CHAPTER 3

CROSS-CUTTING GUIDANCE ON REWETTED PEATLANDS AND ORGANIC SOILS

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3.1 INTRODUCTION

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

For the purpose of this chapter, re-wetting, restoration and rehabilitation are understood as follows:

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

Restoration is the permanent re-establishment, on formerly drained sites, of hydrological and biogeochemical processes characteristics of saturated soils, as well as of the vegetation cover that pre-dated the drainage of these soils. Restoration necessarily includes the re-wetting of formerly drained areas.

Rehabilitation or reclamation is the re-establishment, on formerly drained sites, of some of – but not necessarily all - the hydrological, biogeochemical and ecological processes and functions that characterized pre-drainage conditions. As such, rehabilitation can involve a large variety of practices on formerly drained peatlands or organic soils, which may or may not include re-wetting.

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

The guidance provided in this chapter will include re-wetting and restoration of peatlands and organic soils, excluding other forms of rehabilitation or reclamation, whose outcome is more variable and site-specific. This chapter seeks to avoid repeating guidance already provided, hence wherever appropriate will refer to already existing guidance in these Guidelines. Table 3.1 summarizes the coverage of this chapter.

In keeping with the recommendations in chapter 7, volume 4, 2006 IPCC Guidelines, GHG emissions from re-wetted and restored peatlands or organic soils are quantified as fluxes rather than C stock changes. Likewise, carbon emissions or removals in the form of CO_2 will be described as CO_2-C, and when they occur in the form of CH_4 as CH_4-C.

Contrary to most ecosystems, the distinction between C pools in some wetlands can be difficult, especially between the dead organic matter and soil pools. For example, the dead portion of moss species characteristics of many northern peatlands could be included in the dead organic matter or soil pool. Moreover, the default emission factors in this chapter were all derived from flux measurements; these fluxes, when measured over moss-covered or grass-covered peatlands or organic soils, integrate all C pools. In all cases the guidance in this chapter will clarify which C pools are included in default EFs. Peatlands and organic soils can also support perennial woody vegetation; the default approach will treat this carbon pool as in the remainder of the 2006 GLs.

Evidence of successfully re-wetted peatlands or organic soils in tropical or sub-tropical regions was insufficient to provide a sound basis for the development of default EFs. Specifically, no evidence could be found of success in raising the water table to the level observed in pristine peatlands. As a result, flux measurements from pristine peatlands in tropical or sub-tropical climates could be used as a proxy for EF on re-wetted peatlands in these regions and only provided for CO_2 as a basis for future methodological development. The assumption remains that GHG emissions will respond to re-wetting; however countries in tropical and sub-tropical regions where significant areas of peatlands or organic soils have been re-wetted should are encouraged to develop science-based, documented, country-specific emission factors for both CO_2 and CH_4 emissions.

TABLE 3.1

Peat type / Climate region	Bog	Fen	Tropical peat
Boreal/temperate			
CO_2	Section 3.2.1	Section 3.2.1	-
CH_4	Section 3.2.2	Section 3.2.2	-
N_2O	Section 3.2.3	Section 3.2.3	-
Tropical			
CO_2	-	-	Appendix
CH_4	-	-	Section 3.4.1
N_2O	-	-	Section 3.4.2

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

The post-rewetting land use of peatlands and organic soils can vary according to national circumstances. Depending on the management practices and the national land-use classification, it may be more appropriate to report the GHG estimates of re-wetted peatlands or organic soils under forest land, cropland, grassland or wetlands. It is therefore recommended to consider this guidance as potentially common to several reporting categories. Because the functioning of these ecosystems have already been deeply altered, reporting re-wetted peatlands or organic soils as unmanaged land is not consistent with good practice.

3.2 GREENHOUSE GAS EMISSIONS AND REMOVALS FROM RE-WETTED PEATLANDS AND ORGANIC SOILS

3.2.1 CO_2 Emissions and Removals from Re-wetted Peatlands and Organic Soils

CO_2-C emissions/removals from re-wetted peatlands and organic soils have the following components:

EQUATION 3.1
CO_2-C EMISSIONS/REMOVALS FROM REWETTED PEATLANDS AND ORGANIC SOILS

$$CO_2\text{-}C_{rewetted} = CO_2\text{-}C_{soil} + CO_2\text{-}C_{veg} + CO_2\text{-}C_{woody\ biomass} + CO_2\text{-}C_{DOM} + CO_2\text{-}C_{DOC}$$

Where:

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

$CO_2\text{-}C_{soil}$ =CO_2-C emissions from the soil, tonnes C yr^{-1}

$CO_2\text{-}C_{veg}$ = net CO_2-C emissions by, or removals from re-wetted vegetation, tonnes C yr^{-1}

$CO_2\text{-}C_{woody\ biomass}$ = net CO_2-C emissions by, or removals from perennial woody biomass, tonnes C yr^{-1}

$CO_2\text{-}C_{DOM}$ = CO_2-C emissions from dead organic matter, tonnes C yr^{-1}

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

$CO_2\text{-}C_{soil}$ is produced during the decomposition of the soil/peat by heterotrophic organisms and is controlled strongly by oxygen availability within the soil. $CO_2\text{-}C_{veg}$ is the net result of two processes by the vegetation component: photosynthesis (CO_2 uptake) and autotrophic respiration (CO_2 emissions).

$CO_2\text{-}C_{DOM}$ is produced from the decomposition of dead organic matter, such as litter, root exudates and coarse woody debris.

The default EFs provided in this section capture the components CO_2-C_{soil}, CO_2-C_{veg} and CO_2-C_{DOM} together rather than C stock changes by pool. These default EFs are developed from annualized flux measurements, ensuring that there is no seasonal bias.

This chapter does not provide default methodologies for estimating C stock changes in perennial woody biomass on re-wetted peatlands or organic soils. When the vegetation on re-wetted sites consists of perennial woody biomass, guidance in vol 4, chapter 2, 4, 5 and 6 should be used.

CO_2-C_{DOC} is produced from the decomposition of dissolved organic carbon (DOC) lost via aquatic pathways. DOC is the major component of waterborne carbon export, Particulate Organic Carbon (POC), dissolved CO_2 and Dissolved Inorganic Carbon (DIC) being the other minor components (Billett *et al.* 2004, Billett and Moore 2008, Worrall *et al.* 2009, Billett *et al.* 2010, Dinsmore *et al.* 2010). Re-wetting especially of non-re-vegetated cutaway peatlands could lead to high POC export which can be converted to CO_2. However, POC is likely to be simply translocated from the re-wetted peatlands to other stable carbon stores, such as freshwater or marine sediments and may not lead to CO_2 emission. Due to the uncertain fate of POC export, no estimation methodology is presented in this text. Finally, dissolved CO_2 or DIC emissions form a relatively small component of total land-atmosphere CO_2 exchange.

CHOICE OF METHOD

Tier 1

The decision tree in Figure 3.1 presents guidance in the selection of the appropriate tier for the estimation of greenhouse gas emissions from re-wetted peatlands and organic soils. Under Tier 1, the nationally derived area of rewetted peatlands and organic soils is multiplied by an emission factor, which is disaggregated by climate region and peatland type (Equation 3.2).

EQUATION 3.2

$$CO_2{-}C_{rewetted} = (A_{rewetted} \cdot EF_{CO2\ rewetted}) + (A_{rewetted} \cdot EF_{DOC\ rewetted})$$

Where:

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

$A_{rewetted}$ = total area of peatlands and organic soils that have been rewetted, ha

$EF_{CO2\ rewetted}$ = CO_2-C emission factor for rewetted peatlands and organic soils, tonnes C ha^{-1} yr^{-1}

EF $_{DOC\text{-}rewetted}$ = CO_2-C emission factor for DOC from a re-wetted peatlands and organic soils tonnes C ha^{-1} yr^{-1}

Tier 2

Tier 2 calculations use country-specific emission factors and parameters, spatially disaggregated to reflect regionally important practices and dominant ecological dynamics. It may be appropriate to sub-divide activity data and emission factors according to the present vegetation composition (Couwenberg *et al.* 2011) and previous land use history. CO_2-C fluxes during the time period immediately following rewetting (0-5 years) have been shown to be significantly different to those observed 5 years or more after rewetting (Annex or in Guidance for future methodology to be provided). Countries are encouraged to develop more detailed EFs for rewetted peatlands and organic soils by the use of a 5 year “transition period”.

A Tier 2 approach to quantify DOC fluxes may follow the Tier 1 methodology provided above, but should utilise country-specific information where possible to refine the emission factor used as well as the conversion factor. Refinements could include:

(i) Use of country-level measurements from re-wetted peatlands with various restoration techniques and initial status. Direct measurements of DOC fluxes from re-wetted peats could replace the $DOC_{FLUX\_NATURAL}$ values used in the Tier 1 default approach, i.e. replacing the default assumption that re-wetted peatlands revert to pre-drainage DOC fluxes. Differences between pre-drainage and re-wetted DOC fluxes could occur due to the presence or absence of vegetation on re-wetted sites; if re-wetted vegetation composition differs from natural peatlands, or due to factors associated with peat restoration techniques, such as the creation of pools behind dams, or the application of mulch to support vegetation re-establishment, which has been shown to have a direct impact on DOC fluxes

(Strack *et al.* 2011), or the use of biomass to infill ditches. The use of an initial EF (between 0 and 5 years after restoration) and 5 years or more after rewetting (as per CO_2 emissions) is likely to be applied given the dynamics of the vegetation colonisation/development.

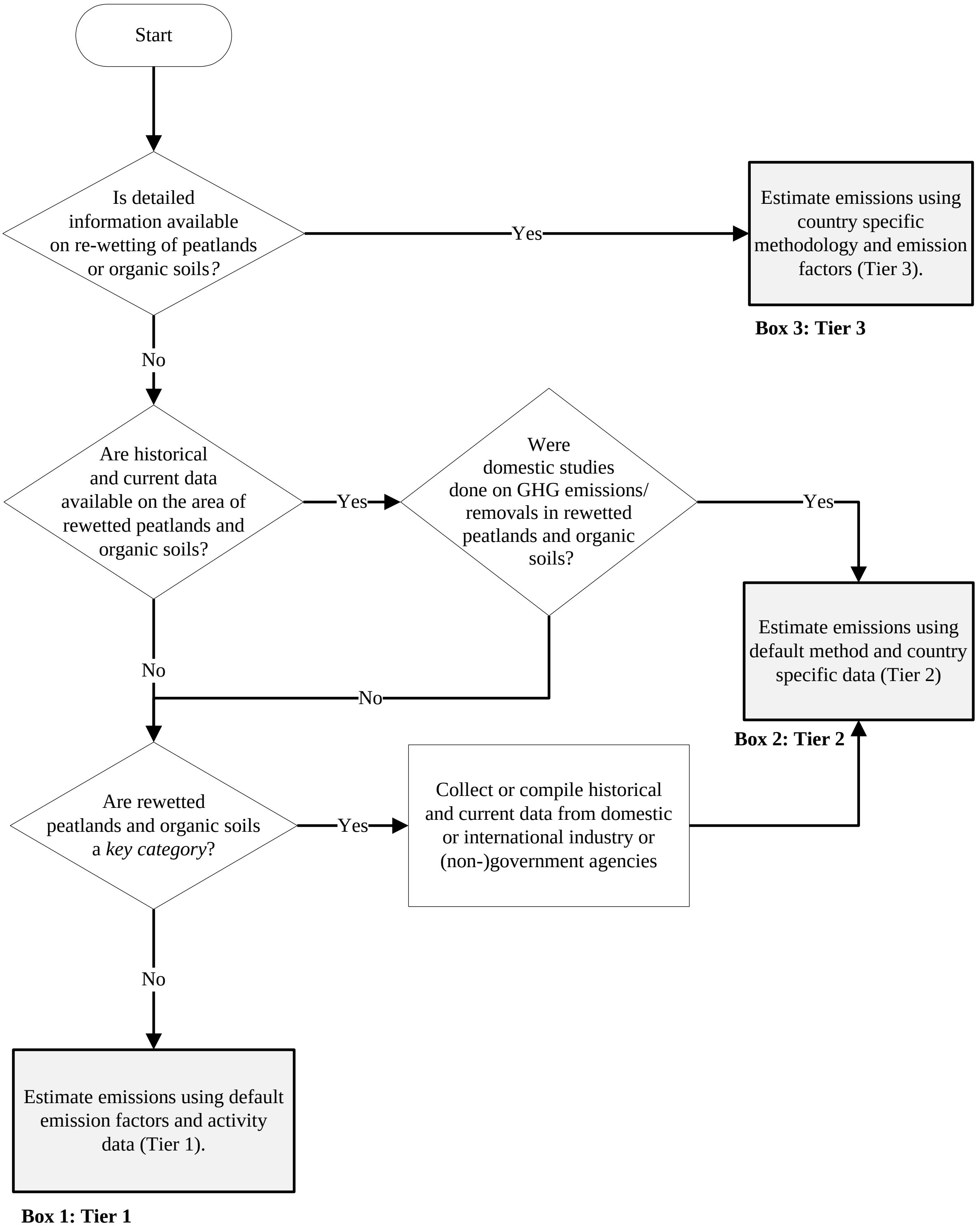
(ii) Use of country-level measurements from natural peatlands to obtain accurate values of $DOC_{FLUX\_NATURAL}$ for that country, for example by developing specific values for raised bogs versus fens, or for blanket bogs under different precipitation levels (see equation used at the bottom of Table 3.2).

(iii) Use of alternative values for $F_{DOC-CO2}$ where evidence is available to indicate that a different proportion of DOC exported from re-wetted peatlands and organic soils is transferred to stable long-term carbon stores, such as lake or marine sediments.

Tier 3

A Tier 3 approach involves a comprehensive understanding and representation of the dynamics of CO_2-C emissions and removals on re-wetted peatlands and organic soils, including the effect of site characteristics, peat type and depth, vegetation composition, soil temperature and mean water table depth (WTD). These parameters could also be used to describe DOC release using process-based models. A Tier 3 approach might also include the entire DOC export from re-wetted sites and consideration of the temporal variability in DOC release in the years following re-wetting (e.g. initial period of less than 5 years) which will be also dependent on the restoration techniques used.

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



CHOICE OF EMISSION FACTORS

Tier 1

The implementation of the Tier 1 method requires the application of default emission factors EFs provided in Table 3.2, where they are disaggregated by climate region (boreal, temperate) and peatland type (bog, fen). There is insufficient data available to permit the inclusion of rewetted tropical peatlands at this time. Peatland type can be inferred from the nutrient status of the peat substrate: e.g. *sphagnum* peat is characteristic of the more nutrient poor (oligotrophic) bogs and *Phragmites* peat is common in nutrient rich (minerotrophic) fens. Countries with significant areas of re-wetted peatlands and organic soils are encouraged to develop domestic emission factors and develop estimates of emissions and/or removals using Tier 2 or 3 methodologies.

The derivation of these default emissions factors values is fully described in Annex 3.1. In summary, while available data indicated that CO_2 fluxes from natural peatlands and re-wetted peatlands are in both cases correlated with water table, it was ascertained that this relationship was not significantly different between the two ecosystems (except for temperate fens). Therefore CO_2 fluxes from natural undrained sites were used in addition to CO_2 fluxes from re-wetted sites in order to provide robust estimation of EFs as shown in Table 3.3. In the case of temperate fens, available data from re-wetted sites only were used to estimate the EF.

TABLE 3.2
EMISSION FACTORS ($EF_{CO2\ REWETTED}$, IN TONNES CO_2-C HA^{-1} YR^{-1}) FOR CO_2-C (± STANDARD DEVIATION) FOR REWETTED PEATLANDS AND ORGANIC SOILS

	BOREAL	**TEMPERATE**
BOGS (raised and blanket)	-0.26 (±0.48)	-0.52 (±1.17)
FENS	-0.93 (±0.94)	+0.72 (±3.42)

EF DOC-rewetted

Robust data show that natural, undrained peatlands export some DOC and these fluxes increase following drainage (see Chapter 2). Available data from re-wetted sites suggest that the level of DOC reduction after re-wetting equates to the DOC increase after drainage. Consequently, it is assumed that re-wetting leads to a reversion to natural DOC flux levels (see Annex 3.2 for explanation). Therefore, to make best use of available data, EFs for re-wetted peatlands have been calculated according to Equation 3.3:

EQUATION 3.3

$$EF_{DOC\ re\text{-}wetted} = DOC_{FLUX\_NATURAL} * F_{DOC\text{-}CO2}$$

Where:

$EF_{DOC\text{-}Re\text{-}wetted}$ = emission factor for DOC from a re-wetted site, tonnes C m^{-2} yr^{-1}

$DOC_{FLUX\_NATURAL}$ = Flux of DOC from natural (undrained) peatland, tonnes C m^{-2} yr^{-1}

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

$EF_{DOC\text{-}re\text{-}wetted}$ values (required in Equation 3.2) are provided in Table 3.3. The $DOC_{FLUX\_NATURAL}$ values were derived based on available data indicating that the rate of DOC export from temperate and boreal raised bogs and fens is positively correlated with water fluxes. A simple schema for deriving values of $DOC_{FLUX\_NATURAL}$ as a function of rainfall was used and provides a separate EF as shown in Table 3.3. This relationship was not ascertained for blanket bogs, which display higher water fluxes in general and, therefore, a separate category using all DOC flux values from natural blanket bogs in the literature has been used and associated EF computed. This was also done separately for tropical peatlands. The derivation of these values is fully described in Annex X.

An understanding of the ultimate fate of DOC export, i.e. whether it is returned to the atmosphere as CO_2 (or even CH_4), is still poor and yet of great significance in terms of GHG reporting. The parameter $F_{DOC\text{-}CO2}$ sets the proportion of DOC exported from peatlands and organic soils which is ultimately converted to CO_2. A value of zero would coincide with all the DOC export being deposited in stable forms in lake or marine sediments, as this would simply represent a translocation of carbon between stable stores, it would not need to be estimated. However, most data on DOC processing do indicate that a high proportion is converted to CO_2 in headwaters, rivers, lakes and coastal seas (see Chapter 2). Therefore, a Tier 1 default $F_{DOC-CO2}$ value of 90% is proposed, with an uncertainty range of 80-100%.

TABLE 3.3
DEFAULT DOC EMISSION FACTORS ($EF_{DOC\_REWETTED}$ IN TONNES CO_2-C HA-1 YR-1) FOR RE-WETTED PEATLANDS AND ORGANIC SOILS (VALUES IN PARENTHESES REPRESENT UNCERTAINTY RANGES)

Peat type	**Precipitation regime (mm yr^{-1})**	**$DOC_{FLUX\_NATURAL}$ (tonnes C m^{-2} yr^{-1})**	**$EF_{DOC\_rewetted}$**
Temperate/boreal raised bog/fen [a]	< 500	5	5 (3-8)
	500-700	12	10 (7-15)
	700-900	18	16 (12-21)_
	> 900	24	22 (17-36)
Temperate blanket bog	All	21	19 (10-28)
Tropical	All	59	53 (38-69)

a DOCFLUX_NATURAL values for boreal/temperate raised bogs and fens are calculated from the equation DOCFLUX_NATURAL = (0.0317 • Precipitation) – 7.5, in the units shown above, using representative mid-range values of 400, 600, 800 and 1000 mm for each of the classes shown. This equation may be used to calculate site-specific estimates where actual precipitation values are known.

Tier 2 and 3

The uncertainty of EFs can be reduced on the basis of spatially disaggregated CO_2 flux measurements. Flux measurements (eddy covariance or chamber methods) should be carried out at temporal resolutions sufficiently defined to capture as wide a range as possible of the abiotic (e.g. irradiation, soil temperature, WTD) and biotic (e.g. vegetation composition) factors that drive CO_2 dynamics in re-wetted peatlands and organic soils.

Countries where perennial woody biomass plays a significant role in the net CO_2-C exchange between re-wetted peatlands or organic soils and the atmosphere should develop country-specific factors reflecting C stock changes in this pool under typical management practices. Guidance to this effect can be found in Vol 4, chapters 3-5.

CHOICE OF ACTIVITY DATA

All Tiers require data on areas of re-wetted peatlands or organic soils, broken down by climate zone, type of peatland or organic soils.

Tier 1

The default methodology assumes that a country has data on the area of re-wetted peatlands or organic soils and the type of peatland or organic soils, consistent with the advice above on the selection of emission factors. Data can be obtained from the peat extraction industry, forestry or agricultural agencies, as well as from government and non-government sources. Re-wetting plans and land use maps are useful sources of information.

Tier 2 and 3

Tier 2 and 3 approaches are likely to involve a more detailed stratification than in Tier 1. This can include further sub-divisions based on time since re-wetting, previous land use history and current land use as well as vegetation composition. It is good practice to further sub-divide default classes based on empirical data that demonstrates significant differences in CO_2-C fluxes among the proposed categories. 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 Tiers 1 and 2 methods, but the exact requirements will depend on the measurement design and country-specific circumstances.

3.2.2 CH4 Emissions and Removals from Re-wetted Peatlands and Organic Soils

CH4 emissions and removals from the soils of re-wetted peatlands and organic soils result from 1) emissions or removals resulting from the balance between CH4 production and oxidation in the soil column and 2) emission of CH4 produced by the combustion of organic matter during fire (Equation 3.4).

EQUATION 3.4

$$CH_4 - C_{rewetted} = \mathrm{CH4}-\mathrm{C}_{soil} + \mathrm{CH4}-\mathrm{C}_{biomass\ burn} + \mathrm{CH4}-\mathrm{C}_{soil\ burn}$$

Where:

$\text{CH4-C}_{\text{rewetted}}$ = CH4-C emissions from re-wetted peatlands or organic, tonnes C yr^{-1}

$\text{CH4-C}_{\text{soil}}$ = emissions of CH4-C from peatlands or organic soils subject to rewetting, tonnes C yr^{-1}

$\text{CH4-C}_{\text{biomass burn}}$ = emissions of CH4-C from biomass burning on rewetted peatlands or organic soils, tonnes C yr^{-1}

$\text{CH4-C}_{\text{soil burn}}$ = emissions of CH4-C from soil or peat burning on rewetted peatlands or organic soils, tonnes C yr^{-1}

The default EFs provided in this section will only cover $\text{CH4-C}_{\text{soil}}$. Generic methodologies for estimating CH4 emissions from the burning of vegetation, dead organic matter ($\text{CH4-C}_{\text{biomass burn}}$) are provided in chapter 2 of volume 4, while methodologies specific to vegetation and DOM burning in forest land, cropland, grassland and wetlands are provided in chapters 3-6 of volume 4. When burning occurs, emissions from the burning of soil should be estimated using country-specific (Tier 2) emission factors.

As noted in Chapter 2, emissions of CH4-C from drainage ditches can be much higher than the surrounding drained peat fields. Few data are available on CH4-C emissions from ditches of rewetted peatlands and organic soils and in some cases ditches may be filled during rewetting activities. When ditches remain, countries are encouraged to include estimates of CH4-C ditch emissions using methodology provided in Chapter 2 (Equation 2.X) and country specific emission factors. Table 2.X can also be consulted for guidance on emission factors for ditches in drained peatlands.

As noted in Chapter 2, emissions of CH4-C from drainage ditches can be much higher than the surrounding drained peat fields. Few data are available on CH4-C emissions from ditches of rewetted peatlands and organic soils and in some cases ditches may be filled during rewetting activities. When ditches remain, countries are encouraged to include estimates of CH4-C ditch emissions using methodology provided in Chapter 2 (Equation 2.X) and country specific emission factors. Table 2.X can also be consulted for guidance on emission factors for ditches in drained peatlands.

CHOICE OF METHOD

Refer to Figure 3.1 for the decision tree to select the appropriate tier for the estimation of estimate CH4 emissions or removals from rewetted peatland or organic soils.

Tier 1

The default methodology covers CH4 emissions and removals from rewetted peatlands soils and re-wetted organic soils (Equation 3.5).

EQUATION 3.5

$$CH_4 - C_{soil} = \left[\frac{(A_{rewetted} * EF_{CH4\ soil})}{1000}\right]$$

Where:

CH_4-C_{soil} = methane emissions from the soils of re-wetted peatlands and organic soils, tonnes C ha^{-1} yr^{-1}

$\text{A}_{\text{rewetted}}$ = total area of peatlands and organic soils that have been rewetted, ha yr^{-1}

$\text{EF}_{\text{CH4 soil}}$ = emission factor from rewetted peatlands or organic soil, kg CH_4-C ha^{-1} yr^{-1}

Rewetted area should be subdivided by climate zone (boreal or temperate) and appropriate emission factors applied. The data available at present is insufficient to support the development of default EF for tropical regions. When information is available on the peatland type, countries are encouraged to further subdivide rewetted area into bogs and fens, multiply each one by the appropriate emission factor and sum the products for the total CH4 emission or removal.

Tier 2

Tier 2 calculations use country-specific emission factors and parameters, spatially disaggregated to reflect regionally important practices and dominant ecological dynamics. In general, methane fluxes from wet peatlands are extremely skewed, approaching a log-normal (right-tailed) distribution. This asymmetry towards rare, but high efflux values causes high mean values compared to the most likely encountered median values. Countries are encouraged to further scientific understanding of methane effluxes from re-wetted peatland sites, allowing for more precise estimation.

Methane fluxes from peat and organic soils strongly depend on the depth of the water table, with efflux increasing steeply from near zero when mean annual water levels stands below -20 cm from the surface, to very variable and high values at water levels less than 20 cm from the surface. Variability is even greater on flooded sites, where both low (Couwenberg & Fritz 2012; Couwenberg et al., 2010) and high (Augustin & Chojnicki 2008; Glatzel et al., 2011) flux values have been observed.

Prior land-use (e.g. agriculture, peat extraction, forestry) can influence CH4 fluxes from re-wetted peatlands or organic soils. For example, CH4 emissions following the re-wetting of some agricultural land with nutrient enriched top-soil appear higher compared to average emission factors (Augustin & Chojnicki, 2008; Hahn-Schöffl et al., 2011; Glatzel et al., 2011) whereas rewetted boreal cutover peatlands may have CH4 emissions below the average emission factors (Waddington and Day, 2007). It may therefore also be appropriate to subdivide activity data and emission factors according to previous land-use when this information is available. The influence of previous land use may diminish over time.

Data on CH4 emissions and removals from rewetted peatlands and organic soils remains relatively sparse, particularly at locations rewetted for longer than 10 years. Due to the limited number of long-term rewetting studies, the change in CH4 emissions over time remains unclear. The pattern of changes in CH4 flux with time since rewetting may be linked to prior land-use. Research on restored cutover peatlands in Canada indicates an increase in CH4 emissions each year during the first three years post-restoration as the emerging vegetation cover provides fresh substrate for CH4 production (Waddington and Day, 2007). In contrast, rewetting of intensive grassland on fen peat suggests that CH4 emissions may decline over time as litter inundated during rewetting activities is rapidly decomposed in the first few years (Augustin and Joosten 2007). Changes in CH4 emissions and removals over time are likely linked to vegetation succession (e.g. Tuittila et al. 2000) and thus understanding the pattern of emissions over time will likely require the inclusion of vegetation information.

Several studies in both undisturbed and rewetted peatlands indicate the important role that vegetation may play for providing substrate for CH4 production and for transporting CH4 from the saturated soil to the atmosphere (e.g. Bubier 1995; Shannon et al. 1996; Marnier et al. 2004; Tuittila et al. 2000; Wilson et al. 2007; Dias et al. 2010). Species known to transport CH4 from the soil to the atmosphere include, but are not limited to *Calla, Carex, Cladium, Eleocharis, Equistem, Eriophorum, Glyceria, Nuphar, Nymphaea, Peltandra, Phalaris, Phragmites, Sagittaria, Scheuchzeria, Scirpus,* and *Typha* (Sebacher *et al.* 1985, Chanton *et al.* 1992, Schimel 1995, Shannon *et al.* 1996, Frenzel & Rudolph 1998, Verville *et al.* 1998, Yavitt & Knapp 1998, Grünfeld & Brix 1999, Frenzel & Karofeld 2000, Tuittila et al. 2000, Arkebauer *et al.* 2001, Armstrong & Armstrong 2011, Askaer *et al.* 2011). The presence of these aerenchymous shunt species has a marked effect on methane efflux from peatlands (Couwenberg & Fritz, 2012). Most of the data available at present are from sites that were rewetted only recently when methane fluxes were measured. Countries are encouraged to use methane flux measurements from longer term rewetted sites and develop nationally specific emission factors that address vegetation composition (see Couwenberg et al., 2011).

Tier 3

A Tier 3 approach involves a comprehensive understanding and representation of the dynamics of CH4 emissions on re-wetted peatlands and organic soils, including the representation of interactions between the dominant drivers of CH4 dynamics, as described above.

CHOICE OF EMISSION FACTORS

Tier 1

The implementation of the Tier 1 method requires the application of default emission factors $EF_{CH4\ soil}$ provided in Table 3.4, where they are disaggregated by climate region (boreal, temperate) and peatland type (bog, fen). Available flux data for rewetted tropical peatlands are insufficient for the development of default EFs. Comparison of hourly flux data suggests that efflux in SE Asian peat swamps (the largest extent of tropical peatland) will be much lower than in temperate/boreal regions (Couwenberg et al., 2010). Annex 3.3 provides more details on the derivation of these default EFs.

TABLE 3.4
DEFAULT EMISSION FACTORS FOR CH4 FROM REWETTED PEATLANDS AND ORGANIC SOILS (ALL VALUES IN KG CH_4-C HA^{-1} YR^{-1})

Climate zone	$EF_{rewetted}$	Uncertainty	Peatland type	$EF_{rewetted}$	Uncertainty
Boreal	80 (n= 27)		Bog	16 (n=12)	
			Fen	162 (n=12)	
Temperate	265 (n=104)		Bog	156 (n=41)	
			Fen	374 (n=63)	
Tropical	p.m.				

Tier 2 and 3

The uncertainty of emission factors can be reduced by using country specific emission factors for each climate zone and peatland type. It can be further reduced by implementing scientific findings relating CH4 emissions to prior land use, the depth of the water table, vegetation cover and time since re-wetting.

CHOICE OF ACTIVITY DATA

All Tiers require data on areas of re-wetted peatlands or organic soils, broken down by climate zone, type of peatland or organic soils.

Tier 1

The default methodology assumes that a country has data on the area of re-wetted peatlands or organic soils and the type of peatland or organic soils, consistent with the advice above on the selection of emission factors.

Tier 2 and 3

More sophisticated estimation methodologies will require the determination of monthly averages of the water table depth; land use and management practices prior to re-wetting; and vegetation composition and the successional changes in vegetation community composition and biomass with time since rewetting. This type of information can be obtained by long-term monitoring of re-wetted sites under various conditions, and should be combined with an enhanced understanding of the processes linking CH4 emissions to these factors.

3.2.3 N2O Emissions and Removals from Re-wetted Peatlands and Organic Soils

The emissions of N2O from re-wetted peatlands or organic soils are controlled by the quantity of N available for nitrification and de-nitrification, and the availability of the oxygen required for these chemical reactions. Oxygen availability is in turned controlled by the depth of the water table. Raising the depth of the water table will cause N2O emissions to decrease rapidly, and practically completely if the depth of the water table is less than 20cm below the surface.

Equation 3.6 includes the essential elements for estimating N2O emissions from re-wetted peatlands or organic soils:

EQUATION 3.6

$$N_2O_{rewetted} = N_2O_{soil} + N_2O_{biomass\ burn} + N_2O_{soil\ burn}$$

Where:

$N_2O_{rewetted}$ = N_2O emissions from re-wetted peatlands or organic soils, tonnes N_2O yr^{-1}

N_2O_{soil} = N_2O emissions from the soil pool of re-wetted peatland or organic soils, tonnes C yr^{-1}

N_2Obiomass burn = N_2O emissions from biomass burning on rewetted peatlands or organic soils, tonnes N_2O yr^{-1}

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

This chapter only covers N2O$_{soil.}$ Generic methodologies for estimating N2O emissions from the burning of vegetation and dead organic matter are provided in chapter 2 of volume 4 in the existing 2006 GLs, while methodologies specific to vegetation and DOM burning in forest land, cropland, grassland and wetlands are provided in chapters 3-6 of volume 4. When burning occurs, emissions from the burning of soil should be estimated using country-specific (Tier 2) emission factors.

Under Tier 1, emissions of nitrous oxides from re-wetted soils are assumed to be insignificant[1].

At higher tiers, countries are encouraged to examine the pattern of N2O emissions from re-wetted peatlands and organic soils by climate zone and peat type, in particularly tropical climate. Country specific emission factors should take into account fluctuations of the water table depth, which controls oxygen availability for nitrification, and previous land use, which may have resulted in top soil enrichment (Nagata et al., 2006; 2010). Caution should be exerted to avoid double-counting N2O emissions from re-wetted sites that can be directly linked to allochtonous (external) nitrogen input, as these emissions may already be reported as indirect emissions from anthropogenic N input within the watershed.

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

3.3.1 Completeness

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

It is good practice to ensure that all *drained* peatlands and organic soils on the national territory are already included in the national inventory, prior to estimating emissions and removals from rewetted peatlands or organic soils.

As for all land categories, countries are encouraged to monitor the fate of rewetted and restored peatlands, and avoid double counting emissions reported from lands in various categories. The greenhouse gas balance of re-wetted lands with peat or organic soils should include all applicable carbon pools, while avoiding double-counting between carbon pools, especially if flux-based estimation methodologies are combined with stock-change approaches.

3.3.2 Developing a consistent time series

General guidance on ensuring time series consistency can be found in Chapter 7 of this Supplement. The emission and removal estimation method should be applied consistently to every year in the time series, at the same level of spatial disaggregation. Moreover, when country-specific data are used, national inventory agencies should use the same measurement protocol (sampling strategy, method, etc.) throughout the time series, or use documented, unbiased methods to ensure the representativeness and applicability of emission factors.

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

3.3.3 Quality Assurance and Quality Control (QA/QC)

Quality assurance/quality control (QA/QC) procedures should be developed and implemented as outlined in Chapter 7 of this Supplement. It is good practice to develop additional, category-specific quality control and quality assurance activities if higher tier methods are used to quantify emissions and removals from this category. Where country-specific emission factors are being used, they should be based on high quality experimental data, developed using a rigorous measurement programme, and be adequately documented, preferably in the peer-reviewed, scientific literature.

3.3.4 Reporting and Documentation

EMISSION FACTORS

The scientific basis of country-specific emission factors, parameters and models should be fully described and documented. This includes describing the input parameters, the derivation of emission factors, parameters and models and the sources of uncertainty, as well as justifying their representativeness.

It is good practice to clearly document the carbon pools that are captured by flux-based emission factors and the completeness in terms of pool coverage.

ACTIVITY DATA

Sources of all activity data used in the calculations (data sources, databases and soil map references) should be recorded, plus (subject to any confidentiality considerations) communication with industry. This documentation should cover the frequency of data collection and estimation, and estimates of accuracy and precision, and reasons for significant changes in activity data.

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

TREND ANALYSIS

Significant fluctuations in emissions and removals between years should be explained. A distinction should be made between changes in activity levels and changes in emission factors, parameters and methods from year to year, and the reasons for these changes documented. If different emission factors, parameters and methods are used for different years, the reasons for this should be explained and documented.

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

An extensive literature review was conducted to collate all greenhouse gas (GHG) studies that are currently available for natural/undrained and rewetted peatlands and organic soils. Literature sources included both published and non-published (grey literature) studies. In the case of the latter, expert judgement was exercised as to whether the study was scientifically acceptable for inclusion. A greater amount of data from natural (undrained) is available than from re-wetted peatlands. A detailed database of annual CO_2 fluxes was then constructed to determine the main drivers (if any) of CO_2 dynamics in rewetted peatlands and organic soils. When available, the following parameters were extracted and included in the database for analysis: climate zone (latitude), peatland types, mean annual water table, median annual water table (as well as minimum and maximum), soil pH, peat thickness, peat C/N ratio, degree of humification, soil moisture, soil bulk density, plant cover and species, previous land-use and time since re-wetting.

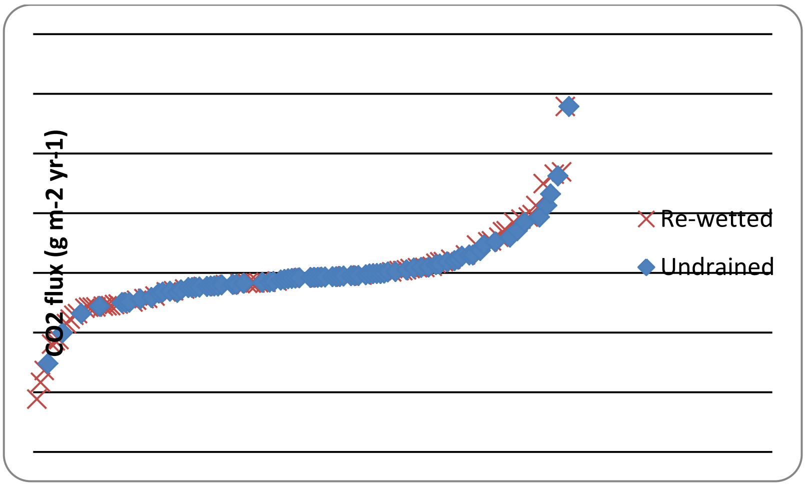
To determine Tier 1 CO_2 emission factors, descriptive statistics allowed the data to be grouped by (1) *climate region*, (2) *peatland type (bog or fen)* and (3) *climate region and peatland type*, and descriptive analysis for each group was computed. Due to difficulties in up-scaling flux data or incomplete data entries a proportion of the CO_2 flux entries in the database (12-33%) were not used in the analysis. Studies that reported daily CO_2 flux values in the database were not used. Seasonal CO_2 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). Tropical peatlands were initially included in the database and although several studies were first extracted, the number of usable entries was deemed very limited (one re-wetted and three undrained/natural entries) and were therefore excluded thereafter.

While all re-wetted entries were included (n=62), data from natural/undrained were further extracted and only entries (n=82) from sites with a mean annual water table of no less than 30 cm was used as a proxy for re-wetted sites. These entries were well distributed between bogs (n=79) and fens (n= 65). There were 63 boreal entries compared with 81 temperate entries with temperate bogs being the most common studied type.

While a total 142 fluxes were entered for the analysis (Figure 3A.1), 130 entries were used in the final database to calculate the emission factors.

Firstly, a comparison was made between re-wetted sites and natural/undrained sites. The range of fluxes from both groups is analogous (Figure 3A.1).

Figure 3A.1



The fitted regression lines (CO_2 flux = a+b1*WT) were compared between re-wetted and natural/undrained groups for each category. The two 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 all but the temperate fen groups. Therefore, emission factors were calculated using re-wetted and natural/undrained entries for all categories except for temperate fens where only re-wetted entries (n=17) were used in the calculation of the emission factor. Total number of entries used overall was 130.

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

Collated data from seven peat re-wetting studies suggest a median DOC reduction of 36%, with a range of 1-69%. While the number of studies is limited, and results are fairly variable, the median reduction is almost exactly equivalent to the observed increase following drainage (a 33% decrease would be required to fully reverse a 50% increase). A study by Glatzel et al. (2003) observed similar DOC concentrations in re-wetted and restored bogs (previously used for peat harvesting) as in a nearby intact reference bog. Therefore, there is some evidence to suggest that peat re-wetting will return DOC loss fluxes to natural levels. This is likely to occur after an initial pulse of DOC associated with disturbance during the re-wetting process (e.g. Zak and Gilbrecht, 2007; Worrall et al., 2007, Strack et al., 2011), which may contribute to the variability shown in Table 3A.X, where some measurements were made soon after re-wetting.

The values derived for the estimation of $DOC_{FLUX\_NATURAL}$ are explained in Annex X of Chapter 2 as well as an explanation of the estimated $F_{DOC-CO2}$

TABLE 3A.1
DOC CONCENTRATION (ABOVE) OR FLUX (BELOW) COMPARISONS BETWEEN DRAINED AND RE-WETTED PEATS

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

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

The same literature database and general approach were used to develop default CH_4 emission factors as was described in Annex 3.1. Similarly, a greater amount of data from natural (undrained) peatlands is available than from re-wetted peatlands. A detailed database of annual CH_4 fluxes was then constructed to determine the main drivers (if any) of CH_4 emissions in rewetted peatlands and organic soils. Where possible, the analysis considered the same parameters : climate zone (latitude), peatland types, mean annual water table, median annual water table (as well as minimum and maximum), soil pH, peat thickness, peat C/N ratio, degree of humification, soil moisture, soil bulk density, plant cover and species, previous land-use and time since re-wetting.

Methane fluxes from rewetted boreal peatlands (mean 80.3 kg CH4-C ha-1 yr-1; variance; n=27[2]) are significantly lower than from undrained (pristine) sites (mean 205.4 kg CH4-C ha-1 yr-1; variance; n=87[3]). The increase in efflux with rising water level is similar, but significantly steeper for undrained sites (n=68 pairs) compared to rewetted sites (n= 13 pairs). Methane efflux from rewetted fens (mean 161.6 kg CH4-C ha-1 yr-1; variance; n=12) is an order of magnitude higher than efflux from rewetted bogs (mean 16.2 kg CH4-C ha-1 yr-1; variance; n=12), which is mirrored by efflux values from undrained fens (mean 392.5 kg CH4-C ha-1 yr-1; variance; n=33) and bogs (65.6 kg CH4-C ha-1 yr-1; variance; n=42).

Whereas methane fluxes from rewetted temperate peatlands (mean 416.1 kg CH4-C ha-1 yr-1; variance; n=47[4]) are considerably higher than from undrained peatlands (mean 148.7 kg CH4-C ha-1 yr-1; variance; n=61[5]), this finding is based mainly on a small number of extremely high efflux values from sites on enriched agricultural soil that were flooded during rewetting (Augustin & Chojnicki 2008; Glatzel et al., 2011). The increase in efflux with rising water level is not significantly different between undrained (n=39 pairs) and rewetted sites (n=40 pairs), nor between undrained bogs (n=35) and undrained fens (n=22). Flux values from rewetted sites do show higher variance, however, which cannot be explained by available parameters (peat type, water level dynamics, pH, C/N ratio, vegetation), although the highest values were measured in recently rewetted fen peatlands, formerly used as high-intensity grassland (time since rewetting ≤ 2 years). Methane effluxes from rewetted temperate bogs are an order of magnitude lower than from fens, but measurements are restricted to only three bog sites. Combined, the increase in efflux with rising water level in undrained and rewetted sites does not show a significant difference between bogs (n=30 pairs) and fens (n=49 pairs). The emission factors presented are based on the total dataset of rewetted and undrained bogs (n=41) and fens (n=63). Because bogs have more relatively dry microsites and the dataset for fens includes the extreme values mentioned above, the EF for temperate bogs is lower than for fens.

Very few methane flux data exist on rewetted tropical peatlands. Comparison of hourly flux data suggests that efflux in SE Asian peat swamps (the largest extent of tropical peatland) will be much lower than in temperate/boreal regions (Couwenberg et al., 2010). Efflux from rice padi on peat soil is comparable to current IPCC estimates (Couwenberg 2011). Efflux from Papyrus marshes has been measured, paper is underway…

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

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

[4] Augustin & Chojnicki 2008; Augustin & Merbach 1998; Augustin 2003; Augustin in Couwenberg et al. 2011; Cleary et al., 2005; Drösler 2005; Flessa et al., 1997; Glatzel et al., 2011; Hendriks et al., 2007; Jungkunst & Fiedler 2007; Waddington & Price 2000; Wild et al., 2001; Wilson et al., 2009; Wilson et al., in press

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

APPENDIX 3.1 CO_2 Emissions/Removals from Re-Wetted Peatlands or Organic Soils in Tropical Climates: a Basis for Future Methodological Development

APPENDIX 3.1 Time-Series of $EF_{DOC\ Rewetted}$; a Basis For Future Methodological Development