# CHAPTER 3

# REWETTED ORGANIC SOILS

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# Contents

# Equations

# Figures

# Tables

# Box

# 3 REWETTED ORGANIC SOILS

## 3.1 INTRODUCTION

### What is rewetting, restoration, rehabilitation and how rewetting affects GHG

Definitions of wetlands and organic soils are provided elsewhere in this supplement (Chapter 1 and Glossary), and will not be repeated here. As in the remainder of this supplement, this chapter considers peatlands to be included in '(land with) organic soil'. Unless stated otherwise, statements referring to organic soils will include soils made of peat; in some instances, examples are provided that are specific to peat soils or peatlands and in such cases peatlands will be mentioned specifically.

Rewetting is the deliberate action of raising the water table on drained soils to re-establish water saturated conditions, e.g. by blocking drainage ditches or disabling pumping facilities. Rewetting can have several objectives, such as wetland restoration or allowing other management practices on saturated organic soils such as paludiculture.

Wetland restoration aims to permanently re-establish the pre-disturbance wetland ecosystem, including the hydrological and biogeochemical processes typical of water saturated soils, as well as the vegetation cover that pre-dated the disturbance (FAO, 2005; Nellemann & Corcoran, 2010). Normally, the restoration of previously drained wetlands is accompanied by rewetting, while the restoration of undrained, but otherwise disturbed wetlands may not require rewetting.

Rehabilitation, as defined by FAO (2005) and Nellemann & Corcoran (2010), can involve a large variety of practices on formerly drained organic soils, which may or may not include rewetting. The re-establishment of a vegetation cover on a drained site without rewetting is a form of site rehabilitation.

The focus of this chapter is the rewetting of organic soils; restoration and other management practices on rewetted organic soils are not specifically addressed. Rehabilitation as an activity separate from rewetting is not covered by this chapter. This chapter does not provide default guidance for the management of undrained inland organic soils or for restoration that does not necessitate rewetting.

The position of the water table is a major control of the biogeochemical processes responsible for GHG fluxes from wetlands (Reddy & DeLaune 2008, pages 162-163). Generally, rewetting decreases $CO_2$ emissions from organic soils compared to the drained condition, and under certain conditions leads to the recovery of a net ecosystem $CO_2$ sink (Komulainen *et al.*, 1999; Tuittila *et al.*, 1999; Waddington *et al.*, 2010). Re-establishing the vegetation cover on rewetted organic soils is necessary to reinstate the carbon sink function that ultimately leads to soil C sequestration. After a vegetation succession promoted by rewetting, the $CO_2$ sink may reach the level typical of undrained ecosystems. However, during the first years after rewetting a site can remain a $CO_2$ source (Petrone *et al.*, 2003; Waddington *et al.*, 2010); upon restoration the ecosystem sink can temporarily be significantly larger (Soini *et al.*, 2010,Wilson *et al.*, 2013). The time needed for the recovery of the sink function may vary from years to several decades (Tuittila *et al.*, 1999, Samaritani *et al.*, 2011) depending on restoration methods and pre-rewetting and climate conditions.

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. If all the other conditions (e.g. vegetation composition, site fertility) are equal, $CH_4$ emissions from rewetted sites are generally comparable to undrained sites after the first years following rewetting as shown later in this chapter. In temperate regions $N_2O$ emissions are found to rapidly decrease close to zero after rewetting (Augustin & Merbach, 1998; Wilson *et al.*, 2013).

Carbon is also lost from rewetted organic soils via water mainly in a form of dissolved organic carbon (DOC). Most of this carbon is eventually released into the atmosphere as $CO_2$. Rewetting is thought to decrease DOC leaching to a level comparable with undrained organic soil.

Generally the likelihood of fire occurrence in rewetted ecosystems is low, but real. The reader is referred to the default approach provided in Chapter 2 of this supplement to quantify this source of emissions for all GHGs.

High spatial variation in microtopography, water level and vegetation cover is typical of undrained organic soils and is also observed in GHG fluxes (Strack *et al.*, 2006; Laine *et al.*, 2007; Riutta *et al.*, 2007; Maanavilja *et al.*, 2011). Rewetting recreates this natural heterogeneity with blocked ditches forming the wetter end of the variation (Strack & Zuback, 2013; Maanavilja *et al.*, submitted). For this reason, in this chapter, (and in contrast to the approach in Chapter 2), former ditches are included as a part of rewetted sites and not treated separately.

### Scope of this guidance: wetland types covered, gases, pools

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

The distinction between C pools in some wetland ecosystems 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. The non-woody biomass on rewetted organic soils cannot be ignored as it is essential in the restoration of the carbon sink function that in turn results in the sequestration over time of large quantities of soil carbon. Because the default emission factors in this chapter were all derived from flux measurements over wetlands on organic soils with moss and/or herbaceous vegetation and/or dwarf shrubs, these default EFs integrate all C fluxes from the soil and the above- and belowground vegetation components other than trees. In all cases the guidance in this chapter will clarify which C pools are included in default EFs.

In this chapter boreal and temperate organic soil wetlands are divided into "nutrient poor" and "nutrient rich" categories (Rydin & Jeglum, 2006). Most nutrient poor wetlands, whether undrained or rewetted, receive water and nutrients from precipitation only, while nutrient rich wetlands also receive water from their surroundings.

Tropical wetlands on organic soils include a great variety of contrasting ecosystems, from papyrus dominated sites in Africa to peat swamp forests in South East Asia. In general much less information is available for wetlands on organic soils in tropical regions than in temperate or boreal regions.

Rewetting activities in tropical regions have been reported from the USA, South Africa and Indonesia. 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 organic soils in tropical regions has been demonstrated, flux data from such sites are lacking. Therefore, a default EF for rewetted tropical organic soils was developed based on surrogate data. It is *good practice*, where significant areas of tropical organic soils have been rewetted, to develop science-based, documented, country-specific emission factors for $CO_2$, $CH_4$ and $N_2O$ emissions.

As in the *2006 IPCC Guidelines*, guidance is provided for three GHGs: $CO_2$, $CH_4$ and $N_2O$.

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

Depending on circumstances and practices, rewetting may or may not involve a change in land use. Hence pre- and post-rewetting land use of organic soils can vary according to national circumstances, and be reported as Forest Land, Cropland, Grassland, Wetlands or Settlements. The guidance in this chapter should be applied regardless of the reporting categories. In particular, no recommendation is provided in relation to transition periods between land-use categories; countries can apply the existing transition period of appropriate land-use categories to rewetted organic soils. Because the functioning of these ecosystems has already been deeply altered due to management, reporting rewetted organic soils as unmanaged land is not consistent with *good practice*.

## 3.2 GREENHOUSE GAS EMISSIONS AND REMOVALS

Equation 2.3 in Chapter 2, Volume 4 of the *2006 IPCC Guidelines* illustrates how in general 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 for the soil pool term $\Delta C_{so}$ of equation 2.3 - in particular for water-saturated organic soils. When practices for the rewetting of organic soils also involve C stock changes in woody biomass or dead organic matter (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 soils, regardless of the ultimate goal of the rewetting activity (e.g. restoration or other land management practices).

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 undrained or rewetted organic soils can accumulate soil organic carbon if covered with vegetation.

Assuming that rewetting is successful in establishing the C sink function, the rewetted organic soils can gain substantial quantities of carbon. Equation 3.1 reflects the fact that the net C stock change of rewetted organic 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 soils, net $CO_2$ emissions (or removals via uptake by vegetation) 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*.

**EQUATION 3.1**
**NET GAINS OR LOSSES OF C RESULTING FROM THE BALANCE BETWEEN $CO_2$ AND $CH_4$ EMISSIONS AND REMOVALS**

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

Where:

$\Delta C_{\text{rewetted org soil}}$ = Net C gain or loss in rewetted organic soils (tonnes C $yr^{-1}$)

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

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

The notations $CO_2$-C and $CH_4$-C will facilitate reconciling net fluxes with C stock changes for estimation purposes. However, the reporting convention remains that used in the *2006 IPCC Guidelines*, where emissions and removals of $CO_2$ are reported as C stock changes, and emissions and removals of $CH_4$ in tonnes of $CH_4$. $CH_4$-C is converted to $CH_4$ using Equation 3.2.

**EQUATION 3.2**
**NET $CH_4$ FLUX**

$$CH_{4\ \text{rewetted org soil}} = CH_4\text{-}C_{\text{rewetted org soil}} \cdot 16/12$$

Where:

$CH_{4\ \text{rewetted org soil}}$ = net flux of $CH_4$ from the rewetted organic soil (tonnes $CH_4$ $yr^{-1}$)

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

## 3.2.1 $CO_2$ emissions/removals from rewetted organic soils

$CO_2$-C emissions/removals from rewetted organic soils have the following components:

**EQUATION 3.3**
**$CO_2$-C EMISSIONS/REMOVALS FROM REWETTED ORGANIC SOILS**

$$CO_2\text{-}C_{\text{rewetted org soil}} = CO_2\text{-}C_{\text{composite}} + CO_2\text{-}C_{DOC} + L_{fire}\text{-}CO_2\text{-}C$$

Where:

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

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

$CO_2\text{-}C_{DOC}$ = off-site $CO_2$-C emissions from dissolved organic carbon exported from rewetted organic soils, tonnes C $yr^{-1}$

$L_{fire}\text{-}CO_2\text{-}C$ = $CO_2$-C emissions from burning of rewetted organic soils, tonnes C $yr^{-1}$

### On-site emissions/removals: $CO_2$- $C_{composite}$

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

Consistent with the *2006 IPCC Guidelines*, the Tier 1 or default approaches assume that the woody biomass and woody DOM stocks and fluxes are zero on all lands except on Forest Land and on Cropland with perennial woody biomass. For rewetting on Forest Land or on Cropland with woody crops, the woody biomass and woody DOM pools 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, 2.8 and the subsequent equations in Chapter 2 of the *2006 IPCC Guidelines* which split the C stock changes in the biomass pool or $\Delta C_B$ into the various gains and losses components, including harvest and fires.

If rewetting is accompanied by a change in land use that involves Forest Land 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 Section 2.3.1.2, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*). These changes occur mostly 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 Land), Chapter 5 (Cropland) and Chapter 2 (Table 2.2 for forest litter) in Volume 4, of the *2006 IPCC Guidelines*.

### Off-site $CO_2$ emissions: $CO_2$-$C_{DOC}$

The importance of waterborne carbon export (in all its different forms) as a pathway linking the organic soil C pool to the atmosphere is described in Chapter 2 of this supplement and the various sources, behaviour and fate of the different forms of waterborne C following rewetting can be found in Annex 3A.2. In all types of organic soils, including natural and 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. It is therefore *good practice* to include DOC in flux-based carbon estimation methods to avoid under-estimation of soil C losses. $CO_2$-$C_{DOC}$ is produced from the decomposition of dissolved organic carbon (DOC) lost from organic soils via aquatic pathways and results in off-site $CO_2$ emissions; a Tier 1 methodology is described below. Other forms of waterborne carbon (Particulate Organic Carbon and dissolved $CO_2$) may also be significant in the early years following rewetting but few data exist (see Annex 3A.2). It should be noted also that although generally not significant, DOC imports (e.g. from precipitation) should in theory be removed from net DOC fluxes.

### Emissions from burning: $L_{fire}$-$CO_2$-C

While the likelihood of fires on rewetted organic soils is considered low (particularly in comparison to drained organic soils), fire risk may still be real. Any emissions from the burning of biomass, dead organic matter as well as from soil ($L_{fire}$-$CO_2$-C) should be included. Generic methodologies for estimating $CO_2$ 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 4-7 in Volume 4 of the *2006 IPCC Guidelines*. Emissions from the burning of organic soils can be estimated following the methodologies in Equation 2.8 of Chapter 2 (this supplement) using the fuel consumption values estimated for undrained organic soils given in Table 2.6 (same value for all climates) as well as emission factors from Table 2.7.

## CHOICE OF METHOD

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

### Tier 1

Under Tier 1, the basic methodology for estimating annual C emissions/removals from rewetted organic soils was presented in Equation 3.3 and can be compiled using Equations 3.4 and 3.5 where the nationally derived area of rewetted organic soils is multiplied by an emission factor, which is disaggregated by climate zone and where applicable by nutrient status (nutrient poor and nutrient rich).

Tier 1 methodology is applicable from the year of rewetting.

**EQUATION 3.4**

**ANNUAL ON-SITE $CO_2$-C EMISSIONS/REMOVALS FROM REWETTED ORGANIC SOILS**

$$CO_2\text{-}C_{composite} = \sum_{c,\,n} \left( A \cdot EF_{CO_2} \right)$$

Where:

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

$A_{c,n}$ = area of rewetted organic soils in climate zone *c* and nutrient status *n*, ha

$EF_{CO_2\,c,n}$ = $CO_2$-C emission factor for rewetted organic soils in climate zone *c*, nutrient status *n,* tonnes C $ha^{-1}$ $yr^{-1}$

**EQUATION 3.5**

**ANNUAL OFF-SITE $CO_2$-C EMISSIONS DUE TO DOC LOSSES FROM REWETTED ORGANIC SOILS**

$$CO_2\text{-}C_{DOC} = \sum_{c} \left( A \cdot EF_{DOC\_REWETTED} \right)$$

Where:

$CO_2\text{-}C_{DOC}$ = off-site $CO_2$-C emissions from dissolved organic carbon exported from rewetted organic soils, tonnes C $yr^{-1}$

$A_c$ = area of rewetted organic soils in climate zone *c*, ha

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

### Tier 2

A Tier 2 methodology uses 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 which is a representation of the water table depth and soil properties or by land use prior to rewetting (e.g. Forest, Grassland, Cropland, Wetland).

Available datasets from rewetted 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 soil oxidation rates are low as a consequence of the anoxic conditions, while most of the newly sequestered C is still contained within the non-woody biomass pool (leaves, stems, and roots). Over longer time frames (a few decades) a decrease in the amount of $CO_2$ that is sequestered annually might be expected as the biomass pool eventually approaches a steady state C sequestration saturation point typical of natural, undrained organic soils. Countries are encouraged to develop more detailed EFs for rewetted 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 organic soils. In particular, countries with a significant non-vegetated (bare organic soil) component (e.g. industrial cutaways or cutovers) at the time of rewetting are encouraged to develop detailed EFs that capture the expected decline in $CO_2$ emissions following rewetting (e.g. Tuittila *et al.*, 1999; Bortoluzzi *et al.*, 2006; Kivimaki *et al.*, 2008; Waddington *et al.*, 2010; Wilson *et al.*, 2013).

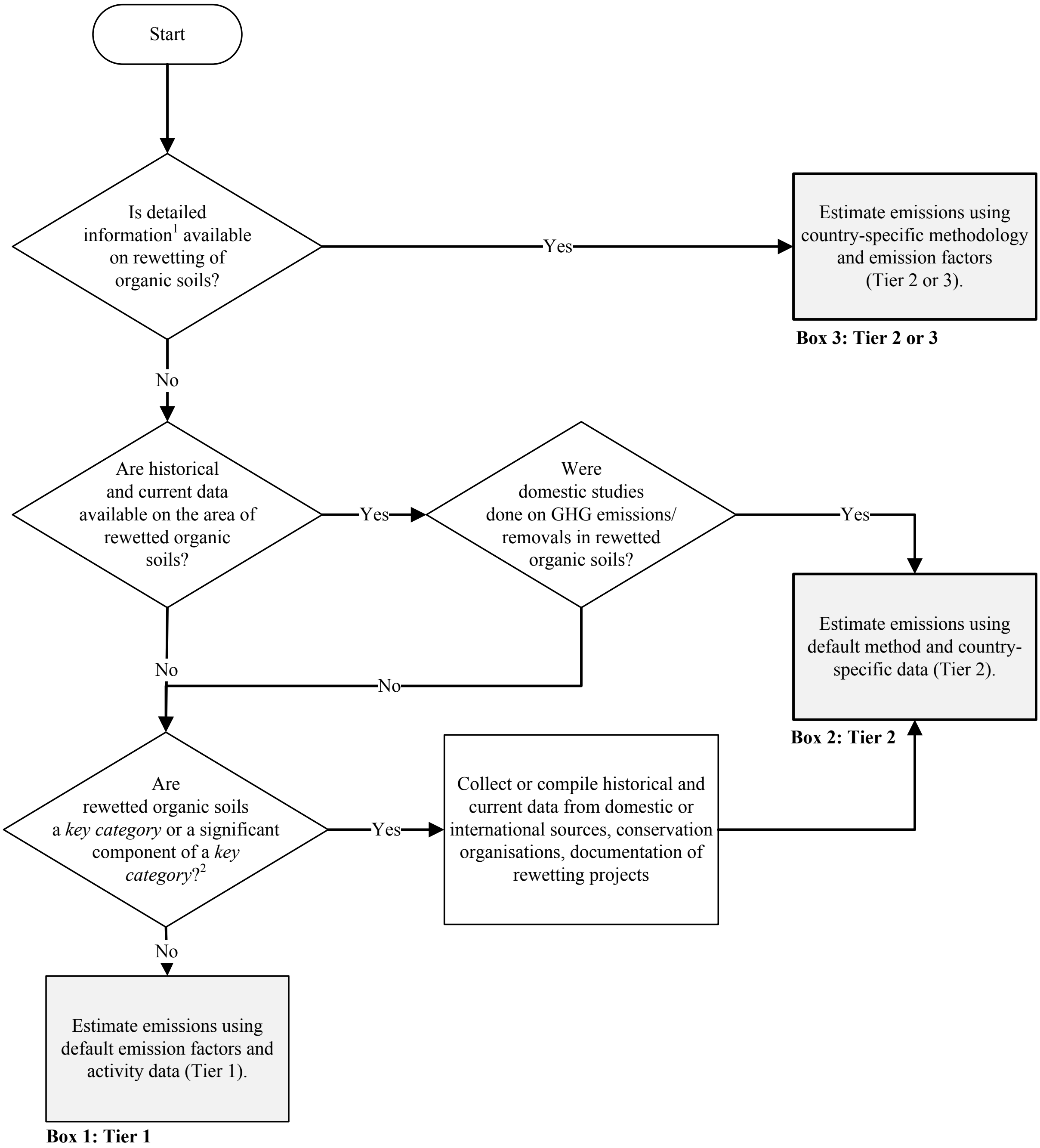
A Tier 2 methodology to derive an estimation of emissions from the decomposition of DOC should utilise country-specific information if experimental data are available to refine the emission factor, especially with regard to different types of natural/undrained and rewetted organic soils (e.g. peatlands with various nutrient status and development, such as raised bogs, blanket bogs, fens). Refined approaches to calculate $EF_{DOC}$ are suggested below under Choice of EF: $EF_{DOC\_rewetted}$. On-site flux measurements will not capture C losses as DOC so it is *good practice* to explicitly add C losses as DOC to flux-based C estimation methods. If a soil subsidence approach is used to derive $CO_2\text{-}C_{composite}$ of Equation 3.3, DOC losses are included in the subsidence data and should not be added a second time.

Tier 2 (as well as Tier 3) methodologies may capture changes in the woody biomass pool as fluxes instead of separately reported stock changes; in such cases the woody biomass component is integrated with the other components of Equation 3.3. 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 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.

### Tier 3

A Tier 3 methodology involves a comprehensive understanding and representation of the dynamics of $CO_2$-C emissions and removals on rewetted organic soils, including the effect of site characteristics, soil characteristics, 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 for examples of such models). These parameters, in addition to further parameters such as water flows and residence time of water, could also be used to describe fluvial C (DOC) lost from the system using process-based models that incorporate hydrology amongst other factors. A Tier 3 methodology 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 techniques used.

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



Note:

1. Detailed information typically includes national area of rewetted organic soils disaggregated by climate and nutrient status, complemented with documentation on previous land management and rewetting practices, and with associated measurements of GHG emissions and removals at high spatial and temporal 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 be performed at the level of land remaining in or converted to a land-use category. If $CO_2$ or $CH_4$ emissions/removals from rewetted organic soils are subcategories to a *key category*, these subcategories should be considered significant if they individually account 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

### $EF_{CO_2}$

### 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 zone (boreal, temperate, tropical) and for boreal and temperate organic soils only, by nutrient status (nutrient poor and nutrient rich).

Nutrient poor organic soils predominate in boreal regions, while in temperate regions nutrient rich sites are more common. In some cases, nutrient poor soil organic layers are underlain by nutrient rich layers; in some situations, after industrial extraction of the nutrient poor top layers the rewetted residual soil layers may be considered nutrient rich due to the influence of incoming water and the high nutrient status of the bottom layers.

If the nutrient status of rewetted organic soils in boreal or temperate zones is not known, countries should use the default nutrient poor EF for sites in the boreal zone, and nutrient rich EF for sites in the temperate zone (Table 3.1).

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 and rewetted organic soils 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 group and the rewetted group. These conclusions were also valid when the analysis was performed for sites 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. There is currently insufficient evidence to support the use of different default EF values for different site conditions, previous land-use or time since rewetting.

Since no data are available for rewetted tropical organic soils, a default EF of zero is provided; this value is supported by observations in undrained sites and reflects the fact that successful rewetting effectively reduces the decay of soil organic matter stops the oxidation of soil organic material, but does not necessarily re-establish a soil C sequestration function (see Annex 3A.1).

**TABLE 3.1**
**DEFAULT EMISSION FACTORS ($EF_{CO_2}$) AND ASSOCIATED UNCERTAINTY, FOR $CO_2$-C FROM REWETTED ORGANIC SOILS (ALL VALUES IN TONNES $CO_2$-C $ha^{-1}$ $yr^{-1}$).**

| Climate zone | Nutrient status | $EF_{CO_2}$ | 95% range |
|---|---|---|---|
| Boreal* | Poor | -0.34 (n=26) | -0.59 – -0.09 |
| | Rich | -0.55 (n=39) | -0.77 – -0.34 |
| Temperate** | Poor | -0.23 (n=43) | -0.64 – +0.18 |
| | Rich | +0.50 (n=15) | -0.71 – +1.71 |
| Tropical*** | | 0 | |

Note: Negative values indicate removal of $CO_2$-C from the atmosphere. n = number of sites. 95% confidence interval is used to give the 95% range.

* Emission factors for boreal rewetted organic soils derived from the following source material (see Annex 3A.1 for details): Bubier *et al*., 1999; Komulainen *et al*., 1999; Soegaard & Nordstroem, 1999; Tuittila *et al*., 1999; Waddington & Price, 2000; Waddington & Roulet, 2000; Alm *et al*., 1997; Laine *et al*., 1997; Suyker *et al*., 1997; Whiting & Chanton, 2001; Heikkinen *et al*., 2002; Harazono *et al*., 2003; Nykänen *et al*., 2003; Yli-Petäys *et al*., 2007; Kivimäki *et al*., 2008; Nilsson *et al*., 2008; Sagerfors *et al*., 2008; Aurela *et al*., 2009; Drewer *et al*., 2010; Soini *et al*., 2010; Maanavilja *et al*., 2011.

**Emission factor for temperate rewetted organic soils derived from the following source material but is not significantly different from zero (see Annex 3 A.1 for details): Shurpali *et al*., 1995; Lafleur *et al*., 2001; Wickland, 2001; Aurela *et al*., 2002; Schulze *et al*., 2002; Petrone *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; Augustin & Chojnicki, 2008; Cagampan & Waddington, 2008; Golovatskaya & Dyukarev, 2009; Kurbatova *et al*., 2009; Drewer *et al*., 2010; Waddington *et al*., 2010; Adkinson *et al*., 2011; Augustin *et al*. in Couwenberg *et al*., 2011; Koehler *et al*., 2011; Christensen *et al*., 2012; Urbanová, 2012; Strack & Zuback, 2013; Drösler *et al*., 2013; Herbst *et al*., 2013; Wilson *et al*., 2013.

***For tropical rewetted organic soils where decayed organic material is not oxidised due to saturated conditions.

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

The default EF of rewetted tropical organic soils applies to sites where water saturation prevents further oxidation of the soil organic matter. Due to the lack of published scientific literature on $CO_2$ fluxes from rewetted tropical organic soils, the emission factor was derived from undrained tropical organic soils (Annex 3A.1). When rewetted tropical organic soils are a significant component of a *key category*, it is *good practice* to use country-specific EFs as opposed to the default EF in Table 3.1.

### Tier 2 and 3

Countries applying Tier 2 methods should use 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 properties including soil temperature, mean water table depth) and biotic (e.g. vegetation composition) factors that drive $CO_2$ dynamics in rewetted organic soils. Subsidence measurements can also be used to determine the medium to long term losses/gains from rewetted organic soils. Emission factors could be developed further by taking into account other factors, such as ‘previous land use’ 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 organic soils and the atmosphere should develop country-specific methods that reflect C stock changes in the tree biomass and tree DOM pools under typical management practices and their interaction with the soil pool. Guidance can be found in Chapter 2, 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 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). Woody biomass is not accounted for in this chapter and care should be taken to avoid double-counting when using whole ecosystem data (e.g. eddy covariance measurements). Tier 3 methodologies may 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 which require a higher level of information of processes than required in Tier 2. It is *good practice* to ensure that the models are calibrated and validated against field measurements (Chapter 2, Volume 4, *2006 IPCC Guidelines*).

## $EF_{DOC\_rewetted}$

### Tier 1

Data show that natural/undrained organic soils export some DOC and these fluxes increase following drainage (see Chapter 2 in this supplement). Available data from rewetted sites is scant but suggest that the level of DOC reduction after rewetting approximately equates to the DOC increase after drainage (Glatzel *et al.*, 2003; O’Brien *et al.*, 2008; Waddington *et al.*, 2008; Armstrong *et al.*, 2010; Strack and Zuback, 2013; Turner *et al.*, 2013). 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 organic soils have been calculated using data from natural/undrained sites as well as from rewetted ones following Equation 3.6:

**EQUATION 3.6**
**EMISSION FACTOR FOR ANNUAL EMISSIONS OF C AS $CO_2$ DUE TO DOC EXPORT FROM REWETTED ORGANIC SOILS**

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

Where:

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

$DOC_{FLUX}$ = Net flux of DOC from natural (undrained) and rewetted organic soils , tonnes C $ha^{-1}$ $yr^{-1}$

$Frac_{DOC\_CO_2}$ = Conversion factor for proportion of DOC converted to $CO_2$ following export from site and equates to 0.9

A detailed description of the derivation of default values for Tier 1 is provided in Annex 2A.3. In summary, data show clear differentiation of natural DOC fluxes between boreal, temperate and tropical organic soils. Therefore, the $DOC_{FLUX}$ values were calculated for each climate zone integrating data from rewetted sites where available (all DOC fluxes measured from rewetted sites were located in the temperate zone). The current data did not support disaggregation by nutrient status. The parameter $Frac_{DOC\_CO_2}$ sets the proportion of DOC exported from organic soils that is ultimately emitted as $CO_2$. An understanding of the fate of DOC export, i.e. whether it is returned to the atmosphere as $CO_2$ (or $CH_4$), is still poor but the form and amount are of significance in terms of GHG reporting. 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.3 for discussion). Reflecting this current scientific uncertainty, a Tier 1 default $Frac_{DOC\_CO_2}$ value of 0.9 is proposed, with an uncertainty range of 0.8 to 1.

$EF_{DOC\_REWETTED}$ values are provided in Table 3.2 and the derivation of these values is fully described in Annex 3A.2.

**TABLE 3.2**
**DEFAULT DOC EMISSION FACTORS ($EF_{DOC\_REWETTED}$ IN TONNES $CO_2$-C $HA^{-1}$ $YR^{-1}$) FOR REWETTED ORGANIC SOILS**

| Climate zone | $DOC_{FLUX}$ (tonnes C $ha^{-1}$ $yr^{-1}$) | Number of sites | $EF_{DOC\_REWETTED}$ (tonnes $CO_2$-C $ha^{-1}$ $yr^{-1}$) |
|---|---|---|---|
| Boreal* | 0.08 (0.06 – 0.11) | 10 undrained | 0.08 (0.05 – 0.11) |
| Temperate** | 0.26 (0.17 – 0.36) | 12 undrained and 3 rewetted | 0.24 (0.14 – 0.36) |
| Tropical*** | 0.57 (0.49 – 0.64) | 4 undrained | 0.51 (0.40 – 0.64) |

Values in parentheses represent 95% confidence intervals.

*Derived from the following source material (see Annex 3 A.2 for details): Koprivnjak & Moore, 1992; Moore *et al*., 2003; Kortelainen *et al*., 2006; Agren *et al*., 2008; Nilsson *et al*., 2008; Jager *et al*., 2009; Rantakari *et al*., 2010; Juutinen *et al*., 2013.

**Derived from the following source material (see Annex 3 A.2 for details): Urban *et al*., 1989; Kolka *et al*., 1999; Clair *et al*., 2002; Moore *et al*., 2003; Dawson *et al*., 2004; Roulet *et al*., 2007; O'Brien *et al*., 2008; Strack *et al*., 2008; Waddington *et al*., 2008; Koehler *et al*., 2009; 2011; Billett *et al*., 2010; Dinsmore *et al*., 2011; Di Folco & Kirkpatrick, 2011; Turner *et al*., 2013; Strack & Zuback, 2013.

***Derived from the following source material (see Annex 3 A.2 for details): Zulkifli, 2002; Alkhatib *et al*., 2007; Baum *et al*., 2007; Yule *et al*., 2009; Moore *et al*., 2013.

### 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:

- Use of country-level measurements from natural and rewetted organic soils to obtain more accurate values of $DOC_{FLUX}$ 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 types of natural and rewetted organic soils (nutrient rich versus nutrient poor and for example raised bogs as well as blanket bogs).
- Use of country-level measurements from rewetted organic soils with various restoration techniques and initial status (peat degradation, previous land use) as well as time since rewetting. When sufficient long-term direct measurements of DOC fluxes from rewetted organic soils have been gathered, this could be used solely in Equation 3.6 to replace $DOC_{FLUX}$ values with $DOC_{FLUX\ REWETTED}$ thus replacing the default assumption that rewetted organic soils revert to pre-drainage DOC fluxes.
- Use of alternative values for the conversion factor $Frac_{DOC\_CO_2}$ where evidence is available to estimate the proportion of DOC exported from rewetted organic soils that is transferred to stable long-term carbon stores, such as lake or marine sediments.

### Tier 3

A Tier 3 methodology might include the use of process models that describe DOC release as a function of hydrology (in particular discharge), vegetation composition, nutrient levels, water table level, as well as temporal variability in DOC release in the years following rewetting and on-going management activity. Differences in DOC fluxes between undisturbed and rewetted organic soils could occur due to the presence or absence of vegetation on rewetted sites, the land-use category prior to rewetting, soil properties (fertility), vegetation composition that differs from the undisturbed organic soils or factors associated with restoration techniques, such as the creation of pools, the application of mulch to support vegetation re-establishment, or the use of biomass to infill ditches.

## 3.2.2 $CH_4$ emissions/removals from rewetted organic soils

$CH_4$ emissions and removals from the soils of rewetted organic soils result from 1) 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 3.7).

**EQUATION 3.7**

**$CH_4$-C EMISSIONS/REMOVALS FROM REWETTED ORGANIC SOILS**

$$CH_4\text{-}C_{rewetted\ org\ soil} = CH_4\text{-}C_{soil} + L_{fire}\text{-}CH_4\text{-}C$$

Where:

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

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

$L_{\text{fire}}\text{-}CH_4\text{-}C$ = emissions of $CH_4$-C from burning of rewetted organic soils, tonnes C $yr^{-1}$

The default EFs provided in this section will only cover $CH_4\text{-}C_{\text{soil}}$. These $CH_4$ emissions result from the decomposition of the organic soil by microbes under anaerobic conditions and are strongly controlled by oxygen availability within the soil and by soil temperature. Methane emissions also originate from the decay of non-tree vegetation, since these pools cannot be easily separated on organic soils they are combined here as $CH_4\text{-}C_{\text{soil}}$.

The probability of fire occurrence in rewetted organic soils 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 ($L_{\text{fire}}\text{-}CH_4\text{-}C$) should be estimated using the guidance provided in Section 2.2.2.3 of this supplement applying the fuel consumption value for wildfire on undrained organic soil (Table 2.6) and $CH_4$ emission factors given in Table 2.7. The EF of Table 2.7 should be multiplied by 12/16 to obtain tonnes of $CH_4$-C $yr^{-1}$.

Care should be taken to report fire emissions only once 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 organic soils.

### Tier 1

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

As in Section 3.2.1, the basic approach makes no distinction on the basis of the objectives of site rewetting (restoration or other management activities). In addition, as in Section 3.2.1 the Tier1 methodology assumes there is no transient period for rewetted organic soils and therefore default EFs are applicable from the year of rewetting.

EQUATION 3.8

ANNUAL $CH_4$-C EMISSIONS FROM REWETTED ORGANIC SOILS

$$CH_4\text{-}C_{soil} = \frac{\sum_{c,n}\left(A \cdot EF_{CH_4\,soil}\right)_{c,n}}{1000}$$

Where:

$CH_4$-$C_{soil}$ = $CH_4$ -C emissions from rewetted organic soils, tonnes C $yr^{-1}$

$A_{c,n}$ = area of rewetted organic soils in climate zone c and nutrient status n, ha

$EF_{CH_4\,soil}$ = emission factor from rewetted organic soils in climate zone c and nutrient status n, kg $CH_4$-C $ha^{-1}$ $yr^{-1}$

Rewetted areas should be subdivided by climate zone (boreal, temperate or tropical) and the appropriate emission factors should be 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 Southeast 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 organic soils, for example the *Papyrus* marshes of Africa or the peatlands of Panama, the Guianas and other parts of the Americas, are lacking. When information is available on the nutrient status of the organic soil, it is recommended to further subdivide the 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 and 3

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 organic soils 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. Nevertheless, use of the mean value will give an unbiased estimate of total emissions from the area in question. For countries where rewetted organic soils are a significant component of a *key category* it is *good practice* to develop EFs based on measurements or experiments within the country and thus contribute to better scientific understanding of $CH_4$ effluxes from rewetted organic soils. Possible factors to consider for disaggregation of rewetted organic soil area include water table depth, the prior land use, time since rewetting, and the presence/absence of vegetation cover and of ditches (see Box 3.1).

### BOX 3.1
### CONTROLS ON $CH_4$ EMISSIONS FROM REWETTED ORGANIC SOILS

$CH_4$ fluxes from organic soils strongly depend on the depth of the water table (Annex 3A.3). Both low and high flux values have been observed from saturated organic soils (Augustin & Chojnicki, 2008; 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.

Prior land use (e.g. agriculture, peat extraction, forestry) can influence $CH_4$ fluxes from rewetted 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 to monitor emissions/removals of $CH_4$ from rewetted organic soils to evaluate this effect.

As noted in Chapter 2, emissions of $CH_4$-C from drainage ditches can be much higher than the surrounding drained fields. Few data are available on $CH_4$-C emissions from ditches of rewetted organic soils and in some cases ditches are filled during rewetting activities. Moreover, rewetting reduces the hydrological differences between fields and neighboring ditches creating a more homogeneous surface from which $CH_4$ is emitted/removed. In some cases rewetting 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 remaining ditches.

The number of long-term rewetting studies is limited and changes in $CH_4$ flux over time remain unclear. Research on restored cutover peatlands in Canada indicates a steady increase in $CH_4$ emissions in the years immediately after rewetting as the emerging vegetation cover provides fresh substrates for $CH_4$ production (Waddington and Day, 2007). In contrast, rewetting of intensively used 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 (Limpens *et al.* 2008). 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 organic soils 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; Marinier *et al.*, 2004; Tuittila *et al.*, 2000; Wilson *et al.*, 2009; 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 significant effect on $CH_4$ efflux from organic soils (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 organic soils has thus far remained unstudied.

A Tier 3 approach involves a comprehensive understanding and representation of the dynamics of $CH_4$ emissions on rewetted organic soils, including the representation of interactions between the dominant drivers of $CH_4$ dynamics, as described above and potentially addressing different flux pathways, including ebullition (Strack *et al.*, 2005). Possible methods include detailed country-specific monitoring of $CH_4$-C emissions/removals across rewetted organic soils representing a variety of water table positions, prior land use and time since rewetting.

$CH_4$ 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 zone (boreal, temperate, tropical) and nutrient status (nutrient poor, rich). If the nutrient status of rewetted organic soils in boreal or temperate zones is not known, countries should use the default nutrient poor EF for sites in the boreal zone, and the nutrient rich EF for sites in the temperate zone The emission factor for rewetted tropical 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 ORGANIC SOILS**
**(ALL VALUES IN KG $CH_4$-C HA$^{-1}$ YR$^{-1}$)**

| Climate zone | Nutrient Status | $EF_{CH_4}$ | 95% range |
|---|---|---|---|
| Boreal* | Poor | 41 (n=39 sites) | 0.5 – 246 |
| | Rich | 137 (n=35 sites) | 0 – 493 |
| Temperate** | Poor | 92 (n=42 sites) | 3 – 445 |
| | Rich | 216 (n=37 sites) | 0 – 856 |
| Tropical*** | | 41 (n=11 sites) | 7 – 134 |

* Derived from the following source material (see Annex 3 A.3 for details): Alm *et al*., 1997; Bubier *et al*., 1993; Clymo & Reddaway, 1971; Drewer *et al*., 2010; Gauci *et al*., 2002; Juottonen *et al*., 2012; Komulainen *et al*., 1998; Laine *et al*., 1996 ; Nykänen *et al*., 1995; Tuittila *et al*., 2000; Urbanová *et al*., 2012; Verma *et al*., 1992; Waddington & Roulet, 2000; Whiting & Chanton, 2001; Yli-Petäys *et al*., 2007; Strack & Zuback, 2013.

** Augustin & Merbach, 1998; Augustin, 2003; Augustin *et al*., 1996; Augustin in Couwenberg *et al*., 2011; Bortoluzzi *et al*., 2006; Cleary *et al*., 2005; Crill in Bartlett & Harris, 1993; Dise & Gorham, 1993; Drösler, 2005; Drösler *et al*., 2013; Flessa *et al*., 1997; Glatzel *et al*., 2011; Harriss *et al*., 1982; Hendriks *et al*., 2007; Jungkunst & Fiedler, 2007; Koehler *et al*., 2011; 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, 2001; Wild *et al*., 2001; Wilson *et al*., 2009, 2013; Beetz *et al*., 2013.

*** Derived from the following source material from undrained sites (see Annex 3 A.3 for details): Furukawa *et al*., 2005; Hadi *et al*., 2001, 2005; Inubushi *et al*., 1998; Jauhiainen *et al*., 2001, 2004, 2005, 2008; Melling *et al*., 2012; Pangala *et al*., 2012.

### Tier 2 and 3

It is *good practice* to develop country-specific emission factors for each climate zone and nutrient status. Differences in water table position explain a large proportion of variation in annual CH4 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 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, Taro or reed plantations on wet organic soils where the scientific evidence is insufficient to support a globally applicable EF. Where such practices are nationally 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.*, 2009; Chimner & Ewel 2004), taking into account water table dynamics. Emission factors for rice cropping on organic soils should follow the guidance provided in the *2006 IPCC Guidelines*.

## 3.2.3 $N_2O$ emissions from rewetted organic soils

The emissions of $N_2O$ from rewetted 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). Saturated conditions may promote denitrification and the consumption of $N_2O$, but in practice this effect is very small and considered negligible in this chapter. This is because anoxic conditions and low $NH_4^+$ availability reduce the rates of mineralisation and nitrification, two processes that are prerequisites for denitrification.

Equation 3.9 includes the essential elements for estimating $N_2O$ emissions from rewetted organic soils:

**EQUATION 3.9**
**$N_2O$-N EMISSIONS FROM REWETTED ORGANIC SOILS**

$$N_2O_{rewetted\ org\ soil}\text{-}N = N_2O_{soil}\text{-}N + L_{fire}\text{-}N_2O\text{-}N$$

Where:

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

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

$L_{fire}$-$N_2O$-N = $N_2O$-N emissions from burning of rewetted 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 4-7, Volume 4 in the *2006 IPCC Guidelines*. If rewetting practices involve burning, $N_2O$ emissions from the burning of organic soils should in theory be estimated. Published data are insufficient to develop default $N_2O$ emission factors for the burning of organic soils (See Chapter 2 in this supplement); therefore $L_{fire}$-$N_2O$-N of Equation 3.9 is not considered in this section.

### Tier 1

Under Tier 1, emissions of nitrous oxides from rewetted soils are assumed to be negligible (Hendriks *et al.*, 2007; Wilson *et al.*, 2013).

### Tier 2 & 3

Countries where rewetted organic soils are a significant component of a *key category* 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.

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.*, 2005; 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*). $N_2O$ emissions from soil fires on rewetted organic soils should be estimated on the basis of scientific evidence.

## 3.2.4 Choice of activity data

All methodological Tiers require data on areas of rewetted organic soils, broken down by climate zone and nutrient status (nutrient poor or nutrient rich) as appropriate. This section clarifies further data requirements and suggests potential data sources.

Activity data used in the calculations can be obtained from various sources: scientific publications, databases and soil map references, reports on rewetting projects, official communications. This information may have been developed in government agencies, conservation organizations, research institutions and industry, subject to any confidentiality considerations. It is *good practice*, when collecting activity data, to also obtain protocols 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.

### Tier 1

The default methodology assumes that a country has data on the area of rewetted organic soils, the nutrient status of organic soils in temperate and boreal climates, and basic information on rewetting practices – such as the duration of the phase without vegetation and any remnant ditches - consistent with the guidance above on the applicability of default emission factors.

Rewetted organic soils have been previously drained. A potential first step to determine the occurrence and location of rewetted organic soils is to investigate historical information on drained organic soils; chapter 2 provides guidance to identify such information.

Depending on national circumstances, it may be more effective to directly identify rewetted organic soils. The data can be obtained from domestic soil statistics and databases, spatial or not, 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. 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. Information relative to rewetting practices is more likely available from regional practitioners, either in extension services, conservation organizations or environmental engineering firms. 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 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.

Remote sensing can also be used for wet area detection and mapping of vegetation type, biomass, and other characteristics. Time series of remotely-sensed imagery (e.g. aerial photography, satellite imagery etc.) can assist in the detection of rewetted organic soils and in the determination of time since rewetting. Such imagery may be produced either by research institutes, departments or agencies, 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; FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria). Inventory compilers 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 as a single rewetting for the area in question.

### Tier 2

Tier 2 mehodology 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 demonstrate significant differences in GHG fluxes among the proposed categories. At Tier 2, higher spatial resolution of activity data is expected 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 are 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 aerial photographs or satellite imagery may also be useful. Further guidance can be found in Chapter 3, Volume 4 of the *2006 IPCC Guidelines.*

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 succession 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 GHG emissions or removals to these factors. Depending on climate and site conditions, it may be appropriate to assess variations in water table depth over annual, seasonal, monthly or even weekly period; the development of cost-effective higher tier methods may involve both monitoring and modelling of water table variations over time.

#### 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 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 by a long-term financial commitment for update and maintenance.

### 3.2.5 Sources of uncertainty

Uncertainty in estimated GHG emissions/removals from rewetted organic soils will arise from uncertainties in EFs and other parameters, uncertainties in activity data, and model structure/parameter error for Tier 3 model-based methods. Further guidance on error estimation and the combination of errors is given in Volume 1, Chapter 3 of the *2006 IPCC Guidelines*.

For Tier 1, uncertainty level for default emission factors represent the 95% confidence interval for $CO_2$-C and DOC as presented in Tables 3.1 and 3.2. Due to the skewed distribution of $CH_4$-C emissions/removals data, the uncertainty is given as the (asymmetric) range of 95% of the data as outlined in Chapter 3, Volume 1 of the *2006 Guidelines*. 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 and Table 3.2 primarily reflect the uncertainty of the use of a single default EF that has been derived from many rewetted and undrained sites that may vary considerably from each other in terms of (1) their current abiotic and biotic characteristics and (2) their land use prior to rewetting. The confidence intervals also capture the uncertainty associated with the spatial variation reported in fluxes from the various study sites. Uncertainty also arises from inter-annual variability, although it has been reduced by using the mean of multi-year datasets from the same site.

Sources of uncertainty when using default emission factors also include under-represented environmental conditions in the dataset (including initial conditions and rewetting practices), lack of data representative of various phases and end-points of the rewetting process (e.g. a transient period).

Countries developing emission factors for their inventories at higher tiers should assess the uncertainty of these factors. Possible sources of uncertainty in country-specific emission factors include limited data for GHG emissions/removals on rewetted organic soils in a given region, application of emission factors measured in a small number of rewetted areas to wide areas with different land-use and rewetting histories, application of emission factors derived from short duration studies regardless of the time since rewetting. It is *good practice* for countries using numerical models for estimating GHG emissions/removals at Tier 3 to estimate uncertainty of these models.

Uncertainty in activity data will depend on its source. Aggregated land-use area statistics for activity data (e.g. FAO), may require a correction factor to minimize possible bias. Sources of uncertainty about activity data may include the omission or duplication of rewetted areas, especially if data are gathered from a variety of sources, missing historical data on rewetted organic soils, insufficient information on rewetting practices, post-rewetting vegetation succession, variation on the water table depths, and on the end-point(s) of the rewetting process. Accuracy can be improved by using country-specific activity data from various national, regional and local institutions, with uncertainty estimated based on data collection method and expert judgment. When information regarding activity data is gathered from a variety of sources, cross-checks should be made to ensure complete and consistent representation of land management practices and areas.

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

## 3.3.1 Completeness

Complete GHG inventories include estimates of emissions from all GHG emissions and removals on rewetted organic soils for which Tier 1 guidance is provided in this chapter, for all types of organic 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 organic soils, as well as those that have been subsequently rewetted.

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 organic soils reported under each land-use categories should equal the total national area of rewetted organic soils.

## 3.3.2 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 with 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. It is useful to incorporate scientific expertise actively 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 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 soils and fluxes from un-drained similar ecosystems; ensuring consistency of the area and location of rewetted organic soils with the information provided on drained organic soils.

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

## Methodologies

An extensive literature review was conducted to collate all $CO_2$ studies that are currently available for (1) rewetted organic soils (as defined in the Introduction of this chapter and including rewetted, restored and wet managed sites) and (2) natural/undrained organic soils. Literature sources included both published and non-peer reviewed (grey literature) studies. In the case of the latter 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-peer reviewed studies were included.

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 gas fluxes at high spatial resolution and is widely employed in conditions where the vegetation is either low or absent. The EC towers are typically used at sites that are relatively flat and homogeneous which includes open and treed organic soils. 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 organic soils. When available, the following parameters were extracted from the literature source and included in the database for analysis: climate zone (see Table 4.1, Chapter 4, Volume 4 of the *2006 IPCC Guidelines*), nutrient status, mean water table depth (WTD), median water table depth (as well as minimum and maximum), soil pH, thickness of the organic soil layer, 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 216 annual flux estimates taken from 52 locations. At each study location a number of sites could be identified with similar dominant vegetation and hydrology, and each as such represented 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 123 and was distributed as follows:

(i) Degradation status (Natural/undrained = 74; Rewetted= 49)

(ii) Climate zone (Boreal = 65; Temperate = 58)

(iii) Nutrient status (Nutrient rich = 54; Nutrient poor = 69).

The criteria for inclusion in the database were as follows: (1) the study reported $CO_2$ fluxes from either rewetted organic soils, abandoned and naturally rewetted organic soils or natural undrained organic soils. All natural sites that had a water table deeper than 30 cm were not included in the final database to calculate the EF, as these were assessed as not being 'wet'. In other words, 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 soil surface) were deemed suitable as a proxy for rewetted sites since the mean water table depths recorded at all the rewetted sites in our database was always at, or shallower than -30 cm. The mean WTD is calculated over one year where the flux measurements cover the full 12 months. In boreal regions, the mean WTD applies to the growing season only. (2) The study had to report either seasonal or annual $CO_2$ fluxes. 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, 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 were not available, a value of 30g $CO_2$-C $m^{-2}$ for non-growing season fluxes was used. (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 that included a woody biomass pool (e.g. treed organic soils) as this would have resulted in double accounting at the Tier 1 level. Calculated default EFs for $CO_2$ exclude woody biomass.

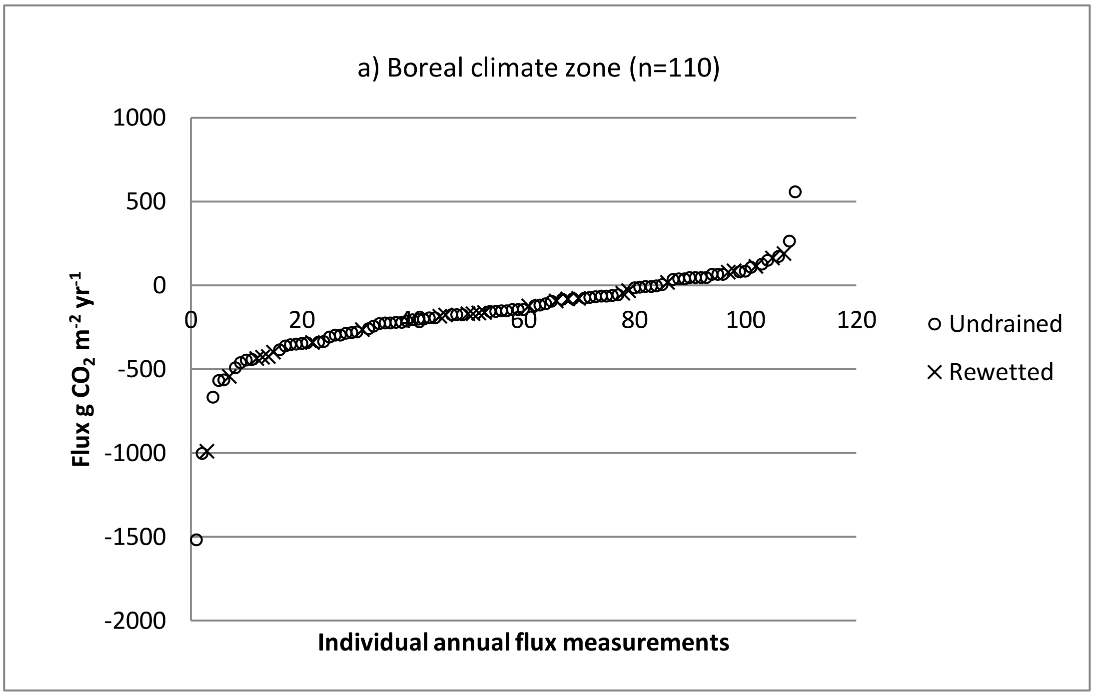
## Results

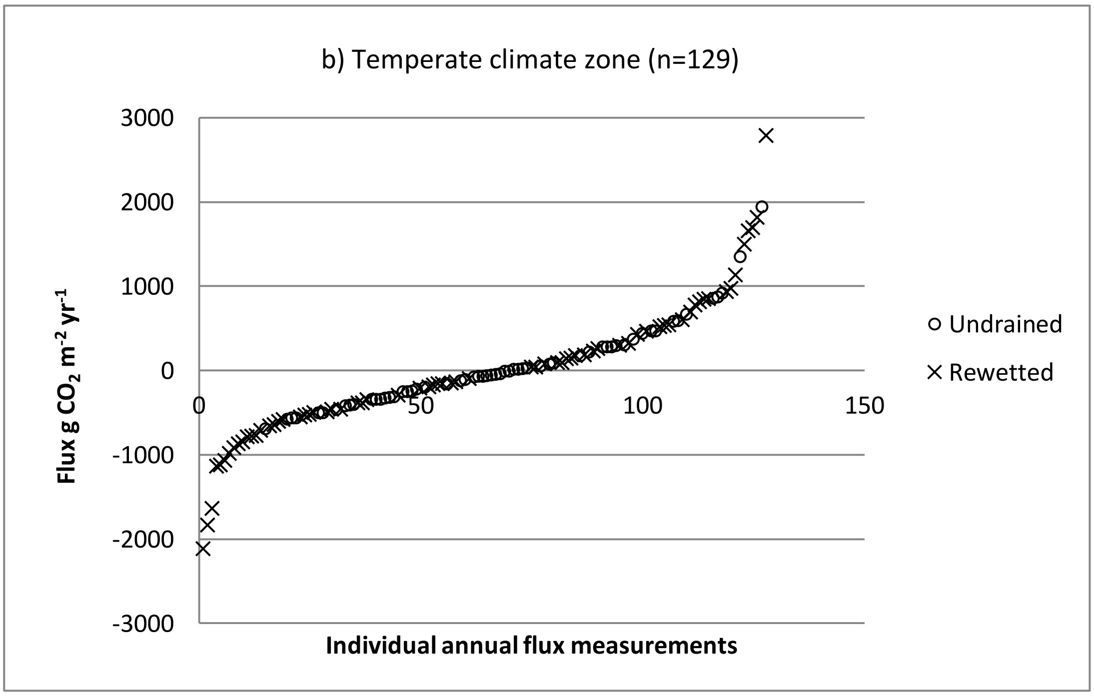
To determine Tier 1 $CO_2$-C EFs, descriptive statistics allowed the data to be grouped by (1) *climate zone* and in some cases by (2) *nutrient status* (poor or rich) and descriptive analysis for each group was computed.

### 1) Temperate and boreal sites

A comparison was made between individual annual net $CO_2$ fluxes from rewetted sites and natural/undrained sites as found in the literature (see reference list in footnote of Table 3.1 in the main text). The wide range of fluxes recorded in rewetted sites can be explained by a number of factors such as 1) vegetation cover (includes non-vegetated surfaces), 2) average annual water table depth, 3) restoration practices (other than rewetting). While noting this large variation, especially within the temperate climate zone (-2115 to 2786 g $CO_2$-C $m^{-2}$ $yr^{-1}$), the array from both groups, natural/undrained vs rewetted is analogous (Figure 3A.1a and b).

**Figure 3A.1** **Ranges of $CO_2$ flux values (g $CO_2$ $m^{-2}$ $yr^{-1}$) found in the published literature for natural/undrained and rewetted organic soils in (a) boreal and (b) temperate climate zones. Positive flux values indicate $CO_2$ emissions from the ecosystem to the atmosphere and negative flux values indicate removal of $CO_2$ from the atmosphere by the ecosystem. References used to compile graph are to be found in Table 3.1.**

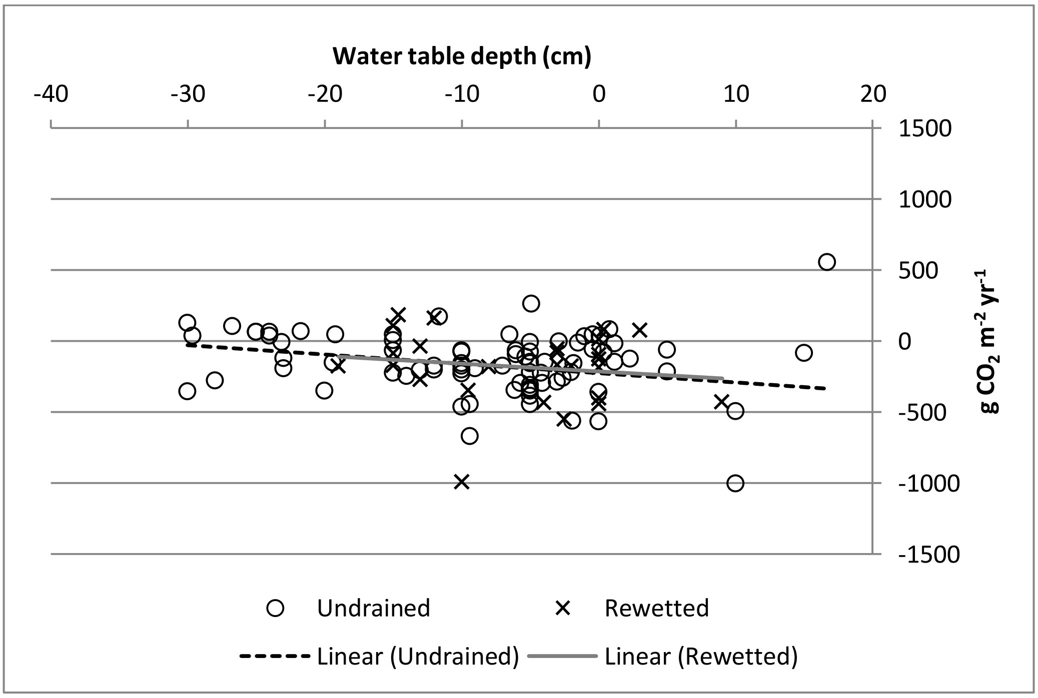




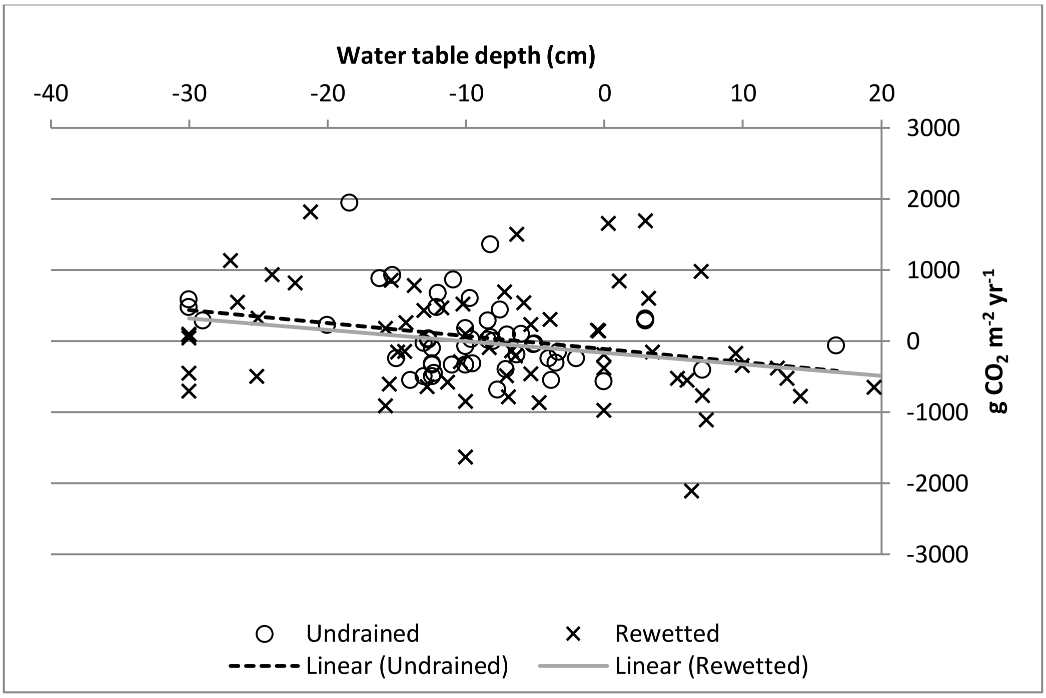
Mean water table depth (WTD) was plotted against annual $CO_2$ flux. The fitted regression lines ($CO_2$ flux = a+b1*WTD) were compared between rewetted and natural/undrained organic soils for each climate zone (see Figures 3A.2a and b). The groups were treated as being non-significantly different when 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 organic soils. Therefore, EFs were calculated using rewetted and natural/undrained data points for each climatic zone. Means of fluxes with their 95% confidence interval were calculated for each of the categories.

**Figure 3A.2** **Relationship between annual $CO_2$ fluxes and mean annual water table depth (cm) for both undrained and rewetted organic soils in (a) boreal and (b) temperate climate zones**

a) Boreal climate zone



b) Temperate climate zone



Note:

1. fitted regression line is $CO_2$ flux = a+b1*WTD.

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

Nutrient rich sites generally display a wider range of flux values than nutrient-poor sites. This wider range can be explained by the higher diversity of nutrient rich sites. For example, plant associations in rich fens are diverse, commonly dominated by brown mosses, sedges and grasses. The majority of the nutrient rich organic soils 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-Petäys et al., 2007). The wider range of flux values can also be explained by the diversity of previous land-uses as nutrient rich organic soils have been used more intensively than nutrient poor sites, especially across the temperate zone.

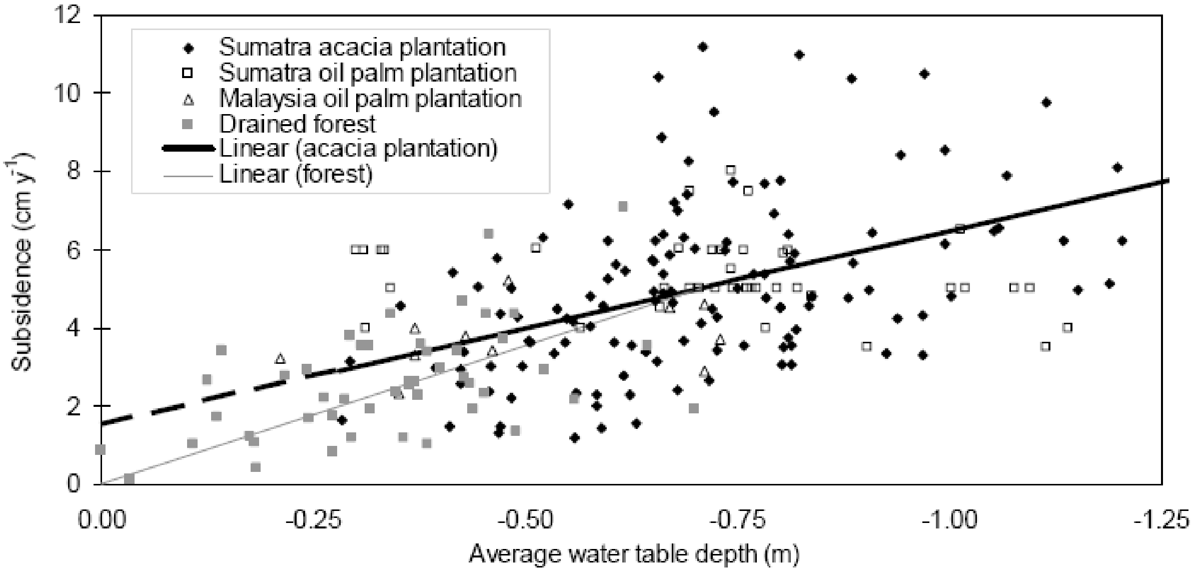
Some studies on natural/undrained nutrient rich organic soils in the temperate zone have reported net annual carbon sources (Nagata et al. 2005, Wickland 2001, Drösler et al 2013), although this may appear inconsistent with the fact that they hold large, long-term stores of carbon. Considerable uncertainty is attached to individual data points used in the derivation of the default EF, as the studies are generally of a short duration (1-2 years) and do not take into account the longer-term natural variation. It should be re-affirmed that over longer time-scales, natural and successfully rewetted nutrient rich organic soils (i.e. with vegetation that accumulates SOM) are $CO_2$ sinks unless another anthropogenic activity is impacting on the site (e.g. pollution, atmospheric deposition, climate change).

By contrast, nutrient poor organic soils displayed less variation in $CO_2$ fluxes across both boreal and temperate zones; the associated EFs suggest that for both boreal and temperate (Table 3.1), they are net long-term sinks for atmospheric $CO_2$, confirming that natural/undrained and rewetted nutrient poor organic soils play as important a role in the contemporary global C cycle as they have in the past.

### 2) Tropical sites

Data on net $CO_2$-C fluxes from successfully rewetted tropical organic soils are lacking. Subsidence measurements provide a good measure of carbon losses from drained organic soils (see Chapter 2 of this supplement) and in tropical organic soils subsidence is near zero when the water table approaches the surface (Figure 3A.3; Hooijer *et al.*, 2012, see also Couwenberg *et al.*, 2010). In undrained/natural conditions tropical organic soils constitute a $CO_2$-C sink of 0.3 – 1.1 t $CO_2$-C $ha^{-1}$ $y^{-1}$ (Lähteenoja *et al.*, 2009, 2011; Dommain *et al.*, 2011). In light of the available evidence the Tier1 default EF is set at 0 t $CO_2$-C $ha^{-1}$ $y^{-1}$. This value is consistent with observations on subsidence and reflects the fact that rewetting effectively stops soil organic matter oxidation but does not necessarily re-establish the soil C sink function.

**Figure 3A.3** **Subsidence rates as measured in drained tropical organic soils in relation to water table depth. From Hooijer *et al.* 2012.**



# Annex 3A.2 Estimation of default emission factors for off-site $CO_2$ emissions via waterborne carbon losses ($CO_2$-DOC) from rewetted organic soils

Waterborne carbon export has been found to be an important pathway linking the organic soils carbon pool to the atmosphere as there is a growing evidence that aquatic system is characterised by high levels of allochthonous Dissolved Organic Carbon (DOC) , a high proportion of which is processed and converted to $CO_2$. A full characterisation of waterborne C losses comprises not only DOC, but also particulate organic carbon (POC), the dissolved gases $CO_2$ and $CH_4$ and the dissolved carbonate species: $HCO_3^-$ and $CO_3^{2-}$. Particulate inorganic carbon (PIC) losses are considered negligible from all types of organic soils.

The various sources, behaviour and fate of these different forms of waterborne C within organic soil systems are further described in Chapter 2 (Annex 2A.3). However, in temperate and boreal, natural/undrained sites, as well as rewetted 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.

Very little data exist pertaining to POC losses from rewetted organic soils and these losses are likely to be site-specific. However, while in-stream processing of POC (respiration/evasion) may be occurring, the greater proportion may be simply translocated from the rewetted organic soil to other stable C stores, such as freshwater or marine sediments where it will 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 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 organic soils as this has been shown to be the largest component of waterborne carbon loss from all types of organic soils (see Chapter 2). Collated data from seven rewetting studies suggest a median DOC reduction of 36%, with a range of 1-83% (Table 3A.1). 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).

Some studies 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. This hypothesis is proposed as an explanation behind the variability shown in Table 3A.1, 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 rewetting impact on DOC loss, a larger number of studies are available that provide reliable DOC flux estimates from natural/undrained organic soils. These were combined with rewetted sites to derive best estimates of the DOC flux (Table 3A.2).

Finally, the proportion of DOC exported from organic soils which is ultimately converted to $CO_2$, called here ($Frac_{DOC\_CO_2}$) is also explained in Annex 2A.3 of Chapter 2.

### TABLE 3A.1
### DOC CONCENTRATION (ABOVE) OR FLUX (BELOW) COMPARISONS BETWEEN DRAINED AND REWETTED ORGANIC SOILS WITH CHANGES IN DOC FOLLOWING REWETTING

| Previous land-use | Climate zone | Study | DOC (mg $l^{-1}$) |  | $\Delta DOC_{Rewetting}$ (%) |
|---|---|---|---|---|---|
|  |  |  | **Drained** | **Rewetted** |  |
| Peat extraction bog | Boreal | Glatzel *et al.*(2003) | 110 | 70 | -36% |
| Drained blanket bog | Temperate | Wallage *et al.* (2006) | 43 | 13 | -69% |
| Drained blanket bog | Temperate | Armstrong *et al.* (2010) | 34 | 30 | -10% |
| Drained blanket bog | Temperate | Gibson *et al.* (2009) | 39 | 39 | -1% |
| Drained agricultural fen | Temperate | Höll *et al.* (2009) | 86 | 57 | -34% |
| Drained extraction bog | Temperate | Strack & Zuback (2013) | 100 | 86 | -14% |
|  |  |  | **DOC (g C $m^{-2}$ $yr^{-1}$)** |  |  |
|  |  |  | **Drained** | **Rewetted** |  |
| Peat extraction bog | Temperate | Waddington *et al.* (2008)<br>Strack & Zuback (2013) | 7.5<br>29 | 3.5<br>5 | -53%<br>-83% |
| Drained blanket bog | Temperate | O'Brien *et al.* (2008) | 7.0 | 4.1 | -41% |
| Drained blanket bog | Temperate | Turner *et al.* (2013) | 79 | 61 | -23% |

### TABLE 3A.2
### ANNUAL DOC FLUX ESTIMATES FROM NATURAL/UNDRAINED AND REWETTED ORGANIC SOILS USED TO DERIVE DEFAULT VALUES FOR $DOC_{FLUX}$

| Climate zone | Country | Study | Status | DOC flux (t C $ha^{-1}$ $yr^{-1}$) |
|---|---|---|---|---|
| Boreal | Finland | Juutinen *et al.* (2013) | Natural/undrained | 0.037 |
| Boreal | Canada | Moore (2003) | Natural/undrained | 0.043 |
| Boreal | Canada | Koprivnjak & Moore (1992) | Natural/undrained | 0.052 |
| Boreal | Canada | Moore (2003) | Natural/undrained | 0.060 |
| Boreal | Finland | Kortelainen *et al.* (2006) | Natural/undrained | 0.060 |
| Boreal | Finland | Jager *et al.* (2009) | Natural/undrained | 0.078 |
| Boreal | Sweden | Agren *et al.* (2008) | Natural/undrained | 0.099 |
| Boreal | Finland | Rantakari *et al.* (2010) | Natural/undrained | 0.120 |
| Boreal | Sweden | Nilsson *et al.* (2008) | Natural/undrained | 0.130 |
| Boreal | Finland | Kortelainen *et al.* (2006) | Natural/undrained | 0.159 |
| Temperate | Canada | Strack *et al.* (2008) | Natural/undrained | 0.053 |
| Temperate | Canada | Roulet *et al.* (2007) | Natural/undrained | 0.164 |
| Temperate | USA | Urban *et al.* (1989) | Natural/undrained | 0.212 |
| Temperate | USA | Kolka *et al.* (1999) | Natural/undrained | 0.235 |
| Temperate | Canada | Moore *et al.* (2003) | Natural/undrained | 0.290 |
| Temperate | Canada | Clair *et al.* (2002) | Natural/undrained | 0.360 |
| Temperate | UK | Dawson *et al.* (2004) | Natural/undrained | 0.194 |
| Temperate | UK | Dinsmore *et al.* (2011) | Natural/undrained | 0.260 |
| Temperate | UK | Billett *et al.* (2010) | Natural/undrained | 0.234 |
| Temperate | UK | Billett *et al.* (2010) | Natural/undrained | 0.276 |
| Temperate | Ireland | Koehler *et al.* (2009,2011) | Natural/undrained | 0.140 |

| | | | | |
|---|---|---|---|---|
| Temperate | Australia | Di Folco & Kirkpatrick (2011) | Natural/undrained | 0.134 |
| Temperate | Canada | Waddington *et al*. (2008), Strack & Zuback (2013) | Rewetted | 0.043 |
| Temperate | UK | O'Brien *et al*. (2008) | Rewetted | 0.041 |
| Temperate | UK | Turener *et al*. (2013) | Rewetted | 0.609 |
| Tropical | Indonesia | Baum *et al*. (2007) | Natural/undrained | 0.470 |
| Tropical | Indonesia | Alkhatib *et al*. (2007) | Natural/undrained | 0.549 |
| Tropical | Malaysia | Yule *et al*. (2009), Zulkifli (2002) | Natural/undrained | 0.632 |
| Tropical | Indonesia | Moore *et al*. (2013) | Natural/undrained | 0.625 |

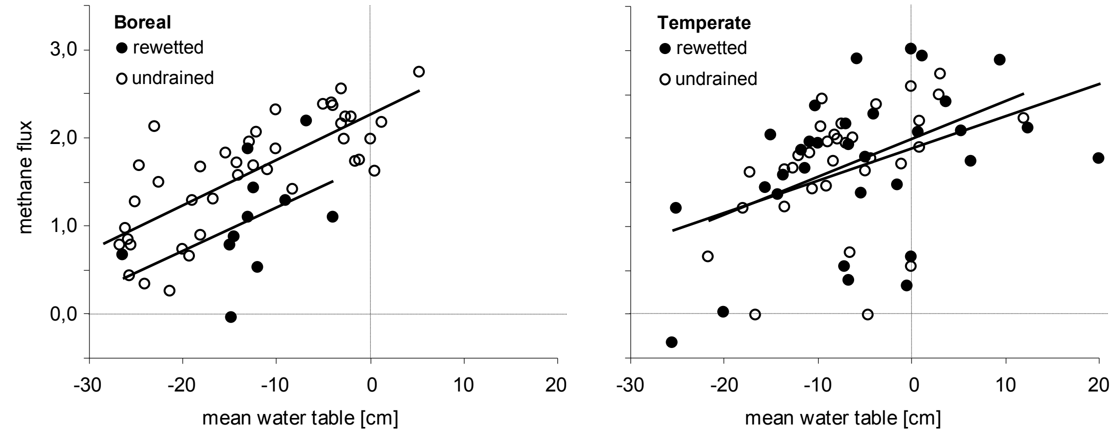
# Annex 3A.3 Estimation of default emission factors for $CH_4$-C in rewetted organic soils

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 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 undrained organic soils only were available and used as proxy for rewetted organic soils.

Where possible, the analysis considered the same parameters as those described in Annex 3A.1: climate zone (latitude), nutrient status, mean annual water table, median annual water table (as well as minimum and maximum), soil pH, organic soil thickness, soil 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 as a measure of variance. Variance pertains to the 95% interval of the observed data.

Methane fluxes from rewetted boreal organic soils (mean 76.3 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance -0.1 – 338.7; n=17[1]) are not significantly different from undrained sites (mean 80.6 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance 0.3 – 420.0; n=68[2]). The increase in efflux with rising water table (Figure 3A.4) does not differ significantly between undrained (n=41 data pairs) and rewetted sites (n= 11 pairs). Methane efflux from rewetted nutrient rich organic soils (mean 161.6 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance -0.1 – 338.7; n=6) is half an order of magnitude higher than efflux from rewetted nutrient poor organic soils (mean 36.5 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance 3.6 – 155; n=8), which is mirrored by efflux values from undrained nutrient rich organic soils (mean 131.5 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance 0.2 – 492.8; n=29) and poor organic soils ( 42.5 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance 0.3 – 245.9; n=31). The derived emission factors for nutrient rich (n=35) and poor sites (n=39) are based on the total respective datasets.

**Figure 3A.4** **Methane flux from boreal and temperate rewetted and undrained organic soils in relation to mean annual water table. Fluxes are expressed as $^{10}\log(1+\text{measured flux})$ [kg $CH_4$-C $ha^{-1}$ $yr^{-1}$].**



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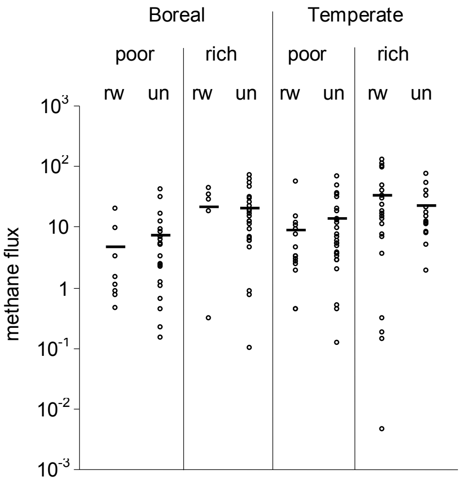
[1] Juottonen *et al.*, 2012; Komulainen *et al.*, 1998; Tuittila *et al.*, 2000 ; Urbanová *et al.*, 2012 ; Yli-Petäys *et al.*, 2007 ; Strack & Zuback, 2013

[2] Alm *et al.*, 1997; Bubier *et al.*, 1993; Clymo & Reddaway, 1971; Drewer *et al.*, 2010; Gauci *et al.*, 2002; Laine *et al.*, 1996 ; Nykänen *et al.*, 1995 ; Verma *et al.*, 1992 ; Waddington & Roulet, 2000 ; Whiting & Chanton, 2001 ; Strack & Zuback, 2013

Whereas methane fluxes from rewetted temperate organic soils (mean 173.8 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance 0 – 856.3; n=38)[3]) are considerably higher than from undrained organic soils (mean 117.6 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance 0 – 528.4; n=48)[4]), 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 table is not significantly different between undrained (n=33 pairs) and rewetted sites (n=33 pairs). Methane effluxes from rewetted temperate nutrient poor organic soils (mean 69.1 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance 3.5 – 444.5; n=15) are lower than from rewetted nutrient rich organic soils (mean 242.2 kg $CH_4$-C $ha^{-1}$ $yr^{-1}$; variance -0.5 – 1027.5; n=23). Combined, the increase in efflux with rising water table in undrained and rewetted sites does not show a significant difference between nutrient poor organic soils (n=32 pairs) and nutrient rich ones (n=33 pairs). The emission factors presented are based on the total dataset of rewetted and undrained nutrient poor (n=42) and nutrient rich sites (n=37). 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.

**Figure 3A.5 Methane flux from boreal and temperate, poor and rich, rewetted (rw) and undrained (un) organic soils. Fluxes (in kg $CH_4$-C $ha^{-1}$ $yr^{-1}$) are expressed on a logarithmic scale.**



Note:

1. Negative and zero flux values are not included in the graph (n=9).
2. Bars indicate mean values.
3. Note that in derivation of EFs, data for rewetted and undrained sites were lumped.

Similar to boreal and temperate organic soils, methane fluxes from tropical swamp forest organic soils 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 ≤30 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 paddy on organic soil are comparable to current IPCC estimates (Couwenberg 2011) and

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[3] Augustin & Merbach, 1998; Augustin, 2003; Augustin in Couwenberg *et al.*, 2011; Cleary *et al.*, 2005; Drösler, 2005; Drösler *et al.*, 2013; 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.*, 2013

[4] 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; Drösler *et al.*, 2013; Harriss *et al.*, 1982; Koehler *et al.*, 2011; 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, 2001; Wilson *et al.*, 1989

were excluded from the analysis. Methane flux data from tropical organic soils outside Southeast Asia are currently not available. Because of the recalcitrance of the woody peat, methane fluxes from tropical swamp forest organic soils in Southeast Asia are considerably lower than from boreal and temperate organic soils (Couwenberg *et al.*, 2010).

TABLE 3A.3
$CH_4$-C FLUX DATA FROM WET SWAMP FOREST ON ORGANIC SOILS

| Site | mg $CH_4$-C $m^{-2}$ $h^{-1}$ (range) | n | Reference |
|---|---|---|---|
| Drained forest | 0.13 (0 – 0.35) | 9* | Furukawa *et al.*, 2005 |
| Swamp forest | 0.67 | 1 | |
| Swamp forest | 0.74 (0.58 – 0.91) | 2 | |
| Secondary forest | 0.14 | 1 | Hadi *et al.*, 2001 |
| Secondary forest | 0.46 (0 – 2.29) | 13 | Hadi *et al.*, 2005 |
| Secondary forest | 0.85 | 1 | Inubushi *et al.*, 1998 |
| Conservation swamp forest | 0.22 (0.03 – 0.70) | 20* | Jauhiainen *et al.*, 2001, 2005 |
| Drained and selectively logged forest | 0.05 (-0.09 – 0.38) | 76* | Jauhiainen *et al.*, 2004, 2008 |
| Young secondary forest | 0.19 (0.10 – 0.26) | 6* | Jauhiainen *et al.*, 2004 |
| Tropical peat swamp forest | 1.53 (1.28 – 1.78) | 2 | Melling *et al.*, 2012 |
| Conservation swamp forest | 0.14 | 1 | Pangala *et al.*, 2012 |
| **Mean** | **0.47 (0.05 – 1.53)** | | |
| | **kg $CH_4$-C $ha^{-1}$ $y^{-1}$)** | | |
| **Annual flux** | **41.2 (7.0 – 134.0)** | | |

Note:

n denotes number of observations

*only measurements pertaining to wet site conditions (water table ≤30 cm below the surface) are considered

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