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# Process-based reconstruction of peatland carbon dynamics in Switzerland

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**Abstract.** In Switzerland, over 90 % of peatlands have been degraded and transitioned from long-term carbon sinks to persistent carbon sources. Assessing peat carbon vulnerability and restoration opportunities requires understanding not only the present-day distribution of peat carbon stocks, but also the historical trajectories that shaped them. Existing assessments are largely based on inventories and emission-factor approaches, limited in representation of the interactive effects of climate, peatland processes, and land-use change over time. By combining the LPX-Bern Dynamic Global Vegetation Model with a historical record-informed peat-derived area and carbon accounting framework, we reconstructed peatland conversion pathways and tracked the fate of peat carbon through successive land-use transitions from the pre-industrial period to the present. Modelled peatland and peat-derived areas in Switzerland declined from approximately 724 $km^2$ in the pre-industrial period (1701–1710) to 376 $km^2$ at present (2011–2020), while only 5 % remained near-natural, in broad agreement with historical reconstructions and recent synthesis products. Over the same period, peat carbon stocks decreased from 121.9 Mt C under near-natural conditions to 30.4–56.4 Mt C. Although only a small fraction of the original peatlands remained near-natural, 86–92 % of the remaining peat carbon was stored in agricultural, forested, and unmanaged drained land-cover classes. By explicitly tracking peat carbon through historical land-use transitions and attributing remaining peat carbon to present-day land-cover classes, this framework provides a spatially explicit basis for assessing peat carbon vulnerability, identifying restoration opportunities, and informing peatland management and climate mitigation strategies. This approach is transferable to other regions where information on peatland extent, land-use history, and peat-specific disturbances is available.

**Keywords**

Peat carbon dynamics, peatland modelling, peat-derived area, peatland restoration, land-use change

**Summary**

We developed a process-based reconstruction of how peatlands and their carbon stocks changed over the past three centuries in Switzerland. Combining historical records with peatland modelling, we traced where peat carbon remains today. Most peat carbon is currently stored outside intact peatlands, showing the opportunities to reduce future carbon losses extend beyond the small fraction of remaining near-natural peatlands.

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


## 1. Introduction

Peatlands accumulate partially decomposed organic matter under waterlogged, anaerobic conditions, forming peat over millennia. Beyond long-term carbon sink, peatlands deliver a suite of ecosystem services including biodiversity support, water purification, and flood attenuation (UNEPs, 2022). Despite their ecological significance, peatlands have been extensively drained for anthropogenic use, fundamentally reversing their carbon exchange functions (Page and Baird, 2016; Loisel et al., 2021). Drainage lowers the water table, exposes peat to aerobic decomposition, and converts peatlands from carbon sinks to persistent carbon sources (Leifeld et al., 2019; Tubiello et al., 2016). Annual $CO_2$ emissions from drained peatlands now account for approximately 5 % of global anthropogenic greenhouse gas emissions (Loisel and Gallego-Sala, 2022; Tubiello et al., 2016; Friedlingstein et al., 2024), with the large majority, ca. 85 %, attributed to agriculturally managed organic soils (Bader et al., 2018; Tubiello et al., 2016). Without intervention, projected carbon losses range from 30 to 95 Gt C between 2015 and 2100, depending on climate and land-use scenarios (Leifeld et al., 2019; Müller and Joos, 2021).

Peatland conservation and restoration are increasingly recognised as critical nature-based climate mitigation measures (e.g., Allan et al., 2024; Leifeld and Menichetti, 2018; Leifeld et al., 2019). Critically, the mitigation potential of peatland management is an irreversibly depleting resource on centennial scales, and peatland or wetland restoration is increasingly being explicitly incorporated in national climate mitigation strategies and Nationally Determined Contributions (NDCs; e.g. Government of Canada, 2025, The Republic of the Congo, 2025, Republic of Indonesia, 2025, Government of Perú, 2025, United Kingdom of Great Britain and Northern Ireland, 2025). This reflects the emerging consensus to embed peatland management within national greenhouse gas accounting frameworks.

Switzerland exemplifies both the extent of peatland degradation and the governance potential of translating protection into effective mitigation. Although constitutional protection of peatlands was introduced through the Rothenthurm Initiative in 1987 (Volksinitiative; Grünig, 1994), the majority of Swiss peatlands remain drained and continue to function as significant net carbon sources (Wüst-Galley et al., 2015, 2019; Wüst-Galley and Leifeld, 2025). Agriculturally managed organic soils represent less than 2 % of national agricultural land area, yet are estimated to contribute 30–60 % of annual $CO_2$ emissions within the land use, land-use change, and forestry (LULUCF) section (Wüst-Galley et al., 2019; FOEN, 2017). Despite this importance, peatland restoration is not explicitly included in Switzerland's NDCs (Switzerland, 2025).

Historical reconstructions based on land-use change records have substantially advanced understanding of peatland degradation (Leifeld et al., 2005; Wüst-Galley et al., 2015, 2019; Wüst-Galley and Leifeld, 2025). However, these reconstructions provide only discrete snapshots in time and do not explicitly represent the interacting effects of climate, vegetation dynamics, and land-use change on peatland evolution. Consequently, the spatial and temporal dynamics of peat-derived area and associated peat carbon stocks remain uncertain. A systematic and spatially explicit framework linking peatland conversion pathways to present-day peat-derived area and carbon is therefore lacking, limiting national-scale assessments on peat carbon vulnerability and restoration opportunities.

Process-based models can provide such a framework by simulating biogeochemical cycles under transient climate conditions (e.g., Qiu et al., 2019; Qiu et al., 2022; Müller and Joos, 2020). The LPX-Bern model ("Land surface Process eXchanges model" of the University of Bern, Lienert and Joos, 2018; Müller and Joos, 2020) includes explicit representations of peatland hydrology, peat accumulation, and land-use change effects on vegetation

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


composition and water table level, making it suitable for simulating peatland area and carbon dynamics (Müller and Joos, 2020). Combined with a peat-derived area and carbon tracking framework, LPX-Bern enables spatially explicit attribution of remaining peat carbon to different present-day land-cover classes.

This study combines process-based modelling with a peat-derived area and carbon accounting framework to reconstruct the evolution of Swiss peatlands and to quantify their dynamics from pre-industrial period to the present. Specifically, we evaluate the capacity of LPX-Bern to reproduce historical peat-derived area and carbon stocks using national records, then quantify the present-day distribution of peat-derived area and remaining peat carbon among different land-cover classes relevant for restoration prioritisation, providing a spatially explicit basis for assessing peat carbon vulnerability and informing peatland restoration planning.

## 2. Materials and Methods

### 2.1. Model description

Peatland dynamics were simulated by the LPX-Bern model. LPX-Bern is a Dynamic Global Vegetation Model (DGVM), also referred to as terrestrial biosphere model (TBM), that simulates coupled carbon, water, and nitrogen cycles with dynamic vegetation composition based on plant functional types (PFTs) (Müller and Joos, 2021, 2020). Peatland vegetation is represented by dedicated peatland PFTs, including Sphagnum and flood-tolerant graminoids (Stocker et al., 2014; Müller and Joos, 2021).

Peatland processes are developed from the LPX-WHyMe framework (Wania et al., 2009) with dynamic peatland area (Stocker et al., 2014). In this study, peatland expansion was constrained using the GIEMS-MC wetland extent product (Bernard et al., 2025; Supplement Table S**1**; Figure S1). Soil carbon in peatlands is structured into a fast-turnover acrotelm (upper 0.3 m depth) with fluctuating water table where the decomposition rates are affected by both soil temperature and water table position (Spahni et al., 2013), and a slow-turnover catotelm (0.3–2 m depth) which is fully saturated while the decomposition rates are controlled primarily by soil temperature (Wania et al., 2009). Carbon exchange between these two pools is determined by the acrotelm carbon balance. Long-term peat carbon accumulation is represented through changes in peat carbon density associated with peat forming processes. Peatland methane emissions are available from the model output, but not applied in this study.

Land-cover classes in the model include natural land, peatland, and three land-use classes that are cropland, pasture, and urban, prescribed by the LUH2 dataset (Hurtt et al., 2020; Supplement Table S**1**; Figure S2). Land-use change is implemented as net area changes, without explicit gross transitions as detailed in Müller and Joos, 2021. Briefly, expanding land-use classes inherit carbon, water, and nutrients from all shrinking classes proportionally, such that peatland area is converted to land-use classes when total land-use area increases; peatland area that is converted to land-use classes cannot be restored to peatland. As LPX-Bern does not explicitly track converted peat area and peat carbon during land-use changes, to quantify the fate of peat carbon following land-use conversion, we developed a peat-derived area and carbon tracer in post-processing described in Sections 2.3 to 2.4.

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


### 2.2. Simulation setup

The simulations were conducted from year 1700–2020 at 0.125° × 0.125° resolution according to the climate forcing data (see Supplement

Table S**1**). Other forcing datasets originally at 0.25° × 0.25° resolutions were remapped to match the same grid (Supplement

Table S**1**). The climate data from 1901 to 1920 were recycled for the spin-up and the 1700–1900 period of transient simulation. The monthly wetland extent from 1992 to 2020 were recycled for spin-up and years prior to 1992. Periods outside of the coverage of other forcing datasets were extended using the first year or last year of data.

### 2.3. Peat-derived area reconstruction

#### 2.3.1. Modelled land-cover transitions

Peat-derived area, $A(t)$, at timestep $t$, refers to the land area that originated from peatland and includes the area that has been converted to other land-cover classes. This concept is used here to represent the area with a peatland origin, rather than imply direct equivalence to inventory-based organic soils. $A(t)$ under other land-cover classes other than peatland was diagnosed during post-processing using a conserved tracer. At each timestep $t$, the fraction of area originating from peatland was redistributed across land-use classes, namely cropland, pasture, and urban areas proportional to their net land-cover change within each grid cell, $S(t)$. At each timestep $t$, the peatland area loss is defined as:

$$L_{peatland}(t) = \max\left(0, A_{peatland}(t - \Delta t) - A_{peatland}(t)\right) \quad , \qquad \text{Eq. 1}$$

This lost peat area is redistributed to expanding land-use classes, such as cropland, pasture, and urban:

$$\Delta A_i(t) = \frac{\max\left(0, \Delta S_i(t)\right)}{\sum_{j\in(cropland,pasture,urban)} \max(0, \Delta S_j(t))} \cdot L_{peatland}(t) \quad , \qquad \text{Eq. 2}$$

where $\Delta S_i(t)$ is the net land-cover change for land use class $i$. A hierarchical allocation scheme prioritises conversion to anthropogenic land-use classes and prevents direct transfer from peatland to natural land (termed forested). Redistribution to forested areas is only permitted through subsequent secondary transitions, such as land abandonment, ensuring that peat-derived areas follow realistic land-use pathways.

#### 2.3.2. Historical peat extraction and drainage

Since the LUH2 dataset does not account for peatland-related activities such as peat extraction and peatland drainage (unlike land-use conversion which does not distinguish unmanaged drained peatlands as a separate class), these transitions were incorporated in post-processing using reconstructed fractions from Wüst-Galley et al. (2019), available for year 1710, 1890–1900, 1943–1951, and 2015, and linearly interpolated in time. Two assumptions were applied: (1) peat extraction and peat drainage occur only on the active peatland class, not on peat-derived areas that already have been converted to land-cover classes, and (2) extracted and drained areas are treated as terminal states, such that any subsequent reduction in these areas results in a permanent loss of peat-derived area from the system. This framework results in a set of peat-derived land-cover classes with distinct representations in terms area and carbon dynamics (see Table 1).

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


**Table 1 Land-cover classes used in this study and their representation in the reconstruction of peat-derived area and peat carbon.**

| Land-cover class | Representation of peat-derived area and carbon | Source |
|---|---|---|
| Peatland | Explicit in LPX-Bern | Model output |
| Cropland | Tracer accounting | Model and tracer |
| Pasture / grassland | Tracer accounting | Model and tracer |
| Urban / built | Tracer accounting | Model and tracer |
| Forested | Tracer accounting | Model and tracer |
| Peat extraction area | Prescribed area and tracer accounting | Model and Wüst-Galley et al. (2019) |
| Unmanaged drained peatland | Prescribed area and tracer accounting | Model and Wüst-Galley et al. (2019) |

For comparison with contemporary inventory-based estimates, forested peat-derived areas and unmanaged drained peatlands are grouped into a single category, termed forested/unmanaged drained peatlands. This grouping broadly overlaps with the wooded and unproductive vegetation organic soil classes reported by Wüst-Galley and Leifeld (2025), although the latter classes also contain near-natural peatlands and do not explicitly distinguish forestry management and drainage status. Therefore, the underlying classification schemes are comparable but not directly equivalent. This land-cover classification was used as an interpretive framework rather than as a formal restoration suitability standard. We therefore do not quantify avoided emissions or restoration feasibility, which would require additional detailed local information on hydrology, drainage infrastructure, land ownership, land-use intensity, biodiversity responses, and socio-economic constraints.

### 2.4. Peat carbon accounting

Peat carbon stocks are calculated by coupling peat-derived area with land-cover specific carbon densities:

$$C_i(t) = D_i(t) \cdot A_i(t) \quad , \qquad \text{Eq. 3}$$

where $A_i(t)$ is peat-derived area defined above and $D_i(t)$ is the peat carbon density associated with this area in land-cover class $i$. Carbon densities in peatlands are output from the model and are applied as boundary conditions at each timestep without being altered during redistribution.

When land-cover transitions occur, the peat carbon associated with the transferred area is calculated using the carbon density of the source land-cover class:

$$\Delta C_{i\rightarrow j}(t) = D_i(t-\Delta t) \cdot \Delta A_{i\rightarrow j}(t) \quad , \qquad \text{Eq. 4}$$

where $\Delta A_{i\rightarrow j}$ is the area transferred from land-cover class $i$ to class $j$.

When the land-cover transition is associated with anthropogenic drainage, either through land-use conversion or unmanaged drained peatlands, two scenarios of peat carbon loss are considered in this study: (1) a shallow drainage scenario which assumes drainage to 0.3 m depth, resulting in the release of all peat carbon stored in the acrotelm during the year of drainage initiation; (2) a deep drainage scenario assumes that, in addition to the complete loss of acrotelm carbon, 50 % of the peat carbon below 0.3 m is decomposed and released during the drainage initiation year. These selected thresholds provide lower and upper bounds spanning the range of plausible peat carbon loss associated with drainage.

Peat carbon remaining in all peat-derived non-peatland categories is subjected to first-order decay:

$$C_i(t) = C_i(t-\Delta t) \cdot e^{-k_i \Delta t} \quad , \qquad \text{Eq. 5}$$

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


where $k_i$ is model computed decay rate that is land-cover specific and temperature dependent.

### 2.5. Comparison with national inventory and peatland reconstructions

Historical national peatland extent and peat carbon stock as well as land-cover types were reconstructed by Wüst-Galley et al. (2019), considering historical record, national surveys, and national statistics reports (Früh and Schröter, 1904; Probst E et al., 1923; Lüdi, 1973; SFSO, 2004-2009). National maps of soil with different uncertainties, historical peat-derived area, and probable peat-derived area distribution were synthesised by Wüst-Galley and Leifeld (2025). The shape files from Wüst-Galley (2025) were converted to grid cell fraction at 0.25° × 0.25° (Figure S3) for direct visual comparison with modelled peatland and peat-derived area fraction, since the wetland extent and land-cover change forcing data at 0.25° × 0.25° largely constrained the modelled peatland and peat-derived area distribution.

### 2.6. Data analysis

The data analysis and visualisation were conducted in Python (Van Rossum and Drake Jr, 1995). Packages numpy (Harris et al., 2020), xarray (Hoyer and J. Hamman, 2017) and pandas (The Pandas Development Team, 2020) were used for processing model output, geopandas (Fleischmann et al., 2026) and fiona (Gillies et al., 2024), and rasterio (Gillies and Others, 2013) were used for processing geodatabase (GDB) files, and matplotlib (Hunter, 2007) was used for plotting.

## 3. Results

### 3.1. Modelled peatland and peat-derived area under land-use change

The modelled peatland area in Switzerland declined continuously from 1700 to 2020, from 724 $km^2$ (1701–1710, decadal mean) to 19 $km^2$ (2011–2020), as peatlands were progressively converted to other land-cover classes (Figure 1). This represents a loss of ca. 97 % of the initial peatland extent. During the eighteenth century, peatland area decreased gradually with approximately 200 $km^2$ lost. The most rapid decline occurred during the nineteenth century, when peat extraction and land-use conversion both accelerated. Consequently, peatland area decreased from nearly 500 $km^2$ (1801–1810) to 131 $km^2$ (1891–1900), and only 18 % of the initial peat extent remained. Peatland loss continued thereafter at a slower rate, reaching 34 $km^2$ in 1941–1950, and stabilising below 20 $km^2$ after 2000.

Peat extraction dominated peatland area loss during the nineteenth century. Extracted peatland increased gradually to 175 $km^2$ by 1801–1810 and continued to expand, reaching a maximum of 339 $km^2$ by 1891–1900. Thereafter, extracted area declined steadily throughout the twentieth century to zero by the present day, reflecting the prescribed historical peat extraction record.

Agriculture represented the largest long-term land-use destination of converted peatland, with peat-derived cropland and pasture reaching 122 and 125 $km^2$ by the present day, respectively. In contrast, peat-derived forested/unmanaged drained area peaked at 110 $km^2$ in early twentieth century before declining to 78 $km^2$, whereas urban and built areas remained comparatively small but increased steadily to 33 $km^2$ in the present day.

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


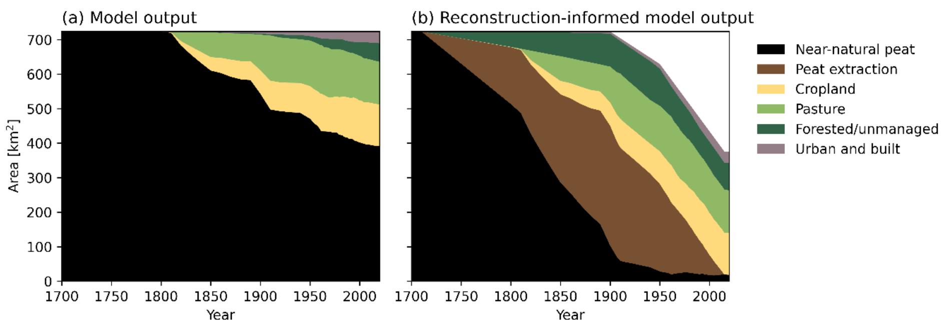


**Figure 1 Evolution of modelled peatland and peat-derived area in Switzerland from 1700 to 2020. (a) Results based solely on model output and peat-derived rea tracking (see section 2.3). (b) Results after incorporating reconstructed peat extraction and unmanaged drained peat from Wüst-Galley et al. (2019) (see section 2.3.2).**

### 3.2. Modelled peat-derived area fractions compared with national inventory and reconstructions

The modelled distribution of Swiss peat-derived area among land-cover categories was compared with historical reconstructions and a recent synthesis of present-day organic soil (hereafter referred to as peat-derived area; Figure 2). The results reproduced the overall transition from predominantly near-natural peatlands to peat-derived areas under managed and unmanaged land-cover categories over the period of 1700–2020.

The modelled near-natural peatland fraction declined continuously from nearly 100 % in 1700 to 18 % by 1891–1900, 5.3 % by 1941–1950, and 5.0 % in 2011–2020. The long-term decline closely followed the reconstructed remaining peatland area trajectory, although the model simulated a more rapid reduction during the nineteenth century, resulting in a lower near-natural fraction than reconstructed around 1891–1900 (18 vs. 25 %). By 2015, the simulated fraction was consistent with both the record (5 %) and the synthesised estimate that less than 10 % of Swiss peatlands remained near-natural (Figure 2a).

Peat-derived cropland and pasture expanded steadily throughout the simulation. By 2011–2020, cropland and pasture accounted for 32 and 33 % of total peat-derived area, respectively. Modelled cropland fractions were close to the historical record during the nineteenth and mid-twentieth century but reached slightly higher than the synthesised present-day estimate of 29 % (mean of 2015–2019; same for below; Figure 2b). Whereas the pasture fraction exceeded the historical records during the nineteenth and early twentieth centuries, but were consistent with the present-day state and the synthesised estimate of approximately 32 % (Figure 2c). Forested/unmanaged peat-derived area increased to 21 % in 2011–2020, matching the historical records and the synthesised estimate of 24 ± 5 % (Figure 2d).

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


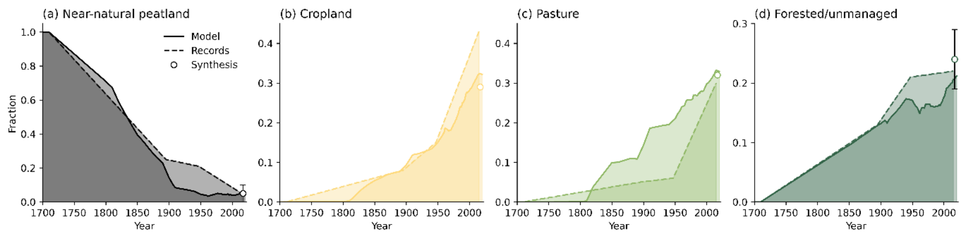


**Figure 2 Swiss near-natural peatland and peat-derived area fractions from record-informed process-based modelling (1700–2020; solid lines), historical records by Wüst-Galley et al. (2019) (year 1710, 1890–1900, 1943–1951, and 2015; connected with dashed lines), and synthesised by Wüst-Galley and Leifeld, 2025 (mean of 2015–2019; circles): (a) near-natural peatland, peat-derived area under (b) cropland or (c) pasture, and (d) forested/unmanaged drained organic soil. The error bars indicate uncertainty in the synthesised current state of Swiss peatlands and organic soil. The synthesised estimate that less than 10 % of peatlands remained near-natural is shown as 5 ± 5 % in (a), while the synthesised wooded and unproductive vegetation category was adjusted to exclude remaining near-natural peatlands, as 24 ± 5 % in (d).**

## 3.3. Spatial distribution of modelled peatland and peat-derived area

Modelled peatland area exhibited strong spatial variability across Switzerland (Figure 3a, b). During the pre-industrial period (1701–1710), peatlands were concentrated in low-elevation regions around the major lake basins, including Lake Geneva, Lake Neuchâtel, Lake Zurich, Lake Lucerne, Lago Maggiore, and Lake Constance (Bodensee). By the present day (2011–2020), the remaining peatland and peat-derived area largely retained the spatial patterns, although with substantially reduced fractions (Figure 3c). Relatively high fractions persisted around Lake Geneva, Lake Zurich, Lago Maggiore, and Lake Constance.

The simulated present-day distribution broadly agreed with the synthesised peatland and peat-derived area map of Wüst-Galley and Leifeld (2025) (also see Figure S3), although the synthesis indicated higher peatland fractions around Lake Neuchâtel and Lake Lucerne.

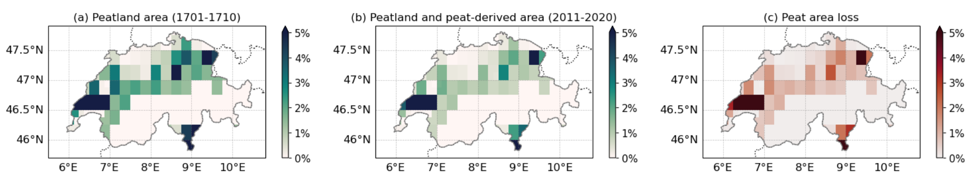


**Figure 3 Modelled fractional peatland area during (a) the pre-industrial period (1701–1710) and (b) the present day (2011–2020), and (c) fractional peatland and peat-derived area loss between the pre-industrial period and present day.**

## 3.4. Modelled peat carbon under land-use change

Despite the almost-complete loss of near-natural peatland area, 86–92 % of the remaining peat carbon was stored in peat-derived cropland, pasture, and forested/unmanaged areas rather than in intact peatlands. These land-cover classes contained 26.0–52.0 Mt C of peat carbon, whereas only 4.4 Mt C remained in near-natural peatlands. The total remaining peat carbon stock across all land-cover classes was 30.4–56.4 Mt C, corresponding to a loss of approximately 54–75 % of the original peat carbon stock (Table 2; Figure 4).

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


Similar to peatland area, modelled peat carbon stocks underwent substantial changes in both magnitude and distribution among land-cover classes from 1700 to 2020 (Figure 4). During the pre-industrial period, virtually all peat carbon was stored in near-natural peatlands, accounting for 121.9 Mt C. As peatlands were drained to convert to land-use types or extracted, peat carbon became increasingly associated with peat-derived land-cover classes. By 2011–2020, only 4.4 Mt C remained in near-natural peatlands, representing less than 3 % of the initial peat carbon stock.

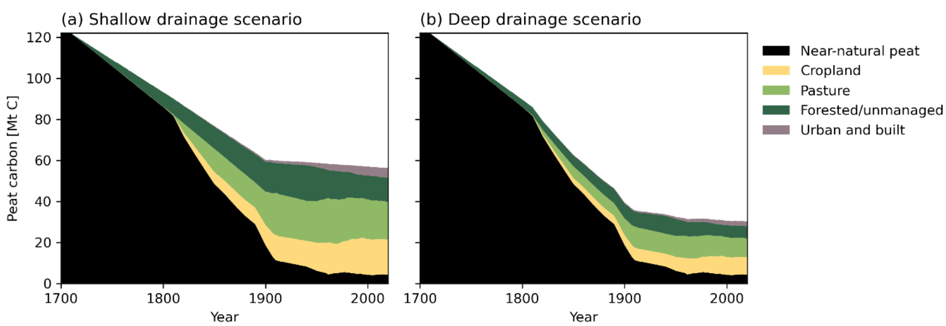


**Figure 4 Modelled peatland and peat-derived carbon of Switzerland from 1700 to 2020 under land-use change**

Carbon stored in peat-derived agricultural land increased throughout the nineteenth and twentieth centuries (Figure 4). Depending on the drainage scenario, peat-derived carbon reached 8.6–17.2 and 9.3–18.5 Mt C in cropland and pasture, respectively, by the present day. Forested/unmanaged peat-derived areas contained 5.8–11.6 Mt C of peat carbon, including abandoned agricultural land (3.8–7.5 Mt C) and drained but unmanaged land (2.1–4.1 Mt C). Peat carbon in urban and built areas increased gradually from the nineteenth century, reaching 2.3–4.7 Mt C by the present day, comparable to the remaining carbon stock of near-natural peatlands (Table 2).

**Table 2 Modelled peat-derived carbon stocks by land-cover classes under the shallow and deep drainage scenarios. The shallow drainage scenario assumes a drainage depth of 0.3 m with a complete loss of acrotelm carbon, whereas the deep drainage scenario additionally assumes loss of 50 % of peat carbon below 0.3 m during drainage.**

| Land-cover class | Peat carbon [Mt C] | |
|---|---|---|
| | Shallow drainage scenario | Deep drainage scenario |
| Near-natural | 4.4 | 4.4 |
| Cropland | 17.2 | 8.6 |
| Pasture | 18.5 | 9.3 |
| Forested/unmanaged | 11.6 | 5.8 |
| Urban and built | 4.7 | 2.3 |
| Sum | 56.4 | 30.4 |

### 3.5. Swiss peat carbon distribution

The spatial distribution of remaining peat carbon varied substantially among land-cover classes (Figure 5). Peat carbon in near-natural peatlands was concentrated primarily in the Swiss pre-Alps and the Jura Mountains, with major clusters around Lake Geneva and the Orbe Plain, between Interlaken and Lake Lucerne, around Lake Zurich, and east of Lago Maggiore (Figure 5a). The highest peat carbon stocks occurred in the Orbe Plain and the Ticino

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


region. The simulated distribution broadly agreed with peatland inventories (FOEN, 2025a, b; also see Figure S4a; Wüst-Galley and Leifeld, 2025), although spatially explicit peat carbon inventories for direct comparison are currently unavailable.

Peat carbon associated with urban and built areas formed a pool of similar magnitude to the remaining near-natural peatlands and was concentrated around major population centres, including Zurich, Geneva, Bern, St. Gallen, and Bellinzona (Figure 5b).

The largest remaining peat carbon pool occurred within agricultural and forested/unmanaged peat-derived areas, including cropland, pasture, forested, and unmanaged drained peatlands (Figure 5c). Their spatial distribution broadly followed the modelled pre-industrial peatland pattern (Figure 3a). Cropland-dominated peat carbon stocks occurred mainly across the Swiss Plateau, particularly around Lake Geneva, the Orbe Plain, the Seeland region, and north of Lake Zurich extending towards Schaffhausen (Figure S5a). Pasture-dominated peat carbon stocks formed a broad belt along the transition between the Swiss Plateau and the pre-Alps (Figure S5b), whereas forested/unmanaged peat-derived carbon was concentrated in higher-elevation regions, particularly east of Lago Maggiore around Bellinzona (Figure S5c).

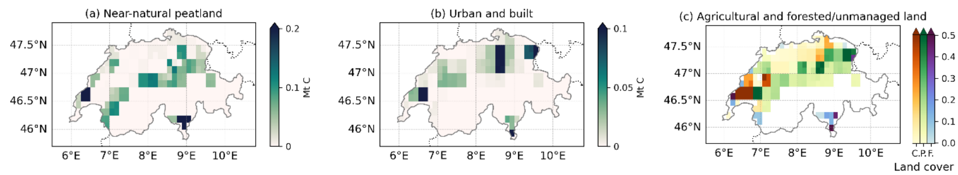


**Figure 5 Modelled peat-derived carbon [Mt C] per grid cell for the present day (2011–2020) under shallow drainage scenario in (a) near-natural peatlands, (b) urban and built areas, and (c) combined agricultural and forested/unmanaged peat-derived areas (sum of cropland, pasture, forested, and unmanaged drained peatlands). Colour hues in (c) indicate the land-cover class with the largest peat carbon sock in each grid cell (C. = cropland, P. = pasture, and F. = forested/unmanaged peatlands), while colour intensity represents the magnitude of total peat carbon stock in this category. Corresponding maps for individual land-cover classes are shown in Figure S5. Note that the colour scales differ among panels.**

## 4. Discussion

### 4.1. Representation of national peatland and peat-derived area

#### 4.1.1. Peatland development and conversion history

The LPX-Bern simulation captures the first-order trajectory of peatland transformation in Switzerland (Figure 2). However, the magnitude and timing of historical peatland loss remain highly uncertain with published reconstructions spanning a wide range (Wüst-Galley et al., 2019; Wüst-Galley and Leifeld, 2025; Table 3), limiting the constraints on peatland loss assessment.

Published estimates of Swiss peatlands span a wide range (Table 3), with pre-industrial values ranging from approximately 400 km$^2$ to over 1000 km$^2$ (Wüst-Galley et al., 2019; Wüst-Galley and Leifeld, 2025). The LPX-

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


Bern estimate of 724 $km^2$ lies within this range. In contrast, the simulated remaining near-natural peatland area (19 $km^2$) is consistent with the inventory-based estimates (15–28 $km^2$), although simulated peatland and peat-derived areas (376 $km^2$) slightly exceed the range of current inventory estimates (186–327 $km^2$). The discrepancies may partly stem from the GIMES-MS constraint (Bernard et al., 2025, Figure S1), which was derived from wetlands and peatlands by remote sensing of recent decades. This constraint could potentially underestimate pre-industrial peatland extent in regions where historical wetlands have lost their surface hydrological features (De Waard et al., 2024; Silva et al., 2024) following drainage, land conversion, and hydraulic engineering in Switzerland (Ewald and Klaus, 2010; Gimmi et al., 2011) as well as globally (Fluet-Chouinard et al., 2023; Convention on Wetlands, 2021). Inventory-based estimates also remain uncertain. The updated synthesis of Wüst-Galley and Leifeld (2025) increased the mapped extent of Swiss organic soils from of 278 (Wüst-Galley et al., 2015) to 327 $km^2$, an increase of 18 % by incorporating newly identified areas and re-evaluating existing records. This substantial revision over a decade indicates the sensitivity of peatland extent estimates to mapping approaches and data availability, implying that past peatland extent may also remain incompletely constrained, even in a country with extensive historical documentation. Similar uncertainties have been reported internationally (Qiu et al., 2021), highlighting that uncertainty in historical peatland extent remains a major limitation for quantifying long-term dynamics, propagating into peat carbon balances.

Despite the uncertainty in absolute peatland extents, the simulated transition from peatland to peat-derived areas agrees reasonably well with historical reconstructions and recent synthesis products (Figure 2), suggesting that the combination of LUH2 land-use forcing and reconstructed peat-specific disturbances captures the broad transient history of peatland conversion. It highlights the importance of incorporating regional information into process-based modelling frameworks (Koch et al., 2023; Silva et al., 2024).

**Table 3 Estimates on peatland and peat-derived area [$km^2$] in Switzerland. * indicates historical records reported by Wüst-Galley et al. (2019), and ** indicates synthesised products reported by Wüst-Galley and Leifeld (2025).**

| | Peatland | Peat-derived area | Sum | Note | Source |
|---|---|---|---|---|---|
| pre-industrial | 400 | 0 | 400 | Sum of current and historical peat-derived areas | ** |
| | 977 | 0 | 977 | Estimates with mean peatland area and number of peatlands | * |
| | ca. 1018 | 0 | 1018 | Theoretical upper bound with ambiguous evidence | ** |
| | 1084 | 0 | 1084 | Associating place names and distance to existing peatlands | * |
| | 1486 | 0 | 1486 | Upper bound from wetland extent | Stuber and Bürgi (2018)* |
| present day | ca. 28 | 158 | 186 | Conservative estimate from synthesised datasets | ** |
| | 15 | 287 | 302 | Estimated as 1950 to present | * |
| | - | - | 327 | Less conservative estimate from synthesised datasets | ** |
| pre-industrial | 724 | 0 | 724 | Constrained by GIEMS-MC (1992–2020) | This study |
| present day | 19 | 357 | 376 | Constrained by reconstructed peat-specific disturbances | This study |

#### 4.1.2. Main uncertainty sources in peat-derived area dynamics

The main temporal discrepancy between simulations and historical records is the more rapid decline in near-natural peatland fraction and expansion of peat-derived pasture during the nineteenth century. This likely results from assumptions required to translate reconstructed peat disturbances into spatially explicit transitions. Specifically, peat extraction and unmanaged drainage were allocated to the active peatland pool, while land-cover transitions followed a hierarchical allocation scheme based on net land-use changes. Historical peatland management likely involved more heterogeneously among peat extraction, drainage, agricultural use, abandonment, and partial recovery, which cannot be fully represented by the simplified peat-derived area tracking framework.

Spatial discrepancies likely reflect both model assumptions and uncertainties in the synthesis products. Relative to Wüst-Galley and Leifeld (2025), LPX-Bern simulated higher peatland and peat-derived area fractions around Lake Geneva, Lago Maggiore, and Lake Constance (Figure 3b), but lower fractions around Lake Neuchâtel and between Lake Lucerne and Interlaken (Figure S3c). Higher simulated fractions in the former regions are likely related to the prescribed GIEMS-MC wetland extent (Figure S1) and also to areas classified as "potentially organic soil with ambiguous evidence only" in the reference dataset (Figure S3e) that are not fully accounted for in the synthesis estimates. Lower fractions in the latter regions may reflect uncertainties associated with nationally uniform peatland disturbance trajectories and the substantial proportion of less-conservative peatland estimates in the reference dataset (Figure S3b). Thus, remaining spatial discrepancies likely reflect uncertainties in both the national synthesis and model representations.

## 4.2. Representation of national peatland carbon stocks and uncertainties

### 4.2.1. Past-to-present peat carbon stocks

The modelled pre-industrial peat carbon stock of 121.9 Mt C falls within the independent historical estimates (84.4–128.4 Mt C; Wüst-Galley et al., 2019; Früh and Schröter, 1904; Probst E et al., 1923; Lüdi, 1973). Similarly, the simulated present-day peat carbon stock of 30.4–56.4 Mt C overlaps with national estimates of 32.4–67.6 Mt C (Wüst-Galley et al., 2019). This general alignment on pre-industrial to present-day peat carbon stocks suggests that our framework captures the first-order, centennial-scale dynamics of national peat carbon. Nonetheless, uncertainties in historical peatland extent and land-use history remain an important limitation, as alternative peatland conversion trajectories can substantially affect historical carbon balance (Qiu et al., 2021).

### 4.2.2. Main uncertainty sources in peat carbon dynamics

Peat extraction represents an important but poorly constrained component of the peat carbon balance (Figure 2b). The peat-derived carbon pool associated with extracted peatland reached approximately 56 Mt C during the early twentieth century, while direct peat carbon losses associated with fuel use estimated by Wüst-Galley et al. (2019) were only 2.5–5.7 Mt C. This discrepancy likely reflects incomplete historical extraction records and uncertainties regarding extraction intensity, end uses of harvested peat, and post-extraction land conditions (Ewald and Klaus, 2010; Wüst-Galley et al., 2019). In our framework, carbon associated with peat extraction is removed immediately from the peat-derived carbon pool, whereas actual peat losses likely occurred more gradually. Consequently, peat extraction remains an important uncertainty in historical peat carbon dynamics.

A second major uncertainty concerns carbon losses following peatland drainage. Water table depth strongly controls peat decomposition and greenhouse gas emissions from drained peatlands (Tiemeyer et al., 2020; Koch et al., 2023; Evans et al., 2021), yet long-term records of drainage intensity and historical water table dynamics at the national scale are unavailable in Switzerland (Wüst-Galley et al., 2019). Consequently, historical drainage-induced carbon losses remain difficult to reconstruct directly. In LPX-Bern, peat decomposition rates respond

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


dynamically to simulated soil temperature and moisture, while the first-order decay approach further assumes declining losses with the shrinking peat carbon pool (Eq. 5). This representation is broadly consistent with the understanding that peat decomposition is regulated by both environmental conditions and the intrinsic peat properties, with deeper peat generally decomposing slower than surface peat (Bader et al., 2018; Qiu et al., 2021). The assumption that 50 % of peat carbon below 0.3 m depth is lost immediately upon drainage initiation in the deep drainage scenario is a simplified approximation, also applied in large-scale peat carbon accounting analysis, including Global Carbon Budget (e.g., Friedlingstein et al., 2024). In reality, drainage likely generates both an initial emission pulse and prolonged peat oxidation typically over extended periods (Leifeld et al., 2019; Page and Baird, 2016; Mander et al., 2024), as also observed in the Swiss Rhine Valley 130 years after drainage (Wang et al., 2021). Thus, the deep drainage scenario may overestimate early carbon losses while underestimating prolonged emissions. Nonetheless, as the area of peatlands actively converted to agricultural use has generally declined since the mid- to late-twentieth century in the prescribed land-use change (Hurtt et al., 2020; Figure S2; also see Qiu et al., 2021), the influence of this assumption on present-day peat carbon stocks is likely smaller than it would be under scenarios with continuing drainage expansion.

A third source of uncertainty originates from differences among methods used to estimate present-day peat carbon stocks. The upper estimate from Wüst-Galley et al. (2019) was derived from land-cover-specific emission factors and does not explicitly account for temporal changes in decomposition rates or spatial heterogeneity in environmental conditions. Combined with uncertainty in the original peat carbon stock, this resulted in a span of 28.6 Mt C, corresponding to the difference between the minimum (81.9 Mt C) and maximum (53.3 Mt C) emission factor scenarios, comparable with our uncertainty range of 26.0 Mt C.

The lower bound estimate of 32.4 Mt C, by comparison, was derived from peat thickness observations from 40 sites to represent a range of land-cover types. While providing valuable field-based constraints, this approach may not fully capture the spatial variability in peat depth and carbon density across Switzerland (see Leifeld et al., 2005; Wüst-Galley et al., 2015; Gupta et al., 2024). Updated national inventories, additional field observations, and emerging Earth observation products, including foundation models for land-surface characterisation, e.g., AlphaEarth (Brown et al., 2025; also see Koch et al., 2026), may help further constrain peat extent and carbon stocks at regional to national scales.

### 4.3. Peat carbon vulnerability and restoration opportunities

Remaining peat-derived carbon is under contrasting land-use intensities and environmental conditions, implying substantial differences in vulnerability to future loss (Loisel et al., 2021; Minich et al., 2026a; Minich et al., 2026b). The reconstructed distribution of peat-derived area and carbon therefore provides a spatial basis for assessing the potential vulnerability, rather than a direct measure of restoration potential. Peatland conservation and restoration are complementary climate mitigation practices, such that conserving near-natural peatlands maintains existing carbon stocks, while rewetting degraded peatlands can reduce ongoing carbon losses (Humpenöder et al., 2020; Strack et al., 2022). The management implications hence depend on both the remaining carbon stock and its current hydrological and land-use state (Tanneberger et al., 2024; Denager et al., 2026).

The 4.4 Mt C remaining in near-natural peatlands represents a conservation priority, as maintaining high water table can reduce the risk of future degradation under current warming and drying trend in Europe (Giese et al., 2025; Denager et al., 2026). In contrast, the 26.0–52.0 Mt C retained in drained peat-derived areas remains

https://doi.org/10.5194/egusphere-2026-5196
Preprint. Discussion started: 15 September 2026


exposed to decomposition and therefore represents an opportunity for reducing further carbon losses, although restoration feasibility depends strongly on site-specific hydrology and land-use constraints (Mander et al., 2024; Tanneberger et al., 2024).

The agricultural peat-derived areas contain the largest remaining peat carbon pool and therefore present the greatest potential for reducing further carbon losses. However, restoration involves trade-offs between carbon conservation and continued land use for production. Rewetting may be more compatible with less intensively managed grasslands and agricultural systems, concerning a subset of the 17.9–35.8 Mt C, than intensive pasture and croplands. Alternatives to conventional drainage management can be considered in the latter cases, including paludiculture (e.g., Temmink et al., 2024; Temmink et al., 2026; Wüst-Galley and Leifeld, 2026). Recent evidence from agriculturally managed peat-derived areas also indicates that $CO_2$ emissions might be underestimated by conventional emission inventories (Liang et al., 2024). Moreover, the effectiveness of water-table management is likely to change under future climate conditions with temperature and water-table dynamics jointly control $CO_2$ and other greenhouse gas emissions from drained peat (Denager et al., 2026; Widmer et al., 2026).Importantly, restoration should not be solely evaluated through avoided $CO_2$ emissions, as changes in CH4 and N2O emissions, land productivity, biodiversity, and other ecosystem services also influence the overall outcome (Zak and Mcinnes, 2022; Mander et al., 2024; Tanneberger et al., 2024; Temmink et al., 2026). This consideration is particularly relevant for Switzerland, where wet agricultural production on wet organic soils is being investigated through field trails, including paddy rice cultivation (Widmer et al., 2026; Wüst-Galley and Leifeld, 2026).

Urban and built peat-derived areas, with a comparable carbon stock size as near-natural peatlands (2.3–4.7 Mt C), yet are unlikely to be practical restoration targets. Although mineral or artificial coverage can alter soil greenhouse gas exchanges, it cannot be considered equivalent to peatland conservation (Wang et al., 2021; Paul et al., 2024). These areas are therefore best viewed as largely irreversible peat transformation. From a policy perspective, the priority is to avoid further conversion of remaining peat-derived areas, not only near-natural peatlands, and to account for residual peat carbon in infrastructure planning.

## 5. Conclusion

This study presents the first process-based reconstruction of Swiss peat-derived area and peat carbon dynamics seamlessly from the pre-industrial period to the present, extending previous inventory-based assessments of national peatland extent and carbon stocks. The reconstruction highlights how historical land conversion and peatland disturbances have shaped the distribution of peat carbon across Switzerland. The majority of remaining peat carbon is now associated with agricultural, forested, and unmanaged land, indicating both continued vulnerability to carbon loss and opportunities for mitigation through restoration and improved management practices.

Our framework provides a quantitative basis for evaluating peat carbon vulnerability, informing restoration scenario assessments, and supporting large-scale peatland and wetland restoration initiatives. The approach can be adapted to other regions and applied at different spatiotemporal scales, although performance will depend on the availability and quality of historical records and observational constraints. Future work should improve regional representation through higher-resolution modelling, additional observations, and further development of peatland processes, including drainage dynamics, land management, nutrient cycling, and multi-greenhouse gas interactions.

## Data availability

Swiss organic soil maps were published by Wüst-Galley and Leifeld (2025) as Wüst-Galley (2025). Processed LPX-Bern outputs and plotting scripts used in this study are available from Zenodo (doi:10.5281/zenodo.22116515).

## Author contributions

QS and ED conceptualised the study. QS designed and conducted the modelling framework, analysed and interpreted the results, and prepared the initial manuscript draft. All authors contributed to the interpretation of the findings and the revision of the manuscript.

## Competing interests

The authors declare that they have no conflict of interest.

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## Supplement

Table S1 Input data and forcing information for modelled peatland dynamics using the LPX-Bern model.
Figure S1 Wetland extent from the GIEMS-MC v1.0 product (Bernard et al., 2025)
Figure S2 Fractional land-use cover from 1700 to 2020 in Switzerland prescribed by the Land-use Harmonization 2 (LUH2) dataset (Hurtt et al., 2020)
Figure S3 Swiss organic soil maps remapped from Wüst-Galley (2025).
Figure S4 Federal inventories of peatlands, including fens (FOEN, 2025b) and bogs (FOEN, 2025a).
Figure S5 Modelled peat-derived carbon stocks [Mt C] under (a) cropland, (b) pasture, and (c) forested/unmanaged land in present day (2011–2020) under shallow drainage scenario.

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