Estimating the soil subsidence and carbon losses from long term anthropogenic use of peatlands: A case study on a Danish raised bog

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SUMMARY

Upon drainage, peatlands subside and release stored carbon (C) into the atmosphere. However, little is known about the magnitude of the total, physical and oxidative subsidence (TS, PS and OS) over long historical periods and the past contribution of humans to the degradation observed in contemporary times. Lack of historical subsidence data may hinder contemporary restoration efforts, highlighting the need for insights into past degradation to inform current management practices. Therefore, the present study aims to assess the effect of human activities on the degradation of a raised bog in Denmark in terms of the TS, PS, OS and the C lost between 1880 and 2010 using legacy datasets. The results indicate that 84 % of the bog had been drained by 1997. The TS was 1.6 m on average with a rate of 1.8 cm y^{-1}. A total of 117 million m^3 of peat was lost in the 130-year period. The PS was most important shortly after the start of drainage while OS gained importance in the long term. Up to 540 t ha^{-1} of C-stock was lost at a rate of 6 t ha^{-1} y^{-1}, translating to 22 t ha^{-1} y^{-1} in carbon dioxide equivalents. Therefore, the bog represents a C source in contemporary times, which necessitates targeted and positive management interventions that favour peat growth and C accumulation.

KEY WORDS: CO_2, drainage, human impacts, peatland cultivation, peatland degradation, Store Vildmose

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INTRODUCTION

Owing to their large carbon (C) stocks (i.e., 20–30 % of the global soil C pool), peatlands are considered to be important wetland ecosystems with great merit for climate and environmental regulation (Schumann & Joosten 2008, Erwin 2009). Nevertheless, many peatland areas across the globe have become degraded, mostly due to their unsustainable use and management by humans. The use of peatlands by people dates back many centuries and is ongoing. At its core is the ditching and drainage of pristine peatlands for conversion to other land uses (LU); and this has facilitated the widespread degradation of many peatland areas (Adesiji *et al*. 2015, Han *et al*. 2021). Peat extraction and drainage for agriculture are among the major contributors to anthropogenically mediated peatland degradation. For instance, drained peatlands reportedly emit approximately 5 % of the global anthropogenic greenhouse gas (GHG) emissions (Joosten 2009, Günther *et al*. 2020). In Europe, about 50 % of pristine peatlands have been lost, which makes Europe a global hotspot for peatland loss and degradation. As is true for the global case, the main driver of the degradation and loss of European peatlands is drainage for agriculture, forestry and peat extraction (Verhoeven 2014, Andersen *et al*. 2017). Agriculture is amongst the most prominent LUs that emerge post-drainage and the total area of drained agricultural peatlands in Europe is approximately 125,000 km^2 (Joosten & Clarke 2002, Page & Baird 2016).

When peatlands are drained, they undergo non-reversible structural and chemical changes that lead to subsidence. As defined by Hooijer *et al*. (2012), subsidence refers to the sinking of the land surface when the groundwater level is lowered. Total subsidence (TS) in peatland ecosystems results from the complex interplay of physical and oxidative processes following drainage. The principal physical processes that contribute to subsidence include permanent shrinkage, compaction and consolidation (Zeitz & Velty 2002, Ma *et al*. 2022, Oleszczuk *et al*. 2022). Permanent shrinkage occurs when peat layers above the water table contract as they dry out, causing irreversible volume losses, increased hydrophobicity and altered peat compressibility and water retention (Erkens *et al*. 2016, Bechtold *et al*. 2018). Pressure from livestock trampling and heavy farm machinery also compacts peat layers above the water table, leading to additional peat volume reductions (Hooijer *et al*. 2012). Conversely, consolidation occurs by the gradual settling and compression of peat layers below the water table due to loss of buoyancy and the increased weight of overlying material, as well as by the expulsion of over-pressurised pore water (Van Asselen *et al*. 2009, Hooijer *et al*. 2012). Moreover, subsidence from oxidative processes is largely attributed to peat mineralisation. Harpenslager *et al*. (2015) described oxidation as the biogeochemical degradation of organic material by microorganisms under aerobic conditions in drained peatlands. In contrast to the water-saturated conditions of pristine peatlands, drainage alters the natural balance between the volume of air-filled and water-filled pore spaces, introducing oxygen and aerating the peat. This shift stimulates microbial respiration, transforming stored C into carbon dioxide (CO_2) emissions (Holden *et al*. 2004, Green & Page 2017, Leifeld & Menichetti 2018). Oxidative subsidence (OS) is reported to be the dominant contributor to TS over the long term (Erkens *et al*. 2016). For instance, Hooijer *et al*. (2012) reported that a substantial portion (75–95 %) of TS was due to peat oxidation. Pronger *et al*. (2014) found that subsidence was rapid and primarily driven by physical subsidence (PS) processes in the early years post-drainage. However, over time, the rate of PS decreases, making OS the more significant contributor to TS. Erkens *et al*. (2016) reported that, over a millennium of cultivating Dutch coastal peatlands, the relative contributions of OS, PS and peat extraction to TS were 48 %, 18 % and 34 %, respectively; while van Asselen *et al*. (2018) found that PS and OS rates varied spatiotemporally due to differences in overburden thickness, organic matter content, groundwater table depth and other related factors. They found that OS contributed the most (70 %) to TS in drained areas with minimal loading, whereas PS was the primary contributor (65 %) to TS at heavily loaded sites. Nevertheless, both PS and OS may lead to substantial peat volume reductions in the long term. Under periods of prolonged anthropogenic disturbance TS may vary spatiotemporally, being influenced by (among other factors) the number of years after drainage, the drainage depth, the peat type and thickness, climatic conditions, land use changes (LUC) through time and other management practices (Pronger *et al*. 2014, Oleszczuk *et al*. 2022).

Peatlands in Denmark (as in most countries) have been subjected to centuries of anthropogenic degradation at both national and local levels. At national level, a supply failure of foreign fuel during the First and Second World Wars stimulated the mapping of peatland areas to ascertain their quality for fuel use, and this led in turn to increased extraction of peat (Thøgersen 1942). Also, many peatland areas have been drained and cultivated for years, making them an important part of the agricultural sector (Nielsen *et al*. 2012). The implications of these disturbances extend beyond subsidence to include a decline in the spatial extent of peat soil areas in Denmark. For example, Greve *et al*. (2014) estimated a 35 % reduction in the extent of cultivated Danish peatland areas in 2010 compared to the peat extent map of 1975. They attributed this change mainly to anthropogenic disturbance arising from agricultural production and peat extraction. Due to the poor historical management of most Danish peatland areas, it is expected that these sites will subside and degrade continuously through time in the absence of restorative management interventions. Although Pedersen (1978) and Greve *et al*. (2021) have assessed TS over shorter (1930–1974) and longer (1880–2010) historical periods respectively, only Pedersen (1978) has reported on the contributions of both PS and OS processes to TS. Pedersen (1978) found that PS accounted for 20 % and OS for 80 % of TS in a bog after cultivation and repeated drainage. However, the relative contribution of these processes to TS over longer historical periods remains unclear. Furthermore, an assessment of the GHG emissions over long historical periods is still lacking. The measurement and quantification of peatland GHG emissions for both international reporting and domestic planning purposes is an arduous task. As mentioned by Huang *et al*. (2021), the use of field experiments to quantify yearly peatland GHG emissions is constrained by short and infrequent sampling, which may not adequately capture relevant management-related feedback. Conducting such assessments over extended historical periods is even more challenging due to unavailable or scarcely available data.

Quantifying the retrospective effects of anthropogenic activities on terrestrial ecosystems such as peatlands is often challenging. However, as stated by Han *et al*. (2021), “research on past human-nature interaction has significant implications not only for exploring the long-term human civilisation but also for further assessment of the current environment dynamics in the case of longer-term human disturbance.” In the context of peatlands, measurements and estimates of subsidence are important for land management decision-making and for developing strategies to curb peatland-related CO_2 emissions. Everett (1983) mentions that the continuous drainage of peatlands is unsustainable, and the subsidence rate (SR) may be used to assess a peatland’s life expectancy. This is echoed by Pronger *et al*. (2014) who asserts that knowledge of the SR is important for future land use planning and C accounting. Nevertheless, Erkens *et al*. (2016) state that for long timescales of intensive peatland use, the measurements of both subsidence and CO_2 emissions are often short and limited to a few years.

Another limitation to the assessment of subsidence over long historical periods lies in the methodology employed. Common methods for assessing historical peatland SR include geodetic measurements using subsidence monitoring poles (Franzén 2006, Green & Page 2017, Grzywna 2017) and Light Detection And Ranging (LiDAR) datasets (Hoogland *et al*. 2012, Boehm *et al*. 2013). Although relevant, the former approach may have limited potential for revealing the spatial variability of subsidence even at field scale. In modern times, the use of extensometers (van Asselen *et al.* 2020), levelling instruments (Oleszczuk *et al*. 2020) and Interferometric Synthetic Aperture Radar (InSAR) (Conroy *et al*. 2022, Umarhadi *et al*. 2022) are among the available methods for monitoring peatland subsidence. However, data generated using these methods may be non-existent for long historical periods. This notwithstanding, legacy soil and topographic databases may allow assessment of the spatial variability of subsidence on the one hand and the anthropogenic contribution to subsidence on the other. Therefore, this study attempts to quantify the historical contribution of human activities towards the degradation of a selected Danish bog based on LUC, disentangle the different processes contributing to TS, and assess C losses for the historical period of interest. Specifically, the study aimed to (1) assess the extent and impact of anthropogenic activities in the Store Vildmose raised bog as a function of LUC from four legacy topographical maps, (2) estimate the TS between 1880 and 2010 as well as the relative contributions of physical and oxidative processes to TS under different scenarios for the time since drainage, and lastly (3) estimate the change in C-stock and total C lost as CO_2 emissions for the same historical period.

METHODS

Study area

This study focuses on the Store Vildmose raised bog, located in Northern Denmark (Figure 1). Underlying the bog is a relatively flat marine plain formed by the last marine transgression which covered Denmark until 8000 BC (Kristensen 1945, Regina *et al*. 2016). Around 3000 BC, the climate in Denmark gradually cooled and became wetter, resulting in acidic and wet soils that favoured the growth of *Sphagnum* and other nutrient-poor and flood-tolerant plant species (Møller 2005). With time, the bog developed over the previously existing forest vegetation. Thus, a layer of forest or minerotrophic peat lies below the oligotrophic bog peat. The peat thickness (PT) in the centre of the bog was approximately 5 m and decreased towards the bog fringes (VHM 2006).

Historically, Store Vildmose was the largest raised bog in Denmark, covering an estimated 5000 ha. However, this size is uncertain as including meadows would increase the total area (VHM 2006, Regina *et al*. 2016). Moreover, anthropogenic activities have led to significant degradation of the bog over the years. Interest in utilisation of the bog dates back to the early 19th century when a few resource-poor farmers began to cultivate its edges (VHM 2006). With increased human activity, the bog diminished in importance with regard to its size and pristine status. For instance, ditching of the bog is reported to have commenced during the 1830s (Møller 2005). Additionally, various changes of ownership further contributed to its degradation. The most prominent of these changes occurred in the 1920s when the Danish State purchased part of the area for agricultural purposes (Møller 2005). Agricultural use of the bog required extensive drainage prior to the establishment of cropping and grazing fields. By 1935, a central farm and 19 cattle farms had been established in the area, and these later served as quarantine farms to contain an outbreak of bovine tuberculosis. In the 1960s, the bog was re-drained and the existing ditches were deepened (VHM 2006). Moreover, failure in the supply of foreign fuel during the First and Second World Wars led to daily extraction of up to 500 tons of peat. Although human activities feature prominently in the alteration of the bog, natural phenomena such as fire have also contributed to its degradation. For instance, fire outbreaks in 1884 and 1976 have been reported (https://trap.lex.dk/Store_Vildmose). Nowadays the study area presents largely as a degraded peatland under various LUs including extensive grasslands, croplands, peat extraction sites and approximately 1,895 ha in the northern and western fringes under protection (https://www.fredninger.dk/fredning/store-vildmose/). The areal extent of the study area shown in Figure 1 is approximately 6600 ha.

Assessment of the historical land use changes

To quantify past human impacts on Store Vildmose, we assessed landscape transformations caused by LUC from the late 19th and 20th centuries. Four legacy topographic maps of different ages were obtained from the Danish Agency for Data Supply and Infrastructure (https://historiskekort.dk/), covering the periods 1885–1929, 1938–1963, 1943–1968 and 1983–1997 (Figure 2). Hereafter, these maps will be

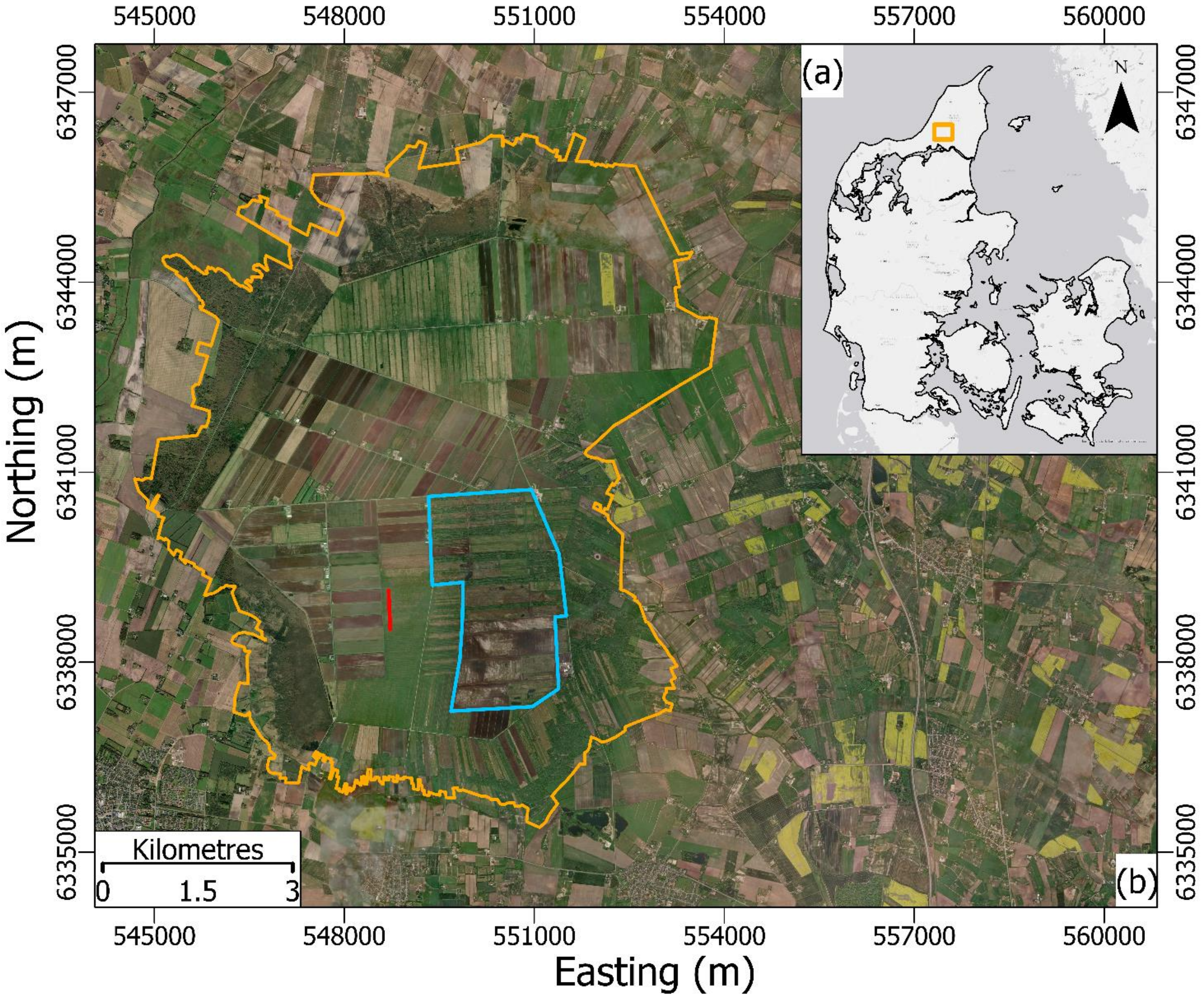

Figure 1. Map showing the location of the Store Vildmose raised bog in northern Denmark (a) and the zoomed extent of the study area showing a diversified landscape (b). The blue polygon indicates the area within which a commercial peat extraction site is located, and the red line denotes a soil characterisation transect (b). An orthophoto from 2022 is displayed as the background map (Copyright Hexagon 2022).

identified by the earliest year that they represent. While the maps from 1885, 1938 and 1983 were formerly georeferenced by the National Mapping Agency of Denmark (Greve *et al*. 2021), only a scanned image of the map from 1943 was available. To assign a spatial reference to the 1943 map, geo-corrections were applied to accurately display its real-world location. The 1938 map served as the reference layer for georeferencing the 1943 image. Areas with various signatures (symbolisations) on all four maps were digitised as LU polygons using the historical map handbook of Korsgaard (2006) as a guide. Examples of signatures for digitised areas are presented in Figure A1 in the Appendix. The different LUs were then assigned to four broad LU classes as shown in Table 1. The total area under each LU class was calculated for each map and compared between maps. The anthropogenic contribution to degradation of the study area was quantified as the percentage areal change of the defined LU classes for each period. All analyses were performed in ArcGIS Pro 3.0 (ESRI, Redlands, California, USA).

Estimation of subsidence

This study employed a GIS-based approach for subsidence estimation. The methodology used includes three steps: (1) assessing TS using elevation and PT measurements; (2) deriving empirical estimates of PS and OS under different scenarios for the time since drainage using TS, percentage OS and drainage duration datasets compiled from the literature on boreal and temperate bogs; and (3) estimating changes in C-stock and CO_2 emissions. Each step is described briefly below.

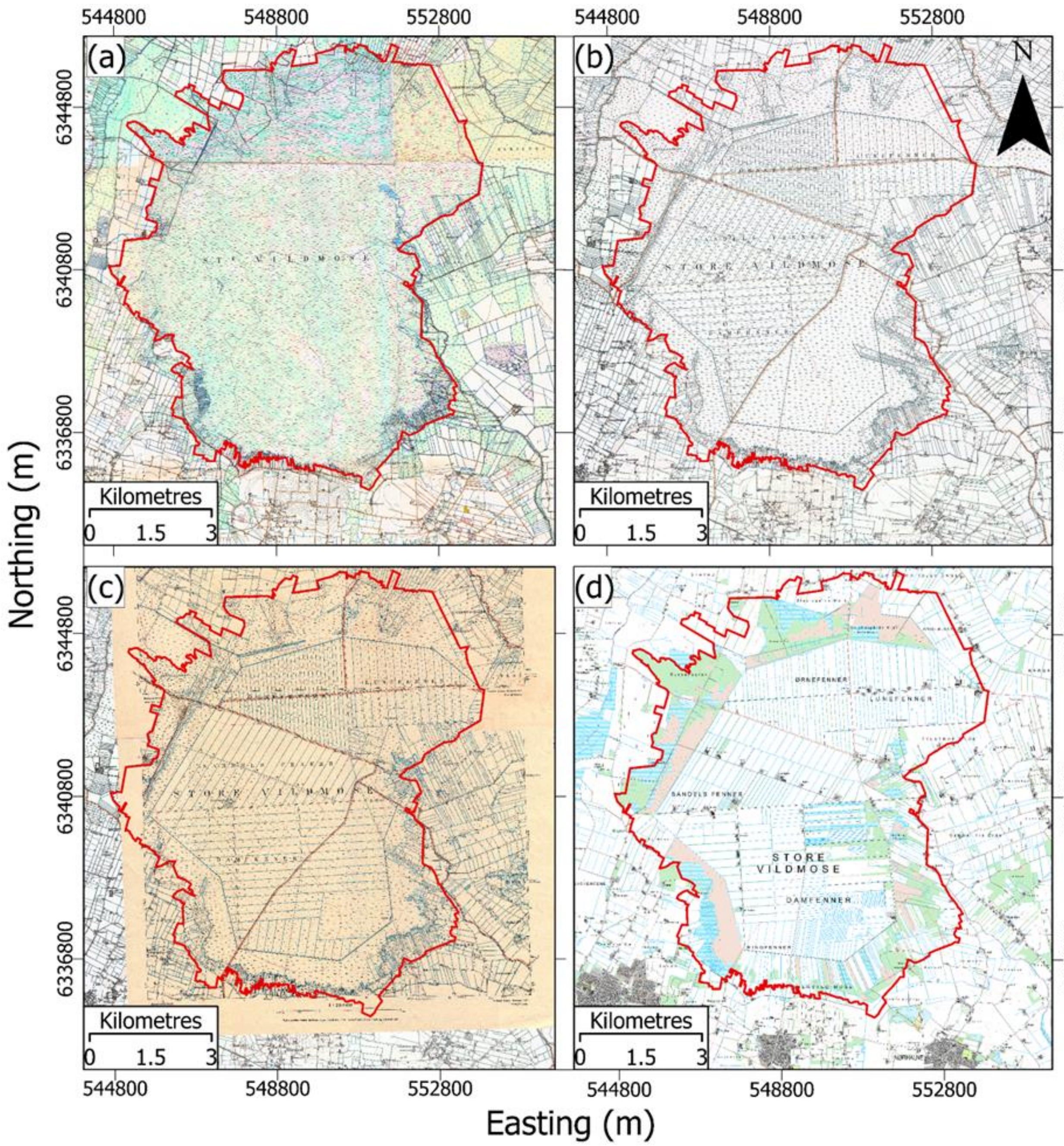

Figure 2. Visualisation of the four legacy topographic maps from which historical land use changes were assessed. These maps are valid for the periods 1885–1929 (a), 1938–1963 (b), 1943–1968 (c) and 1983–1997 (d). All were originally published at a scale of 1:20000 except for the newest (1983) map which was published at a scale of 1:25000. Maps were sourced from The Danish Agency for Data Supply and Infrastructure (https://historiskekort.dk/).

Elevation-based subsidence estimation

The TS between 1880 and 2010 was estimated using legacy soil and land surface elevation data. This included a 2007 LiDAR-based Digital Elevation Model (DEM) (KMS/GIF 2014), a surface model of the bog in 1880 digitised as points from historical city maps and PT measurements from the SINKS 2010 database (Greve *et al*. 2014). The LiDAR data were originally collected with an average point density of one point per 2.2 m^2, resulting in a geographic resolution of 1.6 m and an accuracy of about 70 cm (KMS/GIF 2014). The DEM was aggregated to 8 m spatial resolution and is assumed to represent the surface elevation of the bog in 2010. Hereafter, the 2007 LiDAR-based DEM is referred to as DEM$_{2010}$. The PT measurements were collected by pushing a

Table 1. Descriptions of the land use (LU) classes digitised from four legacy topographic maps covering the period 1885–1997. The LU classes include ‘Peat extraction areas’, ‘Wetlands’ which include all LUs that are denoted by wet signatures, ‘Drained’ which include all LUs with dry signatures and, lastly, the ‘Other’ class which includes LUs that do not fit into any of the above-mentioned LU classes. Detailed descriptions of the LUs are presented in Table A1 in the Appendix.

Land use class	Description
Peat extraction	Areas where peat has been dug.
Wetland	Heathlands, grasslands, bogs and meadows with signatures denoting wet conditions.
Drained	Heathlands, grasslands, coniferous and deciduous forests, croplands and meadows with signatures denoting drained conditions.
Other	Roads, ditches, buildings and water bodies.

glass fibre rod with a metal tip into the peat until resistive firm ground was reached (Greve *et al*. 2014). The point elevation data and PT measurements were kriged to 8 m spatial resolution, to match the resolution of the DEM_{2010} and to provide an elevation model for 1880 and a PT model for 2010. Considering the geology of the area, the elevation of the underlying marine seabed was determined prior to subsidence estimation as:

$$Sand_{surf} = (DEM_{2010} - PT_{2010}) + 0.2 \qquad [1]$$

where $Sand_{surf}$ is the surface elevation of the underlying sandy marine seabed (m), DEM_{2010} is the digital elevation model for 2010 (m) and PT_{2010} is the peat thickness model from 2010 (m). The DEM_{2010} and the 1880 surface model represent the bog surface height during these respective periods. Moreover, northern Denmark has been undergoing isostatic uplift at a rate of 1.5 mm y^{-1} since the last glaciation (Nielsen *et al*. 1995, Gravesen *et al*. 2011). To account for this rise, the elevation of the marine surface layer was adjusted by adding 0.2 m for the 130-year period of interest (Equation 1). With the elevation of the underlying marine layer known, the actual peat thicknesses in the bog for 1880 and 2010, respectively, were calculated as:

$$PT_{ay} = EM_y - Sand_{surf} \qquad [2]$$

where PT_{ay} is the actual peat thickness for a given period and EM_y is the elevation model from the same period.

The total peat subsidence was subsequently calculated as a differential peat thickness map by subtracting the 1880 PT map from the 2010 PT map:

$$TS = PT_{a2010} - PT_{a1880} \qquad [3]$$

where TS is the total subsidence (m); PT_{a1880} and PT_{a2010} are the actual peat thicknesses in 1880 and 2010, respectively. The SR was calculated by dividing the mean estimated subsidence by 90 years. Although the study considers the 130-year period 1880–2010, as determined by the available data, we assume that the bog was nearly pristine in 1880. A 90-year period was considered in calculating the SR in line with the start of local drainage (1920–2010). For accuracy, the SR calculation excludes the area of the contemporary commercial peat extraction site (Figure 1), where peat loss is not exclusively due to subsidence. The total change in the peat volume for the whole area between 1880 and 2010 was calculated in a 3D spatial analysis using the ‘cut-fill’ tool in ArcGIS Pro software 3.0. This involved the estimation of volume changes based on two input surfaces in a before (PT_{a1880}) and after (PT_{a2010}) analysis. From this analysis, areas with net volume loss and net volume gain were identified.

Although the probing method offers rapid measurement of PT, it is prone to inaccuracies when the probe extends past the actual peat boundary or encounters buried obstacles, or when the boundary is uneven. To assess accuracy, the 2010 PT measurements were validated along a dedicated transect using peat samples that were collected in 2022 down to the base of the organic-mineral boundary. Other available data for this location include the humification degree, bulk density (BD) and total organic C (TOC) content for the full peat profile, obtained following standard methods (Zak *et al*. 2010). Despite the 12-year interval between the 2010 and 2022 PT datasets, we assumed similar conditions for both as LU maps indicated no LUC, and we did not account for climatic differences. The validation involved projecting the 2010 PT measurements to an expected 2022 PT by applying the average SR determined using the elevation-based subsidence approach. This rate, multiplied by 12 years, provided the TS for the 12-year period (2010–2022), which was subtracted from each 2010 PT measurement to estimate the expected PT for 2022. We then compared the projected estimates with the actual 2022 PT measurements. To quantify the average deviation between the expected and actual 2022 PT measurements, the root mean square error (RMSE) was calculated as:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(PT_{projected} - PT_{true})^2}{n}} \qquad [4]$$

where $PT_{projected}$ is the estimated PT for 2022, PT_{true} is the measured 2022 PT and n is the total number of observations. All analyses were performed in ArcGIS Pro software 3.0 (ESRI, Redlands, California, USA).

Physical and oxidative subsidence estimation

While the elevation-based subsidence approach considers TS for the period of interest, it does not provide estimates of TS at timepoints in between the endpoints, nor does it account for two of the major processes that contribute most to TS. To explore this further, an attempt was made to disentangle the relative contributions of physical and oxidative processes to subsidence under four scenarios for the period since drainage started. The scenarios were based on the historical record of drainage starting in 1920 and related to the ages of the legacy topographic maps used. Thus, physical and oxidative SR after 18 (1920–1938), 23 (1920–1943), 63 (1920–1997) and 90 (1920–2010) years were estimated. In the absence of necessary inputs such as PT measurements, groundwater level, drainage depth, C mineralisation rates and BD for each scenario, we relied on empirical equations derived from the literature that require minimal inputs. A meta-analysis by Liu *et al*. (2020) provides an overview of subsidence data from northern boreal and temperate peatlands. We refined this dataset, along with additional literature, to compile information on TS, percentage OS and drainage duration in temperate bogs under grassland and agriculture. To obtain the relative contributions of PS and OS, we first estimated the TS with an empirical equation requiring drainage duration as an input (Figure A2). This is given by:

$$TSR_{emp} = 0.0593 \times D^{-0.297} \qquad [5]$$

where TSR_{emp} is the empirically derived total subsidence rate due to drainage (cm y $^{-1}$) and D is the number of years after drainage.

The percentage OS was similarly estimated from the relationship between percentage OS and drainage duration for temperate bogs (Figure A3), as:

$$OS_{\%} = 18.769 \times D^{0.2296} \qquad [6]$$

where $OS_{\%}$ is the percentage oxidative subsidence (%). The $OS_{(cm\,y^{-1})}$ rate was subsequently estimated as the product of TSR_{emp} and $OS_{\%}$ divided by 100.

The relative contributions of PS to TS were estimated by subtracting the rate ($OS_{(cm\,y^{-1})}$) and percentage ($OS_{\%}$) of oxidative subsidence from TSR_{emp} and 100 %, respectively. The PS rate is given by:

$$PS_{(cm\,y^{-1})} = TSR_{emp} - OS_{(cm\,y^{-1})} \qquad [7]$$

where $PS_{(cm\,y^{-1})}$ is the estimated rate of physical subsidence, $OS_{(cm\,y^{-1})}$ is the rate of oxidative subsidence and TSR_{emp} is the total subsidence rate estimated using Equation 3.

C-stock change and CO$_2$ analysis

Carbon stock change and loss between 1880 and 2010 were estimated using legacy soil data, literature sources and recent measurements from the transect shown in Figure 1. Two estimations of the C-stock were made. The first C-stock estimation considered topsoil (0–50 cm) BD and TOC values reported by Kandel *et al*. (2018) for pristine and cultivated areas of the bog. We assumed that the reported values for the pristine and cultivated bog corresponded to the bog's condition in historical and contemporary times, respectively. Due to limited data availability, this estimation also assumed that both the historical and the contemporary bog were homogenous with consistent BD and TOC content throughout the peat profile. This approach is conservative, as soil physicochemical properties are likely to be variable because the peat in the bog has formed from different plant materials and conditions. To address this, a second C-stock estimation was performed following a method similar to that of Leifeld *et al*. (2011), which assumes that the deepest contemporary peat layer is pristine and its BD and TOC reflect the condition of topsoil in the pre-drained peatland. Therefore, BD and TOC values from the transect shown in Figure 1 were used, assuming that values from the deepest peat layer represented the historical bog while those from the surface peat layer represented the contemporary bog. The C-stock was then estimated as:

$$C - stock = PT \times BD \times TOC \qquad [8]$$

where $C-stock$ is the carbon stock (t ha $^{-1}$), PT is the thickness of the peat deposit (cm), BD is the bulk density (g cm $^{-3}$) and TOC is the total organic carbon content (%). The C-stock was estimated for 1880 and 2010, and the change in C-stock was calculated as the difference between these estimated stock values. The rate of C-stock change was calculated by dividing the C-stock change by the 90-year drainage duration. The amount of C lost as CO_2 emissions was estimated as:

$$CO_2 = \Delta C - stock \times 3.67 \qquad [9]$$

where CO_2 is the carbon dioxide emissions (t ha $^{-1}$ y $^{-1}$), $\Delta C - stock$ is the rate of change in C-stock between 1920 and 2010 (t ha $^{-1}$ y $^{-1}$) and 3.67 is a conversion factor (quotient of the molecular weight of CO_2 to the atomic weight of C). All subsidence and GHG emission estimations were performed in ArcGIS Pro 3.0 (ESRI, Redlands, California, USA). Table 2 provides an overview of the data used for both C-stock estimation scenarios. Figure 3 summarises the methodology guiding the study, illustrating the assessment of LUC over the years, various estimations of subsidence and the assessment of CO_2 emissions for the historical period of interest.

Table 2. Overview of the data employed for C-stock estimation using two data sources. The first scenario presents C-stock estimates using bulk density and total organic carbon values from the literature (Kandel *et al*. 2018), while the second uses recent bulk density and total organic carbon measurements along a transect.

C-stock estimations	Data source	Period	Bulk density (g cm $^{-3}$)	Total organic carbon (%)
Scenario 1	Kandel *et al.* (2018)	1880 2010	0.10 0.24	41.0 36.5
Scenario 2	Transect	1880 2010	0.06 0.10	52.9 36.5

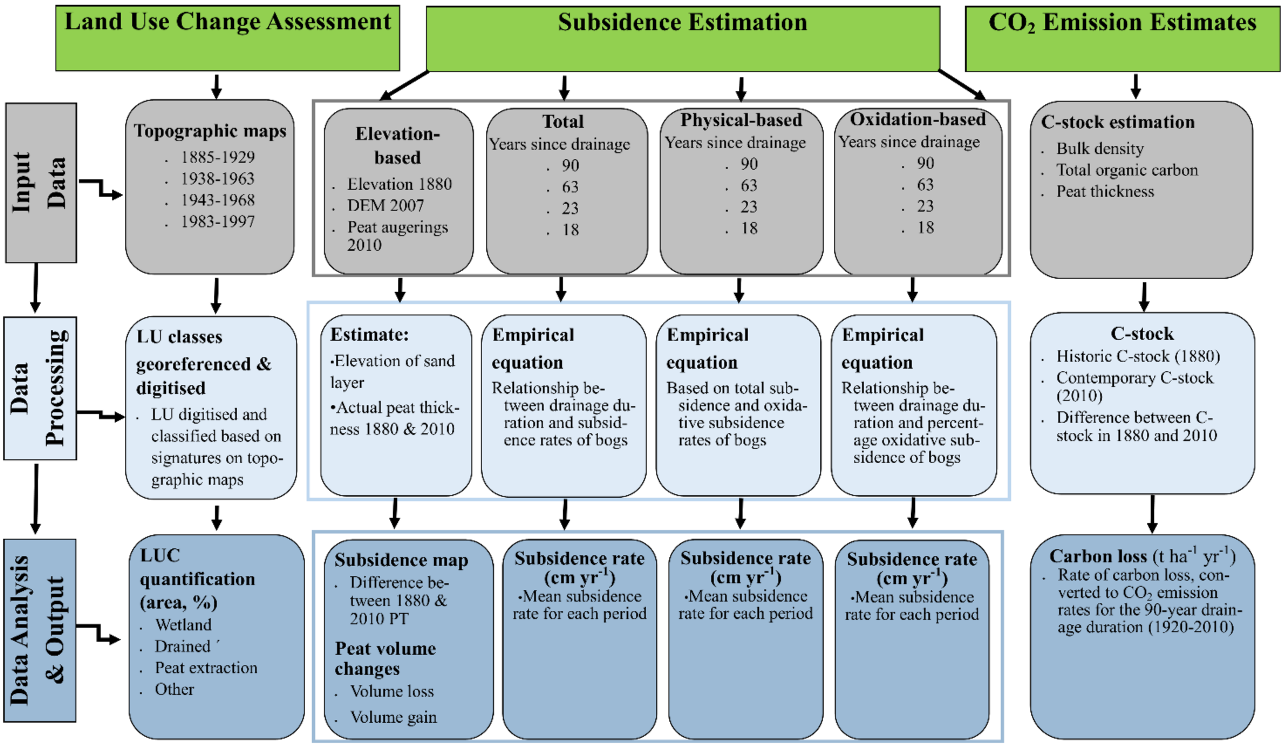

Figure 3. Flow diagram summarising the methodology guiding this study. The threefold methodology includes: digitising and classifying various land uses from four legacy topographic maps; estimating total, physical and oxidative subsidence from elevation data and empirical equations from the literature; then calculating the change in carbon (C) stock and estimating the carbon loss as carbon dioxide (CO_2) emissions over a 90-year period (1920–2010).

RESULTS

Historical land use changes based on legacy maps

Land use changes in the study area between the late 19th and 20th centuries, assessed from the four legacy maps of different ages, are shown as percentage areal changes of the broadly defined LU classes in Figure 4. The oldest map from 1885 (Figure 4a) showed that the site was predominantly a wetland (99.2 %) with only small areas of peat extraction (0.7 %) and drainage (0.1 %). By the late 1930s wetland, drained and peat extraction areas occupied 69.6 %, 19.8 % and 2.3 %, respectively, of the total area, while other LUs (see Table 1 for description) covered 8.3 % of the area (Figure 4b). This reflects a 30 % decrease in wetland area which translates to a 197-fold increase in drained area between 1885 and 1938. By 1943, more than half (52.7 %) of the bog was drained with only 27.1 % of the site remaining a wetland. About 0.9 % of the area was under peat extraction and the area of other LUs increased to 19.4 % (Figure 4c). Moving towards contemporary times (1980s onwards), more than two-thirds (77.4 %) of the area had been drained while only 15.8 % of the site remained a wetland. Peat extraction and other LUs occupied 3.2 % and 3.6 % of the area, respectively (Figure 4d). Compared to 1885, the wetland area had declined by 84 %, while drained areas had increased 773-fold. Areas under peat extraction increased by more than 300 % during the same period. A detailed examination of the drained area in the contemporary period (1983–1997) showed that 44.7 % of it was under grassland, 25.6 % was cropland and about 7.1 % was forested (Figure 4e).

Subsidence

Stratigraphy of the bog

Figure 5 illustrates the stratigraphy of the bog along the transect depicted in Figure 1. The top 5–15 cm consists primarily of highly humified peat with degree of decomposition between H9 and H10 (von Post 1922), indicating fully decomposed peat (a detailed description of the von Post peat decomposition scale is presented in Table A2). Beneath this are layers of undecomposed (H1–H2) and very slightly to slightly decomposed (H3–H4) peat, except at location 2 where the deeper layers are highly to very highly decomposed (H7–H8). The top of the peat generally consists of *Sphagnum* peat overlying cottongrass peat on top of a transition layer of fen peat, gyttja and birch peat. Peat thickness along the transect ranges from 0.6 to 1.9 m with an average of 1.2 m. At some locations a gyttja layer up to 0.6 m thick is present below the peat. At the base of the organic sediments are layers of fine to medium grained sand with varying contents of silt and clay. Location 4 coincides with a ditch.

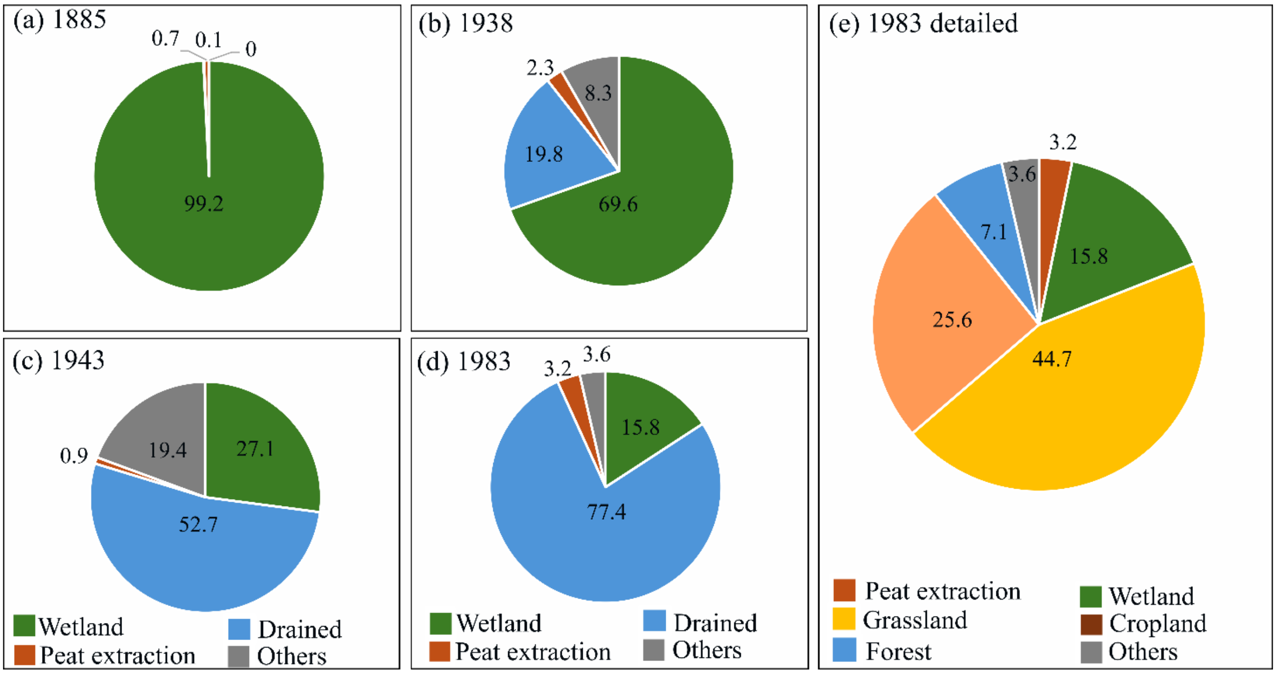

Figure 4. Evolution of the Store Vildmose peat landscape assessed from 1885 to 1997, based on four legacy maps (a–d). Land uses are categorised as ‘wetland’, ‘drained’, ‘peat extraction’ and ‘other’. The pie charts illustrate the percentage area of each land use class. Figure 4e provides a detailed breakdown of the land uses that comprise the ‘drained’ land use class for the contemporary epoch (1983–1997).

Elevation-based subsidence and peatland volume changes

Table 3 presents an estimate of the elevation of the underlying marine layer, the actual PT for 1880 and 2010, the mean subsidence, the SR, and the changes in peat volume for the historical period of interest. The estimated elevation of the underlying marine layer ranged from 2.3 to 9.6 m. As expected, the actual PT in 1880 was larger than in 2010. For 1880, the PT ranged from 0 to 5.8 m while the PT in 2010 ranged from 0 to 2.1 m. Excluding the area with commercial peat extraction, a mean subsidence of 1.6 m was estimated, with a SR of 1.8 cm y^{-1} for the 90-year period (1920–2010) following drainage of the bog. Substantial changes in peat volume occurred over the 130-year period of interest (1880–2010). As much as approximately 117 million m^3 of peat may have been lost whilst only 114 thousand m^3 of peat was gained by peat accumulation. In contemporary times, areas where peat accumulation occurs correspond with permanently wet nature and forest LUs (Figure A4). Additionally, an RMSE of 0.45 m was found when comparing actual PT measurements from 2022 with those projected from 2010 to 2022.

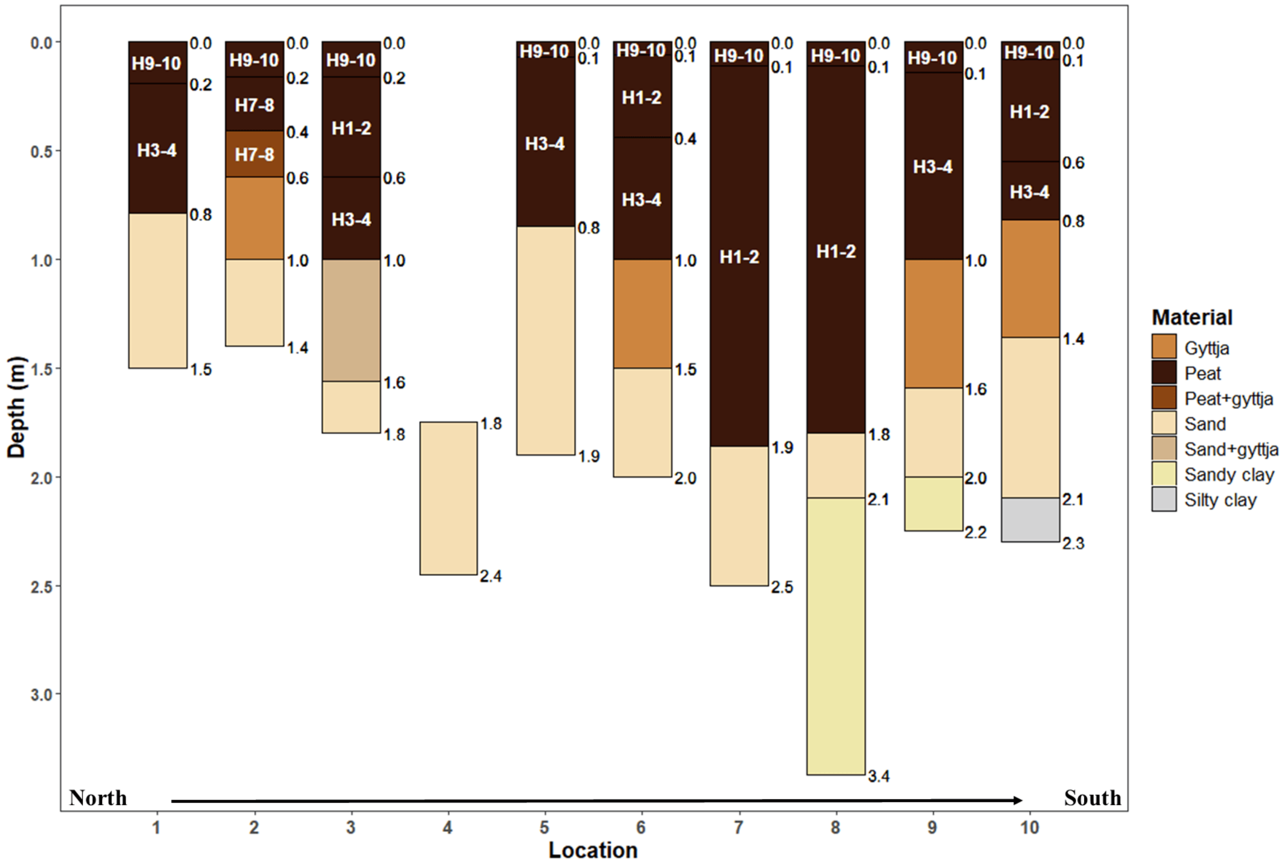

Figure 5. Stratigraphic transect in a contemporary agricultural area of the bog. Ten locations along the transect are illustrated. The arrow at the bottom runs from the beginning (top / northern end) to the (southern) end of the transect. “H” refers to the degree of peat decomposition according to the von Post scale (von Post 1922).

Table 3. The range in surface elevation of the marine layer, the calculated peat thickness (PT), the mean subsidence and subsidence rate, and the changes in peat volume. MSE = marine surface elevation.

Period	Surface elevation		Subsidence		Peat volume changes	
	MSE (m)	PT (m)	Mean (m)	Rate (cm y^{-1})	Net loss (m^3)	Net gain (m^3)
1880 2010	2.3–9.6	0–5.8 0–2.1	1.6	1.8	116,711,981	113,959

Figure 6 shows the total subsidence map for the study area. It must be noted that this PT differential map does not discriminate between true peat subsidence due to drainage and peat extraction or erosion. Nonetheless, for the historical period of interest, almost all of the area had subsided to some extent (brown shades) and only a few areas indicated peat accumulation (green). Considerable subsidence was observed mostly from the southern half of the study area. In contemporary times, subsiding areas generally coincide with intensively cropped fields and grasslands; while areas showing the largest magnitude of subsidence (deepest shades of brown) correspond to intensive agriculture with temporary crops, wet natural areas, grasslands and peat extraction LUs.

Physical and oxidative subsidence estimates

Table 4 shows estimates of the TS, PS and OS based on the number of years since drainage began. An inverse relationship was observed between subsidence and the time since drainage; thus, the longer period over which the duration since drainage was considered, the lower was the estimated SR and vice-versa. Between the shortest and longest periods post-drainage, estimated rates of TS ranged from 2.5 to 1.6 cm y^{-1}. For PS, the 90-year period post-drainage resulted in the lowest estimated rate of subsidence (0.7 cm y^{-1}) while the 63-year and 23-year periods showed higher rates (0.9 and 1.4 cm y^{-1}, respectively). The highest SR of 1.6 cm y^{-1} was obtained for the shortest post-drainage period (18 years). The contributions of PS to TS were

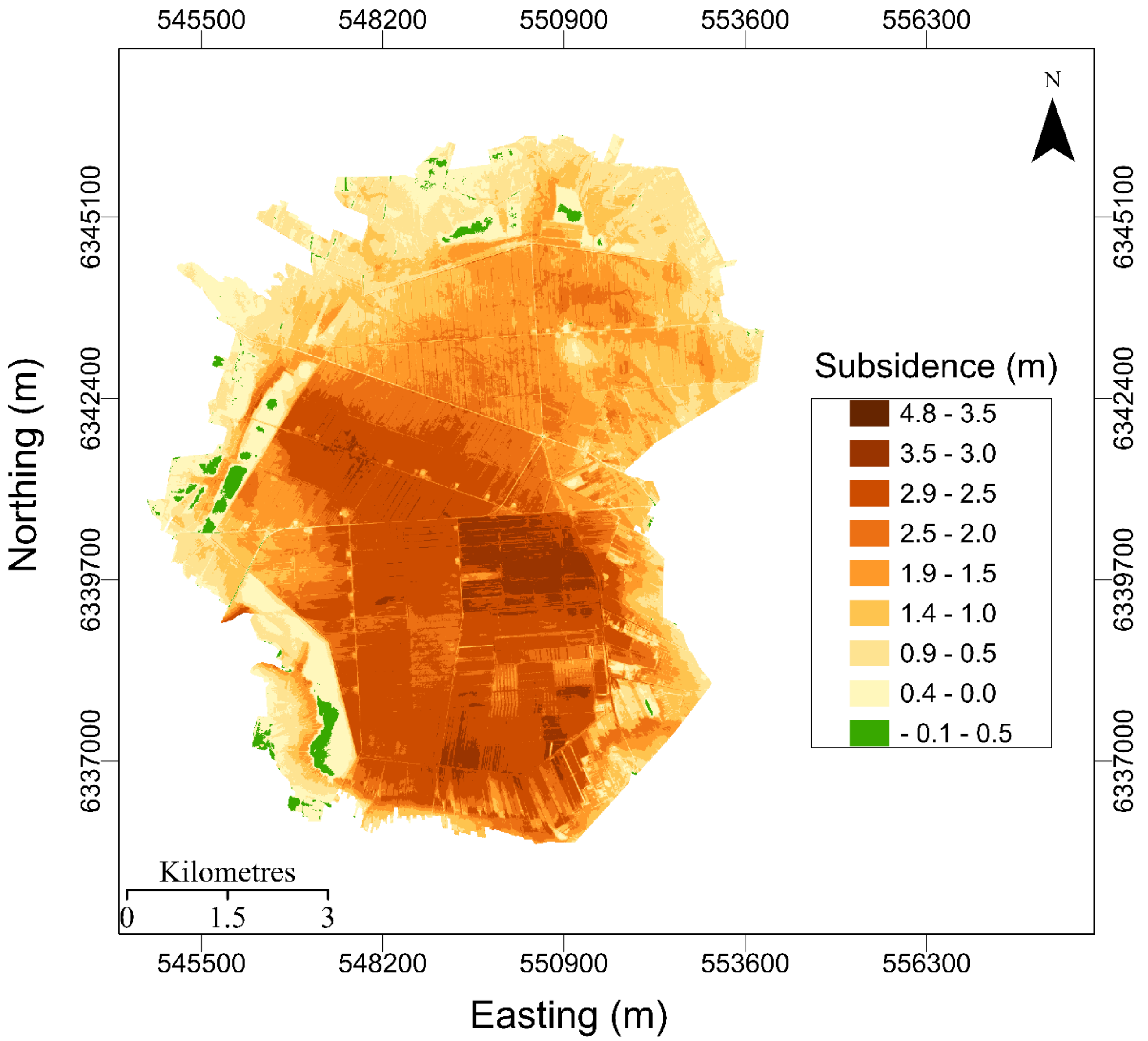

Figure 6. Total peat subsidence map, calculated as the difference in estimated peat thickness between 1880 and 2010. The brown shades indicate subsided areas while green indicates areas of peat growth.

approximately 64 %, 61 %, 51 % and 42 %, respectively, from the shortest to the longest post-drainage period. The same general trend of decreasing SR with increasing time post-drainage was found for OS. This corresponded to OS rates of 0.9–0.8 cm y^{-1} from the shortest (18 years) to the longest (90 years) post-drainage period. In contrast to PS, an increasing trend in the relative contributions of OS and TS was observed with increasing time since drainage. This corresponded to OS values of approximately 36 %, 39 %, 49 % and 53 % for the 18, 23, 63 and 90-year periods, respectively. Nevertheless, the rates of OS were lower than the rates of PS, except for the 90-year period.

Change in the C- stock and CO_2 emissions

Table 5 shows the two scenarios of estimated C-stock changes in the bog from 1880 to 2010. Both C-stock estimations resulted in substantial C losses. The first scenario, based on literature values of BD and TOC contents, resulted in a C-stock reduction from 975 t ha^{-1} to 509 t ha^{-1} for the historical and contemporary periods, respectively. This represents a 48 % decline in C-stock, lost at an annual rate of about 5 t ha^{-1} y^{-1}, and corresponds to CO_2 emissions of 19 t ha^{-1} y^{-1}. The second scenario, based on measured BD and TOC contents from surface and deeper peat layers, resulted in a C-stock decline from 753 t ha^{-1} to 212 t ha^{-1} for the historical and contemporary periods, respectively. This reflects an annual C-stock loss rate of 6 t ha^{-1} y^{-1} and corresponding CO_2 emissions of 22 t ha^{-1} y^{-1}. While both scenarios show comparable C-stock losses, the first scenario tends to overestimate both the historical and contemporary C-stocks, resulting in a slightly lower estimated change in C-stock and CO_2 emissions compared to the second scenario, which uses more representative input data.

Table 4. Estimates of the total, physical and oxidative subsidence using empirical equations from the literature under four scenarios for the time since drainage began in the study area. In the last two columns, values in parentheses represent the estimated percentage physical and oxidative subsidence.

Period of legacy topographic map	Years after drainage	Total subsidence (TS) rate (cm y^{-1})	Physical subsidence (PS) rate (cm y^{-1})	Oxidative subsidence (OS) rate (cm y^{-1})
1920–1938	18	2.51	1.60 (63.5 %)	0.92 (36.5 %)
1920–1943	23	2.34	1.44 (61.4 %)	0.90 (38.6 %)
1920–1983	63	1.73	0.89 (51.4 %)	0.84 (48.6 %)
1920–2010	90	1.56	0.74 (42.3 %)	0.82 (52.7 %)

Table 5. Estimated carbon (C) stock, annual rate of carbon stock loss and carbon dioxide (CO_2) emission in CO_2 equivalents, based on comparison of the total peat thicknesses in 1880 and 2010.

C-stock estimation scenario	Period	C-stock (t ha^{-1})	Change in C-stock (t ha^{-1})	Rate of C-stock change (t ha^{-1} y^{-1})	CO_2eq (t ha^{-1} y^{-1})
Scenario 1	1880	975	466	5.2	19.0
	2010	509			
Scenario 2	1880	753	541	6.0	22.1
	2010	212			

DISCUSSION

Anthropogenic disturbances in the bog

Between 1880 and 2010, the once pristine Store Vildmose raised bog underwent considerable changes. Based on the assessment of legacy topographic maps, it is evident that the transformation of the bog landscape was largely driven by human activities. In particular, the rapid evolution of drainage in the early 20th century led to severe degradation of the bog. According to Greve *et al*. (2021), conversion of the former wetland to an agricultural site dealt a "death blow" to the bog. This was a consequence of the State's purchase of part of the bog in 1920, mostly for cattle and crop farming. Agricultural use of the site involved not only drainage but also tilling, fencing and fertilising, all of which contributed to the degradation of the bog (VHM 2006). In addition to farming, both domestic and commercial peat extraction activities exacerbated the degradation of the bog. The high percentage increase in extracted area over the study period is largely due to the advent of commercial peat extraction in the bog.

The present study demonstrates that large areas of an initially pristine or almost pristine peatland have succumbed to degradation due to human activities. Such long-term anthropogenic disturbances are indicative of specific past land management practices which are likely to have contributed to the subsidence of peat, and thus provide insights about management activities that need to be revised towards more sustainable use of the peatland. It is evident from Figure 4e that agricultural expansion and intensification in the bog exerted a large influence on its widespread transformation to the contemporary situation in which 70 % of its area serves as pastures and farmlands. Such LU changes contributed to the subsidence of peat in the bog. Reports of the human contribution to peatland subsidence and other adverse environmental consequencs are documented in the literature. For example, Pierik *et al*. (2018) reported that human-induced landscape transformations increase risks of flooding due to tidal ingressions and avulsions. Furthermore, Sumarga *et al*. (2016) forecasted that oil palm plantations in Indonesia will be subjected to regular flooding due to subsidence. Other adverse repercussions of poor human management of peatland areas include exacerbated peat drying, severe biodiversity loss and increased GHG emissions (Swindles *et al*. 2019, Grzybowski & Glińska-Lewczuk 2020, Taufik *et al*. 2020). Thus, subsidence is generally a result of human behaviour in exploiting peatland for both economic and non-economic reasons (Saputra 2019).

Subsidence and peat volume loss

Almost the entire bog had undergone subsidence over the historical timescale considered, with minimal areas showing peat accumulation (Figure 6). We emphasise that the spatial distribution of subsidence based on elevation changes observed in this study represents the combined effects of both drainage and peat extraction. Generally, up to 5 m of surface subsidence and only about 0.5 m of peat accumulation had occurred. Peat subsidence and accumulation areas represent 98.5 and 1.5 % of the total land area, respectively. Dominant patterns of subsidence observed in the central-eastern and southern parts of the bog generally coincide with intensive and extensive agriculture, as well as with contemporary peat extraction sites. However, the large degree of land surface lowering in peat extraction areas results from peat mining and not subsidence. Similarly, Erkens *et al*. (2016) noted that the greatest land surface lowering over millennia in Dutch peatlands occurred on peat extraction sites. The SR (1.8 cm y^{-1}) estimated in this study is comparable with rates reported from other temperate and boreal peatland areas. For instance, Leifeld *et al*. (2011) reported a SR of 0.8–1.6 cm y^{-1} for drained Swiss fens over a 140-year period; Pronger *et al*. (2014) reported a SR of 2.6 cm y^{-1} for former bogs in New Zealand over an 80-year period; and Grønlund *et al*. (2008) reported a SR of 2.5 cm y^{-1} for cultivated Norwegian peat soils. For fens in the United Kingdom, Richardson & Smith (1977) and Dawson *et al*. (2010) reported SRs of 1.37 cm y^{-1} and 1.48 cm y^{-1}, respectively, for 30-year and 13-year periods. Franzén (2006) reported a SR of 0.4 cm y^{-1} for Swedish bogs over a 35-year period and Ikkala *et al*. (2021) reported SRs ranging from 0.94 cm y^{-1} to 5.15 cm y^{-1} for a Finnish peatland over a 24–51-year historical period.

Pedersen (1978) determined from PT and levelling measurements that the central farm area within the present study site subsided at a rate of 5 cm y^{-1} from 1930 to 1974, with PT decreasing from a maximum of 3.8 m to 1.6 m. An annual peat oxidation rate of 1 cm y^{-1} was reported for the same site. Thus, more than twice the estimated SR for the near-centennial timescale of this study was reported for the shorter historical timescale. This is due to the rapid initial subsidence that occurs following drainage, which gradually slows over time (Armentano 1980, Hooijer *et al*. 2012, Erkens *et al*. 2016, Liu *et al*. 2020, Ikkala *et al*. 2021). The disparity in SR between the shorter and longer historical periods post-drainage may be due to the initial increase in ditch depth during the former, which facilitates the expulsion of substantial volumes of water from the peatland, leading to rapid subsidence through structural collapse (Hökkä *et al*. 2020). Evidently, this phenomenon of rapid subsidence of peatlands post-drainage is largely due to the control exerted by PS processes such as peat shrinkage, compaction and consolidation (Oleszczuk *et al*. 2022). For instance, a general trend of increasing BD starting below the humified peat topsoil and continuing with increasing depth was observed along the transect in Figure 1 (results not shown). This suggests that the peat has continued to settle for many years after drainage and that the deeper layers have been compressed and consolidated by the weight of the overlying material (Hooijer *et al*. 2012). Additionally, higher BD was observed in the humified topsoil, suggesting compaction of the surface peat (O'Kelly & Pichan 2013). Given that large areas of the bog are now farmland (Figure 4e), in addition to natural settling of the topsoil, human activities such as tillage and livestock grazing may well have contributed to this compaction.

The empirically estimated TS rate of 1.6 cm y^{-1} for the 90-year period aligns closely with the calculated TS rate of 1.8 cm y^{-1} based on elevation datasets, resulting in a relative error of 11.1 %. Although the empirically estimated TS rates are conservative and underestimate the true rate of TS, the approach offers a valuable perspective. The modest discrepancy between the TS estimates may be attributed to the empirical method which focused primarily on drainage duration. In comparison, the elevation-based method provides a more nuanced assessment by incorporating PT data which are influenced by drainage and are specific to the study area. Nevertheless, the 2010 PT measurements have an uncertainty of 0.45 m. While this uncertainty propagates into the elevation-based TS rate, the consistent correlation of different LUs with either subsidence or peat accumulation (Figures 4 and 6) suggests that the method effectively captures real trends in subsidence despite potential uncertainties in individual measurements. Moreover, assuming stable climate and groundwater levels, the results indicate that the rates of both PS and OS were highest close to the start of drainage but decreased with time. Between the 18-year and 90-year post-drainage periods, PS rates decreased by 0.9 cm y^{-1} (from 1.6 to 0.7 cm y^{-1}) and OS rates by 0.1 cm y^{-1} (from 0.9 to 0.8 cm y^{-1}), representing reductions of approximately 54 % and 11 %, respectively. These results align with those of Sohlenius *et al*. (2013) who stated that, in drained bogs, PS rates due to compaction are initially fast but decrease over time. This reduction in PS rates may lead to OS becoming more dominant; however, the latter also declines as the easily oxidisable materials are depleted. The present results indicate that, while subsidence due to physical processes declines significantly over time, peat oxidation remains a slow process that requires considerable time to become the dominant contributor to TS (Hooijer *et al*. 2012, Erkens *et al*. 2016). Additionally, the estimated OS rates in this study (0.8–0.9 cm y^{-1}) are comparable to the rate (1 cm y^{-1}) reported for the study area by Pedersen (1978). For drained cultivated peatlands the rate of peatland oxidation is influenced by peat type, ditch depth, crop type and climate (Sohlenius *et al*. 2013). However, these factors are outside the focus of the present study due to the scarcity of data for historical times. The present study presents a snapshot of two major phases of subsidence. Nevertheless, since the aforementioned factors contribute to either PS, OS, or both, it is likely that the subsidence estimates for the phases investigated also reflect these.

Substantial volumes of peat have been lost from the bog over the 130-year period considered (Table 3). Major drivers of this reduction are drainage for agricultural cultivation and peat extraction. In addition to historical peat extraction by farmers for fuel, commercial peat extraction has contributed significantly to the total volume lost in contemporary times. According to Pedersen *et al*. (2013), part of Store Vildmose was acquired by a horticultural peat company in 1966 (Pedersen & Løes 2022). Over time, the company has acquired permissions to extract peat in more areas and has consequently expanded its operations. In contemporary times it is expected that about 130,000 m^3 of peat can be extracted per year (https://trap.lex.dk/Store_Vildmose). Considering the slow natural rate of peat formation of 1 mm y^{-1} (Parish *et al*. 2008), the high peat volume loss estimated in this study may not be recovered in millennia. Erkens *et al*. (2016) stated that it is vital to differentiate between peat volume losses due to drainage and peat extraction when estimating CO_2 emissions. Over the 44-year period since commercial peat extraction for horticulture began in Store Vildmose, and considering the expected annual extraction volume, up to 5.7 million m^3 of peat volume will be lost. This compares well with the 5.8 million m^3 estimate of peat volume loss based on elevation differences for an existing commercial peat extraction site located in the south-eastern part of the study area (Figure 1). However, at present it is difficult to clearly differentiate the contributions of drainage and extraction to the total peat volume loss due to the lack of high spatiotemporal resolution LU data. Although the historical topographic maps provide a snapshot of various LUCs in time, assessment of the four maps did not allow detailed detection of LUCs for peat extraction areas at finer spatiotemporal resolution. It is possible that previous extraction areas were mapped as other LU classes at the time of the surveys. Nevertheless, Erkens *et al*. (2016) reported that, over long historical periods for which data are scarce, it may be assumed that the peat volume lost by extraction contributes to the oxidative subsidence phase since extracted peat is eventually oxidised.

Carbon stock changes and CO_2 emissions

In estimating the CO_2 emissions based on the amount of C lost, consideration should be given only to the OS phase since PS does not result in C loss (Anshari *et al*. 2021, Oleszczuk *et al*. 2022). However, since the rates of OS in this study were obtained from empirical equations, we anticipate that estimating the C loss from these values would result in additional uncertainties. Therefore, the C loss and emissions were estimated based on changes in C-stock. We assumed that the difference in C-stock for the period of interest represents the C that has been mineralised. Between 1880 and 2010, 466 t ha^{-1} of C was lost at a rate of 5.2 t ha^{-1} y^{-1}, which translates to CO_2 emissions of 19 t ha^{-1} y^{-1}. For the same study areas, Pedersen (1978) reported a C mineralisation rate of 4 t ha^{-1} y^{-1} for a 44-year historical period. We highlight that estimating the C-stock using fixed BD and TC values as in scenario 1 (Table 5) is a simplistic approach that affects the estimates obtained. The literature offers varying results on the trends (either increasing or constant) in BD and TC content with depth for northern bogs under anthropogenic management (Anderson 2002, Koehler *et al*. 2011, Lewis *et al*. 2012, Krüger *et al*. 2015). However, along the transect in Figure 1 the BD measurements throughout the peat profile show less magnitude of variation, which further supports the present approach. An attempt was made to obtain depth-specific C-stock estimates for the 2010 epoch based on sparse measurements available for the top 120 cm of the peat profile. C-stock estimates from this dataset showed strong sensitivity to the variations in the BD and TOC data and resulted in large fluctuations in our estimates (results not shown). Using fixed values for C-stock estimates is a simple and consistent approach that avoids fluctuations arising from small changes in the depth-specific data, which are limited and not representative of the entire peatland. In any case, the C-stock loss and CO_2 emissions estimations for scenario 2 (Table 5) were less conservative and are regarded as the primary results.

Although there was no possibility in the present study to assess associated uncertainties in the estimated emissions, our primary emission estimate (22 t ha^{-1} y^{-1} in CO_2 equivalents) is comparable to the national emission factor (EF) of 24 t ha^{-1} y^{-1} in CO_2 equivalents for drained and cultivated C-rich Danish peatland, as reported to the Inter-governmental Panel on Climate Change (IPCC). However, the national EF reported to the IPCC is based on measurements of eight annual GHG fluxes, collected biweekly and from various agriculturally managed sites (Elsgaard *et al*. 2012, Thers *et al*. 2023). Additionally, the highly humified topsoil peat (Figure 5) may be vulnerable to erosion, especially in unvegetated areas (e.g. croplands tilled for planting) and periods of inclement weather (e.g. winter). This may result in another (erosional) pathway for C loss, aside from direct mineralisation of peat, which may affect C storage, emissions and water quality (Evans & Warburton 2010). Given that the EF estimated in the present study covers a diverse peatland in terms of land use and integrates changes in the peatland over a longer period, the present estimate provides a snapshot of the emissions from a peat landscape that has been heavily altered historically due to human activities. Similar EFs may be anticipated from other Danish peatlands which have been subjected to similar management practices in the past. Thus, there is a need for restoration measures to mitigate the negative effects of past human activities in the bog.

Limitations and future perspective

This study presents a primary approach to retrospectively assess the contribution of humans to the degradation of a major raised bog. Substantial peat volume reductions and C losses were estimated at a centennial timescale. Although these estimates provide a snapshot of the magnitude and rate of degradation of the bog, the lack of detailed soil property data makes any more refined estimation of subsidence and C-stock changes for historical periods challenging. In the context of peatland restoration, the use of methods that allow for the monitoring of subsidence and the acquisition of peat soil property data at finer spatial and temporal resolution are encouraged. For instance, the use of InSAR could be a valuable approach to upscale the monitoring of subsidence across all Danish peatland areas to enable timely identification of areas that are undergoing the most degradation (and thus require urgent attention) in contemporary times. This would allow the development of targeted management interventions to reduce or halt the negative effects of subsidence. Furthermore, proximal soil sensing methods may offer the possibility to map peatland soil properties in a rapid, accurate and cost-effective manner (Koganti *et al*. 2023, Minasny *et al*. 2023). Depending on their management, the condition of peatlands may change over time. However, soil sensing techniques would enable rapid monitoring of relevant peat soil properties, and especially of spatiotemporal changes in C-stock. Therefore, future work should include the monitoring of subsidence and peat soil properties using soil sensing techniques.

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AUTHOR CONTRIBUTIONS

Conceptualisation: DVA, TK, AB, MHG; methodology: DVA, MHG; investigation, formal analysis and visualisation: DVA, IFN, CCH, RJP, DHZ; data curation: MHG, DVA; writing (preparation of original draft): DVA; writing (review and editing): DVA, TK, AB, MHG, IFN, CCH, RJP, DZ; supervision: MHG; funding acquisition: AB, MHG.

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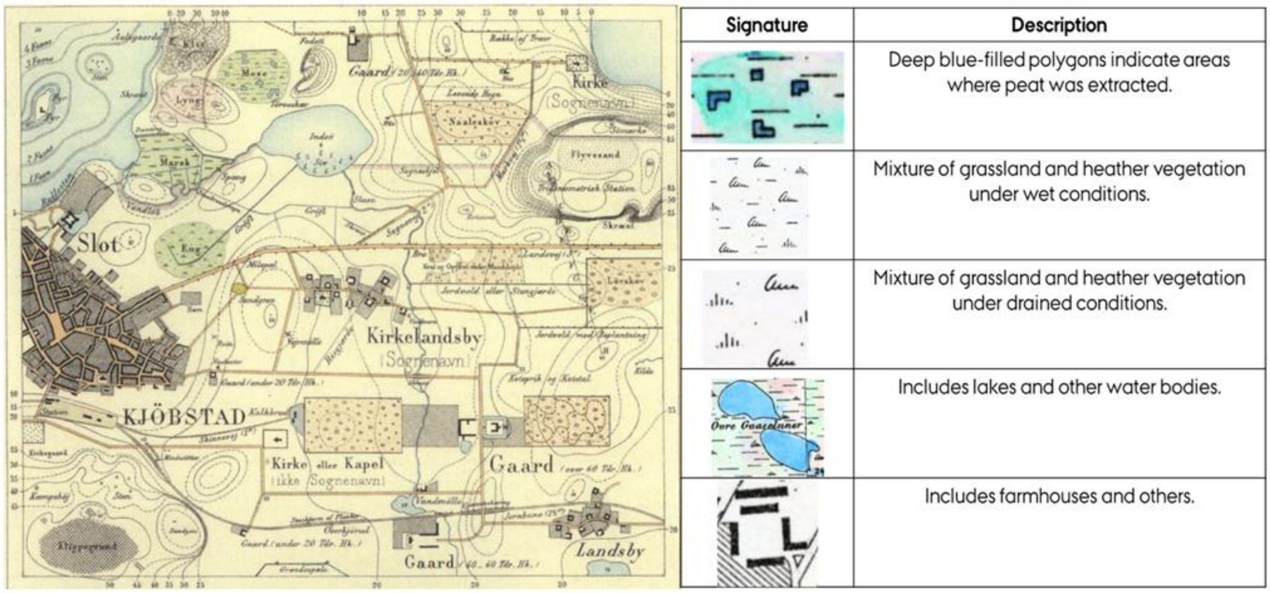
Appendix



Signature	Description
	Deep blue-filled polygons indicate areas where peat was extracted.
	Mixture of grassland and heather vegetation under wet conditions.
	Mixture of grassland and heather vegetation under drained conditions.
	Includes lakes and other water bodies.
	Includes farmhouses and others.

Figure A1. Examples of typical signatures (symbolisations) on a historical (19th century) map from Korsgaard (2006) the on the left, with explanations of a few of the signatures on the right.

Table A1. Detailed description of digitised map signatures which were classified into specific land use types.

Signature	Description	Land use
Olsen signature	Indicates presence of heath.	Heather, large and small scale, respectively
Grass	Indicated by cluster of short, uneven vertical lines arranged randomly.	Grass, large and small scale, respectively
Blue-filled small polygons	Indicate areas where peat has been dug	Peat extraction areas
Wetland	Features showing short dashed horizontal lines on maps	Heather, grasslands, heath and grassland mixtures
Drained/dry	Absence of short horizontal broken lines features on the maps	Heather, grass, heath and grass mixture in drier places
Plantations and forests	Trees drawn in rows	These are classified as forests
Moors	Mainly constitutes *Calluna vulgaris*	Located in few wetland areas and drained areas.
Bog	Oligotrophic peat deposit	
Others	Buildings, water bodies, roads, ditches	

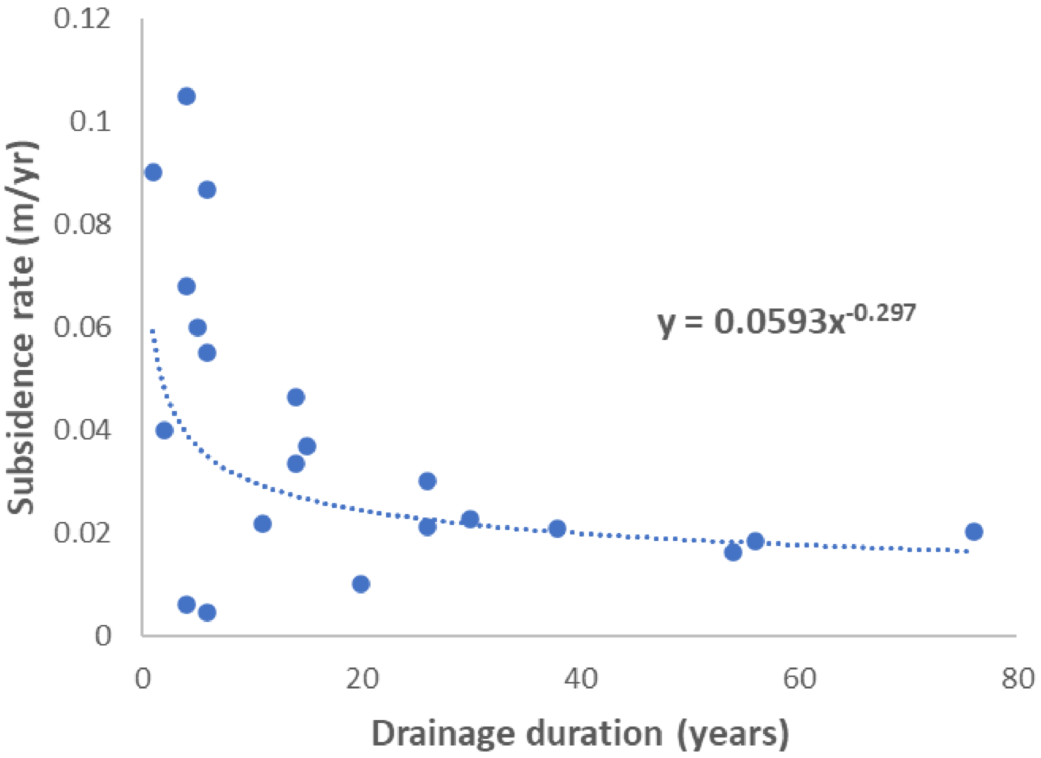


Figure A2. Relationship between subsidence rate and drainage duration derived from a dataset for temperate bog aeras compiled from literature.

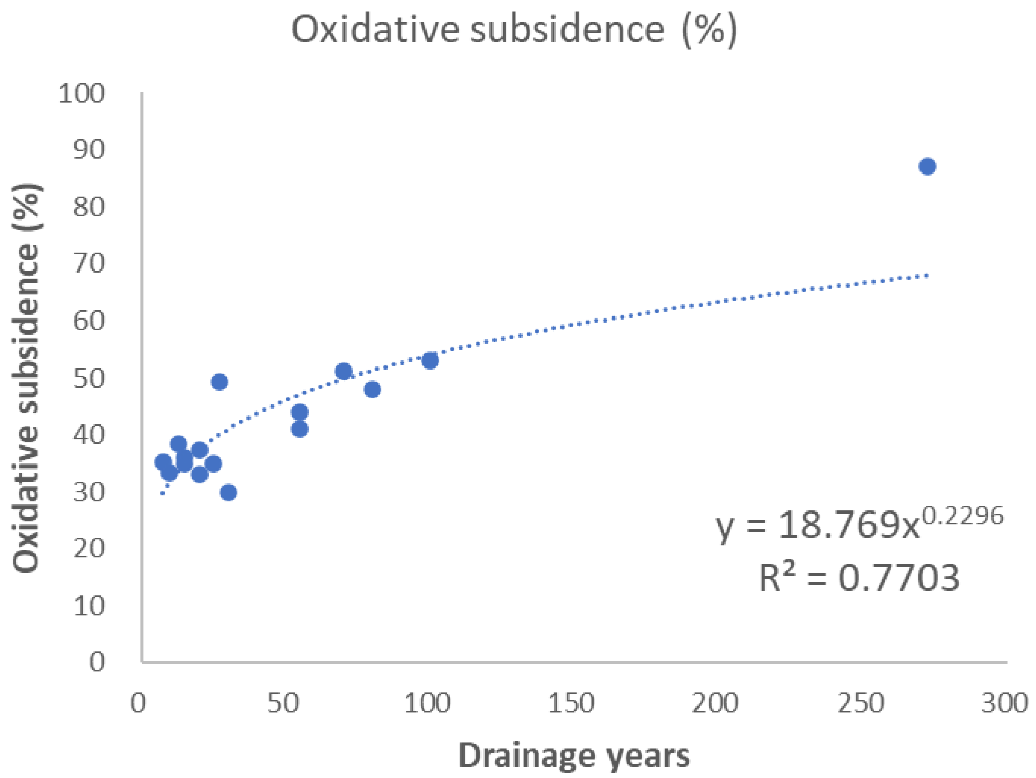
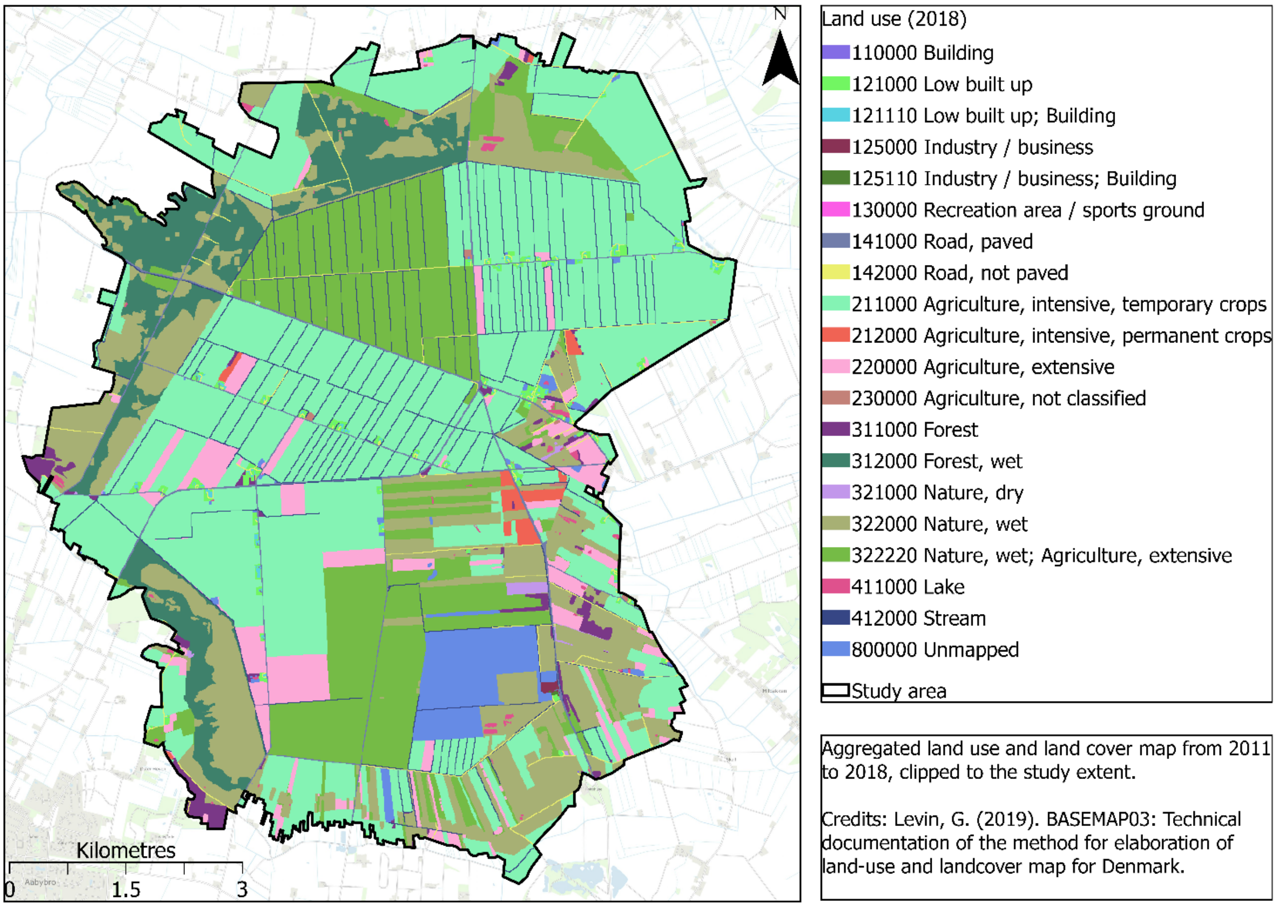


Figure A3. Relationship between the percentage oxidative subsidence and drainage duration derived from a dataset for temperate bog aeras compiled from literature.

Table A2. The von Post peat humification scale, adapted from Andriesse (1988).

Symbol	Description
H1	Completely undecomposed peat which, when squeezed, releases almost clear water. Plant remains easily identifiable. No amorphous material present.
H2	Almost entirely undecomposed peat which, when squeezed, releases clear or yellowish water. Plant remains still easily identifiable. No amorphous material present.
H3	Very slightly decomposed peat which, when squeezed, releases muddy brown water but from which no peat passes between the fingers. Plant remains still identifiable and no amorphous material present.
H4	Slightly decomposed peat which, when squeezed, releases very muddy brown water. No peat is passed between the fingers but plant remains are slightly pasty and have lost some of their identifiable features.
H5	Moderately decomposed peat which, when squeezed, releases very muddy water with a very small amount of amorphous granular peat escaping between the fingers. The structure of the plant remains is quite indistinct although it is still possible to recognise certain features. The residue is very pasty.
H6	Moderately highly decomposed peat with a very indistinct plant structure. When squeezed, about one-third of the peat escapes between the fingers. The residue is very pasty but shows the plant structure more distinctly than before squeezing.
H7	Highly decomposed peat. Contains a lot of amorphous material with very faintly recognisable plant structure. When squeezed, about one-half of the peat escapes between the fingers. The water, if any is released, is very dark and almost pasty.
H8	Very highly decomposed peat with a large quantity of amorphous material and very indistinct plant structure. When squeezed, about two-thirds of the peat escapes between the fingers. A small quantity of pasty water may be released. The plant material remaining in the hand consists of residues such as roots and fibres that resist decomposition.
H9	Practically fully decomposed peat in which there is hardly any recognisable plant structure. When squeezed, it is a fairly uniform paste.
H10	Completely decomposed peat with no discernible plant structure. When squeezed, all the wet peat escapes between the fingers.



Aggregated land use and land cover map from 2011 to 2018, clipped to the study extent.

Credits: Levin, G. (2019). BASEMAP03: Technical documentation of the method for elaboration of land-use and landcover map for Denmark.

Figure A4. Land use and land cover map of the Store Vildmose raised bog, which shows a diversified peatland mostly dominated by farmland in contemporary times. Map adapted from Levin (2019).