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RESEARCH ARTICLE

Land use-driven historical soil carbon losses in Swiss peatlands

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Abstract
Context Globally, the intensive use of peatlands contributes substantially to greenhouse gas emissions. The intensification of peatland use has led to increasing carbon (C) losses over the last centuries, but without historical emissions data, these increases and cumulative emissions are difficult to quantify.
Objectives To understand the magnitude and development of soil C losses through peatland drainage in Switzerland through time, and to relate the situation of peatlands today to this historical development.
Methods Historical records and a published estimate of the peatland extent are used to estimate peatlands' original extent and C stocks, and to understand trends in the historical use of peatlands. Land use-specific emission factors are applied to estimate the C emission through drainage over the last 300 years.
Results Ca. 15 to 55 Mt C have been lost through peatland drainage in Switzerland. Despite a decrease in the area of organic soils, annual C emissions have increased considerably especially since the mid-twentieth century due to intensification of their use, particularly for agriculture. This C loss is a magnitude greater than that lost through extracted peat. Remaining C stocks approximate those lost over the last 300 years.
Conclusions The rate of peatland surface loss in Switzerland is typical of European wetlands. Uncertainties in emission factors remain high and should be refined to justify any mitigation strategies. Although peat is no longer mined in Switzerland, future C emissions from peatlands will remain high as long as the effects of drainage networks and their current intensity of use persist.

Keywords Carbon · Peatlands · Greenhouse gases · Landscape history

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Introduction

Peatlands are areas with a naturally occurring peat layer at the surface (Joosten and Clarke 2002). As a densely-populated continent with a long history of land use change, Europe has seen most of its mires (ecosystems with peat-forming vegetation) altered or destroyed, especially in southern and western Europe (Bragg et al. 2013). The ensuing peatlands, including managed organic soils, with peat layers sometimes many metres thick, remain substantial carbon (C) stocks (Europe: 42 Gt C, Byrne et al. 2004). Yet, because the intensive use of peatlands usually requires drainage, which increases peat oxidation and the loss of dissolved organic C, this large stock is also a potentially large CO_2 source, increasing greenhouse gas (GHG) emissions. Indeed, peatlands of all European countries are currently net GHG emitters (Byrne et al. 2004), and the annual global GHG emissions of peatlands under agriculture and forestry are estimated to be 1.9 Gt CO_2 eq. (0.31–3.38, Leifeld and Menichetti 2018) or approximately five percent of the world's anthropogenic GHG emissions (calculated from IPCC 2014). The reduced role of these peatlands as C sinks has occurred against a background of increasing temperatures over the last centuries, which through increased growing season length might otherwise be expected to result in increased C accumulation rates (Charman et al. 2013).

The long history of use of peatlands by humans is also characteristic of Switzerland (Boscani-Leoni 2017; Mühlethaler 1995), with the most important intensive uses being peat extraction and agriculture (Früh and Schröter 1904; Ewald and Klaus 2010). Peat extraction for fuel, which became widespread in Switzerland during the eighteenth century and was common until the beginning of the twentieth century (Früh and Schröter 1904; Probst et al. 1923), was banned in Switzerland in 1987. The intensive use of peatlands for (non-paludicultural) agriculture is however still common and requires their drainage. The degradation of mires and the disappearance of peatlands is therefore also linked to the development of drainage in Switzerland. The country's landscape 200 years ago was characterised by a dense network of waterways, lakes and wetlands (Ewald and Klaus 2010). The first systematic drainage for agriculture was carried out by canton Geneva in the 1840s (Thut 1996) and wetland drainage became widespread in the second half of that century. The onset of systematic drainage for agriculture was then rapid: By the turn of the twentieth century, Switzerland's mire landscape was so decimated, that it was stated that there were few mires remaining where the impact of drainage could not be seen (Früh and Schröter 1904). Peaks in drainage activity then occurred in both world wars. Between 1885 and 1946 almost 160,000 ha of land was drained (mineral and organic soils) with government subsides (Strüby 1947). Today, 192,000 ha of agricultural land are recorded as drained, though this is certainly an underestimate due to privately-funded projects that are not systematically recorded (Béguin and Smola 2010).

The current state of Switzerland's peatlands reflects this history, most apparent in that the majority of peatlands (90%) are no longer mires (calculated from Wüst-Galley et al. 2015). The majority (ca. 82%) of these ca. 27,000 ha of peatlands are under cropland, grassland or forestry (FOEN 2017) and are thus losing C. Furthermore, although the remaining mires are under federal protection since the federal 'Rothenthurm Initiative' in 1987,[1] the lasting effects of drainage, disturbed hydrological conditions and eutrophication mean their condition is also deteriorating, with only 25% of monitored bogs and fens showing peat accumulation in the period 1997/2002 to 2003/2010 (Küchler et al. 2018). In short, and for various reasons, the vast majority of Switzerland's ca. 28,000 ha of peatlands (Wüst-Galley et al. 2015) are currently a C source.

In this study, we quantify the magnitude and development of C emissions resulting from peatland drainage in Switzerland through time, firstly, to understand the consequences of long-term use of peatlands and secondly, to relate the current peatland C stocks and losses with this historical development. We reconstruct the historical C stocks and C losses through drainage by integrating historical and current information regarding the surface of peatlands in Switzerland, the thickness of the peat layer and their use, as well as emission factors (EFs, described in the methods). Finally, we put the C emissions derived this way into context with historical records on peat extraction to derive a full picture of historical soil carbon loss from peatlands.

Methods

Peatland surface

The Swiss peatland surface estimates were calculated for the following periods: (i) Peatlands present prior to

[1] Federal order on the initiative 'zum Schutz der Moore - Rothenthurm-Initiative ', Art. 24sexies Abs. 5 and UeBest. BV; or Grünig (1994, pp 367–378) for English translation.

1890 (approximate date of completion of the first detailed nationwide topographical maps), including those for which there is no evidence they persisted beyond this date; (ii) those for which there is evidence they persisted until 1950; and (iii) those for which there is evidence they persisted beyond 1950. These periods correspond to the times before, during and after the most intensive peat mining and drainage activities in Switzerland, the first half of the twentieth century, respectively. They are referred to henceforth as '1890', '1950' and '2015'. We additionally consider estimates of the peatland surface at ca. 1710, the time of the first recorded peat exploitation in the country, which also corresponds to the period with the largest extent of peatlands in Switzerland, the 15th to early eighteenth century (Grünig 1994; Klaus 2007; Boscani-Leoni 2017).

The peatland surface estimates are based on the estimate of organic soils (soils with a C-rich peat layer at least 10 to 20 cm thick that contains at least 12 to 18% C, IPCC 2006) from Wüst-Galley et al. (2015). This composite estimate includes evidence of peat from geological, hydrogeological, topographical, habitat and soil maps. For the 2015 peatland estimate, organic soil surfaces recorded since 1950 were used. For the 1950 peatland estimate, organic soil surfaces recorded before 1950, but not later, were used. The peatland estimate for 1890 comprises all surfaces that have or have had organic soil. These three estimates were supplemented with information derived from two publications containing expert observations of hundreds of Swiss peatlands from around the turn of the twentieth century (Früh and Schröter 1904) and from 1943 to 1951 (Lüdi 1973). These descriptions include information on the condition of peatlands as mire habitats, peat thickness, land use, and the presence or absence of peat extraction; they are the most comprehensive set of observations of Swiss peatlands for these periods. These descriptions were geo-referenced and used as follows. Firstly, surfaces identified in Wüst-Galley et al. (2015) as wetlands but for which there was no information that they contain(ed) peat were overlaid with the historical descriptions (indicating peat). This allowed further peatlands to be identified. Furthermore, the historical descriptions were used to indicate which peatlands apparently persisting until 1950 could be moved to the '1890' or '2015' categories, according to whether they were described as denuded of peat or still containing plentiful peat, respectively.

Estimates of the greatest extent of peatlands are based on three sources. Firstly, by combining information from the estimated surface of organic soils around 1890 (37,110 ha, calculated as described above) with a national map (1:530,000) from Früh and Schröter (1904) that shows 5464 peatlands from around this time, reported as still existing (38%) or destroyed (62%) mires. The surface estimate for this period (37,110 ha) was assumed to correspond to the remaining mires, yielding an average of 17.9 ha per mire. This value was applied to the 62% of the 5464 mires reported as destroyed and known only from names, specimens or collective memory (yielding 60,548.5 ha), yielding a total of 97,659 ha. A second estimate was derived in a similar manner from the association between current place names and the current peatland surface. Früh and Schröter (1904) discuss ca. 100 toponyms (place names) considered to be related to mires. We used only those terms that, according to Früh and Schröter (1904) or the Swiss Idioticon [2] (a dictionary of the Swiss German dialect), are most commonly associated with mires or peatlands: "-moor", "-moos", moser, "-möser", "mosses", "mousse", "tourbière", "Torfried" and "Turbenriet/-moos". These terms were searched for in the "swissNAMES^{3D}" database (Swisstopo 2017), a collection of all geographical names still in use in Switzerland and Liechtenstein, yielding 2491 Swiss toponyms for peatlands. We calculated the number of these names occurring within 150 m of a (current) peatland surface. A buffer distance was necessary because it can be expected that a place name associated with a given (often shrunken) peatland might now be some distance from that peatland. The distance, 150 m, was obtained by inspecting a histogram of the distance of peatland toponyms to the nearest peatland; it is the mid-point of the distance range 100 m to 200 m. For distances beyond 200 m the number of toponyms is very low and is no longer related to distance from a peatland. The quotient of peatland surface/peaty toponym was 58 ha. We multiplied this by the number of toponyms not associated with any peatland surface (1857), thus assuming that these were associated with vanished peatlands. We

[2] https://www.idiotikon.ch/ Accessed 7 February 2017.

regard the resulting peatland surface (108,355 ha) as a further estimate of the original peatland surface, and expected that it should approximate the first estimate. A third estimate, 148,560 ha, was obtained from Stuber and Bürgi (2018). This is the surface estimate of Swiss wetlands in the 1850s, reconstructed using the wetland signature on historical topographical maps, correcting for different mapping techniques through time. Because not all wetlands are peatlands, we consider this a maximum estimate.

We consider the first (97,659 ha) and third (148,561 ha) estimates to be minimum and maximum estimates of the 'original' peatland surface, respectively. The estimate derived using the SwissNAMES^{3D} database is considered a mid-estimate. We date these 'original' peatland surface estimates to 1710, based on the beginning of local (1709) and more widespread (1710) peat extraction (von Knonau 1844; Früh and Schröter 1904) in Switzerland.

Land use

Information on historical and modern land use was used to calculate the proportion of the peatland surface under different land use for 1900, 1950 and 2015, dates for which there are substantial records of peatland use. We distinguished six land use types (Table 1): Cropland (CL), Grassland (GL), Forest (FL), peat extraction (PE), mixed land use (MX), drained but not actively managed (DR) and near-natural peatlands (NN). Peatlands under urban areas (6.5%, identifiable only for current peatlands) or lakes and rivers (1.7%) were not considered further. Information on the historical use of peatlands was obtained from Früh and Schröter (1904, from 346 sites) and Lüdi (1973, from 210 sites), representing land use around 1900 and 1950, respectively. For each geo-referenced site that corresponded to a known peatland surface, the surface estimate was used to calculate the proportion of the (total) peatland surface under different land use types for 1900 and for 1950. Information on the modern use of peatlands was obtained by intersecting the peatland surface with land use information from the Swiss land use statistics (Arealstatistik, SFSO 2004–2009) as shown in Table 1. Mires (approximately equal to 'unproductive vegetation' in the Swiss land use statistics) are legally protected in Switzerland. However, we considered only a proportion of these to be NN. This accords with Switzerland's Federal Inventory of Raised and Transitional Bogs (Grünig et al. 1986) where it is stated 35% of raised bogs are primary vegetation (category NN), the remaining 65% being "severely impaired by

Table 1 Definition of land use types as used in this study; 'other' land use types were not considered further; LUS = land use statistics (SFSO, 2004–2009)

Land use	Description, as used in this study
NN, near-natural	- Bog or fen, incl. litter meadow if there is no mention that it is dry
	- A proportion (35%) of 'unproductive vegetation' (Swiss LUS)
DR, drained but otherwise unmanaged	- A mire described as drained or dry, or otherwise damaged, but unused
	- Peat extraction sites where the surface has plants indicative of mire vegetation
	- A proportion (65%) of 'unproductive vegetation' (Swiss LUS)
MX, mixed	- Mixed land use, where there is no indication which land use dominates
PE, peat extraction	- Mention of peat extraction (past or present) unless it is mentioned that the surface is re-growing as mire vegetation or is grassland or cultivated, in which case site was allocated to DR or to GL or to CL, respectively
FL, forest	- A drained wooded bog or forestry on peat
	- All wooded areas (Swiss LUS)
GL, grassland	- Mention of a fen/bog used as a grassland
	- Meadows, pastures, recreational areas and cemeteries (Swiss LUS)
CL, cropland	- Mention of crops; cropland (Swiss LUS)
Other	- Other land uses, dominated by transport, buildings and rivers (Swiss LUS)

human activities”. We assigned these 65% to the category DR.

Lastly, for 1710 we assume that entire peatland surface was NN.

Estimating C stocks

Carbon stocks were calculated as the product of peatland surface, peat thickness and C density, for 1710, 1890, 1950 and 2015. This calculation is referred to as the ‘*direct*’ estimate. For 1710, three C stocks were calculated, using the minimum, mid and maximum estimates of peatland surface.

Historical peat thickness was obtained from descriptions in Früh and Schröter (1904, using information from 20 sites), Lüdi (1973, 42 sites) and Probst et al. (1923). The latter publication contains the results of two national surveys (from 1917 and 1918) quantifying the availability of peat for extraction. Where a range of peat thickness was given, the median value was used and where a depth was given as a minimum depth, the stated depth was used. Peat thickness measurements of 45 Swiss peatlands (Presler and Gysi 1989; Anon 1996; Desaules and Studer 1993; Fenner 2007; Bader et al. 2018a) sampled between 1980 and 2013 were used to obtain an estimate of current peat thickness. Peat thickness was similar across the three historical sources, and was significantly greater than modern peat thickness (see results). We therefore used the mean peat thicknesses of historical peatlands to calculate all C stocks pre-1950, and those of modern peatlands for the calculation of C stocks in 2015.

Peatlands under different land use tend to have different C densities. This was accounted for using the following values: GL (0.05 t C m^{-3}, n = 4), CL (0.10 t C m^{-3}, n = 11), FL (0.07 t C m^{-3}, n = 17) and NN (0.04 t C m^{-3}, n = 8), using the mean peat density values from 40 peatlands from Swiss studies (Fenner 2007; Gubler 2009; Lienert 2013; Wüst-Galley et al. 2016; Bader et al. 2018a). Values at each site comprised replications in space and different soil layers. For the land use ‘peat extraction’ (banned in Switzerland since acceptance of the Rothenthurm Initiative in 1987), the C density value of CL was assumed. For the land use DR, the value mid-way between NN and GL was used (0.045 t C m^{-3}). For the land use ‘mixed’, the mean of all other C density values was used (0.07 t C m^{-3}).

Emission factors (EFs)

Two sets of EFs that differ in their EFs for CL and GL were compared (Table 2). In all cases, C lost through oxidation, leaching and methane were used to determine a total C emission factor. Firstly, the Intergovernmental Panel on Climate Change (IPCC) default EFs for the temperate zone were used (IPCC 2014, Chap. 2) for PE, FL, CL and GL. Where EFs for individual soil fertilities or drainage depths are given, the mean EF was used. For NN peatlands, the long-term average rate of peat C accumulation from Loisel et al. (2014) was applied, representing accumulation during the Holocene, based on peat cores from 127 sites across the northern hemisphere. Our DR category is broad. We used an EF mid-way between that of NN peatlands and extensive grasslands (5.3 t C ha^{-1}), the latter based on studies of Swiss extensive grasslands and as estimated for Switzerland’s national inventory report (NIR) of GHGs (FOEN 2017). The resulting EF, 2.54 (0.96–4.11) t C ha^{-1} a^{-1} (= 9.32 t CO_2e ha^{-1} a^{-1}), corresponds well to C fluxes measured throughout Germany on non-fertilised grasslands on nutrient-rich shallow drained (ca. 5 to 22 t CO_2e ha^{-1} a^{-1}) or nutrient-poor (ca. 3 to 18 t CO_2 e ha^{-1} a^{-1}) organic soils (Tiemeyer et al. 2016). The land use type ‘mixed’ (< 2% of cases) was assigned a mean average of all other land use types. This set of EFs is henceforth referred to as ‘IPCC’, although it contains EFs from other sources. The second set of EFs used differs from the ‘IPCC’ EFs by having higher CL and GL EFs (Table 2). These correspond to those used in Switzerland’s NIR (FOEN 2017). This set of EFs is henceforth referred to as ‘NIR’ though it contains EFs from other sources.

All EFs are associated with uncertainty. We therefore used the minimum and maximum confidence interval (CI) of each EF to calculate minimum and maximum emissions (Table 2).

Change in C stocks over time

The sum of C losses as CO_2, methane and dissolved organic C is considered as C emission due to drainage. Annual C emissions (from 1710 to 2015) due to drainage were calculated as a function of the EF (t C ha^{-1} a^{-1} for each land use) and peatland area (ha) of each different land use, for a given year. A time series of peatland surface was created using linear

Table 2 The two sets of EFs used in the calculation of C emissions from peatlands and their corresponding minimum and maximum estimates (based on 95% confidence interval) for each land use; "IPCC" and "NIR" refer to the two groups of EFs, as described in main text

Land use	Total C emission factor (t C ha^{-1} a^{-1})				Comment
	IPCC		NIR		
	Min	Max	Min	Max	
NN	− 0.27	− 0.19	− 0.27	− 0.19	From Loisel et al. (2014)
DR	0.96	4.11	0.96	4.11	See text for details
MX	2.59	5.09	3.22	6.07	Mean of all other rates
PE	1.53	4.99	1.53	4.99	For NIR, IPCC default used; refers to remaining peatland, annual amount of extracted peat is not taken into account
FL	2.43	4.08	2.43	4.08	
GL	3.93	7.34	7.32	11.72	
CL	6.93	10.18	7.32	11.72	

interpolation between surface estimates for 1710, 1890, 1950 and 2015. A time series of the proportion of peatlands under different land use types was also calculated with linear interpolation of calculated proportions for 1710, 1900, 1950 and 2015. For each land use, these two sets of values were multiplied to give the surface (ha) of peatlands under each land use type, per year. These values were multiplied by the EFs of the respective land use type, allowing total annual C emissions to be calculated, as well as cumulative emissions for the 305-year period.

C stock losses over time (1710 to 2015) were calculated by using the C stock estimates for 1710, then applying the aforementioned annual C emissions to calculate new stocks for each year, where each year's stock equals the previous year's stock minus the emissions for that year. We refer to this calculation as the '*indirect*' method of estimating C stocks (as opposed to the '*direct*' method, see earlier). This indirect estimate was calculated for each of the three peatland surface estimates for 1710, and the minimum and maximum estimates of each of the two sets of EFs (IPCC and NIR), resulting in twelve calculations in total.

Losses of C due to peat extraction

To contextualize our estimates of C losses due to drainage, we estimated cumulative C losses due to peat extraction. Peat extraction in Switzerland was regulated—and thus extraction rates recorded—for only very short periods. For the remaining periods, we therefore derived extraction rates from expert estimates, from information on energy use, and from records of extraction rates for individual sites extrapolated to the national scale based on the number of important active peat extraction sites at that time (Supplementary Table 1). Extraction rates, given in volume of air-dried peat per year, were converted to C losses assuming 14.6% or 16.9% water content of air-dried peat (the lower and upper CI of measurements from 30 sites across the country, KIAA 1941), and 37.2% or 57.6% C content (lower and upper CI from samples from 48 sites across the country covering FL, CL, GL, NN and DR sites, from Leifeld et al. 2011a; Bader et al. 2017, 2018a, b; from Leifeld et al. 2011b, 2012; Wüst-Galley et al. 2016). Minimum and maximum estimates of total C lost through extraction were thus calculated for the 305-year period (Supplementary Fig. 1), incorporating variation in C and water content (%), and rates of peat extraction.

Results

Peatland surface and peat volume

Switzerland's current peatland surface (including mires as well as intensively-used peatlands) is between 20 and 30% of its (NN mire) surface in 1710 (Table 3). The uncertainty of this historical peatland surface is however large, with the maximum estimate over 50% greater than the minimum estimate.

Distributions of peat thickness are shown in Fig. 1. The median peat thickness of the four periods are as follows: 1900 = 200 cm; 1918 = 190 cm; 1950 = 213 cm; modern = 95 cm. An ANOVA showed that the mean ($\log_{10}$-transformed) peat thickness differs little between the three historical sources ($F_{(2, 761)} = 2.7134$, $P = 0.07$). The mean ($\log_{10}$-transformed) peat thickness of modern peatlands is however significantly less than that of historical peatlands ($F_{(1, 806)} = 34.313$, $P < 0.0001$). The data transformation resulted in normally distributed data.

Land use change and C emissions

The use of peatlands has intensified over time, especially in the last 60 years, with a decrease in the proportion of peatlands as DR or NN, from 40 to 11%. Although there was a decrease in peatlands used for peat extraction during this period, from 35 to 0%, there was a concurrent increase in the proportion of peatlands under FL, from 2 to 16%, and CL or GL, from 21 to 73% (Fig. 2).

Originally C sinks, Swiss peatlands—intensively used and/or protected—now emit between 138,906 and 286,708 t C per year (net), with an annual per hectare basis of 4.6 to 9.5 t C (Table 4). Since 1900, annual emissions have increased 1.5- to 2.4-fold (IPCC EFs), or 1.7- to 2.7-fold (NIR EFs). The increase on a per hectare basis for the same period is 1.8- to 3.0-fold (IPCC EFs), or 2.1- to 3.3-fold (NIR EFs, Table 4). The use of NIR EFs rather than IPCC default EFs resulted in 26% higher C emissions for

Table 3 The reconstructed peatland surface (ha) estimates; min = minimum estimate, from this study; mid = mid estimate from this study; max = the estimate of the historical extent of wetlands, from Stuber and Bürgi (2018)

	Peatland surface (ha)		
	Min	Mid	Max
1710	97,659	108,355	148,560
1850–1890		37,110	
1890–1950		36,525	
1950+		30,187	

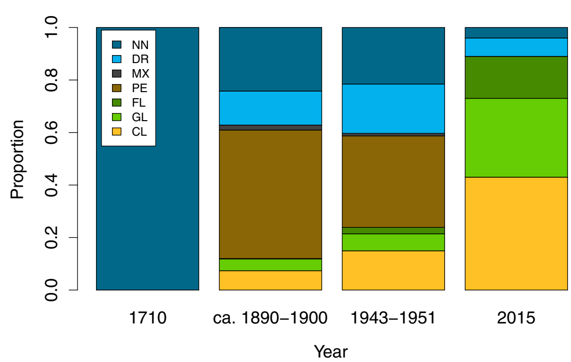

Fig. 2 The distribution of the peatland surface under different land use types for four periods; for land use types see Table 1

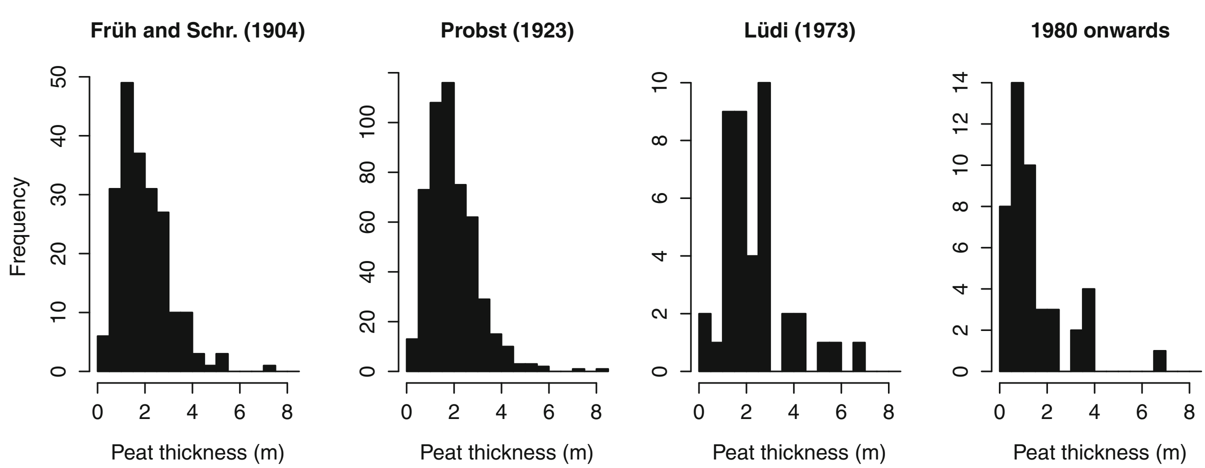

Fig. 1 The distribution of peat thickness from three literature sources and from own data (for 1980 to present day); Lüdi (1973) refers to peatlands surveyed between 1943 and 1951

Table 4 **a** (above) and **b** (below) Annual emissions from Swiss peatlands per year, in total (left-hand columns) and per hectare (right-hand column), using minimum and maximum IPCC (a) or NIR (b) EFs; 'min', 'mid' and 'max' column headers indicate the peatland surface estimate that was used to calculate 1710 emissions

Year	Emission factors	Annual emissions (t C a^{-1})			Annual emissions (t C ha^{-1} a^{-1})
		Min	Mid	Max	
1710	IPCC min	− 26,290	− 29,169	− 39,992	− 0.3
1900			57,286		1.5
1950			74,179		2.0
2015			138,906		4.6
1710	IPCC max	− 18,633	− 20,674	− 28,345	− 0.2
1900			152,046		4.1
1950			168,578		4.6
2015			226,829		7.5
Year	Emission factors	Annual emissions (t C a^{-1})			Annual emissions (t C ha^{-1} a^{-1})
		Min	Mid	Max	
1710	NIR min	− 26,290	− 29,169	− 39,992	− 0.3
1900			64,363		1.7
1950			84,551		2.3
2015			174,930		5.8
1710	NIR max	− 18,633	− 20,674	− 28,345	− 0.2
1900			164,138		4.4
1950			187,695		5.1
2015			286,708		9.5

2015 and the use of maximum estimates of EFs resulted in emissions 64% higher than those calculated with the minimum EF estimates.

The number of years until which C from Swiss peatlands is estimated to disappear (assuming no change in land use) was calculated by dividing the current C stock by the current C emission rate. This lies between 113 and 185 years (max. and min. NIR EFs) and 143 and 233 years (max. and min. IPCC EFs).

Cumulative (net) C emissions since 1710 are between 16.5 and 46.7 Mt C (IPCC EFs) and 19.6 and 52.3 Mt C (NIR EFs, Fig. 3). These cumulative emissions are between 49% less than, or 62% more than, the direct estimate of C stocks remaining in Swiss peatlands (32.4 Mt C, Table 5). The main variation in cumulative emissions is caused by uncertainty in EF estimates. These cause in total 182 to 191% variation (depending on 1710 peatland estimate), whereas the variation ascribable to that of the 1710 peatland surface estimate is only 8 to 14% (depending on the different EFs, Fig. 3).

C loss from Swiss peatlands

The C stocks estimated for 1710 vary from 84.4, to 93.7, to 128.4 Mt C, assuming a minimum, mid or maximum estimate for the peatland area in 1710, respectively (Fig. 4). C emissions, themselves a function of peatland surface and land use, were used to estimate the C stocks of peatlands through time, based on these three initial C stocks (Fig. 4), the 'indirect' estimates. There is a disparity between these indirect estimates and the direct estimate of C stocks for 2015 (Fig. 4): stocks calculated using the indirect method are 34 to 241% (IPCC EFs), or 17 to 231% (NIR EFs, variation due to different estimates of 1710 peatland surface and uncertainty of the EFs, Table 5) higher than stocks calculated using the direct method. This disparity corresponds to 11.0 to 78.0 Mt (IPCC EFs) or 5.5 to 74.7 Mt (NIR EFs) C (Table 5).

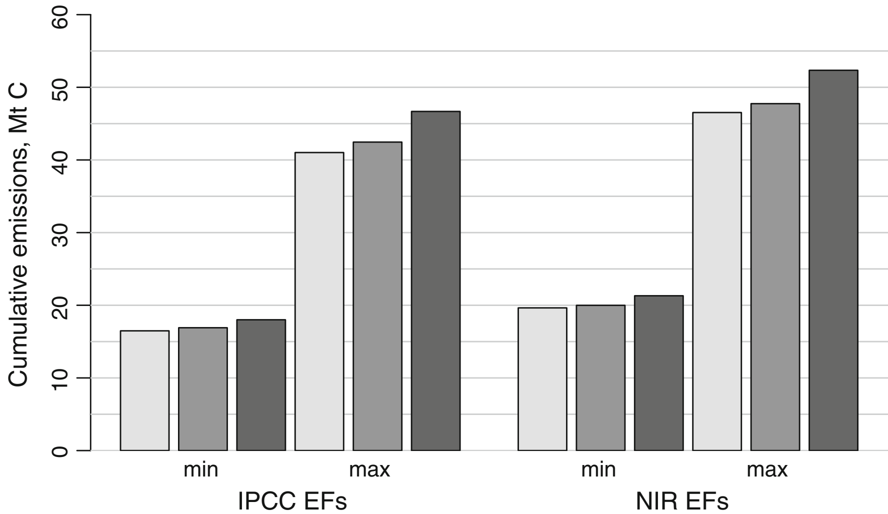

Fig. 3 Cumulative C emissions from Swiss peatlands from 1710 to 2015, assuming IPCC (left-hand side) or NIR (right-hand side) EFs, using the minimum ('min') and maximum ('max') EFs (see text for details), and the minimum (pale gray), mid (mid-gray) or maximum (dark gray) estimate of peatland surface in 1710

Table 5 **a** (above) and **b** (below) Comparison of the C stocks in peatlands in 2015 as estimated by the direct and indirect estimates, using either the min and max IPCC (a) or Swiss NIR (b) EFs; the direct estimate is a function of peatland area, peat thickness and C density; the indirect estimate is a function of the estimated C stocks in 1710 and the cumulative emissions (themselves a function of land use and peatland surface) since then; 'min', 'mid' and 'max' indicate the peatland surface estimate that was used to calculate 1710 emissions

		IPCC EFs, min			IPCC EFs, max		
		Min	Mid	Max	Min	Mid	Max
Direct estimate	Mt C	32.4	32.4	32.4	32.4	32.4	32.4
Indirect estimate	Mt C	67.9	76.7	110.4	43.4	51.2	81.7
Overestimation	%	110	137	241	34	58	152
Disparity in C estimates	Mt C	35.5	44.4	78.0	11.0	18.8	49.4
		NIR EFs, min			NIR EFs, max		
		Min	Mid	Max	Min	Mid	Max
Direct estimate	Mt C	32.4	32.4	32.4	32.4	32.4	32.4
Indirect estimate	Mt C	64.8	73.7	107.1	37.9	45.9	76.1
Overestimation	%	100	127	231	17	42	135
Disparity in C estimates	Mt C	32.4	41.3	74.7	5.5	13.5	43.7

Total C loss due to peat extraction over 305 years was estimated to be between 2.5 and 5.7 Mt.

Discussion

Reconstructing the original Swiss peatland surface

Understanding the history of a habitat usually involves locating the original extent of that habitat. In cases where destructive land use began centuries ago, doing this using documented information alone (e.g. maps, surveys) can result in large uncertainties. This is exemplified by the estimate of Switzerland's original peatland surface, as follows.

The earliest geographically comprehensive documentation regarding peatlands in Switzerland stems from the late nineteenth century: topographical maps showing sites of peat extraction. Their early date makes them potentially very useful, but they indicate only sites where peat was extracted, thus mires or peatlands used for agriculture are not indicated on

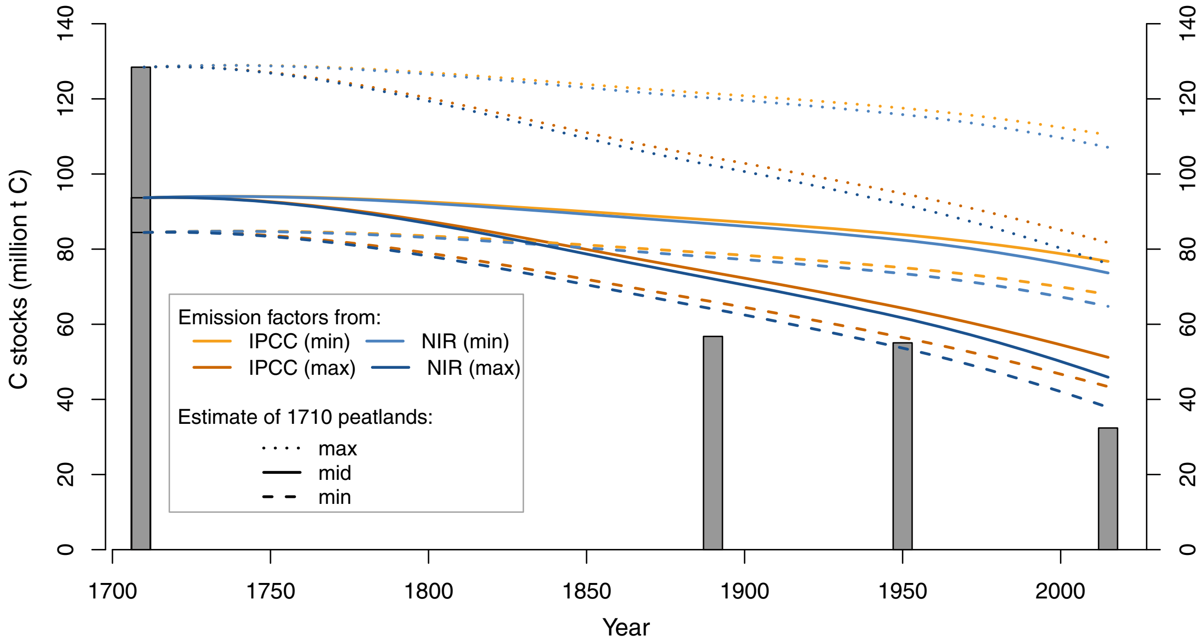

Fig. 4 C stocks estimated directly (vertical bars, with the bar at 1710 showing the C stocks derived using minimum, mid and maximum estimate of 1710 peatland surface) and indirectly (lines), using IPCC (orange lines) or the NIR (blue lines) EFs, with darker lines representing maximum estimates of EFs and paler lines, minimum estimates; C losses estimated using the maximum (dotted lines), mid (solid lines) or minimum (dashed lines) estimate of the 1710 peatland surface

these maps. Surveys in which *peat* was systematically mapped began at the end of the nineteenth century with geological surveys (but at the time with very sparse geographical coverage), or in the mid-twentieth century with soil maps (with incomplete geographical coverage). Furthermore, large drained surfaces are already depicted on the early topographical maps, indicating that mire destruction predated them. For these two reasons, peatlands are under-represented on early maps. We reduced this under-representation by assuming that all peatlands identified in more recent documents existed already in 1890, and were therefore allocated to that period for our analyses. This correction assumes that no substantial mires have been created in the past centuries, an assumption likely to be met given the history of wetland destruction in Switzerland. This approach was also used by Gimmi et al. (2011) in their reconstruction of the historical extent of wetlands. This correction however remedies the under-representation of peatlands only partly: the large-scale destruction of peatlands means that only a proportion of them remain to be used in this correction. For other peatlands, there simply exists no documentation. The consequence of this is that early peatland surface estimates—and thus C stocks estimates—based on documented information (i.e. those of the early- and mid-twentieth century) are probably underestimates.

A comprehensive modern soil survey of the country would not solve this problem because peat loss through drainage and extraction mean many peatlands might have disappeared. Based on the median peat thicknesses from Früh and Schröter (1904, 200 cm), Probst et al. (1923, 190 cm), Lüdi (1973, surveying from 1943 to 1951, 213 cm) and modern studies (106 cm,[3] assumed year 2000), the rate of volumetric loss of the peat layer ranges from 8.5 to 19.5 mm a^{-1} over ca. 30 to 100 years, with a mean rate of 12.7 mm a^{-1}. This distribution of rates is comparable to a previous estimate, based on measured subsidence, for the Seeland plateau in western Switzerland, 7.5–16.4 mm a^{-1} (95% CI, Leifeld et al. 2011b) and other temperate and boreal peatlands (data from 30 sites in total, with references given in Presler and Gysi

[3] This value differs to that reported in the Methods, as modern sites where peat extraction has taken place were excluded from this calculation. This allowed the rate of peat thickness change due to *drainage only* to be calculated.

1989; Zeitz 1997; Kluge et al. 2008) with a mean annual rate of volumetric loss of 7.9–16.1 mm a^{-1} (95% CI). The implication of this is that we can expect a 3 to 6 m thick peat layer drained in the early eighteenth century to have disappeared by now, solely due to drainage. Peat extraction compounds this problem even further, and we know from historical descriptions that from many sites the peat was entirely removed.

We used two methods to pull back the estimate of the peatland surface beyond the mid-nineteenth century. One of these, using toponyms, takes advantage of the fact that these can outlive landscape characteristics after which they were named. Toponomy has been used to understand landscape history in other contexts (e.g. pasture-fires in Switzerland, Conedera et al. 2007; agrarian landscapes in Spain, Donada 2009), and Früh and Schröter (1904) highlighted their potential to identify former mires. Using the meaning of generic parts of toponyms to identify landscape characteristics can however be problematic, if the meaning(s) of words change over time (Derungs et al. 2013), or if a word has multiple meanings. In Switzerland, the German word 'peat' ('Torf'), for example, is also used as a suffix indicating a village ('Dorf')[2]. Furthermore, several words including 'ried' or 'marais' indicate wetlands that may or may not have a peaty substrate. We minimised these problems by using only those names reliably indicative of mires or peatlands according to Früh and Schröter (1904) and the Swiss Idiotikon[2], though this approach means we may have underestimated historical peatlands.

Peatland surface loss

We estimate that Switzerland has lost between 70 and 80% of its peatland surface, resulting in a long-term annual loss of between 0.39 and 0.42% a^{-1}. This is comparable to the loss rate of natural inland wetlands globally (0.39% a^{-1}, SD = 0.32), or for Europe (ca. 0.35% a^{-1}, SD ca. 0.35) for the same time period (Davidson 2014).

C emissions through peatland drainage

Swiss peatlands have changed from being C sinks to substantial C sources: the current annual emissions (currently ca. 0.51 to 1.1 Mt CO_2eq.) are high and correspond to ca. 30–60% of the annual Swiss CO_2 budget of the 'Land use and land-use change and forestry' sector (calculated from FOEN 2017, mean net sink of 1745 kt CO_2 from 1990 to 2015, dominated by forestry).

Although the majority of peatlands were managed already by 1900—mostly as litter meadows—the greatest intensification in peatland use occurred in the last 65 years, shown by per hectare emissions that have more than doubled in this time. This increase in emissions occurred in spite of the abolishment of peat extraction and its associated drainage, and can be attributed to the increased proportion of remaining peatlands under forestry, and especially cropland and intensively-managed grassland. The latter two land uses have the highest EFs and the share of peatlands under this management has increased from 21 to 73% since 1950.

The current emissions are however certainly an underestimate, due to the underestimation of the current peatland surface. Reasons for this include the exclusion of surfaces for which the presence of peat is uncertain, as well as the fact that the coverage of data sets used to reconstruct the peatland surface is incomplete (Wüst-Galley et al. 2015). Additionally, 'anmoorig' (C-rich soils with a C content lower than that of organic soils) and 'antorfig' (soils with only a very thin peat layer) soils were not explicitly included in the peatland estimate, although it is known that such soils lose C at a rate similar to that of organic soils (Leiber-Sauheitl et al. 2014). The C stocks of Switzerland's peatlands and thus the GHGs being released from them should be considered a minimum estimate.

In short, C losses in Switzerland due to peatland drainage are a significant part of the country's GHG budget for land use, they have risen substantially in the last three centuries and last 65 years especially, and the estimate provided here is most likely an underestimate.

The loss of C stocks

We use historical peatland surface estimates and information on historical land use to estimate, indirectly, how much C has been lost from Swiss peatlands through drainage since 1710. This cumulative net loss ranges from 16.5 to 52.3 Mt C. Although the uncertainty in this estimate is large, these estimates are approximately a magnitude larger than the minimum and maximum estimates of C lost through peat extraction for the same period, meaning that the processes of oxidation and leaching have dominated soil C loss in Switzerland. This relationship of C losses is quite different from that derived for C loss from Dutch peatlands, where losses from drainage and extraction were estimated to be approximately equal (average of the last 1000 years, Erkens et al. 2016). The peatlands in the Netherlands however have a much lower average emission rate due to drainage of ca. 0.6 t C ha^{-1} a^{-1} (calculated from Erkens et al. 2016) compared to Switzerland (1.4 to 3.6 t C ha^{-1} a^{-1} average over 305 years), explaining some of this discrepancy.

The range of cumulative C losses in Switzerland, including both emissions and extraction, encompasses the estimate of remaining C in peatlands (estimated directly). This means that roughly the same amount of C lost in the whole history of peatland exploitation has the potential to be lost in the future, at a high rate, through continued oxidation and leaching of the remaining peatlands.

There is however a disparity between the estimated C stocks of 2015 between those derived directly and those derived indirectly by C losses, ranging from 5.5 to 74.7 Mt.

Some of this disparity can be explained by peat loss due to extraction, which for some periods in the last 300 years was considerable. There is evidence of peat extraction for fuel as early as 1709 (von Knonau 1844; Stuber and Bürgi 2018, in canton Zurich). Due to an increasing population, increased per-head energy needs and pressure on forests due to expanding agricultural land, a wood shortage threatened, necessitating an alternative fuel to wood (Ewald and Klaus 2010; Hürlimann 2016). Früh and Schröter (1904) list the locations of peat extraction as they appeared in the following decades, indicating its spread was widespread and rapid. Increased energy demands in the nineteenth century, due in part to an increasing population and secondary industry (Hirt 2007), increased the reliance on peat as an energy source. Mechanised extraction began in the second half of the nineteenth century (Früh and Schröter 1904). By the beginning of the twentieth century however, imported coal was the main source of energy in the country (Anon 1987). A fuel shortage in 1916/1917 however prompted national-scale extraction of peat for energy (Stamm 1919; Probst et al. 1923), a boom which continued until 1921 and which was repeated between 1941 and 1945 (Kuster 1946).

Estimating C losses through peat extraction is difficult because for much of its history peat extraction was carried out locally, without regulation and for personal use (Zimmerli 1944; Hirt 2007), meaning that—except for short periods during which its extraction was promoted by government—there are no records of its extraction. Correspondingly, our estimate of total C loss through extraction is associated with much uncertainty. However, it explains the disparity in estimated C stocks for 2015, assuming maximum rates of emissions and a minimum estimate of mire surface in 1710.

More importantly, the calculation of C losses through drainage over time highlights that the large uncertainty associated with our knowledge of the original peatland surface and of EFs results in massive variation in the estimate of cumulative C losses and annual emissions. Improved estimates of these parameters, as well as those of peat extraction and of the current peatland surface, are needed to better understand historical C losses from peatlands. Estimates of the current peatland surface and EFs are also prerequisites for calculating current emission estimates. Improved estimates of *these* are also necessary for the improved estimate of current and future GHG emissions, as well for the monitoring and justification of mitigation strategies that aim to reduce GHG emissions, such as the re-wetting of drained peatlands (Wilson et al. 2016).

Summary and conclusion

Our historical reconstructions of C loss from peatlands through peatland drainage and peat extraction are associated with uncertainty relating to EFs, the peatland surface and peat extraction itself. In spite of this uncertainty, clear patterns emerge that are informative in placing current peatland emissions in a broader context. The rate of peatland (surface) disappearance in Switzerland is typical of that of wetlands in global and European contexts. Loss of C through peatland drainage has been a much more important cause of C losses than peat extraction: The cumulative oxidative losses are approximately an order of magnitude greater. Annual C emissions have increased continually through time, especially in the second half of the last century during which they approximately doubled. This has occurred despite a shrinking peatland surface and is due to increased intensity in the use of peatlands, in spite of the abolishment of peat extraction. Although the resulting historical cumulative C emissions from peatland drainage are high, the amount of C remaining in peatlands is comparable (32.4 Mt C), meaning that as much C will potentially be emitted in the future, as has been released so far in the history of peatland use.

More problematic for the short-term future is that annual emissions from Swiss peatlands will remain high unless there is a reduction in the intensity of peatland use. These emissions are currently half a million to just over one million t CO_2, with an additional ca. 65,000 t CO_2e of N_2O emissions from drained agricultural peatlands (FOEN 2017). The land uses associated with the highest EFs, cropland and managed grassland, are also the dominant land uses of peatlands in the country, covering ca. 70% of Swiss peatlands. It is argued at the global scale that peatland restoration and protection are vital for the reduction of greenhouse gas emissions, in part due to their relatively low GHG abatement costs (Smith et al. 2008) and especially their large potential future C- and N-based emissions (Leifeld and Menichetti 2018; Pärn et al. 2018). We argue that this is mirrored in Switzerland, even in the absence of peat extraction. Indeed, small re-wetting projects have been realised in the country (Klaus 2007). Stopping drainage or and re-wetting peatlands remains an efficient option to reduce C emissions, especially considering that in Switzerland the share of agricultural land on peatlands is relatively small (< 2% of ca. 1.4 million ha; ca. 3% of cropland, ca. 0.8% of grassland). Without counteracting measures, future emissions from C losses will cumulatively reach more than 115 Mt CO_2. Whether to continue the current intensive use of peatlands or whether to restore them hydrologically and protect them as C stores or even as sinks is thus an important decision in terms of GHG emissions and their mitigation.

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