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Review of Greenhouse Gas Emissions from Rewetted Agricultural Soils

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Abstract

Climate policies encourage the search for greenhouse gas (GHG) mitigation options in all economic sectors and peatland rewetting is one of the most efficient mitigation measures in agriculture and land use. The benefits shown in the national GHG inventories, however, depend not only on the actual mitigation actions on the ground but also how well the effects can be reported. Currently there are no specific emission factors for reporting GHG emissions from rewetted agricultural soils as the current emission factors are aggregated for several pre-rewetting land use types. Also, rewetting can aim at either restoration or different forms of paludiculture which may differ in their GHG profile and thus demand disaggregated emission factors. We compiled the current knowledge on GHG emissions on sites where rewetting has occurred on former agricultural peatland in temperate or boreal climate zones. The recent data suggest that on average the current emission factors for rewetting nutrient-rich sites published by the Intergovernmental Panel for Climate Change (IPCC) provide a good estimate for reporting emissions from rewetting in the temperate zone. However, the total GHG balances differed widely in restoration, *Sphagnum* farming and production of emergent plants in paludiculture and it is evident that disaggregated emission factors will be needed to improve the accuracy of reporting the effects of mitigation measures in the GHG inventories.

Keywords Peatland · Climate · GHG · Rewetting · Paludiculture · Emission factor

Introduction

Although peat soils cover only 3–4% of the global surface area they hold at least 30% of the global soil organic carbon, about 450–700 Gt (Xu et al. 2018; IPCC 2019). Peat accumulates because the low level of oxygen in water-saturated soils reduces aerobic degradation activity, slowing down the decomposition rate of litter and so the carbon dioxide (CO_2) release (Yu 2012). Conversely, anaerobic bacteria and archaea can carry on the decomposition of organic matter in the absence of oxygen, resulting in methane (CH_4) emissions (Saarnio et al. 2009; Couwenberg and Fritz 2012). Generally, the release of carbon in the form of CH_4 is offset by the net CO_2 uptake (Hemes et al. 2018) and nitrous oxide (N_2O) emissions are negligible in undrained peat soils (Regina et al. 1996). Although a natural site can release C during drought (Saarnio et al. 2007), on average the gross primary production (carbon uptake) is higher than the ecosystem respiration (carbon release), resulting in a net build-up of a peat layer (IPCC 2006; Joosten et al. 2016).

Despite their importance as long term carbon stocks and their high ecological value, peat soils are deeply threatened by human activities which may have a significant long-term impact on their carbon balance and their provisioning of ecosystem services (Chimner et al. 2017). Agriculture, forestry, land-use intensification, peat extraction and infrastructure development are the main drivers of peatland drainage (Tanneberger et al. 2020). Such human intervention turns peat soils from sinks to sources of carbon. The drainage process lowers ground water level and lets oxygen into the peat, thereby enhancing its aerobic decomposition which results in high CO_2 emissions (Joosten et al. 2016). While CH_4 fluxes from drained peat soils are very low or negligible, N_2O emissions can be significant, especially in nitrogen-rich sites (Leppelt et al. 2014). Thus, agricultural peatlands are usually a strong source of GHGs (Leifeld and Menichetti 2018). It has been estimated that at least 12% of natural peatlands has been drained globally, leading to their progressive degradation (Joosten 2016). Drained peatlands contribute up to 5% of

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global GHG emissions with an estimated net flux of 0.9–3 Gt CO_2 $year^{-1}$ (Joosten 2016; IPCC 2019).

In order to reduce the GHG emissions from drained peatlands and to re-establish their role as carbon sinks and their capacity to provide essential ecosystem services, the necessity to restore their hydrological and ecological conditions is increasingly recognised (Leifeld and Menichetti 2018; Tanneberger et al. 2021). The concept of restoration denotes all the practices required to assist the recovery of a specific ecosystem after its degradation, damage or destruction (SER 2004). In the case of drained peatlands, it comprises raising the water table and enabling the recovery of ecosystem services. The more disturbed the ecosystem is the more difficult is the full restoration of ecosystem functions, and for agriculturally used lands it may be impossible (Joosten 2016).

Rewetting limits peat mineralization which leads to reduced CO_2 emissions (Strack and Zuback 2013) and negligible N_2O emissions due to lower availability of mineral nitrogen in saturated conditions (Schrier-Uijl et al. 2014). The reactivation of anaerobic respiration, on the other hand, increases the release of CH_4 (Joosten et al. 2016; Jensen et al. 2017). A large number of studies have demonstrated the effectiveness of rewetting in restoring the carbon sink capacity of peat soils similar to natural undrained peatlands (Schrier-Uijl et al. 2014; Renou-Wilson et al. 2016; Nugent et al. 2018; D'Acunha et al. 2019). In other cases, rewetting has not been able to re-establish the carbon sink function (at least in a short-term period) but still highly reduce the emissions compared to drained sites (Strack and Zuback 2013; Renou-Wilson et al. 2016; Wilson et al. 2016a).

This decade was nominated the Decade on Ecosystem Restoration by the United Nations (UN 2019). If this together with different climate and biodiversity targets boosts rewetting it is essential to have reliable estimates of the climate change mitigation potential following rewetting. At country level, accurate data on the emissions and removals of these practices are needed for national GHG inventories. Within the United Nations Framework Convention on Climate Change (UNFCCC), the signatory countries belonging to Annex I, have to report their annual GHG inventory for the different economic and land-use sectors. The UNFCCC protocols require that the Parties use the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which provide internationally recognised methodologies to estimate GHG budgets at country levels. Volume 4 of the 2006 IPCC Guidelines comprises procedures and equations needed to prepare annual inventories for agriculture and land use and, more specifically, chapter 7 refers to managed wetlands (IPCC 2006). However, the latter did not include methodologies specific to rewetting of peatlands. In 2014, the IPCC published the Wetlands Supplement to the 2006 Guidelines in order to provide a broader coverage on wetlands and updated methodologies in the light of new available scientific information, including data and procedures for rewetted organic soils (IPCC 2014; Chapter 3). The most straightforward and widely used Tier 1 methodology implies that the national area of rewetted soils is multiplied by a coefficient defining the emissions or removals of CO_2 and CH_4 per hectare in a year, i.e. the emission factor (EF), disaggregated by climate zone and nutrient status. Within the Tier 1 approach, N_2O emissions from rewetted soils are considered negligible and are not accounted for. The IPCC EFs for rewetted organic soils are derived from an extensive literature review with data from both undrained and rewetted sites (Wilson et al. 2016b).

EFs for boreal and temperate zones in the IPCC Wetlands Supplement include data from papers published up to the year 2011 and 2013, respectively. Since then, new studies on rewetting have been published, and more data on GHG fluxes from rewetted agricultural peat soils are now available. The peat degradation and nutrient status are generally higher in the agricultural sites than in the less intensively managed peatlands and it is still unknown how well the existing aggregated emission factors are suited for reporting the GHG emissions from rewetted agricultural sites. For this reason, we conducted a literature review to summarize the more recent information on GHG emissions and removals associated with rewetting agricultural sites in temperate and boreal regions. The aims of this study were 1) to estimate whether there are sufficient data available for emission factors for rewetting of agricultural soils and 2) how much the different rewetting types of agricultural soils differ with respect to their GHG emissions.

Materials and Methods

Field studies on sites where former agricultural land (cropland or grassland) had been rewetted and the annual average water table depth was equal or shallower than 0.25 m were included in this analysis. Also naturally wet meadows with an agricultural background were included. We made one exception to the criteria on former land use: the *Sphagnum* site reported in (Beyer and Hoeper 2015) which was a former peat mining area was included as removal of the agriculturally affected topsoil is a common practice in *Sphagnum* farming and thus the former land use has less impact on the results of rewetting. Only peer-reviewed papers reporting annual flux estimates were chosen. We report average annual values for CO_2, CH_4 and N_2O fluxes per hectare and year for three categories: restoration to natural conditions, paludiculture with *Sphagnum* farming and paludiculture of emergent biomass crops as well as all of these combined. Carbon in harvest was included in the estimate of annual CO_2 balance in the estimates for emergent plants if harvesting was done.

Global warming potentials 27.2 and 273 were used for CH_4 and N_2O, respectively, to convert the results to CO_2 equivalents (Canadell et al. 2021). Methane emissions from ditches or CO_2 emissions from dissolved carbon were left out from this comparison as measurement results were rarely available. We did not attempt to disaggregate the results by climate zone as according to the climatic zone classification of FAO (2001) used by the IPCC, only the study of Wang et al. (2018) originates from the boreal climatic region. All the other references were from temperate regions.

Differences between the annual GHG rates of the management types were tested using the generalized linear model analysis method of SAS EG software (version 7.1). The values for annual fluxes were log-transformed to normalise their distribution.

Results and Discussion

Restoring highly degraded agricultural sites to conditions corresponding to natural peatlands is challenging but our data compilation showed that fairly favourable GHG balances can still be expected. In general, restored sites likely turn into sinks of CO_2 while emissions of CH_4 and N_2O are high enough to make these sites small net sources of GHGs (Table 1). The measured emission rates are similar to the IPCC emission factors for rewetting nutrient-rich peat sites in the boreal zone (IPCC 2014). However, the data mainly originates from the temperate regions and thus the existing EFs for temperate regions appear too high for reporting the GHG fluxes of rewetted agricultural sites as the total of the reviewed emissions were significantly lower compared to the respective IPCC EFs.

The *Sphagnum* farming sites were sinks of CO_2 when the harvest was not included in the balance of CO_2 (Table 1). The total net GHG rate without the effect of biomass removal also indicated sink. The harvest was not included in the carbon balance values because, unlike with the emergent plants, the site manager can adjust the harvest rate based on various criteria or even leave all biomass at the site for peat formation. A typical harvest rate of 3.2 t of dry matter (Wichmann et al. 2020) would add close to 6 t CO_2 to the annual balance leading to a net emission rate of 3 t CO_2 eq. ha^{-1} yr^{-1}. Overall, the GHG fluxes in restoration and *Sphagnum* farming did not differ significantly but N_2O fluxes were higher from restoration.

The sites with emergent plant biomass production were on the average net sources of all GHGs (Table 1). The sites were generally not carbon neutral with respect to CO_2 balance and emissions of CO_2 and CH_4 were generally higher than in the other management types. Emissions of N_2O were at the same level as those from the restored sites and significantly higher than in *Sphagnum* farming. The total emissions amounted to 18 t CO_2 eq. ha^{-1} yr^{-1} which is close to the total of the emission factors for shallow-drained grasslands which amount to ca. 15 t CO_2 eq. ha^{-1} yr^{-1} (IPCC 2014). This is understandable as most of the reviewed field studies were conducted on wet grasslands.

On average, the reviewed sites representing different rewetting types had a climate warming impact of 6.3 t CO_2 eq. ha^{-1} yr^{-1} (Table 1). The fact that the climatic effect is that high even after considerable management changes illustrates the challenge in GHG mitigation in agricultural peatlands. However, the results also predict significant mitigation potential as the total emissions are still reduced remarkably, approximately by 70–80% compared to agricultural use of drained peatlands which typically involves emissions in the range 25–35 t CO_2 eq. ha^{-1} yr^{-1} (IPCC 2014).

The majority of the reviewed sites were monitored during the early phase after rewetting. The net positive GHG balance after rewetting could be, in some cases, a consequence of the fact that such sites are still in a transitional phase and peat-forming vegetation has not yet re-established completely (Wilson et al. 2016b). However, also rising CH_4 fluxes after rewetting have been observed (Chamberlain et al. 2018). It is known that in some cases a long time is needed for the recovery of a negative C balance, from several years to decades (Beyer and Hoeper 2015), while in other sites ecological and C sink functions similar to pristine peatlands are achieved soon after rewetting (Laine et al. 2019).

Rewetting features the trade-off between CO_2 and CH_4 emissions; also called the "biogeochemical compromise" (Hemes et al. 2018). Although most of the reviewed sites were net C sinks in the long term based on their net ecosystem C balance (Table 1), the relatively high CH_4 emissions are a significant component of the total GHG balance and may appear a challenge when using this simplistic approach based on the GWP coefficients. However, radiative forcing modelling that better takes into account the different lifetimes of the GHGs in the atmosphere shows that the increase in CH_4 emissions generally does not undermine the climate change mitigation potential of peatland rewetting (Guenther et al. 2020). Ojanen and Minkkinen (2020) made a more disaggregated study and reported that most croplands and grasslands worldwide are among the ecosystems providing net cooling effect when rewetted, at least after some decades. Future research might offer ways to avoid high CH_4 emissions by for example targeting rewetting based on site types (Chamberlain et al. 2018).

There are currently two sets of IPCC EFs available for reporting effects of rewetting of agricultural soils: those for shallow-drained grasslands (ground water table higher than 0.3 m) and those for rewetted organic soils and the latter are mostly based on studies on other than agricultural soils (IPCC 2014). More disaggregated EFs would be needed to report the GHG mitigation effects of different management

Table 1 Mean fluxes of CO_2 (harvest included, except for *Sphagnum* farming), CH_4 and N_2O (t CO_2 eq. ha^{-1} $year^{-1}$ with 95% confidence intervals) in former agricultural soils after restoration or transfer to paludiculture and respective IPCC emission factors for comparison (IPCC 2014)

Use	CO_2	CH_4	N_2O	Total	n	References
Restoration	−3.5 (−5.6..-1.4) a	4.1 (2.4..5.8) ab	0.5 (0.05..1.0) a	1.1	$CO_2 = 38$ $CH_4 = 26$ $N_2O = 13$	1–12
Paludiculture, *Sphagnum*	−5.4 (−7.4..-3.3) a	2.5 (−0.5..5.6) a	0.003 (−0.1..0.1) b	−2.8*	$CO_2 = 8$ $CH_4 = 8$ $N_2O = 8$	13–14
Paludiculture; emergent crops	10.5 (5.2..16) b	6.5 (3.0..10) b	0.7 (0.3..1.1) a	18	$CO_2 = 23$ $CH_4 = 23$ $N_2O = 23$	15–20
All rewetted	0.9 (−1.7..3.5)	4.9 (3.2..6.5)	0.5 (0.3..0.8)	6.3	$CO_2 = 69$ $CH_4 = 57$ $N_2O = 44$	1–20
IPCC EFs (rewetting), boreal, nutrient rich	−2	3.7	0	1.7		
IPCC EFs (rewetting), temperate, nutrient rich	1.8	5.9	0	7.7		

Different letters denote statistical differences between rewetting types

*carbon removal in harvest not included

References: 1) Hendriks et al. 2007, 2) Schrier-Uijl et al. 2014, 3) Renou-Wilson et al. 2016, 4) Wang et al. 2018, 5) Jensen et al. 2017, 6) Kandel et al. 2019a, 7) Poyda et al. 2016, 8) D'Acunha et al. 2019, 9) Herbst et al. 2013, 10) Jacobs et al. 2007, 11) Beetz et al. 2013, 12) Guenther et al. 2015, 13) Guenther et al. 2017, 14) Beyer and Hoeper 2015, 15) Huth et al. 2018, 16) Karki et al. 2019, 17) Kandel et al. 2020, 18) Kandel et al. 2019b, 19) Leiber-Sauheitl et al. 2014, 20) Tiemeyer et al. 2016. The Original Data Is Available as a Supplemental file with References to the Numbering in this Table option in different climatic conditions. Our results suggest that the emissions from restoration and *Sphagnum* farming in temperate zone are overestimated with the corresponding IPCC EFs for rewetting as the measured values were actually closer to the EFs for boreal zone than those for the temperate zone. As for restoration, the new data pool is already quite strong at least in the temperate zone and even the data in Table 1 could be used for emission reporting at least in central Europe from where the data mainly originate from. Paludiculture based on grassland species or other emergent plants, on the other hand, should be reported using the IPCC EFs for shallow drained grasslands rather than those developed for rewetting. It is still to be elucidated which EFs would be suitable for rewetting agricultural sites in the boreal zone as sufficient data are still lacking.

This review suggests that the pool of literature on restoring agricultural soils has grown significantly since the acquisition of the current IPCC emission factors but the data for GHG emissions from paludiculture sites are still scarce. Reporting emissions from paludiculture is thus still very uncertain either with the existing emission factors provided by the IPCC or with the reviewed values of Table 1. Different rewetting actions are getting more common in the coming years and it is important to have more research for the development of disaggregated emission factors for rewetted agricultural soils in different management options and climate zones.

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Authors' Contributions A.B. extracted most of the data from the literature and wrote the first version of the manuscript, T.L. extracted part of the data and took part in the writing process, H.K., S.S. and K.R. planned the work and took part in writing the paper. All authors read and approved the final manuscript.

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Data Availability The datasets used and analysed during the current study are provided as a supplement.

Code Availability Not applicable.

Declarations

Ethics Approval We follow the guidelines for the responsible conduct of research and for handling allegations of misconduct (the RCR guidelines) published by the Finnish National Board on Research Integrity TENK, which is appointed by the Ministry of Education and Culture in Finland.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest There are no conflicts of interest.

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