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GREENHOUSE GAS EMISSIONS FACTORS FOR DRAINED AND REWETTED BOREAL, TEMPERATE AND TROPICAL PEATLANDS

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SUMMARY

Organic soils store an estimated 610 Gt of carbon (C) worldwide, an amount equivalent to >70% of the current mass of C in the atmosphere. Organic soils have been drained for forestry, crop production, grazing, water supply, peat extraction and other human-related activities and account for around 10% of all greenhouse gas (GHG) emissions from the agriculture, forestry and other land use sectors (AFOLU). In addition, drainage increases the vulnerability of organic soils to fire which can lead to considerable additional GHG emissions in all climate zones, particularly from tropical organic soils. Rewetting by blocking drainage ditches, construction of bunds or disabling drainage pump facilities can have several objectives, such as nature conservation, GHG emissions reductions, leisure activities or paludiculture. This paper describes the methods and scientific approach used in the IPCC Wetlands Supplement to derive the Tier 1 emission factors (EFs) for the full suite of GHG and waterborne C fluxes associated with rewetting of organic soils and compares these values with data published since that time.

Keywords: *Peatland, carbon dioxide, emission factors, fire, methane, nitrous oxide, peat, rewetting. IPCC*

INTRODUCTION

Drained organic soils are a significant source of greenhouse gas emissions (GHG) to the atmosphere accounting for around 10% of all GHG emissions from the agriculture, forestry and other land-use sectors (AFOLU) (Smith *et al.,* 2014). In addition, drainage increases the vulnerability of organic soils to fire (Turetsky *et al.,* 2015), which can lead to considerable additional GHG emissions, particularly from tropical organic soils (Page *et al.* 2002). Furthermore, waterborne carbon (C) losses may also be accentuated following drainage (Evans *et al.,* 2015). Rewetting of drained organic soils may reduce GHG emissions and waterborne C losses and could be included in mitigation strategies (IPCC 2014a). While emissions from some drained organic soils are reported annually by Annex 1 countries under the UNFCCC Kyoto Protocol, emissions or removals (i.e. C uptake) from rewetted organic soils have not been included thus far owing to an absence of data and a lack of methodological guidance. The IPCC 2013 Wetlands Supplement provides methodological guidance for countries to report GHG emissions/removals from the rewetting of organic soils in their national inventory submissions. This paper expands on the work related to rewetted 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.

METHODS

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 and readers are directed to methodologies contained in the 2006 IPCC Guidelines (IPCC 2006. In organic soils C fluxes are generally small relative to the total stock and are problematic to measure in a stock based approach. Therefore, net CO_2 emissions or removals from organic soils are more accurately measured directly as a flux. Emissions (and removals) of the other main GHGs in the land use sector; CH_4 and N_2O, are commonly approached as fluxes. These are here denoted as CO_2-C and CH_4-C and N_2O-N to be consistent with those used in the 2006 IPCC Guidelines. The net C stock change of rewetted organic soils results from net gains or losses of C resulting from the balance between CO_2 and CH_4 emissions /removals and includes both on- and off-site components (Eq.1).

$$\Delta C_{rewetted\ org\ soil} = CO_2\text{-}C_{rewetted\ org\ soil} + CH_4\text{-}C_{rewetted\ org\ soil} \qquad \textbf{Eq. 1}$$

CO_2 EMISSIONS/REMOVALS FROM REWETTED ORGANIC SOILS

In organic soils, it is difficult to distinguish between the different C pools[9]. 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. The default emission factors presented in this presentation are all derived from published direct flux measurements (eddy covariance (EC) towers and/or static chambers) over organic soils with moss and/or herbaceous and/or dwarf shrub vegetation (in tropical peatland EC towers are over and under forest canopy or on other land uses). Whereas some publications attempt to assess changes in the above ground biomass pool separate from the other pools, most combine all pools together. Therefore, we defined the term $CO_2\text{-}C_{composite}$ in Eq. 2, which integrates all CO_2 fluxes from the soil and the above- and belowground vegetation components other than trees.

$$CO_2\text{-}C_{rewetted\ org\ soil} = CO_2\text{-}C_{composite} + CO_2\text{-}C_{DOC} + CO_2\text{-}\ C_{fire} \qquad \textbf{Eq. 2}$$

CH_4 EMISSIONS/REMOVALS FROM REWETTED ORGANIC SOILS

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 (Eq. 3).

$$CH_4\text{-}C_{rewetted\ org\ soil} = CH_4\text{-}C_{composite} + CH_4\text{-}C_{fire} \qquad \textbf{Eq. 3}$$

The probability of fire occurrence in rewetted organic soils is likely to be low if the water table position is near the surface, although possible soil emissions from fires are included in Eq. 3 for completeness.

N_2O EMISSIONS FROM REWETTED ORGANIC SOILS

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.

$$N_2O_{rewetted\ org\ soil}\text{-}N = N_2O\text{-}N_{composite} + N_2O\text{-}N_{fire} \qquad \textbf{Eq. 4}$$

Published data are currently insufficient to develop default N_2O emission factors for the burning of organic soils (see Chapter 2, IPCC 2014a), therefore $N_2O\text{-}N_{fire}$ of Eq. 4 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 a proxy for rewetted soils, see criteria below). No studies exist on rewetted tropical sites with the water table close to the surface. 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 parameters were extracted from the literature source and included in the database for analysis: climate zone as defined by IPCC (2006), nutrient status, mean water table level (*MWTL*), median water table level (as well as minimum and maximum values), soil pH, thickness of the organic soil layer, C/N ratio, degree of humification, soil moisture, soil bulk density, plant cover and species or functional groups, previous land use and time since rewetting. However, non-annualized 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 a wet and dry season only.

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

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} and t C ha^{-1} yr^{-1} (for DOC). For multi-year studies from the same site, annual flux estimates were averaged over the years. Emission factors (t C ha^{-1} yr^{-1}) were calculated as flux means, with 95% confidence intervals calculated for each of the categories.

COMPARISON WITH DRAINED ORGANIC SOILS

In order to assess the impact of rewetting on GHG dynamics in organic soils, the emission factors derived in Chapter 2, IPCC 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, for the land use categories under drained and rewetted conditions were calculated. 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.

RESULTS

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 of CH_4 entries (11) were recorded for the tropical zone. N_2O entries were mainly found in the temperate and boreal zones, while DOC entries were found for all three climate zones. In most cases, the data could be further disaggregated by nutrient status (i.e. nutrient poor (bog), nutrient rich (fen)), with the exception of tropical data, and DOC entries.

Undrained Sites as Proxies

The relationship between *MWTL* and CO_2/CH_4 fluxes was very similar for undrained and rewetted sites in the boreal and temperate climate zones and we concluded that undrained sites can, for the purposes of emission factor calculations, act as proxies for rewetted sites with the same mean *MWTL*, and hereafter we combined the two datasets. Moreover, we also used tropical undrained organic soils as a proxy for tropical rewetted organic soils for the derivation of CH_4 and N_2O emission factors.

Emissions Factors

CO_2-$C_{composite}$

The CO_2-$C_{composite}$ values varied considerably across climate zones and nutrient status. Boreal nutrient rich sites showed the highest annual CO_2 removals at 0.55 tonnes C ha^{-1} yr^{-1} and temperate nutrient rich sites showed the highest annual emissions at 0.50 tonnes C ha^{-1} yr^{-1}. Boreal and temperate nutrient poor sites showed CO_2 removal values of 0.34 and 0.24 tonnes C ha^{-1} yr^{-1} respectively. Uncertainty 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 CH_4-C ha^{-1} yr^{-1}) and the highest emissions were seen in the temperate nutrient rich sites (216 kg CH_4-C ha^{-1} yr^{-1}). Associated uncertainty was very high across all groups.

CO_2-C_{DOC}

Most data on DOC processing indicate that a high proportion is converted to CO_2 in headwaters, rivers, lakes and coastal seas. A value of 0.9 is proposed for $Frac_{DOC\_CO2}$ with an uncertainty range of 0.8 to 1 (IPCC 2014, Evans *et al.,* 2015).This resulted in CO_2-C_{DOC} values of 0.08, 0.24 and 0.51 tonnes C ha^{-1} yr^{-1} for the boreal, temperate and tropical zones, respectively.

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. 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 owing to the very small sample size (n=5) and the inclusion of a single high data point (Melling *et al.,* 2007).

Comparison with Drained Organic Soils

CO_2 emissions decreased considerably following rewetting of drained organic soils. In contrast, CH_4 emissions were much higher following rewetting and were also characterised by very high variability. N_2O emissions were considerably reduced following rewetting.

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. 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. Although C accumulation data for undrained tropical peatlands 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} 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. Moreover, our derived values for DOC losses 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, although rewetting does result in strongly increased CH_4 emissions following the reversal of drainage. 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.

UNCERTAINTIES

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. 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.

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 by the quantity of available data for rewetted sites and by the quality of ancillary data in published studies.

Time since rewetting

Available datasets from rewetted organic soils generally cover a period of 10 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 (Wilson *et al.,* 2013).

Vegetation composition

Numerous studies have indicated the important role of vegetation in the regulation of GHG fluxes in both undrained and rewetted organic soils. The presence of aerenchymous shunt species, for example, has a significant effect on CH_4 efflux from organic soils (Levy *et al.,* 2012).

Water table levels

The relationship between water table and CO_2/CH_4 emissions/removals was evident in this study. As the water table is one of the main controls on GHG cycling, future emission factors (i.e. country specific) could be derived and disaggregated by water table level provided sufficient ancillary data are available. Drainage ditches have been shown to be ―hotspots" of CH_4 emissions within the wider drained landscape (Cooper *et al.,* 2014) but few data are available on CH_4 emissions from ditches that remain after rewetting or that are filled in during rewetting activities.

INFORMATION GAPS AND ONGOING ISSUES

While the number of GHG studies on organic soils has steadily increased over the last few decades this work 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

Rewetting as a management practice is in its infancy in the tropics and there are no published flux measurement data from 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. If the peat becomes persistently waterlogged, CO_2 fluxes should be near zero from a biochemical perspective. However, it is much more difficult to rewet tropical peat and maintain a stable water table than boreal and temperate peat soils given that the hydraulic conductivity of tropical peat is extremely high (Page *et al.,* 2008). Furthermore, there is also a tendency to flooding during the wet season and near drought in severe dry periods, such as in El Niño years. Moreover, several studies in Southeast Asia have indicated that there could still be sizeable C emissions from former agricultural lands even if these were essentially wet (Hooijer *et al.,* 2012, Jauhiainen *et al.,* 2012) and it could take some considerable time for ecosystem C dynamics to approach those typical of undrained organic soils. 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 Southeast 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.

Waterborne pathways

An understanding of the fate of DOC leaked from organic soils is still poor. Large parts are returned to the atmosphere as CO_2 (or CH_4) or transferred to long-term C stores, such as the deep ocean or marine sediments (Abrams *et al.,* 2016) and the use of alternative values for the conversion factor $Frac_{DOC\_CO2}$ (where sufficient evidence is available) may be more appropriate.

CONCLUSION

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. 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 with organic soils in general. Future research should focus on the information gaps that have been highlighted here, with particular emphases given to 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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