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Accounting for greenhouse gas emissions from Switzerland's farmed transition soils

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Summary

There is growing evidence from scientific studies that many carbon (C)-rich formerly wet soils *other* than C-rich organic soils (C > 20 %) may have high CO_2 emissions when drained. Their emissions are probably being underestimated in Switzerland's greenhouse gas (GHG) reporting because they are classified as mineral soils. As a medium-term solution to this, we propose introducing additional soil categories for GHG reporting (C-rich mineral soils, C-poor organic soils, and organic soils or C-rich mineral soils covered with a mineral layer) and assigning these categories their own sets of emission factors. This is dependent on there being sufficient measurements in the scientific literature from which emission factors could be derived. Additionally, locating these soils in Switzerland requires substantial research. In the longer term, we recommend that GHG emissions of formerly wet soils are calculated as a function of C content and water level.

Zusammenfassung

Wissenschaftliche Studien zeigen zunehmend, dass viele ehemals wassergesättigte, kohlenstoffreiche Böden, die nicht als organische Böden (C > 20 %) klassifiziert sind, erhebliche Mengen an CO_2 freisetzen können, wenn sie entwässert werden. In der Treibhausgasbilanzierung der Schweiz werden diese Emissionen vermutlich unterschätzt, da solche Böden als mineralische Böden eingestuft werden. Als mittelfristige Lösung schlagen wir vor, das Treibhausgasinventar um folgende zusätzliche Bodenkategorien zu erweitern: kohlenstoffreiche mineralische Böden, kohlenstoffarme organische Böden sowie organische oder kohlenstoffreiche mineralische Böden mit einer aufgebrachten mineralischen Deckschicht. Für diese Kategorien sollten spezifische Emissionsfaktoren definiert werden, sofern ausreichend wissenschaftliche Messdaten zur Ableitung solcher Faktoren vorhanden sind. Darüber hinaus erfordert die Identifikation und Lokalisierung dieser Böden in der Schweiz umfangreiche Forschung. Langfristig empfehlen wir, die bodenbürtigen Treibhausgasemissionen ehemals wassergesättigter Böden anhand des Kohlenstoffgehalts und des Wasserstands zu modellieren.

Résumé

Des preuves toujours plus nombreuses résultant d'études scientifiques démontrent que des sols riches en carbone (C) anciennement humides – *autres* que les sols organiques riches en C (C > 20 %) – peuvent générer d'importantes quantités de CO_2 lorsqu'ils sont drainés. Leurs émissions sont probablement sous-estimées dans l'inventaire des gaz à effet de serre (GES) de la Suisse, car ils sont classés comme sols minéraux. Nous proposons, comme solution à moyen terme, d'introduire des catégories de sols supplémentaires pour l'inventaire des GES (sols minéraux riches en C, sols organiques pauvres en C et enfin sols organiques ou sols minéraux riches en C recouverts d'une couche minérale) et d'assigner à ces catégories des facteurs d'émission spécifiques. Ceux-ci pourraient être déduits de la littérature scientifique pour autant que des données suffisantes soient disponibles. Des recherches approfondies seront en outre nécessaires pour localiser ces sols en Suisse. À plus long terme, nous recommandons de calculer les émissions de GES des sols anciennement humides en se basant sur leur teneur en C et sur le niveau d'eau.

Riassunto

Numerosi studi scientifici mostrano sempre più chiaramente che *oltre ai* suoli organici ricchi di C (C > 20 %), anche molti tipi di suolo ricchi di carbonio (C) precedentemente umidi possono presentare elevate emissioni di CO_2 quando vengono drenati. Poiché in Svizzera questi suoli sono classificati come minerali, le loro emissioni risultano con ogni probabilità sottostimate nei rapporti sui gas serra (GES). Come soluzione a medio termine, proponiamo di introdurre categorie aggiuntive di suoli per i rapporti sui GES (suoli minerali ricchi di C, suoli organici poveri di C e suoli organici o suoli minerali ricchi di C ricoperti da uno strato minerale), cui assegnare specifici insiemi di fattori di emissione. Questa proposta presuppone l'esistenza di un numero sufficiente di misurazioni nella letteratura scientifica, dalle quali sia possibile derivare i fattori di emissione. Inoltre, l'individuazione di tali suoli in Svizzera richiede un'attività di ricerca sostanziale. A lungo termine, raccomandiamo che le emissioni di GES dei suoli precedentemente umidi vengano calcolate in funzione del contenuto di C e del livello idrico.

1 Background

In national greenhouse gas (GHG) reporting, Switzerland reports emissions from mineral and organic soils separately. The definition of organic soils is based on IPCC (2006), whereby organic soils are defined as soils that formed under water-logged conditions, with a C-rich layer greater than 20 cm thick (or 10 cm, if C-content >12 % when mixed to 20 cm). For soils that are regularly water-logged, this C-rich layer must have a minimum soil C content of 12 % (if soil has no clay) to 18 % (if clay content >60 %) or an intermediate, proportional C content for intermediate amounts of clay. Alternatively, for soils *not* regularly water-logged, the C-rich layer must have a C-content of >20 %. In accordance with IPCC (2006), all other soils are classified as mineral soils. Mineral and organic soils have separate annual emission factors (EFs), as outline in table 1. Throughout this text, C refers to organic C only.

Table 1 The different emission factors (EFs) currently applied to mineral and organic soils for greenhouse gas reporting.

Soil	EF type	EFs (t C ha^{-1} yr^{-1})	Source
Organic	Constant	Unproductive wetlands and extensively managed soils: 5.3 Intensively farmed surfaces: 9.52	Leifeld (2009, 2011)
Mineral	Variable year to year	In submission 2024* Cropland: 0.068 Grassland: -0.092 (i.e., an uptake)	FOEN (2024), based on Wüst-Galley et al. (2020)

* Average EFs across the inventory period

In Switzerland's GHG inventory, the estimate of the distribution and surface of organic soils from Wüst-Galley and Leifeld (2025) is used. The estimate is based on a collation of various data sets, meaning it relies on pre-existing categories. These categories include 'Moorböden' (translated here as 'peaty soils') and Halbmoorböden ('semi-peaty soils') from the national soil mapping guidelines (BGS 2010), and, for regions without a soil map, the category 'peat'. In the national soil mapping guidelines, the two peaty soil categories have a stricter definition than the IPCC organic soils category i.e., the C content of the C-rich layer must be *higher* (>18 %) than the minimum C content required by IPCC (depending on water-regime), and the C-rich layer *thicker* (>40 cm). These guidelines additionally recognize several soil sub-types also relevant to organic soils, including 'anmoorig' and 'antorfig' soils. These sub-types require a lower C content or a thinner C-rich layer, respectively, than the (semi-)peaty soils. The wide range of C-content or thickness of the C-rich layer of these categories means an 'anmoorig' or 'antorfig' soil might be –depending on the soil in question–, an organic *or* a mineral soil according to IPCC (2006). In part because of this and in part because their distribution is so poorly known, these soils are currently not recognized by Switzerland as organic soils (Wüst-Galley *et al.* 2015). For surveys other than soil maps (e.g. geological surveys), the category 'peat' or 'histosol' is often used. Typically, peat contains > 40 % C (Clymo 1983, Lindsay 2010, references therein), and organic material diagnostic for histic horizons in histosols > 20 % C (WRB 2022); these categories are thus generally more restrictive than the organic soil definition from IPCC (2006).

Also relevant for GHG reporting are those organic soils that have been covered with a layer of mineral soil. This mineral soil coverage is often carried out to reduce the negative impacts of soil compaction and subsidence (Ferré *et al.* 2019). Where the mineral layer in these soils is >30 cm, they are not included in the estimate of Switzerland's organic soils.

Here we suggest introducing new categories for GHG reporting that consider soils in transition between mineral and organic soils (table 2). These 'transition soils' comprise C-poor organic soils, C-rich mineral soils, as well as organic or C-rich mineral soils with a mineral cover; they encompass soils that were originally organic soils as well as C-rich mineral soils.

Table 2 The various soil categories recommended in this article for GHG reporting.

Recommended classification in Switzerland's GHG inventory	C content in upper 30 cm (%)	Current classification in Switzerland's GHG inventory
1: C-rich organic soils	> 20 %	Organic
2: C-poor organic soils*	12-20 %	Variable, mostly mineral
3: C-rich mineral soils*	6-12 %	Mineral
Any of the above (1, 2 or 3), with mineral soil coverage*	Variable	Variable, mostly mineral
4: mineral soils	< 6 %	Mineral

* = transition soils

2 The problem

For several reasons, as explained below, the GHG emissions of transition soils are under-estimated in Switzerland's GHG reporting.

There is a growing body of evidence showing that **C-poor organic soils** (12-20 % C) may have CO_2 emissions close to, or as high as, those with C % > 20 % (i.e., C-rich organic soils) when drained. Evidence includes field CO_2 emission measurements (Leiber-Sauheitl *et al.* 2014, Eickenscheidt *et al.* 2015, Tiemeyer *et al.* 2016), as well as incubation experiments (Liang *et al.* 2024). Accordingly, the underestimation of CO_2 emissions caused by ignoring C-poor organic soils is highlighted in the international scientific literature as problematic (Eickenscheidt *et al.* 2015, Liang *et al.* 2024). Additionally, it can be expected that drained **C-rich mineral soils** (6-12 % C) also emit CO_2 at a higher rate than C-poor or undrained mineral soils. There are few documented CO_2 flux measurements from these soils, because the drainage status of sites for which GHG measurements are made is seldom reported (Leifeld *et al.* 2019). However, some measurements indicate high fluxes: Based on data from long-term C stock measurements in Belgium (Meersmans *et al.* 2011), Leifeld *et al.* (2019) estimated rates of C loss of 39-78 t C ha^{-1} over 46 years, or 0.9–1.7 t C $ha^{-1}a^{-1}$. In New Zealand, a C loss rate of 0.32 t C $ha^{-1}a^{-1}$, attributed to drainage, was observed over circa 30 years in grazed gleysols (Schipper *et al.* 2017). Lastly, there is evidence that the **coverage of organic soils with a mineral cover** *per se* does not reduce GHG emissions, unless it is accompanied by a raised water table that covers the peat body. The few studies that have measured GHG emissions from fields with a mineral cover reported emissions typical of drained organic soils (Beyer 2014, Tiemeyer *et al.* 2016, Weideveld *et al.* 2021). The only study specifically testing the role of a mineral soil layer in reducing in GHG emissions reported reduced N_2O emissions (Paul *et al.* 2024). CO_2 emissions were not reduced by the mineral soil cover layer *per se*; rather, C decomposition was determined primarily by the volume of aerated organic soil, with higher ground water table leading to lower C losses.

In Switzerland, the CO_2 emissions reported from transition soils are thus likely underestimated, because these soils tend to be classified as mineral soils (and are thus allocated a lower CO_2 emission rate) for three reasons, as summarized here. First, the peaty soil sub-types are currently classified as mineral soil for GHG reporting. Second, there are surfaces whose peat is so degraded that it is no longer recognizable as peat, meaning that these surfaces are not classified as 'peaty' in most information sources (e.g. geological maps). Soil maps are the only information sources that would classify such soils explicitly as a C-rich soil, but because soil maps cover a small proportion of the country (for agricultural soils, only 19 % [status 2019], Rehbein *et al.* 2019), such soils tended not to be documented as organic soils in Wüst-Galley and Leifeld (2025). Lastly, because IPCC considers only the upper 30 cm of soil, organic soils that are covered with a thick mineral layer tend also to be classified as mineral soil.

The reclassification of transition soils and the allocation of an appropriate EF to these soils would result in an increased GHG emissions' total for Switzerland. Although the extent of C-poor organic soils and C-rich mineral soils in Switzerland is unknown, their relevance for GHG emissions might be quite high. A survey of drainage systems in Switzerland found at least 192,000 ha (or 18 %) of agricultural land are drained (Béguin and Smola 2010) and a modelling approach suggests this value could be between 110,000 and 470,000 ha (Koch and Prasuhn 2020). Though the soil C content of these surfaces is unknown, it can be expected that previously waterlogged (organic and mineral) soils had an originally higher C content and are losing C. Lastly, the importance of organic soils covered with a mineral layer will increase in the future as farmers deal with continued soil subsidence.

3 Potential solutions

One mid-term solution to correct a possible underestimation of CO_2 emissions from transition soils would be for Switzerland to introduce new soil categories for GHG reporting, each with its own set of EFs. Indeed, such a solution was suggested already by Eickenscheidt *et al.* (2015), who proposed that the IPCC introduce a new category for 'associated' organic soils. The pre-requisites for this would be: i. having a clear definition of these soils; ii. knowing their extent and location; and iii. having EF estimates for these soils. A better definition of these soils than that used here might use a statistical distribution of C content of soils. For the second pre-requisite, a map of transition soils in Switzerland is needed. We do not recommend extending the approach used by Wüst-Galley *et al.* (2015) or Wüst-Galley and Leifeld (2025), as this will always underestimate the occurrence of these soils: C-rich organic soils appear explicitly only in soil maps, yet adequate soil maps cover only a small proportion of the country (see above). An alternative approach might be to use maps of soil properties, e.g. C and clay content (Stumpf *et al.* 2024), but so far predicting the distribution of C-rich soils is hampered by a lack of data. One solution to obtain EFs for C-rich organic soils could be to evaluate whether adequate GHG measurements from temperate Europe have been published (there are no comparable measurements from Switzerland) and if so, to derive EFs from these. This approach is currently used for intensively-managed organic soils (Leifeld 2009). Data comprise measurements from few sites only, meaning this EF would need to be revised as better data become available. Faced with a similar problem, Denmark has used an alternative approach in its national GHG reporting: Soils with a C content between 6 and 12 % are assigned an EF that is half of the EF of organic soils (Nielsen *et al.* 2023). Though pragmatic, this approach has however received critisism in the scientific community (Liang *et al.* 2024). Similar approaches to those mentioned above could in theory be used determine EFs for C-rich mineral soils and for organic soils with mineral coverage, but the basic data for these soils are even sparser.

In the longer term, one approach to report emissions from soils whose C content was or is influenced by water-logged conditions would be to estimate emissions as a function of C content and water level, or the aerated soil carbon stock, thus avoiding the use of aritificially generated categories. This requires information on carbon stocks and ground-water level in the landscape, as well as adequate emission measurements from Switzerland or temperature Europe to calibrate and / or validate a model linking emissions to the aerated carbon stock. These data are curerntly lacking for Switzerland. Results from several published studies indicate however that a modelling approach would be suitable for organic soils (e.g., Tiemeyer *et al.* 2020, Evans *et al.* 2021, Koch *et al.* 2023) and it is used by Germany for annual GHG reporting (Fuss 2025). It might well also be suitable for transition soils.

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