATION 3.4
ANNUAL CO_2-C EMISSIONS DUE TO DOC EXPORT FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$CO_2\text{-}C_{DOC} = \sum_c \left[A \cdot EF_{DOC\_rewetted}\right]_c$$

Where:

CO_2-C_{DOC} = CO_2-C emissions from DOC from rewetted peatlands and organic soils, tonnes C yr^{-1}

A= land area of rewetted peatlands and organic soils in climate region *c*, ha

$EF_{DOC\_rewetted}$ = CO_2-C emission factor from DOC, for rewetted peatlands and organic soils in climate region *c*, tonnes C ha^{-1} yr^{-1}

Tier 2

Tier 2 calculations use country-specific emission factors and parameters, spatially disaggregated to reflect regionally important practices and dominant ecological dynamics. It may be appropriate to sub-divide activity data and emission factors according to the present vegetation composition (Couwenberg *et al.*, 2011) or by land use prior to rewetting (e.g. forest, grassland, cropland, peatland).

Available datasets from rewetted peatlands and organic soils generally cover a period of 10 years or less after rewetting; for this reason it is difficult to identify clear temporal patterns in CO_2 fluxes. Available data demonstrate that the strength of the CO_2 sink may vary over a number of years. In the period immediately following rewetting, it is expected that peat oxidation rates are low as a consequence of the anoxic soil conditions, while most of the C sequestered is contained within the non-woody biomass pool (leaves, stems, roots). Over longer time frames (a few decades) a decrease in the amount of CO_2 that is sequestered annually might be expected (cf. Tuittila *et al.*, 1999, Yli-Petäys *et al.*, 2007, Soini *et al.*, 2010) as the peatland biomass pool eventually approaches a steady state C sequestration saturation point (Anderson *et al.*, 2008) typical of natural, undrained peatlands. Countries are encouraged to develop more detailed EFs for rewetted peatlands and organic soils that capture fully the transient nature of CO_2 fluxes in the time since rewetting and reflect the time needed for the ecosystem to reach CO_2 dynamics typical of natural, undrained peatlands.

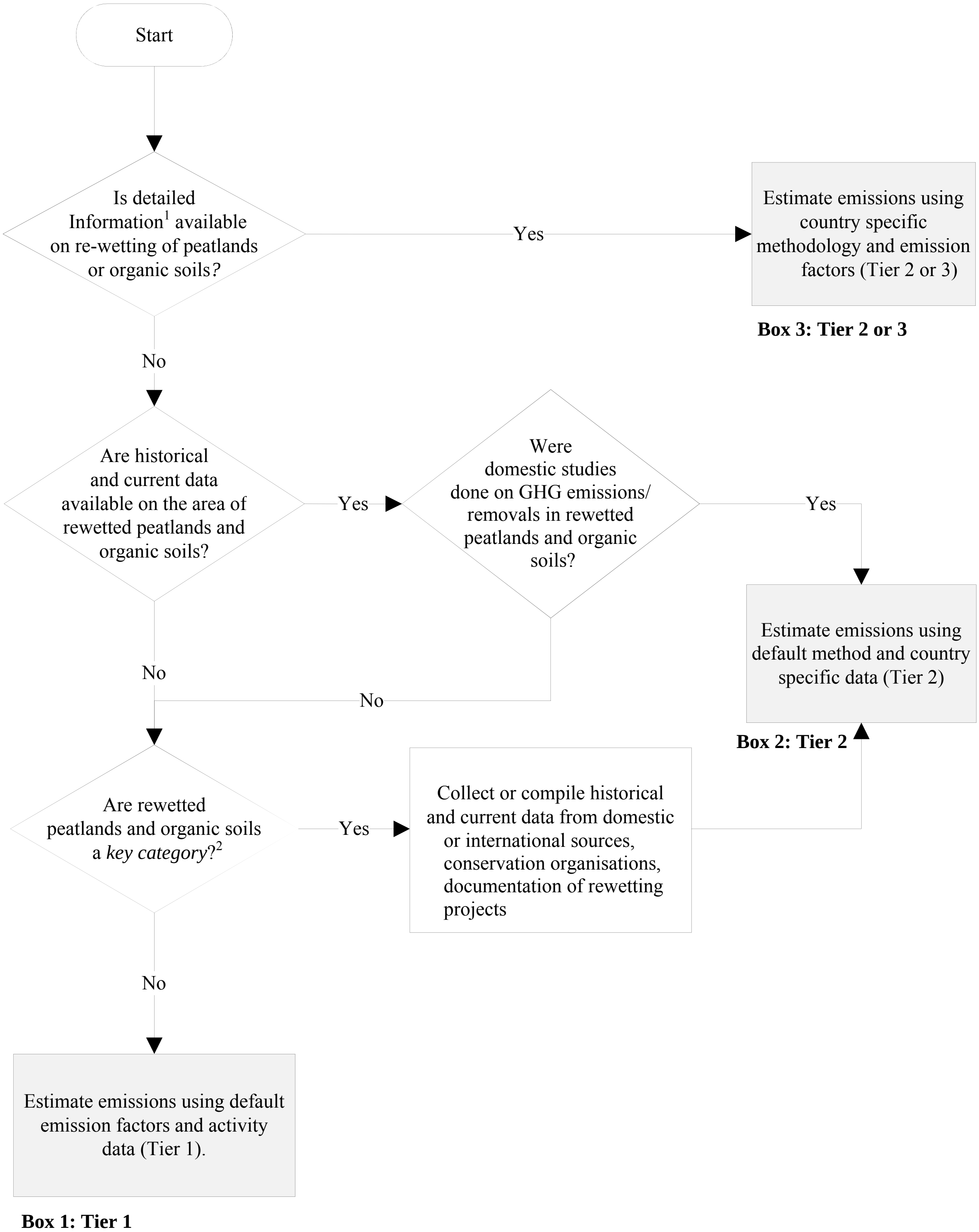
Higher tier approaches may address changes in the woody biomass pool as fluxes instead of stock changes and integrate the woody biomass component with the other components of Equation 3.2. However, it is *good practice* to ensure that double counting does not take place in regard to the woody biomass and DOM pools on rewetted peatlands and organic soils. Data collection using eddy covariance techniques (EC tower) and chamber measurements are adequate at higher tiers; however when CO_2 flux data have been collected with such techniques the C stock changes in perennial woody biomass and woody DOM may already be included and should not be added a second time.

A Tier 2 approach to derive an estimation of emissions from the decomposition of DOC should utilise country-specific information if experimental data is available to refine the emission factor, especially with regard to various peatland types (e.g. raised bogs, blanket bogs, fens) under different precipitation regimes. Refined approaches to calculate EF_{DOC} are suggested below under Choice of EF/ EF $_{DOC\_REWETTED}$ /Tier 2&3. On-site flux measurements will not capture C losses as DOC so these losses should be estimated and added to the C balance. However if a stock difference method (such as soil subsidence) is used to derive CO2-$C_{composite}$ of equation 3.2, DOC losses are included in the subsidence data and should not be added a second time.

Tier 3

A Tier 3 approach involves a comprehensive understanding and representation of the dynamics of CO_2-C emissions and removals on rewetted peatlands and organic soils, including the effect of site characteristics, peat type and depth, vegetation composition, soil temperature and mean water table depth. These could be integrated into a dynamic, mechanistic-based model or through a measurement-based approach (see choice of EF, Tier 3 below). These parameters could also be used to describe fluvial C (DOC) lost from the system using process-based models. A Tier 3 approach might also include the entire DOC export from rewetted sites and consideration of the temporal variability in DOC release in the years following rewetting, which will also be dependent on the rewetting or restoration techniques used.

Figure 3.1 Decision tree to estimate CO_2-C and CH_4-C emissions/removals from rewetted peatlands and organic soils.



Note:

1. Detailed information typically includes national area of rewetted peatlands and organic soils disaggregated by ecosystem with associated emission factors at high resolution.

2. A key source/sink category is defined in Chapter 4, Volume 1 of the *2006 IPCC Guidelines*, "as *one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals*". The *2006 IPCC Guidelines* recommend that the key category analysis is performed at the level land remaining in or converted to a land-use category. If CO_2 or CH_4 emissions/remvoals from rewetted peatlands and organic soils are subcategories to a key category,

these subcategories should be considered as significant if they individually accounts for 25-30% of emissions/removals for the overall key category (see Figures 1.2 and 1.3 in Chapter 1, Volume 4 of the *2006 IPCC Guidelines*.)

CHOICE OF EMISSION FACTORS

EF_{CO2}

Tier 1

The implementation of the Tier 1 method requires the application of default EFs provided in Table 3.1, where they are disaggregated by climate region (boreal, temperate, tropical) and for boreal and temperate peatlands by nutrient status (nutrient poor, nutrient rich).

Nutrient poor peatlands predominate in boreal regions, while in temperate regions nutrient-rich peatlands are more common. Some ombrotrophic bogs (nutrient poor) are underlain by minerotrophic peat layers; after industrial peat extraction and subsequent rewetting, these peatlands could be considered nutrient-rich peatland due to the influence of incoming water and the high nutrient status of the bottom peat.

If it is not possible to stratify by peatland nutrient status, countries should use the EF for climate region (Table 3.1). Countries with significant areas of rewetted peatlands and organic soils are encouraged to develop domestic emission factors and develop estimates of emissions and/or removals using Tier 2 or 3 methodologies.

The derivation of the default EF values for CO_2 is fully described in Annex 3A.1, including the quality criteria for data selection. In summary, robust data indicated that CO_2 fluxes from both natural/undrained peatlands and rewetted peatlands are correlated with mean water table depth. Furthermore, it was ascertained that, in temperate and boreal regions, these correlations were not significantly different between the natural/undrained peatland group and the rewetted peatlands/organic soils group. These conclusions were also valid when the analysis was performed for peatlands under each of these climatic regions. Therefore in these regions CO_2 fluxes from natural/undrained sites were used in addition to CO_2 fluxes from rewetted sites to provide a robust estimation of the EFs shown in Table 3.1.

Since no data are available for rewetted or restored tropical peatlands, a default EF of zero is provided; this value reflects the fact that successful rewetting effectively stops the oxidation of soil organic material, but does not necessarily reestablish a soil C sequestration function. No assumption was made regarding the GHG balance of restored tropical peatlands; provisional guidance is available in Appendix 3.1.

TABLE 3.1
DEFAULT EMISSION FACTORS (EF_{CO2}) AND ASSOCIATED UNCERTAINTY, FOR CO_2-C BY REWETTED PEATLANDS AND ORGANIC SOILS (ALL VALUES IN TONNES CO_2-C HA^{-1} YR^{-1}).

Climate zone	EF_{CO2}	95% range*	Peatland type	EF_{CO2}	95% range
Boreal	-0.49 (n= 64)	-0.65 – -0.32	Nutrient poor	-0.34 (n=26)	-0.59 – -0.09
			Nutrient rich	-0.59 (n=38)	-0.80 – -0.38
Temperate	-0.15 (n=43)	-0.62 – +0.31	Nutrient poor	-0.26 (n=32)	-0.64 – +0.13
			Nutrient rich	+0.15 (n=11)	-1.26 – +1.56
Tropical**	0				

Note: Negative values indicate removal of CO_2-C from the atmosphere.

*95% confidence interval

**for fully rewetted tropical peatlands not allowing organic materials to be oxidized

Source:

Emission factors derived from the following source material: Shurpali et al. 1995, Alm et al. 1997, Laine et al. 1997, Suyker et al. 1997, Bubier et al. 1999, Komulainen et al. 1999, Soegaard & Nordstroem 1999, Tuittila et al. 1999, Waddington & Price 2000, Waddington & Roulet 2000, Lafleur et al. 2001, Whiting & Chanton 2001, Wickland 2001, Aurela et al. 2002, Heikkinen et al. 2002, Schulze et al. 2002, Waddington et al. 2002, Harazono et al. 2003, Nykänen et al. 2003, Roehm & Roulet 2003, Billett et al. 2004, Drösler 2005, Nagata et al. 2005, Bortoluzzi et al. 2006, Hendriks et al. 2007, Jacobs et al. 2007, Lund et al. 2007, Riutta et al. 2007, Roulet et al. 2007, Wilson et al. 2007, Yli-Petäys et al. 2007, Augustin & Chojnicki 2008, Cagampan & Waddington 2008, Kivimäki et al. 2008, Nilsson et al. 2008, Sagerfors et al. 2008, Aurela et al. 2009, Golovatskaya & Dyukarev 2009, Kurbatova et al. 2009, Drewer et al. 2010, Soini et al. 2010, Waddington et al. 2010, Adkinson et al. 2011, Couwenberg et al. 2011, Koehler et al. 2011, Maanavilja et al 2011, Christensen et al 2012, Urbanová 2012, Strack & Zuback 2012, Wilson et al. 2012, Herbst et al. 2013.

Given the limitations in the available scientific literature, the Tier 1 basic methodology assumes that there is no *transient period* and that restored peatlands and organic soils in the temperate and boreal regions behave like undrained/natural peatlands in terms of CO_2 flux dynamics. Combining observations from early in the restoration process with long-term ones was the simplest way to avoid any bias.

While there may be still considerable uncertainty around each datapoint used in the derivation of the EFs, the 95% confidence interval values presented in Table 3.1 mainly reflects the spatial variation reported in CO_2 fluxes from the various study sites (inter-annual variation has been reduced by using the mean of multi-year datasets from the same site).

Nutrient rich peatlands generally display a wider range of flux values than nutrient-poor peatlands . This can be explained by the diversity of nutrient rich peatlands, especially across the temperate zone. For example, plant associations in rich fens are diverse, commonly dominated by brown mosses although sedges can be abundant in fens of intermediate fertility. The majority of the nutrient rich peatlands used in the calculation of the EF for the boreal zone are sedge rich fens which are known to be highly productive ecosystems (Bellisario et al., 1998, Alm et al., 1997, Bubier et al., 1999, Yli-Petays et al., 2007).

Meanwhile, short term studies have suggested that natural temperate nutrient rich peatlands in the temperate zone are currently carbon sources, although this is clearly inconsistent with the fact that they hold large, long-term stores of carbon. Considerable uncertainty is attached to such individual data used in the derivation of the default EF, not taking into account the long-term natural variation. It should be re-affirmed that over longer time-scales, natural and successfully rewetted/restored nutrient rich peatland (i.e with peat-forming vegetation) are likely to be a CO_2 sink.

By contrast, nutrient poor peatlands displayed less variation in CO_2 fluxes across both boreal and temperate zones; the associated default EFs suggest that they are net long-term sinks for atmospheric CO_2, comfirming that natural/undrained and rewetted/restored nutrient poor peatlands play as important a role in the contemporary global C cycle as they have in the past.

The default EF of tropical peatlands applies to fully rewetted sites, where the high water table prevents further oxidation of the soil organic matter or peat. The lack of published scientific evidence on CO_2 fluxes from restored tropical peatlands prevented any comparative analysis with measurements made over undrained tropical peatlands. Hence it was not possible to draw conclusions and develop a default emission factor on the carbon balance of restored tropical peatlands. Where significant areas of such peatlands occur, it is *good practice* to use country-specific EFs as opposed to the default one of Table 3.1. Preliminary data on the CO_2 balance of undrained tropical peatlands are tabulated in Appendix 3.1.

Tier 2 and 3

Countries applying Tier 2 methods can increase the accuracy of results by using country specific emission factors. Empirical flux measurements (eddy covariance or chamber methods) should be carried out at temporal resolutions sufficiently defined to capture as wide a range as possible of the abiotic (e.g. irradiation, soil temperature, water table depth) and biotic (e.g. vegetation composition) factors that drive CO_2 dynamics in rewetted peatlands and organic soils. Emission factors could be developed taking into account other factors, such as 'land-use prior to rewetting' or current vegetation composition as well as disaggregation by 'time since rewetting'.

Countries where perennial woody biomass plays a significant role in the net CO_2-C exchange between rewetted peatlands or organic soils and the atmosphere should develop country-specific EFs that reflect C stock changes in the CO_2-$C_{woody\_biomass}$ and CO_2-C_{woody_DOM} pools under typical management practices and their interaction with the soil pool. Guidance can be found in Chapter 3, Volume 4 of the *2006 IPCC Guidelines*.

Tier 3 methods involve a comprehensive understanding and representation of the dynamics of CO_2 emissions/removals in rewetted peatlands and organic soils, including the impacts of management practices. The methodology includes the fate of C in all pools and C transfers between pools upon conversion. In particular, the fate of the C contained within the biomass pool must also be taken into account, including its eventual release on-site through the decay of DOM, or off-site following harvest of woody biomass (e.g. paludiculture). Methodology should also distinguish between immediate and delayed emissions following rewetting. A Tier 3 approach could include the development of flux based monitoring systems and the use of advanced models (e.g. Holocene Peatland Model, ECOSSE, PEATLAND-VU) which require a higher level of information of processes than required in Tier 2 and it is *good practice* to ensure that the models are calibrated and validated against field measurements (Chapter 2, Volume 4, *2006 IPCC Guidelines*).

EF $_{DOC\text{-}rewetted}$

Tier 1

Robust data show that natural/undrained peatlands export some DOC and these fluxes increase following drainage (see Chapter 2). Available data from rewetted sites suggest that the level of DOC reduction after rewetting approximately equates to the DOC increase after drainage. Consequently, it is assumed that rewetting leads to a reversion to natural DOC flux levels (see Annex 3A.2). Therefore, to make best use of available data, EFs for rewetted peatlands and organic soils have been calculated using data from natural/undrained peatlands and following Equation 3.5:

EQUATION 3.5

EMISSION FACTOR FOR ANNUAL CO_2 EMISSIONS DUE TO DOC EXPORT FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$EF_{DOC\_REWETTED} = DOC_{FLUX\text{-}NATURAL} \cdot Frac_{DOC\text{-}CO_2}$$

Where:

$EF_{DOC\_REWETTED}$ = emission factor for DOC from rewetted peatlands or organic soils, tonnes C ha^{-1} yr^{-1}

$DOC_{FLUX\text{-}NATURAL}$ = Flux of DOC from natural (undrained) peatlands, tonnes C ha^{-1} yr^{-1}

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

$EF_{DOC\_REWETTED}$ values are provided in Table 3.2 and the derivation of these values is fully described in Annex 3A.2. The $DOC_{FLUX\text{-}NATURAL}$ values for temperate and boreal peatlands and organic soils were derived based on available data, grouped by broad precipitation class. Tropical peatland DOC fluxes are typically higher, and a separate EF value was calculated. The current data did not support the disaggregation by peatland nutrient status.

An understanding of the ultimate fate of DOC export, i.e. whether it is returned to the atmosphere as CO_2 (or even CH_4), is still poor and yet of significance in terms of GHG reporting. The parameter $Frac_{DOC\text{-}CO_2}$ sets the proportion of DOC exported from peatlands and organic soils which is ultimately emitted as CO_2. A value of zero would coincide with all the DOC export being deposited in stable forms in lake or marine sediments; as this would simply represent a translocation of carbon between stable stores, it would not need to be estimated. However, most data on DOC processing do indicate that a high proportion is converted to CO_2 in headwaters, rivers, lakes and coastal seas (see Annex 2A.2). Reflecting this current scientific uncertainty, a Tier 1 default $Frac_{DOC\text{-}CO_2}$ value of 0.9 is proposed, with an uncertainty range of 0.8 to 1.

TABLE 3.2

DEFAULT DOC EMISSION FACTORS ($EF_{DOC\_REWETTED}$ IN TONNES CO_2-C HA^{-1} YR^{-1}) FOR REWETTED PEATLANDS AND ORGANIC SOILS (VALUES IN PARENTHESES REPRESENT 95% CONFIDENCE INTERVALS)

Climate zone	Precipitation regime range (mm yr^{-1})	$DOC_{FLUX\text{-}NATURAL}$ (tonnes C ha^{-1} yr^{-1})	$EF_{DOC\_REWETTED}$ (tonnes CO_2-C ha^{-1} yr^{-1})
Temperate/boreal	Dry: < 600	0.05 (0.04 – 0.07)	0.05 (0.03 – 0.07)
	Intermediate: 600-1000	0.16 (0.12 – 0.21)	0.15 (0.09 – 0.21)
	Wet: > 1000	0.23 (0.17 – 0.29)	0.21 (0.14 – 0.29)
Tropical	All	0.57 (0.49 – 0.64)	0.51 (0.40 – 0.64)

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 as well as the conversion factor. Refinements could entail greater disaggregation as follows:

- Where precipitation measurements are available, $DOC_{FLUX\text{-}NATURAL}$ values for boreal/temperate raised bogs and fens may be calculated from the empirical equation (note that this equation is not applicable to blanket bogs, which do not show a clear change in DOC flux as a function of rainfall, see Annex 3A.2 for detailed analysis):

$$DOC_{FLUX\text{-}NATURAL} = (0.000317 \bullet Precipitation)^{a} - 0.075$$

[a] total precipitation (including snow) in mm yr^{-1} regardless of climatic zone

- Use of country-level measurements from natural and rewetted peatlands to obtain more accurate values of $DOC_{FLUX\text{-}NATURAL}$ for that country. Since DOC production has been observed to vary with different vegetation composition and productivity as well as soil temperature, it would be important to develop specific values for different peatland types (e.g. raised bogs and blanket bogs as well as poor, intermediate and rich fens), all under variable existing precipitation levels
- Use of country-level measurements from rewetted peatlands with various restoration techniques and initial status. Direct measurements of DOC fluxes from rewetted peats could replace the $DOC_{FLUX\text{-}NATURAL}$ values used in the Tier 1 default approach, i.e. replacing the default assumption that rewetted peatlands revert to pre-drainage DOC fluxes.
- Use of alternative values for the conversion factor $Frac_{DOC\text{-}CO_2}$ where evidence is available to estimate the proportion of DOC exported from rewetted peatlands and organic soils that is transferred to stable long-term carbon stores, such as lake or marine sediments.

Tier 3

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 rewetting and on-going management activity. Differences between pre-drainage and rewetted DOC fluxes could occur due to the presence or absence of vegetation on rewetted sites (Trinder et al., 2008); the land use category prior to rewetting; soil fertility; vegetation composition that differs from natural peatlands; , or factors associated with peat restoration techniques, such as the creation of pools the application of mulch to support vegetation re-establishment (Artz et al., 2008), or the use of biomass to infill ditches.

CHOICE OF ACTIVITY DATA

All Tiers require data on areas of rewetted peatlands or organic soils, broken down by climate zone, type of peatland or organic soils. This section clarifies data requirements and suggests several potential data sources.

Tier 1

The default methodology requires data on the area of rewetted peatlands or organic soils and the type of peatland or organic soils, consistent with the advice above on the selection of emission factors. Soil data can be obtained from domestic statistics and databases, spatial or not, on soils, land cover (in particular wetlands), land use and agricultural crops (for example specialty crops typically grown on organic soils); this information can be used to identify areas with significant coverage of organic soils and/or peatlands. Useful information on existing or planned activities may be available from the domestic peat extraction industry, regional or national forestry or agricultural agencies or conservation organisations. Agricultural, forestry or other type of government extension services may be able to provide specific information on common management practices on organic soils, for example for certain crop production, forest or plantation management or peat extraction.

Domestic data may also exist on water monitoring or management, including water management plans, areas where water level is regulated, floodplains or groundwater monitoring data. Such information could be available from government agencies involved in operation water management or the insurance industry, and be used in the determination of areas where the water level is naturally high, has been lowered or is managed for various purposes.

In addition to the above information sources, time series of remotely-sensed imagery (e.g. aerial photography, LIDAR etc.) can assist in the detection of rewetted and/or restored peatlands and in the determination of time since rewetting. Such imagery may be produce either by government research institutes, departments or agencies, by universities or by the private sector.

In the absence of domestic data on soils, it is recommended to consult the International Soil Reference and Information Centre (ISRIC; www.isric.org); inventory agencies should also investigate available documentation on rewetting or restoration projects with the International Peat Society (Commission V: Restoration, rehabilitation and after-use of peatlands, www.peatsociety.org), the International Mire Conservation Group (www.imcg.net) and the Verified Carbon Standard (v-c-s.org).

When information is gathered from a variety of sources, cross-checks should be made to ensure complete and consistent representation of land management practices and areas. For example, an area should not be counted twice if it is subject to several management practices over the course of a year. Rather, the combined effect of these practices should be estimated for a single area.

Tier 2

Tier 2 approach is likely to involve a more detailed spatial stratification than in Tier 1, and further sub-divisions based on time since rewetting, previous land use history, current land use and management practices as well as vegetation composition. It is *good practice* to further sub-divide default classes based on empirical data that demonstrates significant differences in CO_2-C fluxes among the proposed categories. At Tier 2, higher spatial resolution of activity data is required and can be obtained by disaggregating global data in country-specific categories, or by collecting country-specific activity data.

Domestic data sources are generally more appropriate than international ones to support higher tiered estimation approaches. In some cases relevant information must be created; it is *good practice* to investigate potential institutional arrangements to optimize the efficiency and effectiveness of data creation efforts, as well as plan for regular updates and long-term maintenance of a domestic information system.

To make use of remote sensing data for inventories, and in particular to relate land cover to land use it is *good practice* to complement the remotely sensed data with ground reference data (often called ground truth data). Land uses that are rapidly changing over the estimation period or that have vegetation cover known to be easily misclassified should be more intensively ground-truthed than other areas. This can only be done by using ground reference data, preferably from actual ground surveys collected independently. High-resolution air photographs or satellite imagery may also be useful. Further guidance can be found in Chapter 3, Volume 4, *2006 IPCC Guidelines*.

Tier 3

For application of a direct measurement-based inventory in Tier 3, similar or more detailed data on the combinations of climate, soil, topographic and management data are needed, relative to the Tier 1 and 2 methods. Comprehensive field sampling, where appropriate combined with remote sensing systems repeated at regular time intervals, will provide high spatial resolution on organic or peat soils, time since rewetting, and land-use and management activity data.

Scientific teams are usually actively involved in the development of Tier 3 methods. The viability of advanced estimation methodologies relies in part on well-designed information systems, that are able to provide relevant activity data with the appropriate spatial and temporal coverage and resolution, have well documented data collection protocols and quality control, and are supported with a long-term financial commitment for update and maintenance.

3.2.2 CH4 Emissions from Rewetted Peatlands and Organic Soils

CH_4 emissions and removals from the soils of rewetted peatlands and organic soils result from 1) emissions or removals resulting from the balance between CH_4 production and oxidation and 2) emission of CH_4 produced by the combustion of soil organic matter during fire (Equation 3.6).

EQUATION 3.6
CH_4-C EMISSIONS FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$CH_4\text{-}C_{rewetted\ org\ soil} = CH_4\text{-}C_{soil} + CH_4\text{-}C_{soil\ burn}$$

Where:

$CH_4\text{-}C_{rewetted\ org\ soil}$ = CH_4-C emissions/removals from rewetted lands on organic soils, tonnes C yr^{-1}

$CH_4\text{-}C_{soil}$ = emissions/removals of CH_4-C from organic soils subject to rewetting, tonnes C yr^{-1}

$CH_4\text{-}C_{soil\ burn}$ = emissions of CH_4-C from soil or peat burning on rewetted peatlands or organic soils, tonnes C yr^{-1}

The default EFs provided in this section will only cover $CH_4\text{-}C_{soil}$. These CH_4 emissions are produced during the decomposition of the peat/soil by heterotrophic organisms under anaerobic conditions and are strongly controlled by oxygen availability within the soil and by soil temperature. Methane emissions are also originating from the decay of non-woody vegetation; since these pools cannot be easily separated in peatlands they are combined here as $CH_4\text{-}C_{soil}$.

The area of rewetted and restored peatland and organic soils that burns is likely small if water table position is near the surface, but possible soil emissions from fires are included here for completeness. If rewetting or restoration practices involve biomass burning, CH_4 emissions from biomass burning must be estimated in a way consistent with the guidance provided in Chapters 2 (generic methods), 4 (Forest Land) and 5 (Cropland), Volume 4 of the *2006 IPCC Guidelines*. Emissions from soil burning ($CH_4\text{-}C_{soil\ burn}$) should be estimated using country-specific (Tier 2 or 3) emission factors.

Care should be taken to account for fire emissions under only one land-use category to avoid double-counting fire emissions.

CHOICE OF METHOD

Refer to Figure 3.1 for the decision tree to select the appropriate Tier for the estimation of CH_4 emissions or removals from rewetted peatland or organic soils.

Tier 1

The default methodology covers CH_4 emissions from rewetted peatlands and organic soils (Equation 3.7).

As in Section 3.2.1, the basic approach makes no distinction between rewetted and restored peatlands and therefore the term ‘rewetted peatlands and organic soils’ is used throughout the default methodology to encompass both activities.

In addition, the basic methodology is based on the assumption of no transient period for rewetted peatlands and organic soils.

EQUATION 3.7
ANNUAL CH_4-C EMISSIONS FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$CH_4 - C_{soil} = \left[\frac{\sum_{i,j}\left(A_{i,j} \cdot EF_{CH_4\ soil\ i,j}\right)}{1000}\right]$$

Where:

$CH_4\text{-}C_{soil}$ = CH_4 -Cemissions from rewetted peatlands and organic soils, tonnes C yr^{-1}

A_{ij} = total area of peatlands and organic soils that have been rewetted in i climate zone and j peatland type, ha

$EF_{CH4\ soil\ i,j}$ = emission factor from rewetted peatland and organic soils in i climate zone and j peatland type, kg CH_4-C ha^{-1} yr^{-1}

Rewetted area should be subdivided by climate zone (boreal, temperate or tropical) and the appropriate emission factors applied. Thus far flux data on CH_4-C emissions from successfully rewetted tropical sites are lacking. Thus, the default EF has been developed from data on undrained tropical peat swamp forests in SE Asia which represent the largest extent of peatland in the tropics (Joosten 2009, Page et al., 2010). The representativeness of this default EF should be assessed prior to its application outside peat swamp in Southeast Asia. Annex 3A.3 describes the derivation method. Data on methane fluxes from other tropical peatlands, like for example the *Papyrus* marshes of Africa or the peatlands of Panama and the Guianas and other parts of the Americas, are lacking. When information is available on the peatland type, it is recommended to further subdivide rewetted area into nutrient-poor and nutrient-rich, multiply each one by the appropriate emission factor and sum the products for the total CH_4 emissions.

Tier 2

Tier 2 calculations use country-specific emission factors and parameters, spatially disaggregated to reflect regionally important ecosystems or practices such as papyrus, Sago palm or reed cultivation, and dominant ecological dynamics. In general, CH_4-C fluxes from wet peatlands are extremely skewed, approaching a log-normal (right-tailed) distribution (see Annex 3A.3). This asymmetry towards rare, but high efflux values causes high mean values compared to the most likely encountered median values. Countries with extensive areas of rewetted peatlands or organic soils should develop EFs based on measurements or experiments within the country and thus contribute to better scientific understanding of CH_4 effluxes from rewetted peatland sites.

Methane fluxes from peat and organic soils strongly depend on the depth of the water table, with potential efflux increasing steeply from near zero when mean annual water table is deeper than 20 cm below the surface, to very variable and high values when the mean annual water table is shallower than 20 cm below the surface (Annex 3A.3). Variability is even greater on flooded sites, where both low and high flux values have been observed (Augustin & Chojnicki 2008; Couwenberg et al., 2010; Couwenberg & Fritz 2012; Glatzel et al., 2011). It is *good practice*, when developing and using country-specific CH_4 emission factors, to examine their relationship with water table position. In this case, activity data on mean annual water table position and its distribution in space would also be required.

As noted in Chapter 2, emissions of CH_4-C from drainage ditches can be much higher than the surrounding drained peat fields. Few data are available on CH_4-C emissions from ditches of rewetted peatlands and organic soils and in some cases ditches may be filled during rewetting activities. Moreover, rewetting reduces the hydrological differences between peat fields and neighboring ditches creating a more homogeneous surface from which CH_4 is emitted/removed. In some cases rewetting and restoration practices may retain ditches (e.g. Waddington et al., 2010) and when ditches remain, it is *good practice* to include estimates of CH_4-C ditch emissions using methodology provided in Chapter 2 (Equation 2.6) and country-specific emission factors. Table 2A.1 can also be consulted for guidance on emission factors for ditches in drained peatlands. Activity data on remnant ditches could be obtained from restoration practitioners or assessed with remote sensing imagery of rewetted areas.

Prior land use (e.g. agriculture, peat extraction, forestry) can influence CH_4 fluxes from rewetted peatlands or organic soils. For example, CH_4 emissions following the flooding of some agricultural land with nutrient enriched top-soil appear higher compared to average emission factors (Augustin & Chojnicki, 2008; Glatzel et al., 2011) whereas rewetted boreal cutover peatlands may have CH_4 emissions below the average emission factors (Waddington and Day, 2007). It may therefore increase accuracy to subdivide activity data and emission factors according to previous land-use. The influence of previous land use may diminish over time and countries are encouraged monitor emissions/removals of CH_4 from rewetted peatlands and organic soils to evaluate this effect.

The number of long-term rewetting studies is limited and changes in CH_4 flux over time remain unclear. Changes in CH_4 flux with time since rewetting are likely linked to prior land-use. Research on restored cutover peatlands in Canada indicates an increase in CH_4 emissions each year during the first three years post-restoration as the emerging vegetation cover provides fresh substrate for CH_4 production (Waddington and Day, 2007). In contrast, rewetting of high intensity grassland on fen peat suggests that CH_4 emissions may decline over time as litter inundated during rewetting activities is rapidly decomposed in the first few years (Augustin and Joosten 2007). Changes in CH_4 emissions and removals over time appear to be linked to vegetation succession (e.g. Tuittila et al., 2000) and thus understanding the pattern of emissions over time would require the inclusion of vegetation information.

Several studies in both undisturbed and rewetted peatlands indicate the important role that vegetation may play for providing substrate for CH_4 production and for transporting CH_4 from the saturated soil to the atmosphere (e.g. Bubier 1995; Shannon et al., 1996; Marnier et al., 2004; Tuittila et al., 2000; Wilson et al., 2007; Dias et al., 2010 ;). Species known to transport CH_4 from the soil to the atmosphere include, but are not limited to *Alnus, Calla, Carex, Cladium, Eleocharis, Equisetum, Eriophorum, Glyceria, Nuphar, Nymphaea, Peltandra, Phalaris, Phragmites, Sagittaria, Scheuchzeria, Scirpus, Typha* and various peat swamp forest trees (Sebacher *et al.,* 1985, Brix et al., 1992; Chanton *et al.,* 1992, Schimel 1995, Shannon *et al.,* 1996, Frenzel & Rudolph 1998, Rusch & Rennenberg 1998, Verville *et al.,* 1998, Yavitt & Knapp 1998, Grünfeld & Brix 1999, Frenzel & Karofeld 2000, Tuittila et al., 2000, Arkebauer *et al.,* 2001, Gauci et al., 2010, Armstrong & Armstrong 2011, Askaer *et al.,* 2011; Konnerup et al., 2011; Pangala et al., 2012). The presence of these aerenchymous shunt species has a marked effect on methane efflux from peatlands (Couwenberg & Fritz 2012). Countries are encouraged to develop nationally specific emission factors that address vegetation composition (see Riutta et al., 2007, Dias et al., 2010, Couwenberg et al., 2011; Forbrich et al., 2011). The effect of biomass harvesting on CH_4 fluxes from rewetted peatlands has thus far remained unstudied.

Tier 3

A Tier 3 approach involves a comprehensive understanding and representation of the dynamics of CH_4 emissions on rewetted peatlands and organic soils, including the representation of interactions between the dominant drivers of CH_4 dynamics, as described above. Possible methods include detailed country-specific monitoring of CH_4-C emissions/removals across rewetted peatlands and organic soils representing a variety of water table positions, prior land use and time since rewetting. Methane emissions/removals could also be estimated using process-based models including factors described above (see e.g. Walter et al., 2001, Frolking et al., 2002, Van Huissteden et al., 2006, Baird et al., 2009, Li et al., 2009, Meng et al., 2012).

CHOICE OF EMISSION FACTORS

Tier 1

The implementation of the Tier 1 method requires the application of default emission factors EF_{CH4} provided in Table 3.3, where they are disaggregated by climate region (boreal, temperate, tropical) and peatland type (nutrient poor, rich). The emission factor for rewetted tropical peat and organic soils assumes a near surface water table throughout the year. For tropical areas experiencing a distinct dry season, where water tables drop below 20 cm below surface, the emission factor in Table 3.3 should be multiplied by the number of wet months divided by 12. Annex 3A.3 provides more details on the derivation of the default EFs and references used for their determination.

TABLE 3.3
DEFAULT EMISSION FACTORS FOR CH_4 FROM REWETTED PEATLANDS AND ORGANIC SOILS
(ALL VALUES IN KG CH_4-C HA^{-1} YR^{-1})

Climate Region	EF_{CH4}	95% range	Nutrient Status	EF_{CH4}	95% range
Boreal	80 (n= 85 sites)	0 – 420	Poor	41 (n=39 sites)	0.5 – 246
			Rich	137 (n=35 sites)	0 – 493
Temperate	158 (n=68 sites)	0 – 795	Poor	97 (n=28 sites)	3 – 382
			Rich	216 (n=33 sites)	0 – 856
Tropical	41 (n=11 sites)	7 - 134			

Tier 2 and 3

The uncertainty of EFs can be reduced by using country-specific emission factors for each climate and peatland type. Differences in water table position explain a large proportion of variation in annual CH_4 flux between sites (Annex 3A.3). Thus, estimation of CH_4-C emissions/removals using country-specific EFs related to water table position will greatly improve estimation. Estimates of CH_4-C emissions/removals from rewetted peatland and organic soils can be further improved by implementing scientific findings relating CH_4-C emissions to specific cropping practices, prior land use, vegetation cover and time since rewetting.

Default emission factors are not provided for specific wet cropping practices, such as for Sago or reed plantations on wet peat where the scientific evidence is insufficient to support a globally applicable EF. Where such practices are regionally important, it is *good practice* to derive country specific emission factors from pertinent publications (e.g. Inubushi et al., 1998, Melling et al., 2005, Watanabe et al., 2010), taking into account water table dynamics.

CHOICE OF ACTIVITY DATA

All Tiers require data on areas of rewetted peatlands or organic soils, broken down by climate region. When information on nutrient status is also available it is *good practice* to further disaggregate into nutrient poor and nutrient rich type of peatland and organic soils.

Tier 1

The default methodology assumes that a country has data on the area of rewetted peatlands or organic soils and the type of peatland or organic soils, consistent with the advice above on the selection of emission factors. As recommended in the guidance on CO_2 emissions/removals, such data can be obtained from the peat extraction industry, forestry or agricultural agencies, as well as from government and non-government sources. Remote sensing can also be used for wet area detection and mapping of vegetation type and biomass.

Potential sources of activity data, both domestic and international, are provided in section 3.2.1.

Tier 2 and 3

More sophisticated estimation methodologies will require the determination of annual average water table depth; land use and management practices prior to rewetting; and vegetation composition and the successional changes in vegetation community composition and biomass with time since rewetting. This type of information can be obtained by long-term monitoring of rewetted sites under various conditions, and should be combined with an enhanced understanding of the processes linking CH_4 emissions to these factors.

3.2.3 N_2O Emissions from Rewetted Peatlands and Organic Soils

The emissions of N_2O from rewetted peatlands or organic soils are controlled by the quantity of N available for nitrification and denitrification, and the availability of the oxygen required for these chemical reactions. Oxygen availability is in turn controlled by the depth of the water table. Raising the depth of the water table will cause N_2O emissions to decrease rapidly, and fall practically to zero if the depth of the water table is less than 20cm below the surface (Couwenberg et al., 2011). Flooded conditions may promote denitrification and N_2O removals, but in practice this effect is very small and considered negligible in this chapter.

Equation 3.8 includes the essential elements for estimating N_2O emissions from rewetted peatlands or organic soils:

EQUATION 3.8
N_2O-N EMISSIONS FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$N_2O_{\text{rewetted org soil}} = N_2O_{\text{soil}} + N_2O_{\text{soil burn}}$$

Where:

$N_2O_{\text{rewetted org soil}}$ = N_2O emissions from rewetted peatlands or organic soils, kg N_2O-N yr^{-1}

N_2O_{soil} = N_2O emissions from the soil pool of rewetted peatland or organic soils, kg N_2O-N yr^{-1}

$N_2O_{\text{soil burn}}$ = N_2O emissions from soil or peat burning on rewetted peatlands or organic soils, kg N_2O-N yr^{-1}

Generic methodologies for estimating N_2O emissions from the burning of vegetation and dead organic matter are provided in Chapter 2, Volume 4 in the *2006 IPCC Guidelines*, while methodologies specific to vegetation and DOM burning in Forest land, Cropland, Grassland and Wetlands are provided in Chapters 3-6, Volume 4 in the *2006 IPCC Guidelines*. Consistent with guidance in the previous sections, emissions from soil burning ($N_2O_{\text{soil burn}}$ of equation 3.8) should be estimated using country-specific (Tier 2) emission factors.

Under Tier 1, emissions of nitrous oxides from rewetted soils are assumed to be negligible[1].

Tier 2 & 3

Countries with large areas of rewetted peatlands or organic soils should take into account patterns of N_2O emissions from these sites, particularly where the nitrogen budget of the watershed is potentially influenced by significant local or regional N inputs such as in large-scale farmland development.

[1] Augustin, 2003; Augustin and Chojnicki, 2008; Drösler, 2005; Hendriks et al., 2005; Jungkunst and Fiedler, 2007; Wild et al., 2001, Wilson et al., in press.

Country-specific emission factors should take into account fluctuations of the water table depth, which controls oxygen availability for nitrification, and previous land use, which may have resulted in top soil enrichment (Nagata et al., 2006; 2010). The development of country-specific emission factors should take into consideration that significant N inputs into rewetted ecosystems may originate from allochtonous (external) sources, such as fertilizer use in the surrounding watershed. Measurement protocols should be designed in such a way as to allow separating such inputs, to avoid double-counting N_2O emissions that may already be reported as indirect emissions from anthropogenic N input within the watershed (Chapter 11, Volume 4 of *2006 IPCC Guidelines*).

3.3 COMPLETENESS, TIME SERIES, CONSISTENCY, AND QA/QC

3.3.1 Completeness

Complete greenhouse gas inventories will include estimates of emissions from all greenhouse gas emissions and removals on rewetted and restored peatlands for which Tier 1 guidance is provided in this chapter, for all types of organic or peat soils that occur on the national territory.

Not all drained soils in the national territory may have been rewetted, but all rewetted sites were drained at some point in the past. A complete inventory will include all drained peatlands and organic soils, as well as those that have been subsequently rewetted.

Countries are encouraged to monitor the evolving land use of all drained, rewetted and restored lands on organic or peat soils, avoiding double counting emissions or removals that are reported from lands in various categories, preferably by using a consistent system for land representation. The greenhouse gas estimates from rewetted lands with organic or peat soils should include all applicable carbon pools; double counting emissions or removals between carbon pools has to be avoided, especially if country-specific flux-based estimation methodologies are combined with stock change approaches (see section 3.3.3 below). Regardless of the estimation methodology it is *good practice* to clearly demonstrate the completeness of pool coverage.

Implementing higher Tier methodologies will improve both inventory accuracy and completeness by developing estimates for gases, pools, conditions or practices for which Tier 1 methods are not provided in this document. It is *good practice* to assess the completeness of all methods and data sources against all known sources or sinks of greenhouse gases. Due to material limitations, all combinations of ecosystem types, management practices and environmental conditions are rarely captured. However, information of the most common combinations combined with basic Tier 1 calculations should provide a first estimation of sites and management practices that most contribute to the total GHG budget; this information allows not only prioritizing quantification efforts, but also assessing the extent to which a given data set can be deemed representative of a larger area of interest.

3.3.2 Developing a consistent time series

General guidance on ensuring time series consistency can be found in Chapter 7 of this Supplement. Consistent time series are essential to producing real trends. Inventory agencies should critically assess the spatial and temporal consistency of definitions and classification schemes, information on management practices, sources of activity data, and key estimation parameters used over the entire time series. In particular, countries should strive to apply consistent definitional parameter(s) to determine the land areas on organic or peat soils that are drained or rewetted, across all land use categories.

The emission and removal estimation method should be applied consistently to every year in the time series, at the same level of spatial disaggregation. When country-specific data are used, national inventory agencies should use the same measurement protocol (sampling strategy, method, etc.) or modelling approach throughout the time series.

It is likely that changes will occur over time in the quality or availability of various inputs to the inventory. Inventory agencies should determine the influence of changing data or methods on trends, and use methods provided in the Chapter 5, Volume 1 of the *2006 IPCC Guidelines* to correct for any significant inconsistency and re-calculate the time series.

The implementation of higher Tier methods often involves developing a full time series for the new, additional parameters required by a more spatially disaggregated or complex estimation methodology. It is *good practice* to incorporate considerations of time-series consistency in the design, development and implementation of refinements in inventory methods.

In general, significant fluctuations in emissions and removals between years should be explained. Higher tier methods usually better represent the true inter-annual variability observed in wetland ecosystems, which is often obscured in simple, time-integrated methods such as differences in C stocks. A distinction should be made between changes in activity levels and refinements in methods that may affect the trend, and the reasons for these changes documented. If the method changes it is *good practice* to recalculate the entire time series.

3.3.3 Quality Assurance and Quality Control (QA/QC)

Quality assurance/quality control (QA/QC) procedures should be developed and implemented as outlined in Chapter 7 of this Supplement.

It is *good practice* that countries using Tier 1 methods critically assess the applicability of the default assumptions to their national circumstances. For example, countries are encouraged to determine in what way, if any, drainage or rewetting with no change in land use affects biomass and dead-organic matter pools and adjust assumptions or methods to incorporate their findings in estimates. In light of their strong influence on GHG emissions, the frequency and any periodicity of possible water table fluctuations in rewetted ecosystems should be factored into the assessment or development of emission factors.

Higher tier methods should be carefully designed to ensure that resulting estimates are compatible across different pools. In particular, potential double-counting of emissions or removals could occur if estimates derived from flux-based emission factors are combined to estimates calculated from stock change; this could occur for example if C uptake by vegetation is included in both a net flux to/from the atmosphere and the stock change in the biomass pool. Likewise, a net flux and the stock change of the dead organic matter pool could both include emissions to the atmosphere as a result of DOM decay. Therefore scientific expertise must be actively involved in the design of domestic methods and the development of country-specific parameter values to ensure that C transfers to and from carbon pools, and between the biosphere and the atmosphere, are all captured to the extent possible and not double-counted. Where country-specific emission factors are being used, they should be based on high quality field data, developed using a rigorous measurement programme, and be adequately documented, preferably in the peer-reviewed, scientific literature. Documentation should be provided to establish the representativeness and applicability of country-specific emission factors to the national circumstances, including regionally significant rewetting and restoration practices and relevant ecosystems.

It is *good practice* to develop additional, category-specific quality control and quality assurance procedures for emissions and removals in this category. Examples of such procedures include, but are not limited to, examining the time series of the total area of managed land on peat or organic soils across all land use categories to ensure there is no unexplained gains or losses of land; conducting a comparative analysis of emission factors applied to rewetted land on organic or peat soils and fluxes from un-drained similar ecosystems; ensuring consistency of the area and location of rewetted peatlands or organic soils with the information provided on drained peatlands and organic soils.

3.3.4 Reporting and Documentation

EMISSION FACTORS

The scientific basis of country-specific emission factors, parameters models and their evaluations should be fully described and documented. This includes describing the input parameters, the derivation of emission factors and parameters and the sources of uncertainty, as well as justifying their representativeness. Representativeness can be assessed by comparing the range of conditions under which measurements were made to real-world circumstances to which a parameter or emission factor is applied. A representative data set provides a balanced representation of the range of conditions and practices found in rewetted ecosystems. The determination of representativeness generally requires knowledge of types and areas of rewetted ecosystems and associated management practices in the country or region. For example, in seasonal climates flux measurements conducted during the growing or wet season are not representative of the entire year and therefore flux rates observed during part of the year only may not be directly scaled up over a year. Generally, it is more challenging to achieve a representative data set when there is high spatial and temporal variability in environmental conditions, ecosystem diversity and management practices.

Tier 3 approaches are likely to involve both extensive use of flux measurement techniques, combined to some modelling framework. The growing use of flux measurements in the field over the last decade has resulted in a rich literature source of information and guidance on the use and documentation of flux measurement techniques (Evans et al., 2011; Alm et al., 2007; Pattey et al., 2006).

Model documentation should be exhaustive, and generally follow expert recommendations (IPCC, 2011) to include:

- Basis and type of model (statistical, deterministic, process-based, empirical, top-down, bottom-up etc)
- Domain of application of the model

- Key assumptions
- Main equations/processes and their adaptation to domestic conditions if appropriate
- How the model parameters were estimated
- Description of key inputs and outputs
- Details of calibration and evaluation with calibration data and independent data
- Description of the approach taken to the uncertainty analysis and to the sensitivity analysis, and the results of these analyses
- QA/QC procedures adopted
- References to peer-reviewed literature where details of the supporting research can be found

ACTIVITY DATA

Sources of all activity data used in the calculations (publications, databases and soil map references, reports on rewetting projects, official communications) should be recorded, along with their origin: government agencies, conservation organizations, research institutions and industry, subject to any confidentiality considerations. This documentation should cover the protocol for data collection (frequency, measurement methods and time span), estimation methods, and estimates of accuracy and precision. Reasons for significant changes in activity data and inter-annual fluctuations should be explained.

Information should be provided, for each land-use category, on the proportion of drained and rewetted areas with organic soils. Overall, the sum of rewetted areas with peat or organic soils reported under each land use categories should equal the total national area of rewetted peatlands or organic soils.

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Annex 3A.1 Estimation of default emission factors for CO_2-C in rewetted peatlands and organic soils

An extensive literature review was conducted to collate all CO_2 studies that are currently available for (1) rewetted peatlands and organic soils and (2) natural/undrained peatlands. Literature sources included both published and non-published (grey literature) studies. In the case of the latter where a peer reviewed process had not formed part of the publication process the study was reviewed by all Lead Authors in this Chapter and expert judgement was exercised as to whether the study was scientifically acceptable for inclusion. In total, 3 non-published studies were reviewed (Drösler 2005, Augustin and Chojnicki 2008, Wilson *et al.,* 2012).

All studies included in the database reported CO_2 flux based estimation methodologies using either the chamber or eddy covariance (EC) techniques. The chamber method involves the measurement of fluxes at high spatial resolution and is widely employed in conditions where the vegetation is either low or absent. In contrast, EC towers operate at lower spatial resolutions but are suitable for sites where the biomass is vertically high (e.g. treed peatlands). For a more detailed description of both methodologies see Alm et al., 2007. A detailed database of annual CO_2 fluxes was then constructed to determine the main drivers (if any) of CO_2 dynamics in rewetted peatlands and organic soils. When available, the following parameters were extracted from the literature source and included in the database for analysis: climate region (see Table 4.1, Chapter 4, Volume 4 of the *2006 IPCC Guidelines*), peatland types, mean annual water table (WTD), median annual water table (as well as minimum and maximum), soil pH, peat thickness, peat C/N ratio, degree of humification, soil moisture, soil bulk density, plant cover and species, previous land-use and time since rewetting.

The CO_2 flux database initially contained a total of 187 annual flux estimates taken from 48 locations. At each study location, a number of sites could be identified (similar dominant vegetation and hydrology) and each represented as such an entry in the database. For multi-year studies from the same site, annual flux estimates were averaged over the years. The final number of entries came to 107 and was distributed as follows:

(i) Peatland state (Natural/undrained = 74; Rewetted: 33);

(ii) Climate zone (Boreal = 64; Temperate = 43)

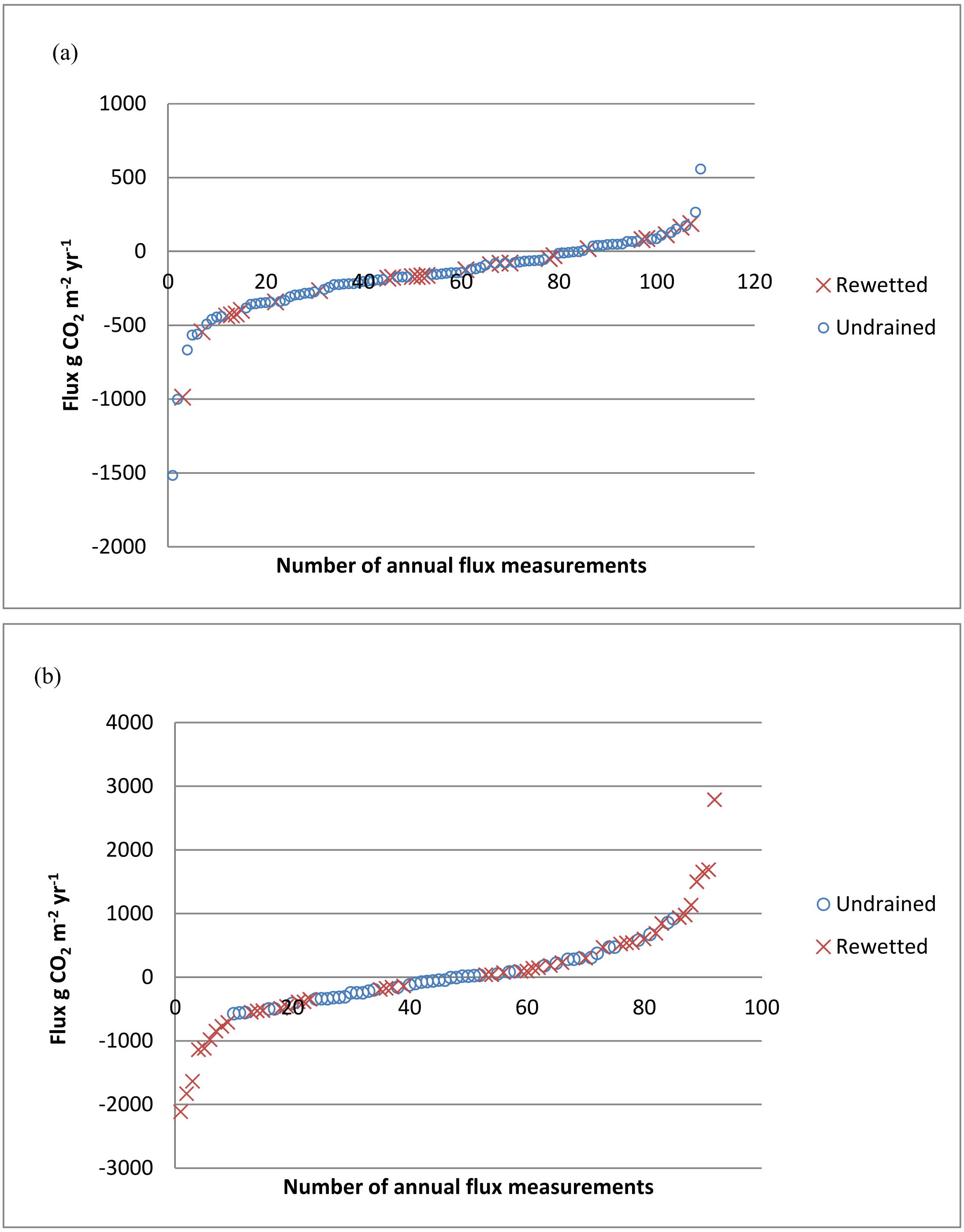
(iii) Peatland nutrient status (Nutrient rich = 49; Nutrient poor = 58).

The criteria for inclusion in the database were as follows; (1) the study reported CO_2 fluxes from either rewetted peatlands/organic soils or natural, undrained peatlands. If a natural site had a WTD of deeper than 30 cm it was considered to be drained effectively (Minkkinen *et al.,* 1999, Haapalehto *et al.,* 2010, Hooijer *et al.,* 2010). Only natural sites with a WTD of -30 cm (negative values indicate a mean WTD below the peat/soil surface) or shallower (i.e. close to or above the peat/soil surface) were used as a proxy for rewetted sites. (2) The study had to report either seasonal or annual CO_2 fluxes from the peatland. Studies in the database that reported daily CO_2 flux values were not used as upscaling to an annual flux value would have led to very high under- or over estimations. Seasonal CO_2 fluxes (typically reported for the snow free May to October growing period) were converted to annual fluxes using 15% of the seasonal ecosystem respiration data from each study to estimate CO_2 fluxes from the non-growing season (Saarnio *et al.,* 2007), although this may represent a slight overestimation given that photosynthesis (and hence C uptake) may have occurred for a short time following the ending of those seasonal studies . For studies where such data was not available, a value of 30g C m^{-2} for non-growing season fluxes was used (Alm *et al.,* 1999). (3) Studies had to indicate a mean WTD for each annual CO_2 flux reported. In some cases, this information was available from other publications and the CO_2 flux value was accepted for inclusion. (4) For studies using the EC technique, care was taken not to use annual CO_2 fluxes, which included a woody biomass pool (e.g. treed peatlands) as this would have resulted in double accounting at the Tier 1 level. Calculated default EFs for CO_2 exclude woody biomass.

To determine Tier 1 CO_2-C EFs, descriptive statistics allowed the data to be grouped by (1) *climate region*, (2) *peatland type* (nutrient poor or nutrient rich) and (3) *climate region and peatland type,* and descriptive analysis for each group was computed.

A comparison was made between annual CO_2 fluxes from rewetted sites and natural/undrained sites. While noting the wide range of fluxes especially within the temperate climate zone (-2115 to 2786 g m^{-2} yr^{-1}), the array from both groups, natural/undrained vs rewetted is analogous (Figure 3A.1a and b).

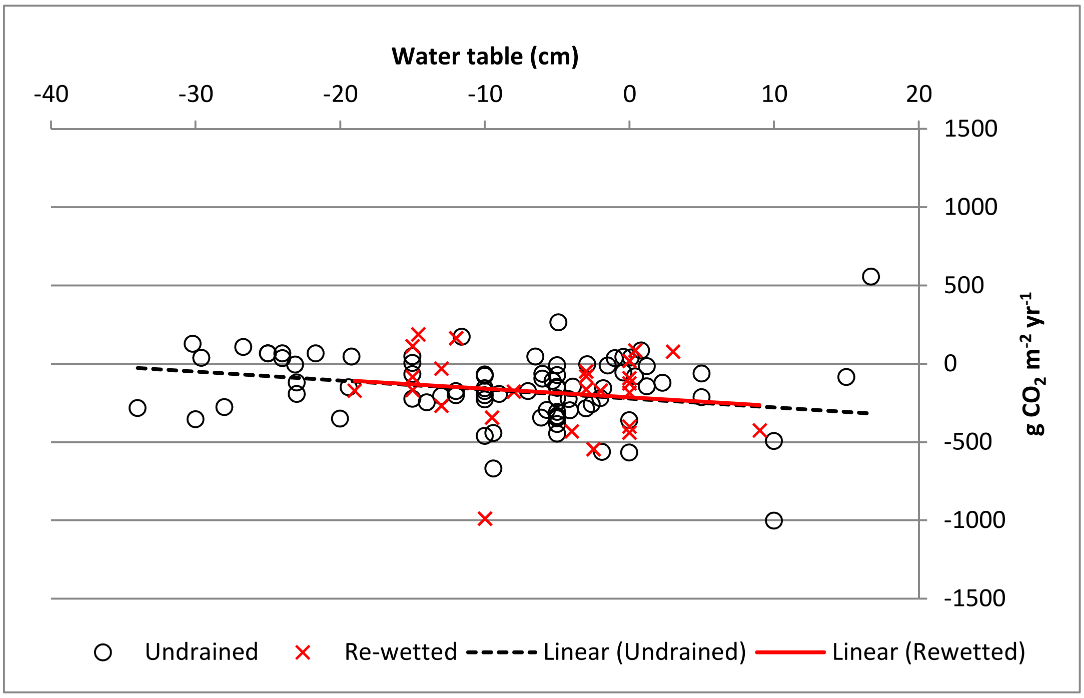
Figure 3A.1 Distribution of CO_2 flux values (g CO_2 m^{-2} yr^{-1}) found in the published literature for natural/undrained and rewetted peatlands in (a) boreal and (b) temperate climate zones.



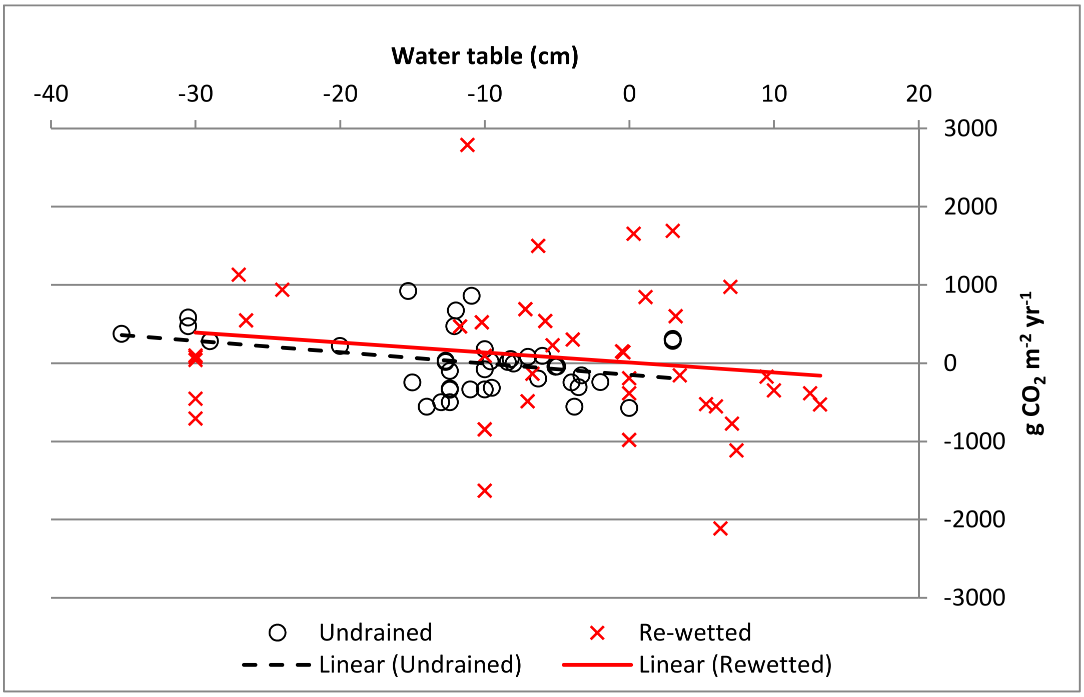
Mean water table (WT) was plotted against each annual CO_2 fluxes. The fitted regression lines (CO_2 flux = a+b1*WT) were compared between rewetted and natural/undrained peatlands for each climate region (see Figures 3A.2a and b). The groups were treated as being non-significantly different when it was ascertained statistically that b1 ±S.E. (rewetted) fitted within b1-S.E. and b1+S.E for the natural/undrained group. This was the case for both boreal and temperate peatlands (Table 3.A.1). Therefore, EFs were calculated using rewetted and natural/undrained data points.

Figure 3A.2 Relationship between annual CO_2 fluxes and mean annual water table (WT) in cm for both undrained and rewetted peatland groups in (a) boreal and (b) temperate climate zones

(a) Boreal zone



(b) Temperate zone



Note:

1. the fitted regression line is CO_2 flux = a+b1*WT, see Table 3.A.1.

2. Negative water table values indicate a mean water table position below the peat/soil surface and positive values indicate a mean water table position above the peat/soil surface.

TABLE 3A.1
RELATIONSHIP BETWEEN CO_2 FLUXES AND WATER TABLE (WT) SHOWING B1 PARAMETER FROM THE FITTED REGRESSION LINE (CO_2 FLUX = A+B1*WT) FOR BOTH THE REWETTED GROUP AND FOR THE NATURAL/UNDRAINED GROUP FOR EACH CLIMATIC REGION

Climate zone	Natural/undrained b1±Std Err.	Rewetted b1± Std Err.
Boreal	-5.18±2.68	-5.55±7.24
Temperate	-14.40±6.66	-12.76±11.1

Annex 3A.2 Estimation of default emission factors for CO_2-DOC in rewetted peatlands and organic soils

Fluvial C export has been found to be an important pathway linking the peatland C pool to the atmosphere as there is a growing evidence that peatland aquatic system is characterised by high levels of allochthonous DOC (Billett *et al.,* 2004, Dinsmore *et al.,* 2010, Rowson *et al.,* 2010), a high proportion of which is processed and converted to CO_2 (e.g. Cole *et al.,* 2007, Wickland *et al.,* 2007, Rowan 2009). A full characterisation of fluvial C losses comprises not only DOC, but also particulate organic carbon (POC), dissolved inorganic carbon (DIC) and dissolved CO_2 and CH_4 and the dissolved carbonate species HCO_3^- and CO_3^{2-}.

The various sources, behaviour and ultimate fate of these different forms of fluvial C within peatland and organic soils system are further described in Chapter 2 (Annex 2A.2). However, in temperate and boreal, natural/undrained peatlands, as well as rewetted peatlands and organic soils, DOC has been found to be by far the major component of fluvial C export, while POC, DIC and dissolved CO_2 are minor components of the total land-atmosphere CO_2 exchange and are therefore not estimated here (Jonsson *et al.,* 2007, Waddington *et al.,* 2008, Ramchunder *et al.,* 2009, Worrall *et al.,* 2009, Dinsmore *et al.,* 2010, Dinsmore *et al.,* 2011, Schafer *et al.,* 2012).

It should be noted here however that rewetting of bare cutaway peatlands has been found to produce relative high POC concentrations, albeit variable, both temporally in relation to storm flow events and spatially due to the patchiness of soil erosion. However, while in-stream processing of POC (respiration/evasion) may be occurring, the greater proportion may be simply translocated from the rewetted peatlands to other stable C stores, such as freshwater or marine sediments and may not lead to CO_2 emission. Therefore, due to current scientific uncertainty of the ultimate fate of POC export, no estimation methodology is presented here for emissions produced from the decomposition of POC lost from rewetted peatlands or organic soils (see Appendix 2A.1 for future methodological development to estimate POC).

This section describes the methodology that has been used to derive emission factors for DOC losses from rewetted peatlands and organic soils as this has been shown to be the largest component of waterborne carbon loss from all types of peatlands and organic soils (see Chapter 2). Collated data from seven peat rewetting studies suggest a median DOC reduction of 36%, with a range of 1-69% (Table 3A.2). While the number of studies is limited, and results are variable, the median reduction is almost exactly equivalent to the observed increase following drainage (a 33% decrease in DOC would be required to fully reverse a 50% increase).

In addition, some studies (e.g. Glatzel *et al.,* 2003, Wallage *et al.,* 2006) observed similar DOC concentrations in rewetted and restored bogs (previously used for peat extraction) as in a nearby intact reference bog. Therefore, there is some evidence to suggest that rewetting will return DOC loss fluxes to natural levels. It should be noted here that this reversal is likely to occur after an initial pulse of DOC associated with disturbance during the rewetting process, depending on the techniques used (e.g. Worrall *et al.,* 2007, Strack *et al.,* 2011). This hypothesis is proposed as an explanation behind the variability shown in Table 3A.2, where some measurements were made less than a year or during the first two years after rewetting.

While there are a limited number of published studies of re-wetting impact on DOC loss, a larger number of studies are available that provide reliable DOC flux estimates from natural/undrained peatlands. These were combined to derive best estimates of the DOC flux from rewetted sites. The values derived for the estimation of $DOC_{FLUX\text{-}NATURAL}$ needed in Equation 3.5 are explained in Annex 2A.2 of Chapter 2. Finally, the proportion of DOC exported from peats which is ultimately converted to CO_2, called here ($Frac_{DOC\text{-}CO_2}$) is also explained in Annex 2A.2 of Chapter 2.

TABLE 3A.2
DOC CONCENTRATION (ABOVE) OR FLUX (BELOW) COMPARISONS BETWEEN DRAINED AND REWETTED PEATS

Previous land-use	Country	Study	DOC ($mg\ l^{-1}$)		DOC_{RE-WET} (%)
			Drained	**Rewetted**	
Peat extraction bog	Canada	Glatzel *et al.*, 2003	110	70	-36%
Drained blanket bog	UK	Wallage *et al.*, 2006	43	13	-69%
Drained blanket bog	UK	Armstrong *et al.*, 2010	34	30	-10%
Drained blanket bog	UK	Gibson *et al.*, 2009	39	39	-1%
Drained agricultural fen	Germany	Höll *et al.*, 2009	86	57	-34%
Previous land-use	**Country**	**Study**	**DOC ($g\ C\ m^{-2}\ yr^{-1}$)**		**DOC_{RE-WET} (%)**
			Drained	**Rewetted**	
Peat extraction bog	Canada	Waddington *et al.*, 2008	7.5	3.5	-53%
Drained blanket bog	UK	O'Brien *et al.*, 2008	7.0	4.1	-41%

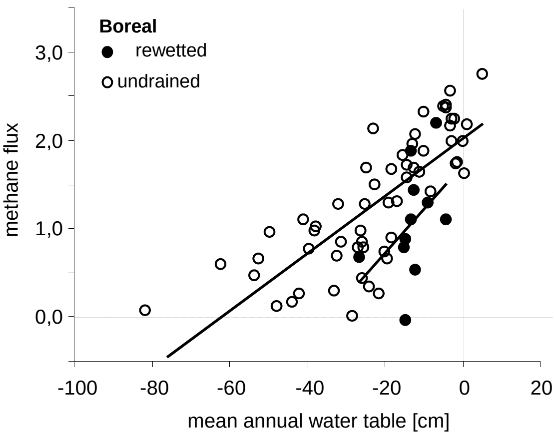
Annex 3A.3 Estimation of default emission factors for CH_4-C in rewetted peatlands and organic soils

The same literature database and general approach were used to develop default CH_4 emission factors as was described in Annex 3A.1. A detailed database of annual CH_4 fluxes was constructed to determine the main drivers (if any) of CH_4 emissions in rewetted peatlands and organic soils. The collated data are based on closed chamber and eddy covariance flux measurements with a temporal coverage of at least one measurement per month during the snow-free period. Seasonal fluxes (typically May to October) were converted to annual fluxes by assuming that 15% of the flux occurs in the non-growing season (Saarnio et al., 2007). For tropical Southeast Asia, annual data are scarce and direct, non-annualized measurement values were used. Similar to CO_2 flux measurements, data from natural (undrained) peatlands only were available and used as proxy for rewetted peatlands.

Where possible, the analysis considered the same parameters as those described in Annex 3A.1: climate zone (latitude), peatland types, mean annual water table, median annual water table (as well as minimum and maximum), soil pH, peat thickness, peat C/N ratio, degree of humification, soil moisture, soil bulk density, plant cover and species, previous land-use and time since rewetting. For all subsets mentioned below the collected data show a near log-normal distribution, which, however, did not allow for derivation of standard deviation. Variance pertains to the 95% interval of the observed data.

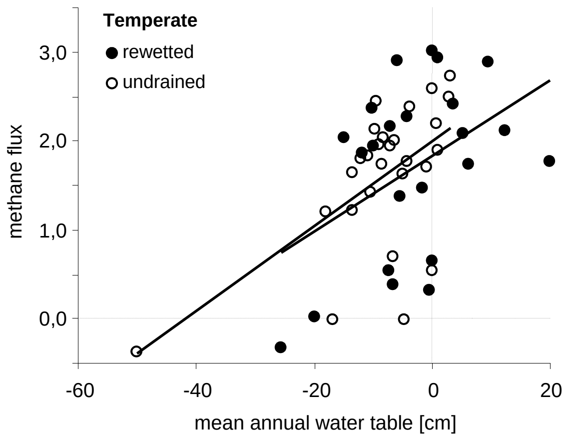
Methane fluxes from rewetted boreal peatlands (mean 75.9 kg CH_4-C ha^{-1} yr^{-1}; variance -0.1 – 338.7; n=15[2]) are not significantly different from undrained (pristine) sites (mean 80.8 kg CH_4-C ha^{-1} yr^{-1}; variance 0 – 492.8; n=67[3]). The increase in efflux with rising water table (Figure 3A.2) is similar for undrained (n=57 pairs) and rewetted sites (n= 9 pairs). Methane efflux from rewetted nutrient rich peatlands (mean 161.6 kg CH_4-C ha^{-1} yr^{-1}; variance -0.1 – 338.7; n=6) is an order of magnitude higher than efflux from rewetted nutrient poor peatlands (mean 22.2 kg CH_4-C ha^{-1} yr^{-1}; variance 5.8 – 74.8; n=6), which is mirrored by efflux values from undrained nutrient rich peatlands (mean 131.5 kg CH_4-C ha^{-1} yr^{-1}; variance 0.2 – 492.8; n=29) and poor peatlands (41.7 kg CH_4-C ha^{-1} yr^{-1}; variance 0.3 – 245.9; n=30). The derived emission factors for nutrient rich (n=35) and poor sites (n=36) are based on the total respective datasets of rewetted and undrained sites.

Figure 3A.2 Methane flux from boreal and temperate rewetted and undrained peat and organic soils in relation to mean annual water table. Fluxes are expressed as $^{10}\log(1+\text{measured flux})$ [kg CH_4-C ha^{-1} yr^{-1}].



[2] Juottonen et al., 2012; Komulainen et al., 1998; Tuittila et al., 2000 ; Urbanová et al., 2012 ; Yli-Petäys et al., 2007 ; Strack & Zuback 2012

[3] Alm et al., 1997; Bubier et al., 1993; Clymo & Reddaway, 1971; Drewer et al., 2010; Gauci & Dise 2002; Laine et al., 1996 ; Nykänen et al., 1995 ; Verma et al., 1992 ; Waddington & Roulet 2000 ; Whiting & Chanton 2001 ; Strack & Zuback, 2012

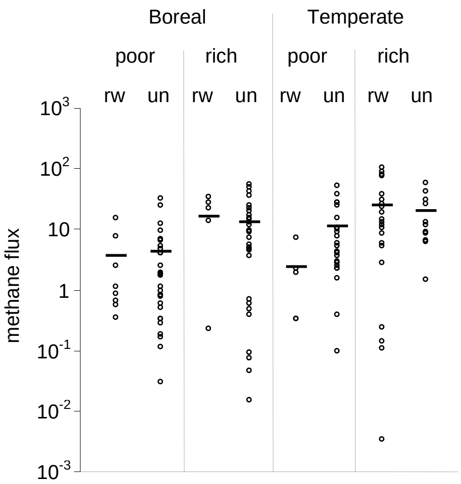


Whereas methane fluxes from rewetted temperate peatlands (mean 209.1 kg CH_4-C ha^{-1} yr^{-1}; variance 0 – 856.3; n=27[4]) are considerably higher than from undrained peatlands (mean 125.0 kg CH_4-C ha^{-1} yr^{-1}; variance 0 – 528.4; n=41[5]), this finding is based mainly on inclusion of sites that were slightly flooded during rewetting. Extremely high efflux values from sites on enriched agricultural soil that were turned into shallow lakes during rewetting are not included (Augustin & Chojnicki 2008; Glatzel et al., 2011). The increase in efflux with rising water level is not significantly different between undrained (n=27 pairs) and rewetted sites (n=22 pairs), nor between undrained nutrient poor (n=15 pairs) and undrained nutrient rich sites (n=7 pairs). Methane effluxes from rewetted temperate nutrient poor peatlands are an order of magnitude lower than from nutrient rich peatlands, but measurements are restricted to only 5 poor sites. Combined, the increase in efflux with rising water level in undrained and rewetted sites does not show a significant difference between poor peatlands (n=18 pairs) and rich ones (n=27 pairs). The emission factors presented are based on the total dataset of rewetted and undrained nutrient poor (n=28) and nutrient rich sites (n=33). Because nutrient poor sites have more relatively dry microsites and the dataset for nutrient rich sites includes the high values mentioned above, the EF for temperate nutrient poor sites is lower than for nutrient rich sites.

[4] Augustin & Merbach 1998; Augustin 2003; Augustin in Couwenberg et al., 2011; Cleary et al., 2005; Drösler 2005; Flessa et al., 1997; Glatzel et al., 2011; Hendriks et al., 2007; Jungkunst & Fiedler 2007; Waddington & Price 2000; Wild et al., 2001; Wilson et al., 2009; Wilson et al., in press

[5] Augustin & Merbach 1998; Augustin 2003; Augustin et al., 1996; Augustin in Couwenberg et al., 2011; Bortoluzzi et al., 2006; Crill in Bartlett & Harris 1993; Dise & Gorham 1993; Drösler 2005; Harriss et al., 1982; Koehler et al., 2010; Nagata et al., 2005; Nilsson et al., 2008; Roulet et al., 2007; Scottish Executive, 2007; Shannon & White 1994; Sommer et al., 2003; Tauchnitz et al., 2008; Von Arnold 2004; Waddington & Price 2000; Wickland et al., 2001; Wilson et al., 1989

Figure 3A.3 Methane flux from boreal and temperate, poor and rich, rewetted (rw) and undrained (un) peat and organic soils.



Note:

1. Fluxes (in kg CH_4-C ha^{-1} yr^{-1}) are expressed on a logarithmic scale.

2. Negative and zero flux values are not included in the graph (n=9).

3. Bars indicate mean values.

4. Note that in derivation of EFs, data for rewetted and undrained temperate sites were lumped and temperate EFs are onlydisaggregated for poor and rich.

Similar to boreal and temperate peatlands, methane fluxes from tropical swamp forest peatlands in Southeast Asia depend on water table with high methane efflux restricted to high water tables (Couwenberg et al., 2010). To derive the emission factor for rewetted swamp forest peat in Southeast Asia, flux data were compiled from literature. Data were limited to measurements associated with wet conditions (water table ≤20 cm below surface), either based on actual water table data or if wet conditions could reasonably be assumed (Table 3A.3). Flux data from rice padi on peat soil are comparable to current IPCC estimates (Couwenberg 2011) and were excluded from the analysis. Methane flux data from tropical peatlands outside Southeast Asia are currently not available. Because of the recalcitrance of the woody peat, methane fluxes from tropical swamp forest peatlands in Southeast Asia are considerably lower than from boreal and temperate peatlands (Couwenbert et al., 2010).

TABLE 3A.3
CH_4-C FLUX DATA FROM WET SWAMP FOREST PEATLANDS AND ORGANIC SOILS

Reference	Site	mg CH_4-C m^{-2} h^{-1}	n
Furukawa et al., 2005	S1 (drained forest)	0.13 (0 – 0.35)	9*
	S6 (swamp forest)	0.67	1
	S7/S8 (swamp forest)	0.74 (0.58 – 0.91)	2
Hadi et al., 2001	A1 (secondary forest)	0.14	1
Hadi et al., 2005	A1 (secondary forest)	0.46 (0 – 2.29)	13
Inubushi et al., 1998	Secondary forest	0.85	1
Jauhiainen et al., 2001, 2005	Conservation swamp forest	0.22 (0.03 – 0.70)	20*
Jauhiainen et al., 2004, 2008	Drained and selectively logged forest	0.08 (-0.02 – 0.22)	44*
Jauhiainen et al., 2004	Young secondary forest	0.19 (0.10 – 0.26)	5*
Melling et al., 2012	Tropical peat swamp forest	1.53 (1.28 – 1.78)	2
Pangala et al., 2012	Conservation swamp forest	0.14	1
Mean		**0.47 (0.08 – 1.53)**	**11**
		kg CH_4-C ha^{-1} y^{-1})	
Annual flux		**41.2 (7.0 – 134.0)**	

Note:

*only measurements pertaining to wet site conditions (water table ≤20 cm below the surface) are considered

Appendix 3.1 CO_2 emissions/removals from rewetted peatlands and organic soils in Tropical climate: a basis for future methodological develpment

INTRODUCTION

Natural tropical peatlands are undergoing extensive conversions for agriculture development (Koh et al., 2011; Mietinnen et al., 2012). The clearance of forest cover followed by drainage and use of fires have been widely practiced (van der Werf et al., 2008; Hooijer et al., 2012) resulting in large amount of CO_2 release into the atmosphere. Rewetting drained organic soils followed by restoring or reestablishing the vegetation cover that pre-dated the drainage of these areas could reduce the rates of emission or increase the rate of removal of CO_2 from the atmosphere. It has also been suggested that water management and fire suppression on drained and degraded peatlands could provide potential mitigation opportunities (Murdiyarso et al., 2010).

Water table is generally elevated when drained organic soils are rewetted by blocking the existing canals or ditches, which were constructed to drain water and transport logs or other purposes. Following the water table rise to pre-drainage levels, the vegetation may recover naturally or the site may undergo human-supported restoration with planting of indigenous vegetation.

The basis for methodological development in this Appendix focuses on changes in CO_2 emissions and removals from the restoration of rewetted tropical peatlands. The approach is consistent with the default EF of Table 3.1, which assumes that rewetting effectively stops soil organic matter oxidation but, in the absence of vegetation regrowth, does not reestablish a soil C sequestration function. Carbon uptake by vegetation on restored sites eventually allows the water saturated soil to accumulate carbon.

This appendix only considers the soil C pool of rewetted and restored tropical peatlands. The sequestration of atmospheric CO2 in the biomass and dead organic matter pool should follow the guidance in Chapter 7, Volume 4 of the *2006 IPCC Guidelines*. The area rewetted and subsequently restored will be considered as activity data (AD).

CHOICE OF METHOD

The method may be developed in two pathways:

- Reduction of CO_2 emission due to elevated water table following rewetting of organic soils
- Increase of CO_2 removal due to re-introduction of vegetation in rewetted peatlands

Tier 1

In the absence of published data on the soil emissions from rewetted tropical organic soil, the default EF as considered in Section 3.2.1 is zero. In rewetted areas where vegetation is introduced, a default EF for soil carbon accumulation has yet to be determined.

Tier 2

Where rewetted tropical peatlands cover significant areas, it is recommended to develop country specific soil EFs. Preliminary indications of CO2 emissions/removals from undrained peatlands as summarized in Table A3.1 below. However, these values apply to entire ecosystems; the information currently available is insufficient to allow further separation by ecosystem C pool. It has been suggested that the mean Holocene soil carbon sequestration rates amount to 1.16 t CO_2-C ha^{-2} y^{-1} for inland tropical peatlands and 2.85 t CO_2-C ha^{-2} y^{-1} for coastal sites (Dommain et al., 2011). Countries using such values should demonstrate the applicability of the scientific data to their national circumstances. Depending on measurement techniques used to develop emission factors, an estimate of C losses in the dissolved form (DOC) should be added for a complete C budget. Section 3.3.3 provides further guidance on how to combine flux estimates developed with various measurement techniques.

TABLE A3.1
CARBON DIOXIDE (CO_2) EMISSIONS FROM UNDRAINED PEATLANDS WITH DIFFERENT VEGETATION COVER OR SUB CATEGORY

Ecosystem	Site/Location	Flux rate (tonnes CO_2-C ha^{-1} y^{-1})	Reference
Forested peatland	Jambi, Indonesia	0.08	Furukawa et al., 2005
Forested peatland	Sarawak, Malaysia	0.03 – 0.18	Melling et al., 2005
Secondary forest	S. Kalimantan, Indonesia	0.05	Hadi et al., 2001
Secondary forest	S. Kalimantan, Indonesia	12	Inubushi et al., 2003
Secondary forest	Amazonia, Peru	1.44 – 3.14	Lahteenoja et al., 2009
Secondary forest	Aucayacu, Peru	0.24 – 2.73	Lahteenoja et al., 2011
Secondary forest	Lagunas, Peru	1.07 – 4.00	Lahteenoja et al., 2011
Secondary forest	Maquia, Peru	0.32	Lahteenoja et al., 2011
Secondary forest	Roca Fuerte, Peru	1.25 – 2.41	Lahteenoja et al., 2011
Sago	Sarawak, Malaysia	0.0 – 0.08	Melling et al., 2005

Tier 3

- Comprehensive and integrated estimates of CO_2 emissions and removals from all C pools are based on the dynamic of water level, vegetation development and ecosystem C cycling
- CO_2 emissions on-site and off-site are both incorporated