BOREAL ENVIRONMENT RESEARCH 30: 125–132
ISSN 1797-2469 (online)

Helsinki 12 June 2025

# IPCC default emission factors for boreal drained organic agricultural soils do not capture the enhanced emissions after grass renewal

Viktoriia Hetmanenko[1)], Kristiina Lång[2)], Sanna Saarnio[3)] and Hanna Kekkonen[4)]

[1)] *Natural Resources Institute Finland, Latokartanonkaari 9, 00790 Helsinki, Finland*
[2)] *Natural Resources Institute Finland, Tietotie 4, 31600 Jokioinen, Finland*
[3)] *Natural Resources Institute Finland, Yliopistokatu 6 B, 80100 Joensuu, Finland*
[4)] *Natural Resources Institute Finland, Paavo Havaksentie 3, 90570 Oulu, Finland*
**corresponding author's e-mail: viktoriia.hetmanenko@luke.fi*

*Received 25 Sep. 2024, final version received 8 May 2025, accepted 12 May 2025*

Hetmanenko V., Lång K., Saarnio S. & Kekkonen H. 2025: IPCC default emission factors for boreal drained organic agricultural soils do not capture the enhanced emissions after grass renewal. *Boreal Env. Res.* 30: 125–132.

Based on the default emission factors, grass cultivation on drained organic soils is a lower source of greenhouse gas emissions than an annual crop cultivation. However, the emission factors may be biased because the published measurement data are limited and often short-term. Most of the publications cited in the "2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands" for grasslands on drained organic soils in the boreal climate exclude measurements from long-term leys and do not provide data on GHG emissions following practices such as ploughing, re-seeding, or chemical treatments. Only a limited number of studies document the occurrence of soil tillage and herbicide application during experiments, and those that do often fail to include varied seasonal combinations of these events. This rapid communication highlights the need for long-term greenhouse gases exchange observations across larger variations of grass renewal techniques to provide further insights into carbon and nitrogen emissions from drained organic soils.

## Introduction

Grasslands are one of the most widely distributed terrestrial ecosystems accounting for approximately 40% of the Earth's terrestrial surface with carbon stocks being about 50% more than the amount stored in forests globally (O'Mara 2012). In Europe, 17.4% of the total land area is covered by grassland and 24.2% by cropland (Eurostat, 2018). Even though grasslands have high carbon sequestration potential, human management activities have caused grasslands to become a net source of greenhouse gas (GHG) emissions (2.0 +/–0.4 Gt $CO_2$eq $yr^{-1}$) which is comparable to croplands emissions, even without considering the shrinking of grassland area and its conversion to croplands (Chang *et al.* 2021). Emissions of carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$) from managed, including grazing, grasslands on organic soils are among the highest emissions per unit of the area of agriculturally managed soil (Maljanen *et al.* 2010; Leppelt *et al.* 2014).

*Editor in charge of this article: Christina Biasi*
https://doi.org/10.60910/ber2025.kr34-0w83

Cultivated grassland or grassland in rotations can be a greater source of GHG than undisturbed permanent grassland swards because usually, grass-to-grass re-seeding requires soil disturbance which intensifies GHG emissions from soil (Kayser *et al.* 2018). Grass-to-grass re-seeding or grass cycle renewal techniques vary from rejuvenation (no seed, but improving drainage, grazing, etc.) to minimal disturbance without altering the soil structure (e.g. direct re-seeding) and herbicide application followed by ploughing. On farms in the intensive grass production areas in the boreal region, regular ploughing and reseeding of grass typically occur every three and a half years. During the first year, it is common practice to cultivate annual crops with grass undersown. Autumn re-seeding is more often applied by farmers not to lose the period of high grass production and because of comparatively low weed infestation of grassland after autumn grass renewal (Velthof *et al.* 2010).

Grassland renewal imposes the risk of diminishing soil carbon stock, increasing N losses to watercourses and enhanced GHG emissions from soil (Kayser *et al.* 2018). The underlaying reasons for this are ploughing-induced structure disturbances, incorporation of plant residues, changes in moisture and microbial decomposition of organic substances that disturb carbon (C) and nitrogen (N) cycling (Necpálová *et al.* 2013). As the carbon stock of organic soils is large, even minor disturbance might lead to high losses through priming, i.e. acceleration of soil organic matter (SOM) turnover as the result of fresh organic residues to the soil (Kuzyakov *et al.* 2000). In mineral soils, the addition of crop residues generally enhances carbon stocks, but their impact on SOM in current and former peatlands remains poorly understood. The phenomenon of peat priming, where fresh organic inputs accelerate decomposition of stable peat carbon and increase GHG emissions was verified through laboratory incubation experiments (Hamer & Marschner 2002; Wen *et al.* 2019). Cédric *et al.* 2018 found neutral priming effect of biomass incorporation in cropland and increased peat decomposition in grassland.

Nitrogen mineralization associated with organic matter decomposition after soil disturbance leads to increased $N_2O$ emissions. Bleken *et al.* (2022) showed that stubble could be considered the major source for $N_2O$ emissions originating from grassland renewal. Tiemeyer *et al.* (2024) reported that $N_2O$ emissions following grassland ploughing on bog peat were twice as high as those from the original swards. However, direct grass sowing did not lead to increased $N_2O$ emissions. Buchen *et al.* (2017) found no differences in $N_2O$ emissions between direct seeding and ploughing, emphasizing that grassland renewal, in general, had no significant effect on annual $N_2O$ losses.

The Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories provide methods for estimating GHG emissions and management of greenhouse gas inventory, data gathering, compilation, and reporting. The 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Hiraishi *et al.* 2014) provides emission factors (EFs) across climate domains with attribution of the area assigned to different land-use categories including croplands and grasslands. The 2019 Refinement to the 2006 IPCC Guidelines for GHG inventories refined the Tier 1 methodology through assessment of the most novel research to accurately estimate data for anthropogenic emissions and removals of GHG from mineral soils, but the method for cultivated organic soils was not refined. The IPCC default EFs for drained inland organic soils account for GHG emissions resulting from SOM decomposition. $N_2O$ emissions from crop residues are reported separately, including those associated with grassland renewal. What is potentially lacking from the emission statistics, are the extra $CO_2$ and $N_2O$ emissions from organic soil priming.

In boreal areas grass cultivation differs from the IPCC definition where "grasslands generally have vegetation dominated by perennial grasses, and grazing is the predominant land use". In boreal areas, cultivated grasslands are fertilized repeatedly to maximize yields during short growing season, they are harvested by machines several times a year, and the plant population is renewed intermittently usually every three to five years (Tiainen *et al.* 2020). Crop is harvested, preserved and utilized for feeding livestock during winter season. This practice is partly in conflict with the IPCC definition of grasslands and thus these grasslands should be included in the area of croplands. However, the data behind the EFs for boreal grasslands was derived mainly from studies on short-term grasslands and can potentially be used to report emissions of a typical boreal grassland.

However, it is not clear if the current EFs for grasslands include the emissions related to the renewal of grasslands. If not, the emissions can be underestimated. This rapid communication aimed to resolve uncertainty about the inclusion of effects of grassland renewal to IPCC EFs on drained organic soil in boreal climate conditions.

## Materials and methods

We conducted a comprehensive review of the studies referenced in the 2013 Supplement to the 2006 IPCC Guidelines for $CO_2$ and $N_2O$ emission factors from boreal drained organic soils under grassland and cropland. Organic soil, as defined by the 2006 IPCC Guidelines, is soil with an organic horizon of at least 10 cm thickness or, if thinner, containing at least 12% organic carbon when mixed to a depth of 20 cm, and it either remains unsaturated for extended periods with more than 20% organic carbon by weight or experiences water saturation episodes with organic carbon content varying based on clay percentage.

Our objective was to assess the experimental designs employed in these studies and determine whether grass renewal occurred during the measurement periods in the respective articles. Methane ($CH_4$) fluxes on cultivated drained organic soils are close to zero and thus ignored in this rapid communication. The parameters collected from the studies were research site location, mean annual air temperature, mean annual precipitation, water table level, organic layer depth, soil pH, duration of the experiment, crop rotation during the experiment, occurrence and method of grassland renewal, and the type and timeline of soil disturbance.

## Results and discussion

The research sites in the publications cited represent organic soils with different organic layer depths (from 20 to 300 cm), carbon content (from 13% to 49% of total C content), and pH in the range of 3.5–7.2. The experimental site locations, along with their corresponding temperatures and precipitation patterns presented in the "Grassland, drained" section, fall within the expected climatic range characteristic of the boreal zone, thereby ensuring their representativeness. However, the "Cropland, drained" section includes references to sites situated outside the boreal zone, notably in Southern Germany and Denmark.

Data from six articles were used to develop the $CO_2$ emission factors (Table 1). Grassland renewal during the measurement period was documented in only one of the seven experiments cited within the grassland category for $EFCO_2$. One experiment involved autumn ploughing without the application of herbicides for grass termination (Lohila *et al.*, 2004). The cropping system in two studies included annual crop (barley) with grass undersown during the first experimental year. Notably, only one publication investigated $CO_2$ emissions from "old grass," specifically examining a six-year-old grass stand. The mass of below-ground crop residues increases with grass age. Acharya *et al.* (2012) showed that the 4-year-old grasslands have significantly greater root mass than the 1-year-old. Two contrasting processes occur in soil regarding C stocks changes under C input. Increased root mortality, including human-induced disturbances such as grassland renewal, can enhance soil C input, potentially promoting C stock accumulation. Conversely, the addition of fresh root mass can trigger a priming effect, stimulating the decomposition of stable organic matter and leading to increased gross $CO_2$ emissions (Wen *et al.*, 2019). Therefore, management practices that disturb root systems or incorporate crop residues play a critical role in determining C dynamics and GHG emissions.

Three publications cited in the 2013 Supplement to the 2006 IPCC Guidelines reported no grassland renewal on research sites during the GHG measurement period. Although there is no information available in other publications, we can assume the nonoccurrence of grassland renewal during the GHG measurements considering the studies duration and age of perennial grass at the end of experiments.

**Table 1**. Description of the study sites used to develop the IPCC emission factors for $CO_2$ from grasslands on drained organic soils in boreal climate

| Site location | Mean annual temp (ºC) | Mean annual precip (mm.) | Mean water table (m) | Measurement duration (yrs) | Vegetation | Grass age at measurement end (years) | Grassland renewal during measurements | Reference |
|---|---|---|---|---|---|---|---|---|
| Northern Norway (678°170′N, 148°280′E) | 4.3 | 1055 | NIA | 2 | perennial grass | NIA | NIA | Grønlund *et al*, 2006 |
| Southern Finland (6053°9320′N, 2330°8610′E) | 5.9 | 719 | NIA | 2 | spring barley with grass undersown; grass | 2 | Yes | Lohila *et al*, 2004 |
| Eastern Finland (62°31′N, 29°23′E) | 2.2 | 612 | 1 | 2 | barley with grass undersown; grass | 2 | NIA | Maljanen *et al.* 2001 |
| Western Finland (65°55′N, 23°51′E) | 2.4 | 561 | NIA | 2 | perennial grass | 2 | NIA | Maljanen *et al.* 2004 |
| Eastern Finland (62°40'N, 30°50'E) | 1.9 | 650 | 0.3–0.5 | 2 | perennial grass | NIA | No | Nykänen *et al.* 1995 |
| Eastern Finland (62°30′N, 30°30′E) | 2.1 | 669 | NIA | 4 | reed canary grass | 6 | No | Shurpali *et al.*, 2009 |

NIA — no informationavailable

There were eight publications on grass cultivation cited for the $N_2O$ EFs for grasslands (Table 2). Grassland renewal occurrence during the measurements was recorded in none of the experiments cited for $EFN_2O$. During the fallow phase between ploughing and reseeding grass, there is a period with negligible crop uptake of nitrogen until the following crop is grown, which is longer in the case of autumn ploughing. However, it is difficult to distinguish from the measurement data which part of the measured emission comes from crop residues and which part should be included in the EFs for drained organic soils.

We also examined if part of the effects of grassland renewal is reflected in the EFs for croplands (see Supplementary Information). The undersowing of grass with the annual crop cultivation which is the typical practice in boreal climate might capture the effect of grass on GHG emissions by EFs in the "Cropland, drained" section. Out of 14 experiments cited for $N_2O$ emission factor in this section only one annual crop with grass undersown (Petersen *et al.*, 2012) was presented. Ploughing occurred on two sites during spring (Flessa *et al.* 1998; Kasimir-Klemedtsson *et al.* 2009). Five studies that reported $CO_2$ emissions on croplands had an annual crop with grass undersown during the measurements, but no information on the occurrence of grass seeding and ploughing is available. Two studies out of 14 cited for $CO_2$ emission factor were measuring soil respiration under annual grass without mentioning soil tillage practices or herbicide application for grass killing during the experiments.

Default IPCC EF values of $CO_2$ and $N_2O$ emissions for drained grasslands in boreal climate are 5.7 t $CO_2$-C ha$^{-1}$ yr$^{-1}$ and 9.6 kg $N_2O$-N ha$^{-1}$ yr$^{-1}$ accordingly. We can assume that they may be underestimated because emissions from grassland renewal are not considered in the majority of the input data for EFs elaboration. While new studies have been published on GHG emissions under grassland renewal in temperate climate (Tiemeyer *et al.* 2024), there is still a lack of systematic research in boreal climate conditions. Using targeted adjustment coefficients for specific years when grassland renewal occurs aligns with the established approach for $N_2O$ emissions from crop residues during renewal and can provide a more precise method for GHG reporting. However, it is also crucial to account for emissions from organic soil priming during the renewal year, alongside $N_2O$ emissions from crop residues.

## Conclusions

The IPCC default EFs for boreal drained organic soils do not adequately capture GHG emissions associated with grassland renewal. This limitation stems from the lack of measurements in long-term grasslands and the exclusion of critical grassland management practices, such as ploughing, re-seeding, and herbicide application, in the studies used to develop EFs. Emission factors would be more accurate if they were derived from data including the whole grass production cycle from renewal to the next renewal. This would require longer monitoring periods than usually applied. There should also be grassland renewal experiments in different environmental conditions and seasons as they can strongly affect the magnitude and rate of GHG emissions. Some data currently used for cropland EF development may also be relevant for grassland EFs, as they capture emissions associated with undersowing grass with annual crops, a common practice in the boreal region. However, further cross-analysis of original datasets is required to refine emission estimates for both land-use categories.

Further systematic long-term measurements of GHG fluxes on drained organic soils across a variety of technological operations on cultivated grasslands and croplands are essential to improve the accuracy of EFs. The remaining challenge is to reliably quantify rates of $CO_2$ and $N_2O$ emissions associated with ploughing and chemical treatment of cultivated grasslands considering their combination during different seasons.

*Acknowledgements*: This publication was produced as part of the OMAIHKA project, which was funded by Ministry of Agriculture and Forestry of Finland, Valio Oyj, Atria Oy, Salaojituksen tukisäätiö sr and The Central Union of Agricultural Producers and Forest Owners MTK ry.

*Supplementary Information*: The supplementary information related to this article is available online at: http://www.borenv.net/BER/archive/pdfs/ber30/ber30-125-132-supplement.pdf

**Table 2**. Description of the study sites used to develop the IPCC emission factors for N2O from grasslands on drained organic soils in boreal climate

| Site location | Mean annual temp (ºC) | Mean annual precip (mm.) | Mean water table (m) | Measurement duration (yrs) | Vegetation | Grass age at measurement end (years) | Grassland renewal during measurements | Reference |
|---|---|---|---|---|---|---|---|---|
| Northern Norway (678°170′N, 148°280′E) | 4.3 | 1055 | NIA | 2 | annual ryegrass; | NIA annual ryegrass | NIA | Grønlund *et al.* 2006 |
| Northern Norway (678°170′N, 148 °280′E) | 4.3 | 1055 | NIA | 2 | perennial grass | NIA | NIA | Grønlund *et al.* 2006 |
| Eastern Finland (62°30′N 30°30′E) | 2.1 | 667 | 0.7 | 4 | reed canary grass | 6 | No | Hyvönen *et al.*, 2009 |
| Eastern Finland (62°31′N, 29°23′E) | 2.6 | 643 | 0.7–1.7 | 1 | grass | NIA | NIA | Maljanen *et al.* 2003 |
| Western Finland (65°55′N, 23°51′E) | 2.4 | 561 | NIA | 2 | grass | 2 | NIA | Maljanen *et al.* 2004 |
| Eastern Finland (63°090′N, 27°200′E) | 2.4 | 609 | 1–2 | 2.5 | timothy grass and | 1 yr 3 mo. meadow fescue | No | Maljanen *et al.* 2009 |
| Western Finland (63°540′N, 23°560′E) | 2.8 | 561 | 0.6 | 2.5 | timothy grass and | 1 yr 3 mo. meadow fescue | No | Maljanen *et al.* 2009 |
| Eastern Finland (62°40′N, 30°50′E) | 1.9 | 650 | 0.3–0.5 | 2 | grass | NIA | No | Nykänen *et al.* 1995 |
| Eastern Finland (62°46′N, 30°58′E) | 1.9 | 650 | 0.6 | 2 | grass | NIA | NIA | Regina *et al.* 1996 |
| Southern Finland (60°49′N, 23°30′E) | 4.3 | 607 | 0.8 | 3 | timothy grass and meadow fescue | 3 | No | Regina *et al.* 2004 |
| Northern Finland (66°35′N, 26°01′E) | 0.0 | 573 | 0.4 | 2 | timothy grass and meadow fescue | 2 | No | Regina *et al.* 2004 |

NIA — no information available

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