# Greenhouse gas emission factors associated with rewetting of organic soils

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## SUMMARY

Drained organic soils are a significant source of greenhouse gas (GHG) emissions to the atmosphere. Rewetting these soils may reduce GHG emissions and could also create suitable conditions for return of the carbon (C) sink function characteristic of undrained organic soils. In this article we expand on the work relating to rewetted organic soils that was carried out for the 2014 Intergovernmental Panel on Climate Change (IPCC) *Wetlands Supplement*. We describe the methods and scientific approach used to derive the Tier 1 emission factors (the rate of emission *per* unit of activity) for the full suite of GHG and waterborne C fluxes associated with rewetting of organic soils. We recorded a total of 352 GHG and waterborne annual flux data points from an extensive literature search and these were disaggregated by flux type (i.e. $CO_2$, $CH_4$, $N_2O$ and DOC), climate zone and nutrient status. Our results showed fundamental differences between the GHG dynamics of drained and rewetted organic soils and, based on the 100 year global warming potential of each gas, indicated that rewetting of drained organic soils leads to: net annual removals of $CO_2$ in the majority of organic soil classes; an increase in annual $CH_4$ emissions; a decrease in $N_2O$ and DOC losses; and a lowering of net GHG emissions. Data published since the *Wetlands Supplement* (n = 58) generally support our derivations. Significant data gaps exist, particularly with regard to tropical organic soils, DOC and $N_2O$. We propose that the uncertainty associated with our derivations could be significantly reduced by the development of country specific emission factors that could in turn be disaggregated by factors such as vegetation composition, water table level, time since rewetting and previous land use history.

**KEY WORDS:** carbon, carbon dioxide, DOC, emission factors, methane, nitrous oxide, peat

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## INTRODUCTION

Organic soils store an estimated 600 Gt of carbon (C) worldwide (Page *et al.* 2011, Yu 2012), more than is currently held in the biomass of all the forests of the world (Köhl *et al.* 2015, Joosten *et al.* in press). Anthropogenic disturbance can destabilise these C stocks, often by accelerating decomposition of organic matter through drainage, which is commonly carried out to allow for conventional agricultural activities, forestry, infrastructure development or extraction of the peat.

Drained organic soils are significant sources of greenhouse gas (GHG) emissions to the atmosphere, accounting for around 10 % of all GHG emissions from the agriculture, forestry and other land use (AFOLU) sectors (Smith *et al.* 2014). The decrease in water table levels following drainage leads to increased emissions of carbon dioxide ($CO_2$) (e.g. Chistotin *et al.* 2006, Maljanen *et al.* 2007, Jauhiainen *et al.* 2012, Salm *et al.* 2012, Renou-Wilson *et al.* 2014), methane ($CH_4$) ‘hotspots’ in drainage ditches (e.g. Minkkinen & Laine 2006, Schrier-Uijl *et al.* 2011, Jauhiainen & Silvennoinen 2012, Sirin *et al.* 2012, Evans *et al.* 2015), reduced $CH_4$ emissions from drained land surfaces (e.g. Chistotin *et al.* 2006, Wilson *et al.* 2009) and high nitrous oxide ($N_2O$) emissions, particularly in association with nutrient rich organic soils (e.g. Regina *et al.* 1996, van den Pol-van Dasselaar *et al.* 1998, Ernfors *et al.* 2008). In addition, drainage increases the vulnerability of organic soils to fire (Kettridge *et al.* 2015, Turetsky *et al.* 2015) which can lead to considerable additional GHG emissions, particularly from tropical organic soils (Page *et al.* 2002). Furthermore, waterborne C losses may be accentuated following drainage (Evans *et al.* 2015).

Rewetting of drained organic soils may reduce GHG emissions and waterborne C losses. Given the development of global climate policy and the high emissions associated with drained organic soils, it has been argued that rewetting and restoration of these soils should be included in mitigation strategies (Joosten *et al.* 2012, IPCC 2014a). Rewetting is the deliberate action of raising the water table in soils that have previously been drained for forestry, agriculture (crop production and grazing), water supply, peat extraction and other human-related activities, in order to re-establish and maintain water saturated conditions, e.g. by blocking drainage ditches, construction of bunds or disabling drainage pump facilities. Rewetting[1] can have several objectives such as nature conservation, GHG emission reductions and the promotion of leisure activities or paludiculture on saturated organic soils.

Under the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, Annex 1 countries prepare annual National Inventory Reports detailing GHG emissions and removals from six different sectors[2]. While emissions from some drained organic soils are reported annually, the emissions and removals (i.e. C uptake) associated with rewetted organic soils have not been included thus far owing to an absence of data and a lack of methodological guidance (IPCC 2006). However, this gap has been addressed by the recent *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014a; hereafter referred to as the *Wetlands Supplement*), in which Tier 1 (default) emission factors are provided for rewetted organic soils, disaggregated by climate region and nutrient status. The *Wetlands Supplement* provides methodological guidance for countries to report GHG emissions/removals arising from the rewetting of organic soils in their national inventory submissions. A second supplement (not discussed in this paper) provides guidance for accounting of these emissions/removals under Articles 3.3 and 3.4 of the Kyoto Protocol (second commitment period) (IPCC 2014b).

This article expands on the work relating to rewetted organic soils that was carried out for the *Wetlands Supplement*. Specifically, we describe here the methods and scientific approach used in the *Wetlands Supplement* to derive the Tier 1 emission factors for the full suite of GHG and waterborne C fluxes associated with rewetting of organic soils. We examine the robustness of the emission factors by comparing the Tier 1 values in the *Wetlands Supplement* with data published since that time. We compare GHG emissions and the global warming potential (GWP) of selected land use categories as defined by IPCC (2014a) under drained and rewetted conditions. Finally, we provide detailed information for countries that wish to move to higher reporting Tiers, identify current research gaps, and highlight priority areas for future research.

## METHODS

In the land use sector, changes in C pools are commonly addressed using a stock-based approach: stocks are assessed at two points in time and the difference is interpreted as a flux of $CO_2$. However, C fluxes in organic soils are generally small relative to the total stock and are thus problematic to measure in a stock based approach. Net $CO_2$ emissions or removals from organic soils are more accurately measured directly as fluxes (IPCC 1996). Emissions (and removals) of the other main GHGs originating from the land use sector ($CH_4$ and $N_2O$) are commonly treated as fluxes. Fluxes are denoted here as $CO_2\text{-}C$, $CH_4\text{-}C$ and $N_2O\text{-}N$. This notation is consistent with that used in the *2006 IPCC Guidelines for Greenhouse Gas Inventories* (IPCC 2006). We follow the sign convention that uses the atmosphere as a reference, whereby an emission is a positive flux from the soil to the atmosphere (and a removal is a negative flux).

The focus of this article is on GHG emissions/removals associated with *only* the soil C pool in rewetted organic soils. While the C contained in the woody biomass pool may be substantial in treed peatlands, particularly in the tropics, it is outside the scope of this paper. Instead,

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[1] Wetland *restoration* always aims to permanently re-establish the pre-disturbance ecosystem, including the hydrological and biogeochemical processes typical of water saturated soils, as well as the vegetation cover that pre-dated the disturbance (Nelleman & Corcoran 2010). Normally, the restoration of drained organic soils is accompanied by rewetting, while the restoration of undrained but otherwise disturbed wetlands may not require rewetting. *Rehabilitation*, as defined by Poopathy *et al*. (2005) and Nelleman & Corcoran (2010), can involve a large variety of practices on formerly drained organic soils, which may or may not include rewetting. For example, the re-establishment of vegetation on a drained site without rewetting is a form of site rehabilitation.

[2] Energy; industrial processes; solvents and other product use; agriculture; land use, land use change and forestry (LULUCF); waste.

readers are directed to methodologies contained in the 2006 IPCC Guidelines (IPCC 2006) for quantifying C stock changes in the woody biomass and dead wood pools.

It is difficult to distinguish between the other C pools[3] in organic soils. Living non-woody biomass (mosses, sedges, grasses) can be hard to separate from the dead litter derived from it, and the litter can be hard to separate from the (organic) soil. For example, the separation between the live and dead portions of mosses is not always clear; nor is it clear whether recently dead mosses should be included in the litter or the soil pool. Similarly, the (organic) soil in sedge dominated and forested tropical peatlands is made up mainly of dead root material and the distinction between the soil and recently dead roots is not easily made; nor is the distinction between recently dead and live roots straightforward. The default emission factors presented in this paper are all derived from published direct flux measurements (from eddy covariance (EC) towers and/or static chambers) over organic soils with moss and/or herbaceous and/or dwarf shrub vegetation. While some publications attempt to assess changes in the aboveground biomass pool separately from changes in the other pools, most combine all pools together. Therefore, we define the composite terms $CO_2\text{-}C_{composite}$ in [2], $CH_4\text{-}C_{composite}$ in [3] and $N_2O\text{-}N_{composite}$ in [4], which integrate all emissions (i.e. ecosystem respiration (autotrophic and heterotrophic), $CH_4$ production, denitrification, nitrification) and removals (i.e. photosynthesis, $CH_4$ oxidation) arising from the soil and the aboveground and belowground vegetation components other than trees.

### Net annual C stock change

The net annual C stock change of rewetted organic soils $\Delta C_R$ (t C ha$^{-1}$ yr$^{-1}$) is the total net loss (or gain) of C from the soil (a loss is indicated by a positive value and a gain by a negative value) resulting from the balance between emissions and removals of both $CO_2$ and $CH_4$, including on-site and off-site components:

$$\Delta C_R = CO_2\text{-}C_R + CH_4\text{-}C_R \qquad [1]$$

where $CO_2\text{-}C_R$ is the net flux of C as $CO_2$ (both on-site and off-site) from the rewetted organic soil (t C ha$^{-1}$ yr$^{-1}$) and $CH_4\text{-}C_R$ is the net flux of $CH_4$ from the rewetted organic soil (kg C ha$^{-1}$ yr$^{-1}$).

### $CO_2$ emissions/removals

For carbon dioxide ($CO_2$) emissions/removals, we can write:

$$CO_2\text{-}C_R = CO_2\text{-}C_{composite} + CO_2\text{-}C_{DOC} + CO_2\text{-}C_{fire} \qquad [2]$$

where $CO_2\text{-}C_{composite}$ denotes net $CO_2$ fluxes from the soil and non-tree vegetation (t C ha$^{-1}$ yr$^{-1}$), $CO_2\text{-}C_{DOC}$ is off-site $CO_2$ emissions from dissolved organic carbon exported from rewetted organic soils (t C ha$^{-1}$ yr$^{-1}$) and $CO_2\text{-}C_{fire}$ is C lost as $CO_2$ emissions from the burning of rewetted organic soils (t C ha$^{-1}$ yr$^{-1}$).

### $CH_4$ emissions/removals

Methane ($CH_4$) emissions/removals from rewetted organic soils result from (a) the balance between biochemical $CH_4$ production and oxidation and (b) emissions of $CH_4$ produced by the combustion of soil organic matter during fire, and can be summarised by the equation

$$CH_4\text{-}C_R = CH_4\text{-}C_{composite} + CH_4\text{-}C_{fire} \qquad [3]$$

where $CH_4\text{-}C_{composite}$ denotes net $CH_4$ fluxes from the soil and non-tree vegetation (kg C ha$^{-1}$ yr$^{-1}$), and $CH_4\text{-}C_{fire}$ is C lost as $CH_4$ from the burning of rewetted organic soils (kg C ha$^{-1}$ yr$^{-1}$).

The $CH_4$ emission factors provided here relate to $CH_4\text{-}C_{composite}$ only (i.e. emissions from livestock and the burning of biomass are excluded). $CH_4$ emissions result from the decomposition of organic soil material by microbes under anoxic conditions, which is strongly controlled by the redox potential within the soil (Fiedler & Sommer 2000) and by soil temperature (van Winden *et al.* 2012). Emissions also originate from the partial decay of non-tree vegetation, but since this cannot easily be separated from the organic soil the emissions are combined here as $CH_4\text{-}C_{composite}$. The probability of fire in rewetted organic soils is low because the water table should be near the surface, but possible soil emissions from fires are included in [3] for completeness. High spatial variation in microtopography, water table depth and vegetation cover is typical of undrained organic soils and is reflected in $CH_4$ fluxes (Strack *et al.* 2006, A. Laine *et al.* 2007a, Riutta *et al.* 2007, Maanavilja *et al.* 2011). Rewetting recreates this natural heterogeneity to some extent, with blocked ditches forming the wetter end of the variation (Strack & Zuback 2013). For this reason, former ditches are included as a part of rewetted sites and not treated separately.

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[3] The six pools in AFOLU are (1) aboveground biomass, (2) belowground biomass, (3) dead wood, (4) litter, (5) soil and (6) harvested wood products.

### $N_2O$ emissions/removals

The emissions of $N_2O$ from rewetted organic soils are controlled by the quantity of nitrogen available for nitrification and denitrification, and the redox potential. They are summarised by:

$$N_2O\text{-}N_R = N_2O\text{-}N_{composite} + N_2O\text{-}N_{fire} \qquad [4]$$

where $N_2O\text{-}N_R$ denotes the net flux of N as $N_2O$ from rewetted organic soils (kg N $ha^{-1}$ $yr^{-1}$), $N_2O\text{-}N_{composite}$ is net $N_2O$ fluxes from the soil and non-tree vegetation (kg N $ha^{-1}$ $yr^{-1}$), and $N_2O\text{-}N_{fire}$ is N lost as $N_2O$ from the burning of rewetted organic soils (kg N $ha^{-1}$ $yr^{-1}$). Published data are currently insufficient to develop default $N_2O$ emission factors for the burning of organic soils (see Chapter 2, IPCC 2014a). Therefore, $N_2O\text{-}N_{fire}$ is not considered further here.

### Derivation of emission factors

An extensive literature review was conducted to collate all GHG ($CO_2$, $CH_4$, $N_2O$) and DOC studies that were available at the time the *Wetlands Supplement* was prepared (i.e. 2013) for (1) rewetted organic soils (includes rewetted, restored and wet managed sites) and (2) natural/undrained organic soils (to be used as proxies for rewetted soils, see criteria below). Laboratory and manipulation experiments were excluded. Literature sources included both peer reviewed and ‘grey literature’ (i.e. not peer reviewed) studies. In the case of the latter, we reviewed the studies and expert judgement was exercised as to whether they were scientifically acceptable for inclusion. In total, three grey literature studies were included.

No studies exist on rewetted tropical sites with the water table close to the surface. For temperate and boreal sites we plotted annual $CO_2$ and $CH_4$ fluxes against the mean water table level (*MWTL*) (positive values upwards from the soil surface) for both natural/undrained soils and rewetted soils to assess whether natural/undrained organic soils could function as proxies for rewetted organic soils. In temperate regions *MWTL* was calculated over one year where the flux measurements covered the full 12 months, while in boreal regions the *MWTL* applied to the growing season only. The non-normally distributed $CH_4$ fluxes (assessed using the Kolmogorov-Smirnov test) were log transformed prior to regression analyses. Fitted linear regression lines ($CO_2$ and $\log_{10}CH_4$ fluxes = $a + (b \times MWTL)$) were compared for each climate zone. Differences between the undrained and rewetted groups were compared using General Linear Models (IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY, USA) to examine the homogeneity of the regression slopes. The 95 % confidence intervals of the intercepts (parameter $a$) were also compared.

All studies included in the database reported GHG flux estimates using either static chamber or EC techniques. The chamber method involves the measurement of gas fluxes at high spatial resolution and is widely employed in circumstances where vegetation is either short (i.e. of low stature) or absent. 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 GHG fluxes was then constructed to evaluate the main drivers of GHG dynamics in rewetted organic soils. When available, the following attributes were extracted from the literature source and included in the database for analysis: climate zone as defined by IPCC (2006), nutrient status[4], mean and median water table level (as well as minimum and maximum values), soil pH, thickness of the organic soil layer, C/N quotient, degree of humification, soil moisture, soil bulk density, plant cover and species or functional groups, previous land use and time since rewetting. The criteria for inclusion in the database were as follows:

(1) The study reported GHG fluxes from rewetted organic soils, abandoned and spontaneously rewetted organic soils, and natural (undrained) organic soils. Natural sites with *MWTL* lower than -30 cm were designated as ‘not wet’, and were not included in the final database. In other words, only natural sites with an annual or seasonal *MWTL* of -30 cm or shallower (i.e. closer to or above the soil surface) were deemed suitable as proxies for rewetted sites since the *MWTL* recorded at all the rewetted sites in our database was at or shallower than -30 cm. Studies from rewetted sites with *MWTL* more than 10 cm above the soil surface were not included either, as they were judged to refer to flooded land. Flooded land is considered a separate type of land in IPCC terms (IPCC 2006).

(2) The study had to report either seasonal or annual GHG fluxes. Studies in the database that reported

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[4] Nutrient poor organic soils (bog) predominate in boreal regions, while in temperate regions nutrient rich (fen) sites are more common. In many cases, nutrient poor organic soil 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 groundwater and the high nutrient status of the bottom layers.

daily flux values were not used, as upscaling to annual flux values could have led to very high errors. However, non-annualised $CH_4$ flux values were used for tropical sites as annual data from those sites are scarce and seasonality is either absent or relates to wet and dry seasons only. During the dry season some tropical sites show very large (> 1 m) drops in water table level. We discarded the measurements made during these times because the conditions cannot be deemed wet, and accepted that the omission of data for naturally dry periods may result in slight overestimation of the $CH_4$ emission factor. In boreal sites, seasonal $CH_4$ fluxes (typically May to October) were converted to annual fluxes by assuming that an additional 15 % of flux occurs in the non-growing season (Saarnio *et al.* 2007). For $CO_2$, seasonal flux data were converted to annual fluxes by adding 15 % to the seasonal ecosystem respiration data from each study (Saarnio *et al.* 2007) and making the assumption that no photosynthesis occurs under snow. This adjustment may result in a slight overestimation of losses outwith the growing season because photosynthesis (and hence C uptake) may occur for a short time outside the period covered by seasonal studies. For studies where ecosystem respiration data were not explicitly reported, a value of 0.30 t $CO_2$-C $ha^{-1}$ (30g $CO_2$-C $m^{-2}$) for non-growing-season respiration was used (Saarnio *et al.* 2007).

(3) Studies had to indicate a *MWTL* for each annual GHG flux reported. In some cases, the GHG flux value was accepted for inclusion on the basis that water table information was available from other publications.

(4) For studies using the EC technique, care was taken not to use annual $CO_2$ fluxes that included accumulation of C into the tree biomass pool (e.g. in the case of treed organic soils) as this would have resulted in double counting under IPCC rules. As such, our derived default emission factors for $CO_2$ exclude $CO_2$ uptake into the tree biomass.

(5) Rewetting as a management practice is in its infancy in the tropics, and while projects to rehabilitate drained peatlands are being initiated in south-east Asia, there are no published flux measurement data for successfully rewetted tropical organic soils from which to derive emission factors. Therefore, a default emission factor for rewetted tropical organic soils was developed based on surrogate data. Subsidence measurements provide a good measure of C losses from drained organic soils (see Chapter 2 in IPCC 2014a) and in tropical organic soils subsidence is near zero when the water table approaches the surface (Hooijer *et al.* 2012, see also Couwenberg *et al*. 2010). In light of the available evidence, the Tier 1 default emission factor was set at 0 t $CO_2$-C $ha^{-1}$ $yr^{-1}$. This value is consistent with observations of subsidence and reflects the fact that rewetting effectively stops soil organic matter oxidation but does not necessarily re-establish the soil C sink function.

### Data treatment

In the database, flux values were standardised to the following units; t $CO_2$-C $ha^{-1}$ $yr^{-1}$, kg $CH_4$-C $ha^{-1}$ $yr^{-1}$, t C $ha^{-1}$ $yr^{-1}$ (for DOC) and kg $N_2O$-N $ha^{-1}$ $yr^{-1}$. For multi-year studies from the same site, annual flux estimates were averaged over the years. Emission factors were calculated as mean fluxes, with 95 % confidence intervals calculated for each of the categories. In order to examine the robustness of the derived emission factor values, we conducted a similar literature search for publications that might have been missed in the original literature search and for new datasets published since the *Wetlands Supplement*.

### Comparison with drained organic soils

To assess the impact of rewetting on GHG dynamics in organic soils, the emission factors derived in Chapter 2 of the *Wetlands Supplement* (IPCC 2014a) for drained land use categories were compared to the emission factors derived here for their rewetted counterparts. The net GHG emissions, based on the global warming potential (GWP; t $CO_2$-eq $ha^{-1}$ $yr^{-1}$) of each gas, were calculated for the land use categories under drained and rewetted conditions. $CH_4$ and $N_2O$ fluxes were converted to $CO_2$ equivalents according to their GWP on a 100-year timescale including climate–carbon feedbacks: $CH_4$ = 34 and $N_2O$ = 298 (Myhre *et al.* 2013).

## RESULTS

### Undrained sites as proxies

The relationships between *MWTL* and $CO_2$/$CH_4$ fluxes were very similar for undrained and rewetted sites in the boreal and temperate climate zones (Figure 1, Figure 2). In the boreal zone, the change in magnitude of the $CO_2$ flux *per* unit change in *MWTL* was small (Figure 1a), whereas it was more pronounced in the temperate zone (Figure 1b). Variance was clearly larger in the temperate data than in the boreal data. $CH_4$ fluxes in both climate

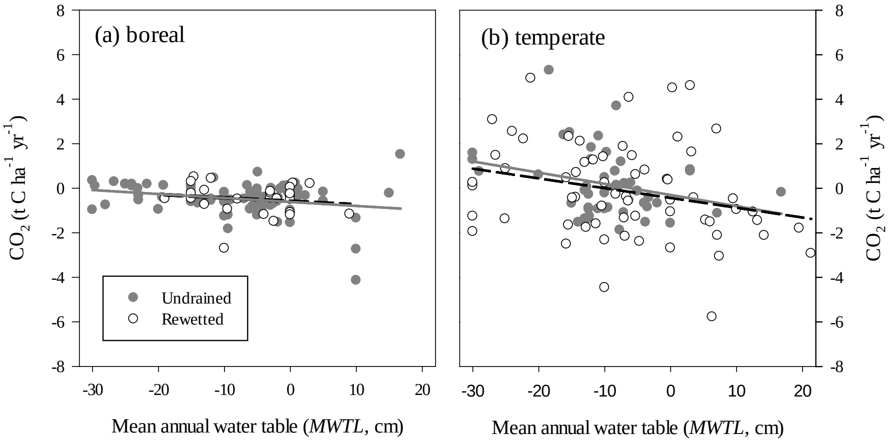

Figure 1. Relationship between annual carbon dioxide ($CO_2$) flux (t C ha$^{-1}$ yr$^{-1}$) and mean water table level (*MWTL*, cm) for undrained and rewetted organic soils in (a) boreal and (b) temperate climate zones. Solid grey and dashed lines are the regression lines for the undrained and rewetted sites respectively. Regression equations and parameters are shown in Table 1. Negative *MWTL* indicates mean water table level below the soil surface and positive *MWTL* indicates mean water table above the soil surface. Negative $CO_2$ values indicate annual $CO_2$ removals and positive values indicate annual $CO_2$ emissions.

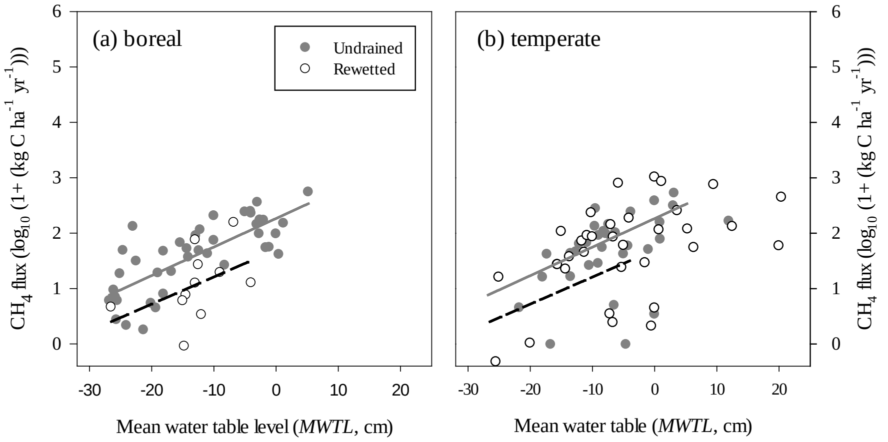

Figure 2. Relationships between annual methane ($CH_4$) fluxes ($\log_{10}$(1 + (kg C ha$^{-1}$ yr$^{-1}$))) and mean water table level (*MWTL*, cm) for undrained and rewetted organic soils in (a) boreal and (b) temperate climate zones. Solid grey and dashed lines are the regression lines for the undrained and rewetted sites respectively. Regression equations and parameters are shown in Table 1. Negative *MWTL* indicates mean water table level below the soil surface and positive *MWTL* indicates mean water table above the soil surface. Positive $CH_4$ values indicate annual emissions and negative values indicate annual removals.

zones showed strong sensitivity to changes in *MWTL*, with lower fluxes observed in conjunction with deeper water table levels (Figure 2). No significant difference in the homogeneity of regression slopes was observed (Table 1) and the 95 % confidence intervals of the intercepts (parameter *a*) overlapped in comparable datasets; so we concluded that undrained sites can, for the purposes of emission factor calculations, act as proxies for rewetted sites with the same *MWTL*, and thereafter we combined the two datasets. Moreover, given the observed similarity between rewetted and undrained soils in the boreal and temperate climate zones, in the absence of existing data we also made the highly generalised assumption that, for the derivation of $CH_4$ and $N_2O$ emission factors, tropical undrained organic soils can act as proxies for tropical rewetted organic soils.

Table 1. Results of General Linear Models (model equations: flux = $a + (b \times MWTL)$) used to test for homogeneity of regression slopes between undrained and rewetted sites in the boreal and temperate climate zones. Test results are given as $F$ and $p$ values. Standard errors of the model parameters are shown in parentheses. Note: sample size (n) includes all annual flux measurements (i.e. not averaged multi-year datasets from the same site) recorded in the *Wetlands Supplement* database and, therefore, differs from the sample sizes described in Figure 3.

| | | Sample size | Model parameters | | | |
|---|---|---|---|---|---|---|
| | | n | *a* | *b* | *F* | *p* |
| ***CO₂*** | | | (t C ha$^{-1}$ yr$^{-1}$) | | | |
| **Boreal** | Undrained | 82 | -0.61 (0.10) | -0.02 (0.01) | *0.02* | *0.90* |
| | Rewetted | 26 | -0.58 (0.18) | -0.02 (0.02) | | |
| **Temperate** | Undrained | 52 | -0.29 (0.28) | -0.05 (0.02) | *0.03* | *0.86* |
| | Rewetted | 64 | -0.43 (0.29) | -0.04 (0.02) | | |
| ***CH₄*** | | | (log$_{10}$ (1+(kg C ha$^{-1}$ yr$^{-1}$))) | | | |
| **Boreal** | Undrained | 49 | 2.27 (0.11) | 0.052 (0.007) | *0.01* | *0.92* |
| | Rewetted | 15 | 1.70 (0.45) | 0.049 (0.033) | | |
| **Temperate** | Undrained | 47 | 1.99 (0.15) | 0.043 (0.016) | *0.10* | *0.76* |
| | Rewetted | 38 | 1.88 (0.14) | 0.036 (0.012) | | |

### Data distribution

A total of 123 ($CO_2$), 164 ($CH_4$), 36 ($N_2O$) and 29 (DOC) data entries satisfied the criteria outlined above and were included in the final database (Figure 3). Data entries for $CO_2$ and $CH_4$ were relatively evenly spread between the boreal and temperate zones, while no $CO_2$ entries and only a small number (11) of $CH_4$ entries were recorded for the tropical zone. In the *Wetlands Supplement*, only two $N_2O$ entries were reported for rewetted organic soils (Hendriks *et al.* 2007, Wilson *et al.* 2013), and we provide here a further 32 data entries mainly from the temperate and boreal zones. DOC entries were found for all three climate zones. In most cases (with the exceptions of tropical data and DOC entries), the data could be further disaggregated by nutrient status (i.e. nutrient poor (bog), nutrient rich (fen)) (Figure 3). Largely due to the small number of data points within any given category, there was insufficient evidence to support the disaggregation of data by additional site conditions, previous land use, time since rewetting or drainage status (i.e. undrained and rewetted).

The $CO_2$ flux data were normally distributed (Shapiro-Wilk test; $p > 0.05$) when disaggregated by climate zone (Figure 4a). The range of values was markedly wider in the temperate zone data (-4.4 to 4.78 t C ha$^{-1}$ yr$^{-1}$) than in the boreal data (-2.68 to 1.48 t C ha$^{-1}$ yr$^{-1}$). The $CH_4$ flux data for both boreal and temperate zones had a log normal distribution characterised by a high number of flux values close

Figure 3. Number of data entries (see main text for inclusion criteria) used to derive carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and dissolved organic carbon (DOC) emission factors. Entries are disaggregated by climate zone (boreal, temperate and tropical), nutrient status (NP = nutrient poor, NR = nutrient rich) and drainage status (U = undrained, R = rewetted).

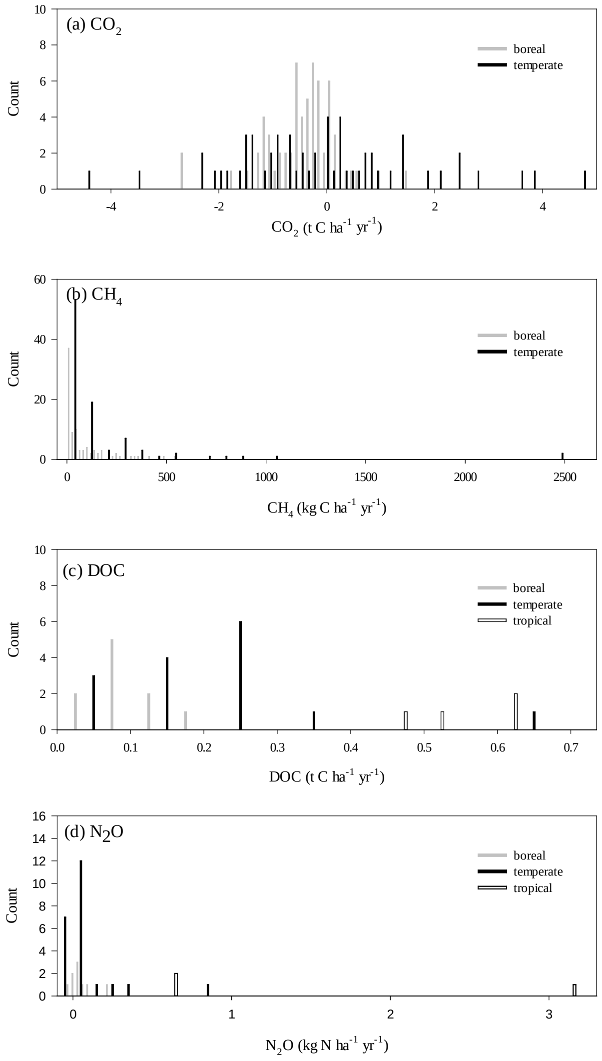

Figure 4. Frequency distributions of (a) carbon dioxide ($CO_2$; t C $ha^{-1}$ $yr^{-1}$), (b) methane ($CH_4$; kg C $ha^{-1}$ $yr^{-1}$), (c) dissolved organic carbon (DOC; t C $ha^{-1}$ $yr^{-1}$) and (d) nitrous oxide ($N_2O$; kg N $ha^{-1}$ $yr^{-1}$) fluxes in undrained and rewetted organic soils in the boreal, temperate and tropical (DOC and $N_2O$) climate zones. Negative values indicate annual removals and positive values indicate annual emissions.

to zero together with some very high values (Figure 4b). As with the $CO_2$ data, the range of $CH_4$ flux values was larger in the temperate zone than in the boreal (Figure 4b). DOC data were normally distributed (Shapiro-Wilk test; $p > 0.05$) in all three climate zones (Figure 4c), with the widest range of values observed in the temperate zone data (0.05 to 0.61 t C $ha^{-1}$ $yr^{-1}$). Similarly, $N_2O$ flux values were mainly congregated around zero with the exception of one high value from a sago (*Metroxylon sagu*) plantation in the tropical zone (Figure 4d).

## Emission factors

### $CO_2$-$C_{composite}$

The $CO_2$-$C_{composite}$ values varied considerably across climate zones and nutrient status (Table 2). Boreal nutrient rich sites showed the highest annual $CO_2$ removals at 0.55 t C $ha^{-1}$ $yr^{-1}$ and temperate nutrient rich sites showed the highest annual emissions of 0.50 t C $ha^{-1}$ $yr^{-1}$. Boreal and temperate nutrient poor sites showed $CO_2$ removal values of 0.34 and 0.24 t C $ha^{-1}$ $yr^{-1}$ respectively. Uncertainty associated with the $CO_2$-$C_{composite}$ values was lowest for boreal nutrient rich sites (± 40 %) and highest in the temperate nutrient rich sites (± 242 %).

### $CH_4$-$C_{composite}$

The lowest emissions were observed in the boreal nutrient poor and tropical sites (41 kg C $ha^{-1}$ $yr^{-1}$) and the highest emissions were seen in the temperate nutrient rich sites (216 kg C $ha^{-1}$ $yr^{-1}$). Associated uncertainty was very high across all groups (Table 2).

### $CO_2$-$C_{DOC}$

The DOC data did not support disaggregation by nutrient status. DOC flux values were 0.08, 0.26 and 0.57 t C $ha^{-1}$ $yr^{-1}$ from the boreal, temperate and tropical zones, respectively (Table 3). The parameter $Frac_{DOC\_CO2}$ sets the proportion of DOC exported from organic soils that is ultimately emitted as $CO_2$. A value of zero would coincide with all the DOC export being deposited in stable forms in lake or marine sediments; as this would simply represent a translocation of C between stable stores, it would not need to be estimated. However, most data on DOC processing indicate that a high proportion is converted to $CO_2$ in headwaters, rivers, lakes and coastal seas (IPCC 2014a). A value of 0.9 is proposed for $Frac_{DOC\_CO2}$ with an uncertainty range of 0.8 to 1 (IPCC 2014a, Evans *et al.* 2015). This resulted in $CO_2$-$C_{DOC}$ values of 0.08, 0.24 and 0.51 t C $ha^{-1}$ $yr^{-1}$ for the boreal, temperate and tropical zones, respectively (Table 3).

### $N_2O$-$N_{composite}$

As the sample sizes were low, it was not possible to derive a robust $N_2O$-$N_{composite}$ value disaggregated by nutrient status (Table 4). Values for the boreal and temperate zones were very similar (0.06–0.07 kg N $ha^{-1}$ $yr^{-1}$). Average emissions from the tropical zone were higher at 0.94 kg N $ha^{-1}$ $yr^{-1}$ but displayed very high uncertainty due to the very small sample size ($n = 5$) and the inclusion of a single high data point (see Melling *et al.* 2007).

Table 2. Emission factors for carbon dioxide ($CO_2$-$C_{composite}$: t C ha$^{-1}$ yr$^{-1}$) and methane ($CH_4$-$C_{composite}$: kg C ha$^{-1}$ yr$^{-1}$) in wet organic soils, and associated uncertainty ranges (95 % confidence intervals). Emission factors disaggregated by climate zone and by nutrient status where appropriate. Positive emission factors indicate emissions to the atmosphere and negative values indicate removals from the atmosphere.

| **Climate zone** | **Nutrient status** | **$CO_2$-$C_{composite}$** | **95 % range** | **$CH_4$-$C_{composite}$** | **95 % range** |
|---|---|---|---|---|---|
| | | (t C ha$^{-1}$ yr$^{-1}$) | | (kg C ha$^{-1}$ yr$^{-1}$) | |
| Boreal* | Poor | -0.34 | -0.59 to -0.09 | 41 | 0.5 to 246 |
| | Rich | -0.55 | -0.77 to -0.34 | 137 | 0 to 493 |
| Temperate** | Poor | -0.23 | -0.64 to +0.18 | 92 | 3 to 445 |
| | Rich | 0.50 | -0.71 to +1.71 | 216 | 0 to 856 |
| Tropical*** | | 0 | | 41 | 7 to 134 |

* $CO_2$-$C_{composite}$ derived from Alm *et al.* 1997, J. Laine *et al.* 1997, Suyker *et al.* 1997, Bubier *et al.* 1999, Komulainen *et al.* 1999, Soegaard & Nordstroem 1999, Tuittila *et al.* 1999, Waddington & Price 2000, Waddington & Roulet 2000, 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.

$CH_4$-$C_{composite}$ derived from the following source material Clymo & Reddaway 1971, Verma *et al.* 1992, Bubier *et al.* 1993, Nykänen *et al.* 1995, J. Laine *et al.* 1996, Alm *et al.* 1997, Komulainen *et al.* 1998, Tuittila *et al.* 2000, Waddington & Roulet 2000, Whiting & Chanton 2001, Gauci *et al.* 2002, Yli-Petäys *et al.* 2007, Drewer *et al.* 2010, Juottonen *et al.* 2012, Urbanová 2012, Strack & Zuback 2013.

** $CO_2$-$C_{composite}$ derived from 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, Cagampan & Waddington 2008, Golovatskaya & Dyukarev 2009, Kurbatova *et al.* 2009, Drewer *et al.* 2010, Waddington *et al.* 2010, Adkinson *et al.* 2011, Couwenberg *et al.* 2011, Koehler *et al.* 2011, Christensen *et al.* 2012, Urbanová 2012, Drösler *et al.* 2013, Herbst *et al.* 2013, Strack & Zuback 2013, Wilson *et al.* 2013.

$CH_4$-$C_{composite}$ derived from Bartlett & Harriss 1993, Dise *et al.* 1993, Shannon & White 1994, Flessa *et al.* 1997, Augustin & Merbach 1998, Waddington & Price 2000, Wickland 2001, Wild *et al.* 2001, Augustin 2003, Sommer *et al.* 2004, von Arnold 2004, Cleary *et al.* 2005, Drösler 2005, Nagata *et al.* 2005, Augustin *et al.* 2006, Bortoluzzi *et al.* 2006, Hendriks *et al.* 2007, Jungkunst & Fiedler 2007, Roulet *et al.* 2007, Scottish Executive 2007, Nilsson *et al.* 2008, Tauchnitz *et al.* 2008, Wilson *et al.* 2009, Couwenberg *et al.* 2011, Glatzel *et al.* 2011, Koehler *et al.* 2011, Beetz *et al.* 2013, Drösler *et al.* 2013, Wilson *et al.* 2013.

*** For tropical rewetted organic soils where decayed organic material is not oxidised due to saturated conditions. $CH_4$-$C_{composite}$ derived from Inubushi *et al.* 1998, Hadi *et al.* 2001, Jauhiainen *et al.* 2001, Jauhiainen *et al.* 2004, Furukawa *et al.* 2005, Hadi *et al.* 2005, Jauhiainen *et al.* 2005, Jauhiainen *et al.* 2008, Melling *et al.* 2012, Pangala *et al.* 2013.

Table 3. Emission factors for dissolved organic carbon (*DOC*: t C ha$^{-1}$ yr$^{-1}$) and $CO_2$-$C_{DOC}$ (t $CO_2$-C ha$^{-1}$ yr$^{-1}$) and associated uncertainty ranges (95 % confidence intervals). Note rounding artefact on *DOC* values for boreal climate zone.

| **Climate zone** | ***DOC*** | **95 % range** | **$CO_2$-$C_{DOC}$** | **95 % range** |
|---|---|---|---|---|
| | (t C ha$^{-1}$ yr$^{-1}$) | | (t $CO_2$-C ha$^{-1}$ yr$^{-1}$) | |
| Boreal* | 0.08 | 0.06 to 0.11 | 0.08 | 0.05 – 0.11 |
| Temperate** | 0.26 | 0.17 to 0.36 | 0.24 | 0.14 – 0.36 |
| Tropical*** | 0.57 | 0.49 to 0.64 | 0.51 | 0.40 – 0.64 |

* Derived from Koprivnjak & Moore 1992, Moore *et al.* 2003, Kortelainen *et al.* 2006, Ågren *et al.* 2008, Nilsson *et al.* 2008, Jager *et al.* 2009, Rantakari *et al.* 2010, Juutinen *et al.* 2013.

** Derived from 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 2009, Strack *et al.* 2008, Waddington *et al.* 2008, Koehler *et al.* 2009, Billet *et al.* 2010, di Folco & Kirkpatrick 2011, Dinsmore *et al.* 2011, Koehler *et al.* 2011, Strack & Zuback 2013, Turner *et al.* 2013.

*** Derived from Zulkifli 2002, Alkhatib *et al.* 2007, Baum *et al.* 2007, Yule & Gomez 2009, Moore *et al.* 2013.

Table 4. Emission factors for nitrous oxide ($N_2O$-$N_{composite}$; kg N $ha^{-1}$ $yr^{-1}$) in rewetted organic soils and associated uncertainty range (95 % confidence intervals).

| **Climate zone** | **$N_2O$-$N_{composite}$** (kg N $ha^{-1}$ $yr^{-1}$) | **95 % range** |
|---|---|---|
| Boreal* | 0.06 | 0.00 to 0.14 |
| Temperate** | 0.07 | -0.03 to 0.14 |
| Tropical*** | 0.94 | -0.03 to 1.90 |

*Derived from Martikainen *et al.* 1995, Nykänen *et al.* 1995, J. Laine *et al.* 1996, Drewer *et al.* 2010, Salm *et al.* 2012.

**Derived from Wild *et al.* 2001, Drösler 2005, Nagata *et al.* 2005, Hendriks *et al.* 2007, Tauchnitz *et al.* 2008, Drewer *et al.* 2010, Beetz *et al.* 2013, Juszczak & Augustin 2013, Wilson *et al.* 2013, Beyer & Höper 2015, Günther *et al.* 2015, Minke *et al.* 2015, Vanselow-Algan *et al.* 2015.

***Derived from Inubushi *et al.* 2003, Melling *et al.* 2007, D. Murdiyarso unpublished data.

## Robustness of EF derivation

We examined the robustness of the $CO_2$ and $CH_4$ emission factors by comparing the values derived above for the *Wetlands Supplement* with data published since that time (Figure 5). The variance in the new $CO_2$ and $CH_4$ values was high, but lay within that of the original dataset. New values for undrained and rewetted sites did not differ significantly from the respective original datasets (Figure 5). The majority of the new $CO_2$ data values were negative (i.e. $CO_2$ removal). Whereas the original dataset provided a positive (i.e. $CO_2$ emission) $CO_2$-$C_{composite}$ value for temperate nutrient rich sites, the new data indicate that this may have been an overestimation of $CO_2$ emissions from these sites (Figures 5a and 6). For both $CO_2$ and $CH_4$, the updated mean flux values (calculated from both the *Wetlands Supplement* data and the new data) for each of the five land types was within the 95 % confidence intervals of the original emission factors (Table 5).

## Comparison with drained organic soils

$CO_2$ emissions decreased considerably following rewetting of drained organic soils (Figure 6a and Table 5). In contrast, $CH_4$ emissions were much higher following rewetting (Figure 6b and Table 5) and were also characterised by very high variability (Figure 6b). $N_2O$ emissions were considerably reduced following rewetting (Figure 6c). The soil GWP was largely dominated by $CH_4$ emissions in the rewetted sites, and by $CO_2$ emissions in the drained sites, although $N_2O$ emissions were also significant in the latter (Table 5). Both the drained and rewetted sites had a net warming effect on the

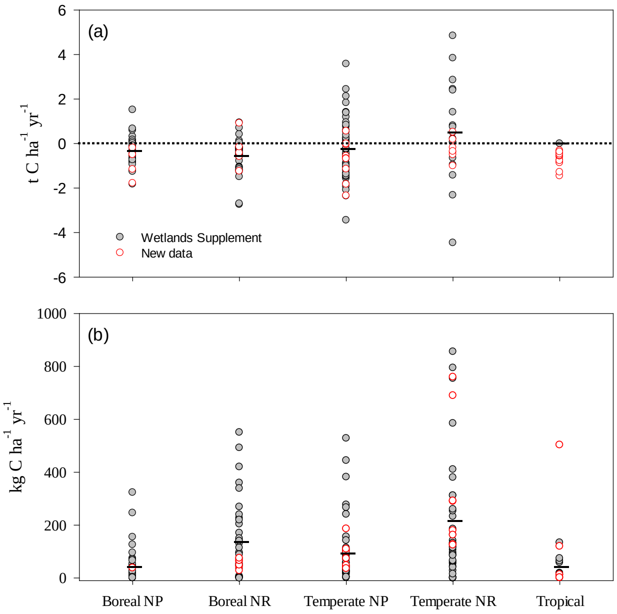

Figure 5. (a) Carbon dioxide ($CO_2$; t C $ha^{-1}$ $yr^{-1}$) and (b) methane ($CH_4$; kg C $ha^{-1}$ $yr^{-1}$) fluxes disaggregated by climate zone and nutrient status (NP = nutrient poor, NR = nutrient rich). Negative values indicate annual removals and positive values indicate annual emissions. *Wetlands Supplement* data are shown as grey circles and new data as red circles. Black horizontal line indicates the mean value (derived emission factor) calculated for the *Wetlands Supplement* data.

For literature used in the derivation of emission factors for the *Wetlands Supplement* (grey circles), see Tables 2 and 3. **New $CO_2$ values** taken from Neuzil 1997, Page *et al.* 2004, Chimner & Karberg 2008, Lähteenoja *et al.* 2009, Dommain *et al.* 2011, Lähteenoja *et al.* 2012, Lund *et al.* 2012, Beetz *et al.* 2013, Gažovič *et al.* 2013, Koebsch *et al.* 2013a, Olson *et al.* 2013, Urbanová *et al.* 2013b, Campbell *et al.* 2014, Cliche Trudeau *et al.* 2014, Humphreys *et al.* 2014, McVeigh *et al.* 2014, Peichl *et al.* 2014, Strack *et al.* 2014, Aurela *et al.* 2015, Dommain *et al.* 2015, Günther *et al.* 2015, Helfter *et al.* 2015, Hribljan *et al.* 2015, Kareksela *et al.* 2015, Levy & Gray 2015, Lund *et al.* 2015, Minke *et al.* 2015, Vanselow-Algan *et al.* 2015, C.D. Evans *et al.* in preparation, D. Wilson unpublished data. **New $CH_4$ values** taken from Inubushi *et al.* 2003, Melling *et al.* 2005, Rinne *et al.* 2007, Hirano *et al.* 2009, Long *et al.* 2010, Forbrich *et al.* 2011, Cliche Trudeau *et al.* 2013, Gažovič *et al.* 2013, Huth *et al.* 2013, Juszczak & Augustin 2013, Koebsch *et al.* 2013b, Nadeau *et al.* 2013, Olson *et al.* 2013, Urbanová *et al.* 2013a, Urbanová *et al.* 2013b, Adji *et al.* 2014, Ballantyne *et al.* 2014, Cooper *et al.* 2014, Günther *et al.* 2014, Strack *et al.* 2014, Beyer & Höper 2015, Goodrich *et al.* 2015, Koebsch *et al.* 2015, Levy & Gray 2015, Minke *et al.* 2015.

Table 5. Global warming potential (GWP) for drained and rewetted (presented here using the derived value from the *Wetlands Supplement* and an updated value that incorporates the new data published post 2013) organic soils for selected land use categories as defined by IPCC (2014a). Methane ($CH_4$) fluxes include emissions from ditches and were calculated using the default ditch area provided by IPCC (2014a). $CH_4$ and nitrous oxide ($N_2O$) fluxes are converted to $CO_2$ eq. (t $CO_2$-eq ha$^{-1}$ yr$^{-1}$) according to their GWPs on a 100-year timescale including climate–carbon feedbacks: $CH_4$ = 34 and $N_2O$ = 298 (Myhre *et al*. 2013). Positive values indicate a net warming effect on the climate and negative values indicate a net cooling effect. ER = emission reduction, NR = nutrient rich, NP = nutrient poor, DD = deeply drained, SD = shallow drained. Values in bold indicate the dominant GHG within each land use category.

| | Land use category | Drained | | | | | Rewetted | | | | | | Rewetted (updated) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$ | DOC | $CH_4$ | $N_2O$ | GWP | $CO_2$ | DOC | $CH_4$ | $N_2O$ | GWP | ER | $CO_2$ | DOC | $CH_4$ | $N_2O$ | GWP | ER |
| boreal | Forest Land NP | **0.92** | 0.44 | 0.42 | 0.10 | 1.88 | -1.25 | 0.29 | **1.86** | 0 | 0.90 | 0.98 | -1.52 | 0.29 | **1.87** | 0.03 | 0.67 | 1.21 |
| | Forest Land NR | **3.41** | 0.44 | 0.25 | 1.50 | 5.60 | -2.02 | 0.29 | **6.21** | 0 | 4.48 | 1.12 | -1.93 | 0.29 | **5.64** | 0.03 | 4.03 | 1.57 |
| | Cropland | **28.97** | 0.44 | 1.98 | 6.09 | 37.48 | -2.02 | 0.29 | **6.21** | 0 | 4.48 | 33.00 | -1.93 | 0.29 | **5.64** | 0.03 | 4.03 | 33.45 |
| | Grassland | **20.90** | 0.44 | 2.03 | 4.45 | 27.82 | -2.02 | 0.29 | **6.21** | 0 | 4.48 | 23.34 | -1.93 | 0.29 | **5.64** | 0.03 | 4.03 | 23.79 |
| | Peat extraction | **10.27** | 0.44 | 1.12 | 0.14 | 11.97 | -1.25 | 0.29 | **1.86** | 0 | 0.91 | 11.06 | -1.52 | 0.29 | **1.87** | 0.03 | 0.67 | 11.30 |
| temperate | Forest Land NP | **9.53** | 1.14 | 0.27 | 1.31 | 12.25 | -0.84 | 0.88 | **4.17** | 0 | 4.21 | 8.04 | -1.22 | 0.88 | **4.09** | 0.03 | 3.78 | 8.47 |
| | Forest Land NR | **9.53** | 1.14 | 0.27 | 1.31 | 12.25 | 1.83 | 0.88 | **9.79** | 0 | 12.50 | -0.25 | 0.96 | 0.88 | **10.7** | 0.03 | 12.57 | -0.32 |
| | Cropland | **28.97** | 1.14 | 1.98 | 6.09 | 38.18 | 1.83 | 0.88 | **9.79** | 0 | 12.50 | 25.68 | 0.96 | 0.88 | **10.7** | 0.03 | 12.57 | 25.61 |
| | Grassland NP | **19.43** | 1.14 | 2.04 | 2.01 | 24.62 | -0.84 | 0.88 | **4.17** | 0 | 4.21 | 20.41 | -1.22 | 0.88 | **4.09** | 0.03 | 3.78 | 20.84 |
| | Grassland NR, DD | **22.37** | 1.14 | 2.50 | 3.84 | 29.85 | 1.83 | 0.88 | **9.79** | 0 | 12.50 | 17.35 | 0.96 | 0.88 | **10.7** | 0.03 | 12.57 | 17.28 |
| | Grassland NR, SD | **13.20** | 1.14 | 2.16 | 0.75 | 17.25 | 1.83 | 0.88 | **9.79** | 0 | 12.50 | 4.75 | 0.96 | 0.88 | **10.7** | 0.03 | 12.57 | 4.68 |
| | Peat extraction | **10.27** | 1.14 | 1.12 | 0.14 | 12.67 | -0.84 | 0.88 | **4.17** | 0 | 4.21 | 8.46 | -1.22 | 0.88 | **4.09** | 0.03 | 3.78 | 8.89 |
| tropical | Plantation | **55.00** | 3.01 | 1.58 | 0.56 | 60.15 | 0.00 | **2.09** | 1.86 | 0 | 3.95 | 56.20 | 0.00 | 2.09 | **2.77** | 0.44 | 5.30 | 54.85 |
| | Cropland | **51.33** | 3.01 | 1.77 | 2.34 | 58.45 | 0.00 | **2.09** | 1.86 | 0 | 3.95 | 54.50 | 0.00 | 2.09 | **2.77** | 0.44 | 5.30 | 53.15 |

Note that $CO_2$ and DOC values for Rewetted (updated) are the same as Rewetted for tropical land use categories, and that GHG and GWP values are for soil emissions/removals and do not take into account C emissions/removals associated with the woody biomass pool.

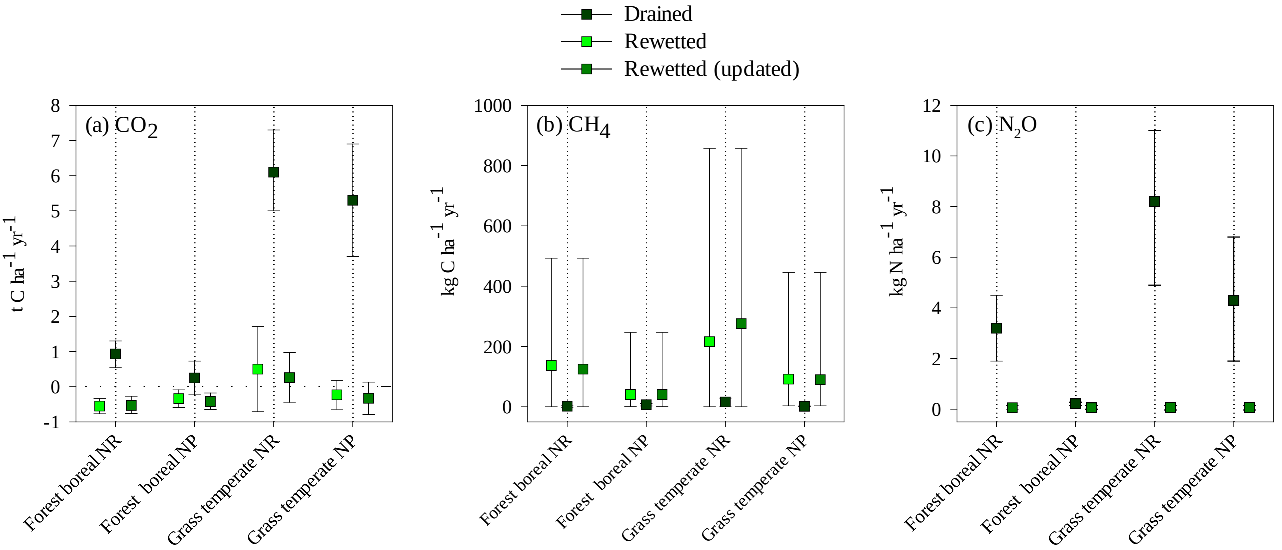

Figure 6. Mean annual (a) carbon dioxide ($CO_2$; t C $ha^{-1}$ $yr^{-1}$), (b) methane ($CH_4$; kg C $ha^{-1}$ $yr^{-1}$) and (c) nitrous oxide ($N_2O$; kg N $ha^{-1}$ $yr^{-1}$) emission factors for drained (values taken from IPCC 2014a, Chapter 2) and rewetted (presented using the derived value from the *Wetlands Supplement* and an updated value that incorporates the new data published post 2013) organic soils for selected land use categories as defined by IPCC (2014a). Error bars represent the 95 % confidence intervals. Positive values indicate annual emissions and negative values indicate annual removals. NR = nutrient rich, NP = nutrient poor.

climate, although rewetting did result in large emissions reductions across most land use categories (Table 5). However, higher emissions were estimated from the rewetted temperate nutrient rich forest sites compared to their drained counterparts, an apparent anomaly caused by the lack of disaggregation by nutrient status in the drained sites (due to a low sample size), compounded by disaggregation in the rewetted sites.

## DISCUSSION

With the exception of temperate nutrient rich organic soils, all rewetted organic soils were estimated to be net $CO_2$ sinks, although the inclusion of the most recent data suggests that $CO_2$ emissions from temperate nutrient rich soils may be much lower than those derived from the original dataset, with many studies indicating a net $CO_2$ sink (Figure 5a). Since undrained temperate nutrient rich organic soils must (in order to exist) have acted as net $CO_2$ sinks during the course of their formation, it seems reasonable to assume that a successfully rewetted nutrient rich peatland should also ultimately act as a $CO_2$ sink, or at least cease to act as a $CO_2$ source. The positive emission factor associated with this category may therefore be a consequence of incorporating data from studies undertaken on incompletely rewetted sites, sites at which the natural peat-forming vegetation has not re-established, or recently rewetted sites that are still undergoing transitional changes, for example the decomposition of a residual biomass pool. Inclusion of other data (for example, core-based C accumulation rates from undrained sites or additional flux data from sites that have been rewetted for longer time periods) may help to redress this issue.

Data on net $CO_2$ fluxes from successfully rewetted tropical organic soils are completely lacking, and data on the $CO_2$ balance of undrained tropical organic soils are also scarce. Some of the peat swamps in this area may have been degrading naturally for the past 2000 years (Dommain *et al.* 2014). Yet, most tropical peatlands are a net sink of $CO_2$ (Page *et al.* 2004, Lähteenoja *et al.* 2009, Dommain *et al.* 2011, Lähteenoja *et al.* 2012, Dommain *et al.* 2015), displaying the highest long-term accumulation rates of peatlands worldwide (Dommain *et al.* 2011, Dommain *et al.* 2015). Although the C accumulation data for undrained tropical peatlands (Figure 5) indicate a net sink, the re-establishment of such a sink after rewetting may present a considerable challenge. As such, the default emission factor of 0 t $CO_2$-C $ha^{-1}$ $yr^{-1}$ (Table 2) probably applies to best case rewetting scenarios only.

The removals of $CO_2$ in rewetted organic soils are in sharp contrast to the high emissions associated with drained organic soils (Table 5 and Figure 6). Moreover, our derived values for DOC losses (Table 3) are lower than those reported for drained organic soils (Evans *et al.* 2015). In addition, $N_2O$ emissions in rewetted soils were very low across all climate zones (Figure 5), although rewetting does result in strongly increased $CH_4$ emissions following the reversal of drainage (Table 5 and Figure 6b). However, rewetting in general represents a significant climate change mitigation action as a result of (a) the considerable decrease in $CO_2$ emissions and (b) the accompanying reduction of $N_2O$ emissions (with its high global warming potential) relative to drained organic soils (Table 5 and Figure 6c).

**Uncertainties**

GHG emissions/removals were characterised by variations both *within* and *between* the disaggregated groups (Figures 4 and 5). Considerable uncertainty is attached to individual data points used in the derivation of the emission factors as most of the studies in the database are generally of a short duration (1–2 years) and do not take into account the longer-term natural variation, a feature captured in long-term datasets (e.g. Roulet *et al.* 2007, McVeigh *et al.* 2014, Aurela *et al.* 2015, Helfter *et al.* 2015). Uncertainty is reduced by using the mean value of multi-year data from the same site and by averaging over multiple sites in each disaggregated group.

The large uncertainties associated with the derived emission factors indicate that individual rewetted and undrained sites may differ considerably in terms of their current abiotic and biotic conditions and resulting vegetation cover. On the one hand, the variation relates to spatial variation found within the various study sites. For example, following rewetting a site may develop as a mosaic of microsites, both vegetated and non-vegetated, characterised by differences in vegetation composition, productivity and *MWTL*, with consequent variations in the magnitude and direction of GHG fluxes (Tuittila *et al.* 1999, Wilson *et al.* 2013). On the other hand, variation between sites can be even larger. Nutrient rich sites in particular display a wider range of flux values between sites than nutrient poor sites (Figure 5), which can be explained by their high hydrological, biogeochemical and botanical diversity. For example, plant associations in rich fens are diverse, ranging from brown moss dominated to sedge stands and reed beds, whereas nutrient poor temperate and boreal bogs may support a more limited range of plant assemblages. The wide range of flux values in nutrient rich organic soils can also be explained by the diversity of previous land-uses, as nutrient rich organic soils tend to have been used more intensively than nutrient poor sites, especially across the temperate zone (Joosten & Clarke 2002).

The highly generic approach adopted in deriving the IPCC Tier 1 (default) emission factors for rewetted organic soils means that a high level of uncertainty will remain, as is further evidenced by the wide range in the new data values (Figure 5). Clearly, a move towards more specific emission factors (Tier 2) that take into account the factors that control GHG fluxes in rewetted organic soils, and thereby lead to a reduction in the associated uncertainty, is desirable.

**Refinement of emission factors**

GHG fluxes in rewetted organic soils are controlled by a wide range of external and internal factors, which include the prevailing climate, nutrient status, water table position, previous land use history, time since rewetting, absence or presence of vegetation and vegetation composition. However, in seeking to determine the overarching driver(s) of GHG exchange for rewetted organic soils, the exercise here was constrained to some extent by the quantity of available data for rewetted sites and by the quality of ancillary data in published studies. For the former, we were able to significantly expand the datasets by the inclusion of undrained sites as proxies (Figures 1 and 2), while for the latter it was possible to augment the data in some cases with information contained in other publications from the same site. Our analysis of GHG flux data from rewetted (and undrained) organic soils allowed for an initial disaggregation of the data by climate zone and nutrient status (Figure 3). This is in keeping with the good practices recommended by the IPCC (2006). However, there were insufficient data available to determine the strength of relationships between GHG fluxes and other variables such as previous land use history, time since rewetting and vegetation composition.

*Previous land use*

Although not captured in the general dataset, the influence of previous land use history (e.g. forest, grassland, cropland and wetland) on GHG fluxes in rewetted organic soils is likely to be profound. For example, $CH_4$ emissions following the rewetting of former agricultural land can be very high (Hendriks *et al.* 2007, Harpenslager *et al.* 2015) whereas rewetted boreal cutover peatlands may show $CH_4$

emissions well below the average (Tuittila *et al.* 2000, Waddington & Day 2007). While the influence of previous land use may diminish over time, sub-division of the flux data according to previous land use would, given a sufficient number of studies, undoubtedly improve the accuracy of emissions factors.

*Time since rewetting*

Available datasets from rewetted organic soils generally cover a period of ten years or less after rewetting and for this reason it is difficult to identify clear temporal patterns in GHG fluxes and determine with accuracy the transition time required to fully capture the changes following rewetting (e.g. Tuittila *et al.* 1999, Bortoluzzi *et al.* 2006, Kivimäki *et al.* 2008, Waddington *et al.* 2010, Wilson *et al.* 2013). Given the limitations in the available scientific literature, our derived emission factors assume that there is no transient period and that rewetted organic soils immediately behave like undrained organic soils in terms of GHG dynamics.

Whereas the high $CO_2$ emissions observed at drained sites will be reduced immediately upon rewetting, the time needed for recovery of the C sink function may vary from several years to many decades (Tuittila *et al.* 1999, Samaritani *et al.* 2011, Wilson *et al.* 2013) depending on the type of restoration methods employed, how long these methods are continued, and the pre-rewetting climate and hydrological boundary conditions. Re-establishment of the peat-forming vegetation cover on rewetted organic soils is necessary to reinstate the C sink function that ultimately leads to long-term C sequestration in the soil. In the period immediately following rewetting, soil oxidation rates will be low as a consequence of the anoxic conditions, while most of the newly sequestered C is contained within the non-woody biomass pool (leaves, stems, roots and litter). As a result, the ecosystem sink can temporarily be much larger upon restoration (Soini *et al.* 2010, Wilson *et al.* 2013), although a site can remain a $CO_2$ source during the first years after rewetting as well (Petrone *et al.* 2003, Waddington *et al.* 2010). 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 rate typical of undrained organic soils.

The impact of rewetting on changes in $CH_4$ fluxes over time differs between nutrient poor and rich sites. The rewetting of nutrient poor cutover peatlands results in 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 (Tuittila *et al.* 2000, Waddington & Day 2007). Indeed, work by Vanselow-Algan *et al.* (2015) has indicated that high $CH_4$ emissions could persist for decades after rewetting, particularly if the vegetation is periodically inundated. In contrast, rewetting of nutrient rich sites seems to result in high initial $CH_4$ emissions that decline over time as the litter inundated during rewetting activities is decomposed (Limpens *et al.* 2008, Augustin *et al.* 2012). Thus, changes in $CH_4$ emissions and removals over time appear to be linked to vegetation succession (Tuittila *et al.* 2000, Cooper *et al.* 2014) and understanding how emissions change over time would require the inclusion of vegetation information.

*Vegetation composition*

Numerous studies have indicated the important role of vegetation in the regulation of GHG fluxes in both undrained and rewetted organic soils. Plants remove $CO_2$ from the atmosphere *via* photosynthesis, utilise available nitrogen in the soil, and provide the substrate for $CH_4$ production and a pathway for the transportation of $CH_4$ from the saturated soil to the atmosphere (e.g. Bubier 1995, Shannon *et al.* 1996, Tuittila *et al.* 2000, Marinier *et al.* 2004, Wilson *et al.* 2009, Dias *et al.* 2010). Indeed, the presence of shunt species (i.e. wetland adapted vascular plant species known to transport $CH_4$ from the soil to the atmosphere) has a significant effect on $CH_4$ efflux from organic soils (e.g. Couwenberg & Fritz 2012, Levy *et al.* 2012) and a refinement of emission factors could be achieved through the development of nationally or regionally specific emission factors that directly address vegetation composition (see Riutta *et al.* 2007, Dias *et al.* 2010, Couwenberg *et al.* 2011, Forbrich *et al.* 2011). In particular, where perennial woody biomass plays a significant role in the net $CO_2$ and $CH_4$ exchange (e.g. pneumatophore species in the tropics) between rewetted organic soils and the atmosphere (e.g. Pangala *et al*. 2013), country-specific methods should be developed that reflect the C stock changes in the tree biomass and dead tree organic matter pools under typical management practices and their interaction with the soil pool.

*Water table level*

The relationship between water table level and $CO_2/CH_4$ emissions/removals was evident in this study (Figures 1 and 2). As the water table is one of the main controls on GHG cycling, future (i.e. country specific) emission factors could be derived and disaggregated by water table level provided sufficient ancillary data are available (e.g. mean annual, maximum and minimum water table values). Drainage ditches have been shown to be “hotspots” of $CH_4$ emissions within the wider drained landscape (Cooper *et al.* 2014, IPCC 2014a). Few data are available on $CH_4$ emissions from ditches that remain after rewetting or that are filled in during rewetting activities, although there is some evidence to suggest that $CH_4$ emissions may remain high after rewetting (Waddington & Day 2007, Cooper *et al.* 2014). However, rewetting reduces the hydrological differences between fields and neighbouring ditches creating a more homogeneous surface that is not so different from undrained sites where hollows are major hotspots of $CH_4$ emissions (e.g. A. Laine *et al.* 2007b). Improved estimates of water table level distribution across a site would better capture the spatial variability associated with $CH_4$ fluxes. Our literature search also identified the impact of inundation on GHG dynamics in rewetted sites. In many cases, where the water table is maintained at very high levels ($>$ 20cm above the soil surface), $CH_4$ emissions can be extremely high (e.g. Augustin & Chojnicki 2008, Koch *et al.* 2014, Hahn *et al.* 2015, Vanselow-Algan *et al.* 2015), although much lower values have been observed as well (Koch *et al.* 2014, Minke *et al.* 2015). More research will be needed to assess the drivers behind the wide variation found in essentially flooded ecosystems.

### *Improved data collection*

Emission factors could be further refined by the use of advanced process-based (mechanistic) models. Annual GHG fluxes are commonly calculated using quasi-mechanistic models that rely on descriptive attributes (*WTD*, temperature, photon flux density, vegetation cover, *etc*.) fitted to intermittent measurement data (Minke *et al.* 2012). Process-based models have the potential to integrate the interactions between biomass, dead organic matter and soil carbon pools, and to provide improved spatial and temporal estimates of GHG exchange; they do require, however, a very high level of information and complexity in regard to the interactions and processes described above (e.g. Walter *et al.* 2001, Frolking *et al.* 2002, Li *et al.* 2010, Baird *et al.* 2012, Meng *et al.* 2012, Gong *et al.* 2013, Metzger *et al.* 2015). Furthermore, the use of more sophisticated models would not remove the need for robust field measurements, which are required to support model development, parameterisation and testing.

More refined emission factors of course need to be accompanied by equally disaggregated land cover data. Recent advances in high resolution remote sensing and aerial imagery have the potential to significantly improve data collection. For example, unmanned aerial vehicles (UAVs) have been shown to provide extremely high resolution imagery in terms of the areal cover of vegetation communities (Kalacska *et al.* 2013) and could be particularly useful for sites where there is a mosaic of microsites (e.g. Knoth *et al.* 2013). Moreover, the availability of new satellite platforms, such as the Sentinel 2B (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/sentinel-2), could provide highly detailed imagery that would allow further disaggregation by vegetation type at a relatively low cost. Similarly, aerial platforms could potentially provide more detailed information to allow disaggregation by soil moisture or water table level (Kasischke *et al.* 2009, Jaenicke *et al.* 2011, Torbick *et al.* 2012).

## Information gaps and ongoing issues

While the number of GHG studies on organic soils has steadily increased over the last few decades (see reviews by Lai 2009, Haddaway *et al.* 2014, IPCC 2014a), our work here has highlighted the existence of some research gaps, in particular the paucity of GHG data from the tropical climate zones as well as specific issues associated with rewetting.

### *Tropical data*

GHG emissions from drained tropical peatlands are affected by a number of factors, such as higher peat surface temperatures following removal of the forest vegetation, aerobic conditions in the upper part of the peat column resulting from both drainage and disturbance caused by management operations and fertiliser applications (Jauhiainen *et al.* 2012, Jauhiainen *et al.* 2014). The effect of rewetting on GHG fluxes from tropical organic soils has yet to be measured. If the soil becomes persistently waterlogged, $CO_2$ fluxes should be near zero from a biochemical perspective. However, it is much more difficult to rewet and maintain a stable water table in tropical peat than in boreal and temperate peat soils because the hydraulic conductivity of tropical peat is extremely high (Page *et al.* 2008). Furthermore, there is a tendency to flooding during the wet season and near drought in severely dry periods such as El Niño years (Dommain *et al.* 2011). Moreover, several studies in south-east Asia have indicated that there could be sizeable C emissions from former agricultural lands even if these are essentially wet (Hooijer *et al.* 2012, Jauhiainen *et al.* 2012, Husnain *et al.* 2014), while Gandois *et al*. (2013) reported substantial impacts on the C balance of an undrained tropical peat swamp forest following deforestation alone. The inference from these studies is that it may take considerable time for C losses from tropical peat swamp forests to reduce after rewetting. Moreover, achieving pre-disturbance C accumulation rates will be a long and largely unpredictable process that will probably only be realised following the re-establishment of closed-canopy forest, along with the accompanying environmental conditions conducive to peat formation. Additional research on rewetting techniques and associated GHG fluxes will be needed as a basis for higher tier emission factors. Furthermore, reliable data on GHG fluxes from organic soils in Africa, the tropical Americas or other tropical regions outside south-east Asia are very rare and virtually nothing is known about the effects of rewetting.

### *Fire*

Due to high moisture contents, organic soils in intact ecosystems are protected to some degree from burning (Turetsky *et al.* 2015), although fires do occur on undrained organic soils. It can be assumed that the probability of fire occurrence in rewetted organic soils is likely to be small if the water table position is maintained at or near the surface, although there may still be a major risk of fire affecting trees in tropical regions where the temperature is high, even if the water table is near the peat surface. If the surface peat does become dry and flammable, for example during periods of drought, wet layers deeper in the peat profile will serve as fire barriers, limiting the depth of peat burning and hence C loss.

### Waterborne pathways

An understanding of the fate of DOC leaked from organic soils is still poor. While DOC can be returned to the atmosphere as $CO_2$ (or $CH_4$), or transferred to lake sediments or long term C stores such as the deep ocean or marine sediments (Müller *et al.* 2015, Abrams *et al.* 2016), further studies should be carried out to improve the values for the conversion factor $Frac_{DOC\_CO2}$. Measurements from undrained and rewetted organic soils should be undertaken to obtain more accurate and country-specific values of $DOC_{FLUX}$. Furthermore, since DOC production has been observed to vary with vegetation composition and productivity as well as with soil temperature, research should focus on developing specific values for different types of rewetted organic soils (e.g. nutrient rich *versus* nutrient poor). Additional waterborne C losses come from leaching of inorganic carbon (DIC) and from erosion (particulate organic carbon; POC), as well as evasion of $CO_2$ and $CH_4$ from the waterbodies within or close to the peatlands themselves. However, these are not treated in the *Wetlands Supplement* as very few data exist from rewetted sites and these losses are likely to be site specific (Evans *et al.* 2015). Although, compared to DOC, a greater proportion of POC 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 $CO_2$ emissions), there is now some evidence to suggest that POC may also undergo significant mineralisation during riverine transport or (since POC fluxes are typically highest during flood events) following overbank deposition onto floodplains (Evans *et al.* 2015).

## CONCLUSIONS

Rewetting of organic soils results in a decrease in $CO_2$ and $N_2O$ emissions, DOC losses and GHG emissions based on the global warming potential; but also leads to an increase in $CH_4$ emissions. In general, the emission factors derived in the *Wetlands Supplement* for rewetted organic soils appear robust and compare well to the new data ($n = 58$) published since the Supplement. However, the GHG emission factor estimates derived in this paper are subject to uncertainty as a consequence of the lack of data for some climate zones and land use categories, and the wide variation in GHG emissions/removals inherent to organic soils in general. Future research should focus on the information gaps that have been highlighted here, with particular emphasis on determining the transient period following rewetting, reducing uncertainty through the derivation of country specific emission factors and, perhaps most critically given the high emissions associated with drainage, the quantification of GHG emissions/removals in rewetted tropical organic soils.

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