Quantifying historically mined peat volumes and CO_2 emissions of the former Bargerveen peat-mining site, The Netherlands

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SUMMARY

We present legacy data from a peat thickness survey conducted in the Bargerveen peat mining area (The Netherlands) in 1880 CE. We use these data to determine past peat volume and carbon stock, then compare the results with information from a recently published 3D geological subsurface model to quantify the volume of peat mined in the past. We use the quantified mined peat volume to estimate the amount of soil carbon that has disappeared and how much carbon dioxide (CO_2) has been emitted into the atmosphere. We find that the thickness of the original peat layer was between 1.5 and 12.0 m, with an average thickness of 5.28 m. The initial peat volume was about 0.26 km^3, whereas the remaining peat volume is around 0.10 km^3. The mined peat contained ~8.32 Mton of soil carbon which, when fully oxidised, represents a CO_2 emission of ~30.53 Mton. This analysis aids the process of peatland recovery by enabling a better understanding of the dimensions of the former pristine peat landscapes that once abundantly prevailed in The Netherlands but have now largely vanished as a result of human activities.

KEY WORDS: bog, historical data, peat extraction, soil carbon

INTRODUCTION

Industrialisation and agricultural developments in north-western Europe have severely degraded natural environments. Especially, the extent of peatlands has been drastically reduced during past centuries owing to peat mining, drainage and overall denudation. This has devastated natural peatland ecosystems, which accommodate valuable ecology, store enormous volumes of water, and sequester carbon.

The Netherlands is a prime example of a country where vast peatland areas have been erased by human activities (e.g., van Beek *et al.* 2015). Erkens *et al.* (2016) estimated that, in total, 19.8 km^3 of surficial Holocene coastal peat deposits have disappeared in historical times, of which ~36 % is related to peat mining. The remaining peat stock in the coastal plains is estimated at 15.0 km^3 (Koster 2017, Koster *et al.* 2018). A nationwide reconstruction of peat mining showed that, in total, ~100,000 hectares of raised bog peat disappeared over the course of 400 years (Gerding 1995, Gerding *et al*. 2015).

At present, legislation prohibits peat cutting in The Netherlands to protect the remaining bogs, turning their remnants into nature reserves. However, peat beds outside nature reserves are still progressively reducing in volume as a result of groundwater level management because many former peatlands are currently in use for agriculture or have been urbanised (van Bergen & Koster 2025). At those locations, groundwater levels are kept artificially low, resulting in slow-paced peat oxidation and consequently land subsidence and greenhouse gas emissions (Koster *et al.* 2020, Blondeau *et al.* 2024).

The Bargerveen raised bog is a historic peat cutting site in the eastern part of The Netherlands that has been turned into a nature reserve (Figure 1; (Casparie 1972, Casparie & Streefkerk 1992, Joosten *et al*. 2017). The peat was only partly excavated and the bog remnant is now largely kept waterlogged to prevent further degradation. The waterlogged parts are flanked by relatively thin peat beds that are still artificially drained and used for agriculture or urbanisation. In this article we present a quantification of the volumetric peat loss from a section of the Bargerveen since 1880 CE, which is the year when the area was transformed from a relatively pristine mire into a peat extraction site. By doing this we aim to better understand the dimensions of the former pristine peat landscapes of this part of The Netherlands. Quantifying volumetric losses of peat, especially in the recent past, is often challenging (Jongepier *et al.* 2011, Quik *et al.* 2023). However, we deploy a unique mapping dataset consisting of historic boreholes describing the peat deposit prior to

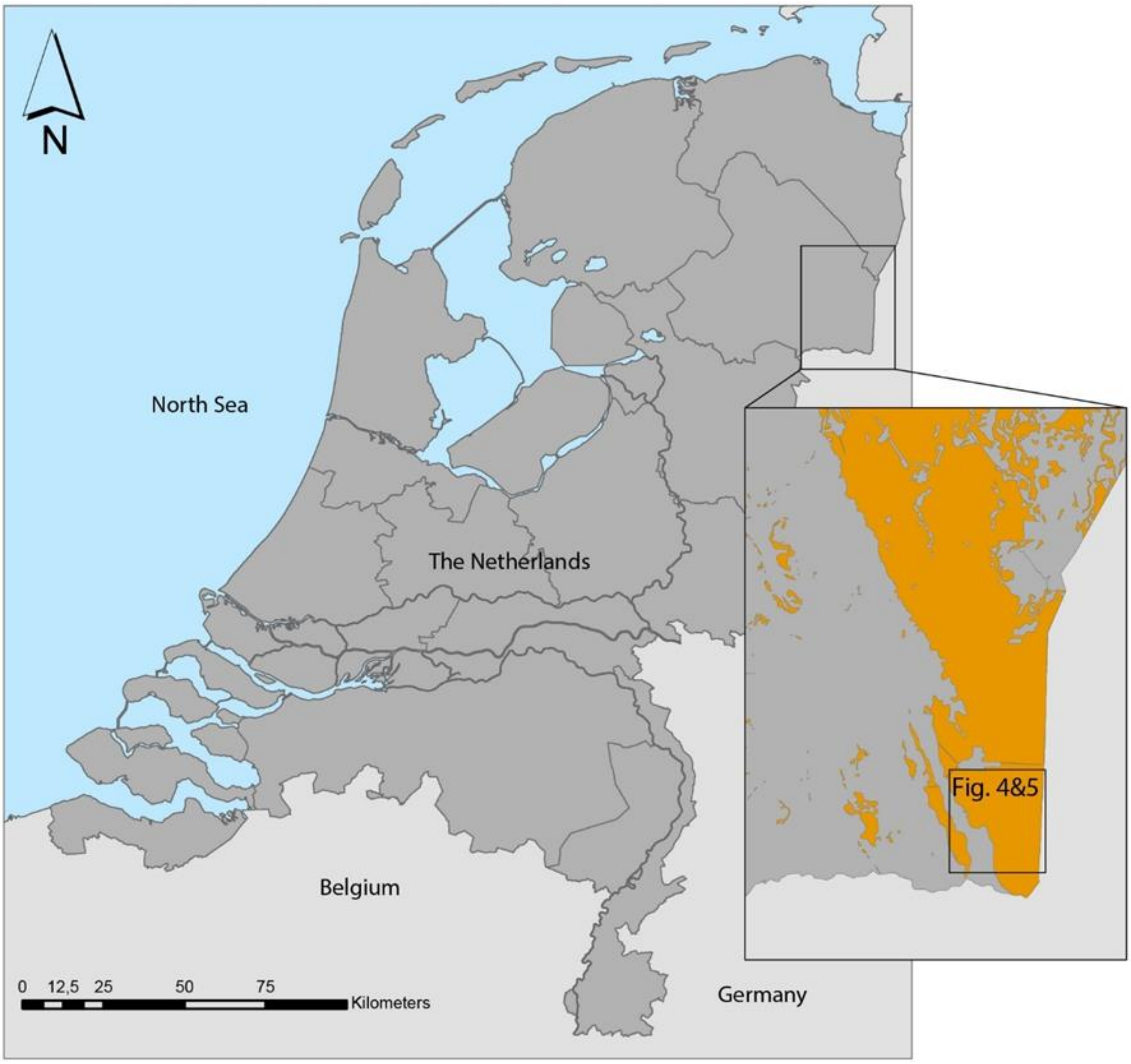

Figure 1. Topographical overview of the study area. Orange-brown shading indicates the spatial distribution of peat remnants and bogs in the general vicinity of the study area (source: TNO-GSN 2024).

mining, that provides valuable insights into past peat thickness. We combine this information with schematised volumes of present-day peat reserves derived from state-of-the-art 3D geological subsurface models to provide insights into past peat losses.

METHODS

Bargerveen peat area

The Bargerveen used to be part of the Bourtanger Moor, a large area of Holocene raised bogs stretching in a northerly direction along the Dutch–German border. According to Casparie (1993), more than 98 % of these raised bogs disappeared during previous centuries as a result of peat cutting and drainage, leaving only a few patches that are currently actively preserved as nature reserves. Peat cutting took place in different parts of The Netherlands during different periods, starting as early as the 13th century (Borger 1992). In the Bargerveen area, however, peat mining at an industrial scale did not commence until the second half of the 19th century; although it is known that minor local-scale excavation was already in progress during the Middle Ages (Casparie 1972). Additionally, according to Paulissen & van Beek (2024), the outer fringes of the peatland were being developed for buckwheat cultivation and pasture before large-scale peat cutting and drainage commenced. The mined peat was used not only as fuel, but also for a wide range of other purposes such as compost and active coal production. Large-scale peat cutting ceased in 1968 when parts of the bog remnants were turned into nature reserves, but continued locally until the 1990s.

The Holocene peat covers a Late Pleistocene topography, primarily consisting of incised brook valleys and aeolian dunes, which in turn overlie stiff and relatively impermeable glacial till (TNO-GSN

2024; Figure 2). Quik *et al.* (2021) used a series of ^{14}C dates for the bases of remnants of this vast stretch of peatland to reconstruct its initiation. They found that the peatland formed in two major stages: first, locally in mires in brook valleys around 14,000 cal years BP (Late Pleistocene); and secondly, regionally around 4,500 cal years BP (Middle Holocene). They state that the onset of peat formation was possible as a result of favourable climatic conditions during an interstadial (Bølling-Allerød); however, peat formation ceased when the climate cooled down again (Younger Dryas). It was only in the Middle Holocene, when inland regional groundwater levels were rising as a result of sea-level rise, that peat formation reinitiated in the mires which subsequently expanded to cover vast areas and developed into bogs.

The remaining peat is still situated directly at the surface in parts of the area, especially in the nature reserves. However, in areas that are presently in use for agriculture or are urbanised, the peat is covered by a mixture of sand and silt as a result of farming practices. Figure 2 illustrates the latter situation in a core taken from a former peat mining area adjacent to the study area (TNO-GSN 2024).

Historical data

To determine the volumetric loss of peat from the bog, we deploy a newly discovered dataset consisting of peat thickness observations derived from boreholes, arising from a systematic survey conducted on a 200 × 200 m grid by the former local water authority in 1880 CE (Figure 3). The goal of this survey was to determine the financial value of the peat stock. The survey covered an area of approximately 7 × 8 km, and for every core location recorded elevation information for the top and base of the peat; with the ‘top’ value equating to coeval surface level and the ‘base’ value corresponding to the top of deposits of Pleistocene age. On the survey map, landscape features that have now disappeared such as peat lakes (‘Zwarte Meer’) and peat brooks (‘Runde’) are visible.

These historical data were acquired by VU University Amsterdam during the period 2005–2008, for a project (SPARC: Strategic Partnerships in River Corridors) aiming to reconstruct the Runde peat brook that once naturally drained the Bargerveen area. Part of this reconstruction was based on information published on historic maps curated at the Drenthe Archive in Assen, which included the 1880 CE borehole map. Multiple peat thickness survey maps were encountered in the archive, but only those showing the former course of the Runde peat brook were digitised because of the scope of the SPARC project.

Peat volume and carbon stock

The set of historical survey maps was georeferenced using topographical features that are recognisable on both the historic maps and present-day topographic maps, such as crossroads and canals (Figure 3). The maps themselves show signs of wrinkling, potentially introducing some error at the edges; however, in view of the 200 × 200 m resolution and the match with topographical features, this potential error was unlikely to significantly influence the surveyed areas in the centres of the maps.

The georeferenced maps were subsequently used to determine their corresponding coordinates, using the Dutch national RD-coordinate system (Rijksdriehoek). Every borehole location on the maps is attributed with elevations of the top of the peat and the base of the peat; the elevations are relative to Dutch Ordnance Datum (NAP). This information was added to the coordinates of each borehole, so the pristine peat thickness during the historical survey for each surveyed location could be determined. Finally, the mire thickness point information was scaled to 200 × 200 m cells, equaling the survey grid size, to obtain peat volumes prior to mining.

To determine the volume of cut peat, present day volumes of the peat remnants for the same site were selected from the 3D geological subsurface model NL3D (Stafleu & de Bruin 2024, TNO-GSN 2024) (Figure 4). NL3D is a voxel (volumetric pixel) model with cell sizes of 250 × 250 × 1 m, covering the upper 50 m of the Dutch subsurface, and is based on 26,500 digitally stored and interpreted geological boreholes. For each 1880 CE borehole location, the present day peat thickness was derived from NL3D.

The amount of CO_2 emitted into the atmosphere by the cut peat is also determined - assuming that all mined peat was combusted or oxidised when exposed to the atmosphere. We follow the workflow proposed by Erkens *et al.* (2016) to quantify past cut peat into emitted CO_2, using an average organic matter density for peat in The Netherlands of 103 kg m^{-3}, a carbon content for peat organic matter of 50 %, and a soil carbon into CO_2 conversion ratio of 1.00 : 3.67.

RESULTS

Peat surveyed during the 1880 CE campaign had an average thickness of 5.28 m, with a minimum of 1.50 m and a maximum of 12 m (Figure 5A). The thickest part of the raised bog was concentrated in the south-east, although in general the peat was thickest in the centre of the bog, grading downwards gradually towards the outer boundaries. This configuration can partly be explained by differences

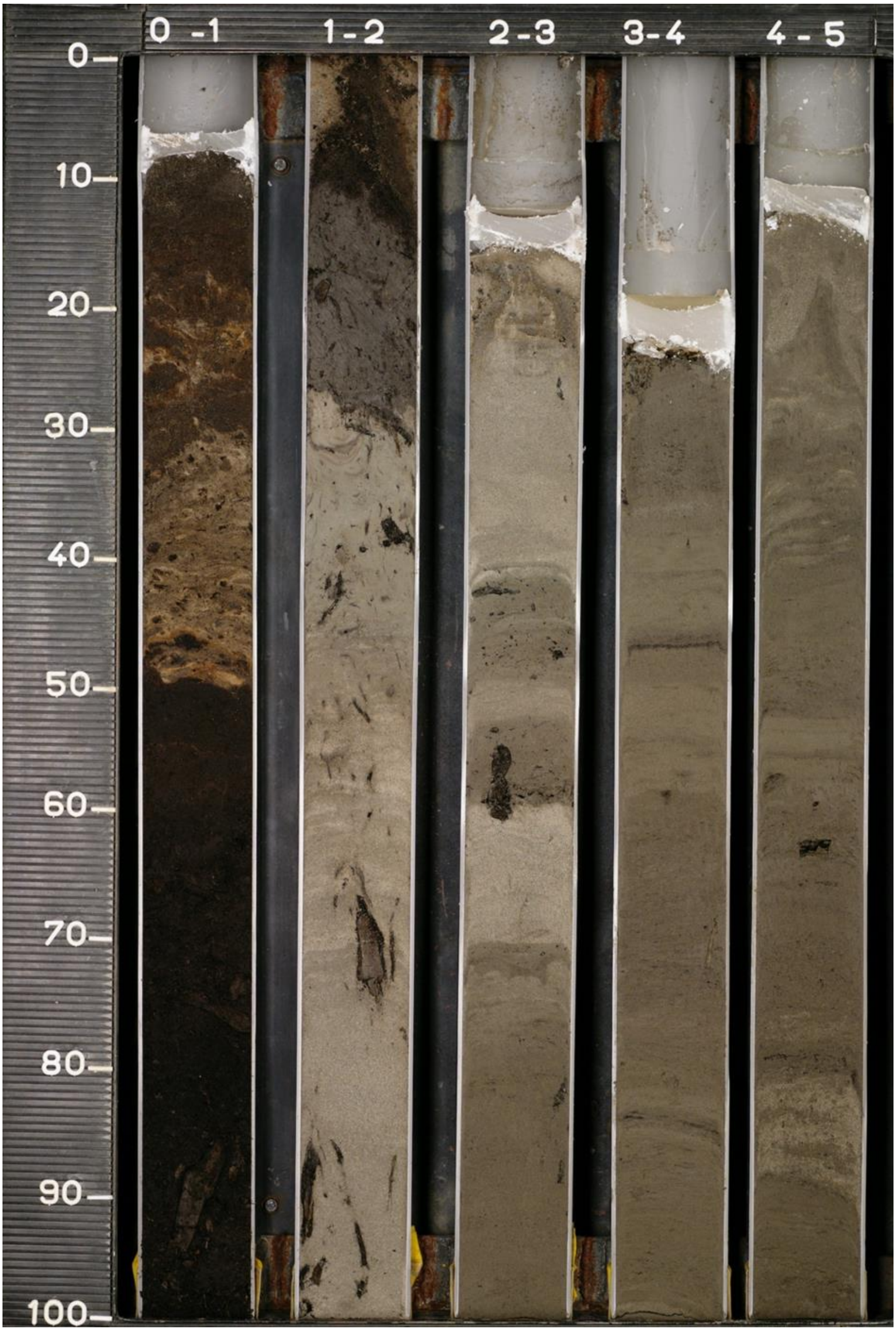

Figure 2. Sediment core from a borehole near the former Bargerveen peat-mining site, showing the top five metres of the profile in one-metre sections arranged sequentially from shallowest (left) to deepest (right). The dark-coloured material at depth 0.50–1.00 m is remnant Holocene peat. A layer of anthropogenically applied soil is visible above the peat. This is mainly sand and silt which was added to increase the bearing capacity of the former bog. Directly below the peat (to 1.25 m depth) are greyish clay brook deposits probably dating from around the Late Pleistocene to early Holocene. The underlying brownish sand beds represent various local brook, aeolian and lacustrine deposits from the Late Pleistocene. Borehole: B22F0636; TNO-GSN (2024).

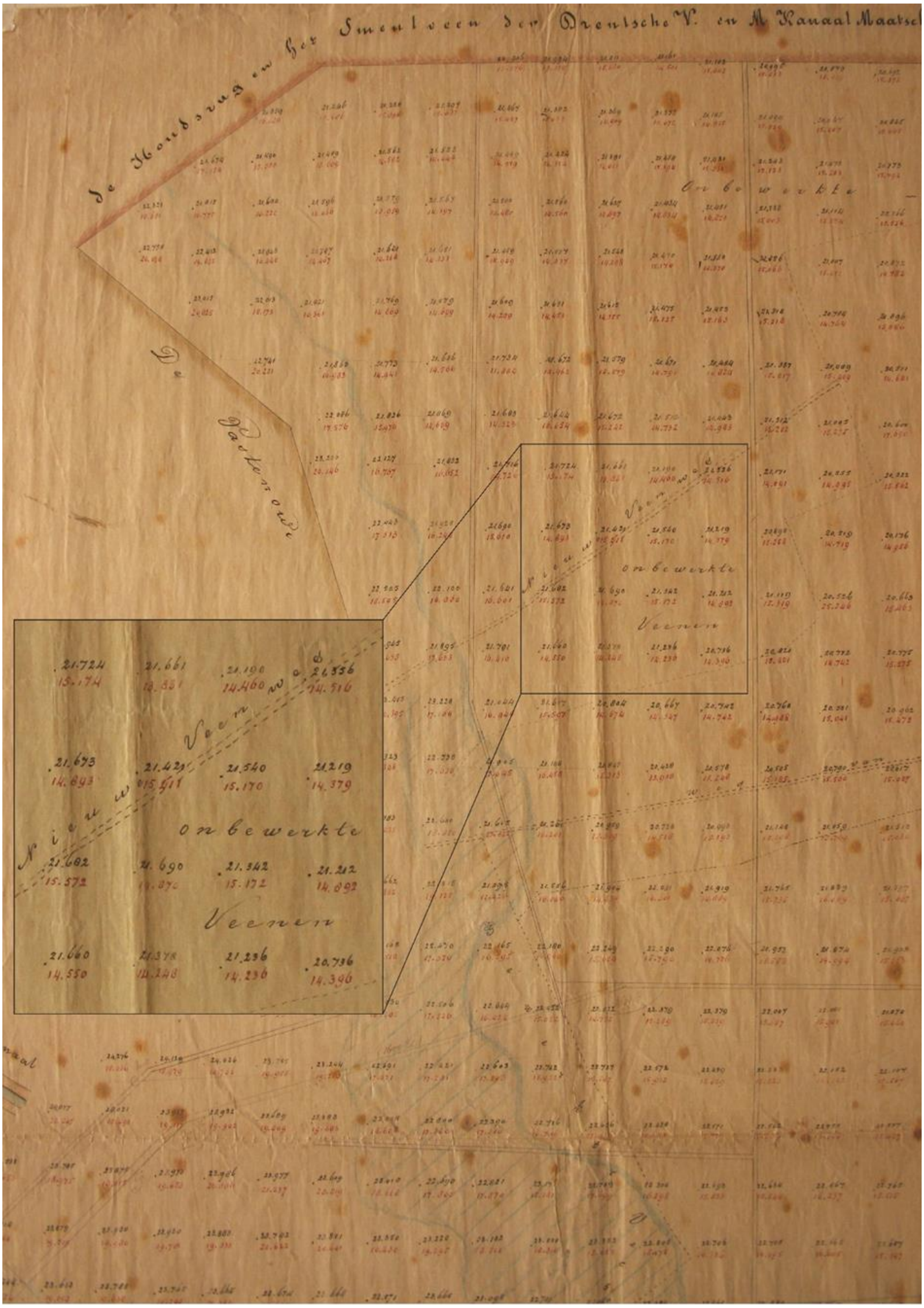

Figure 3. Part of a map showing results from the 1880 CE peat stock survey, depicting a western edge of the bog. Each grid point is annotated with elevation information for the top (black) and base (red) of the bog. Topographical features such as canals were used for georeferencing. The enlarged section superposed on the left side shows the surveyed bog metrics clearly. This part of the map is labelled '*onbewerkte veenen*', which translates from Dutch as 'pristine peat' or 'unprocessed peat'. Source: Drents Archief (2005–2008).

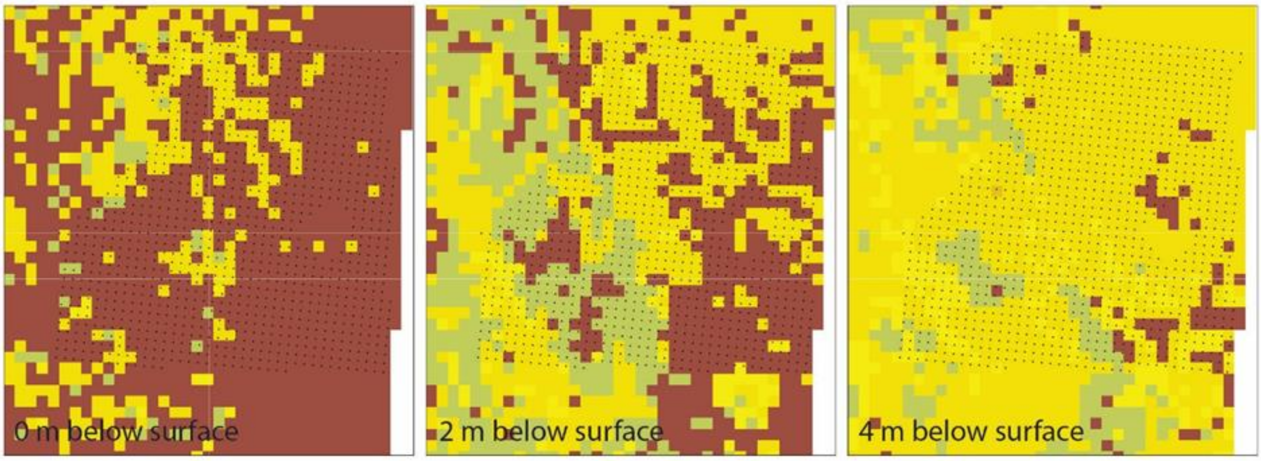

Figure 4. Lithological composition of the study area at 0, 2 and 4 m below the surface extracted from NL3D (TNO-GSN 2024). Brown pixels indicate peat, whereas the yellowish colours indicate loam and sand. The amount of peat diminishes strongly with depth. The locations of the 1880 CE boreholes are indicated by dots.

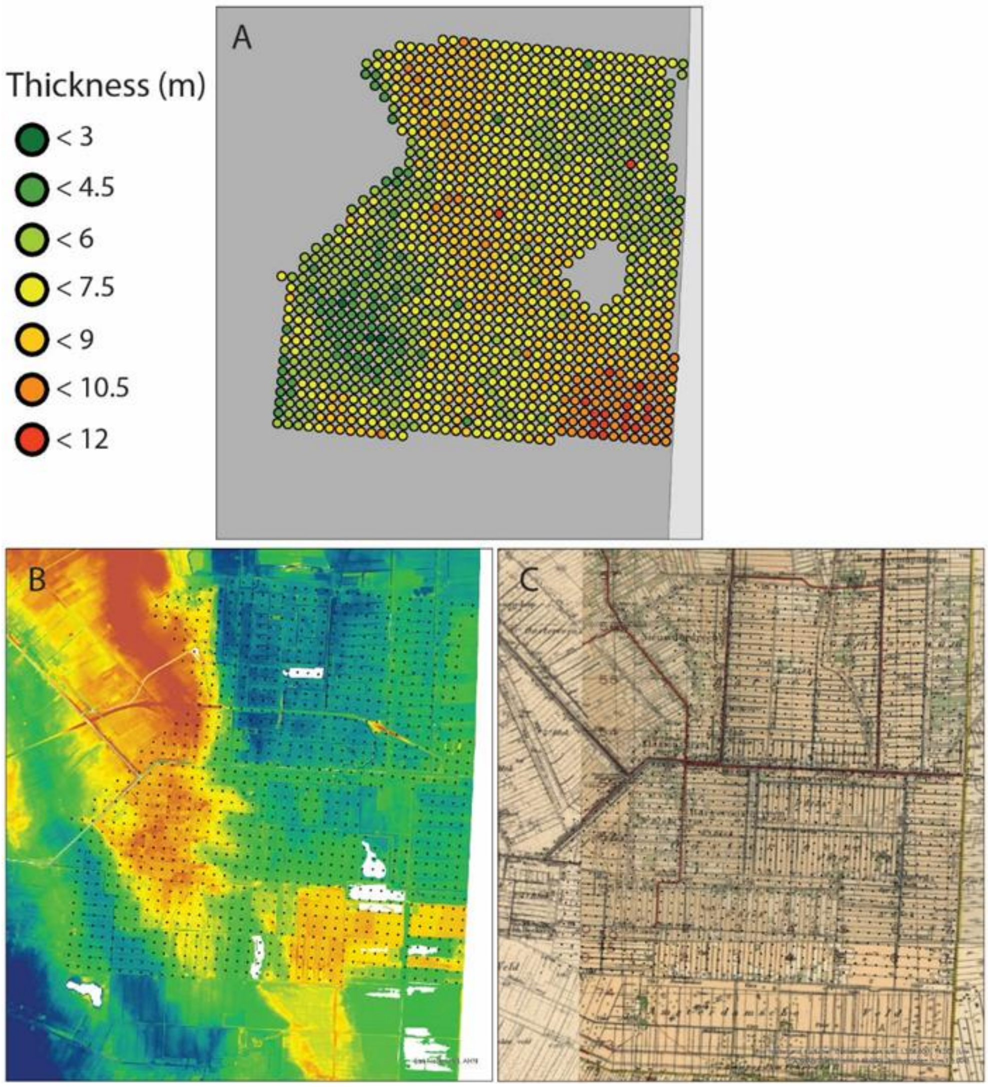

Figure 5. Overview of: (A) thickness of the peat surveyed in 1880 CE; (B) present-day surface elevation (AHN4); red and yellow areas are elevated relative to the blue and green areas; and (C) historical topographical map of 1929. The grids of dots in (B) and (C) indicate the locations of the 1880 CE boreholes.

in local morphology of the underlying Pleistocene strata, determining accommodation space for peat formation. Figure 5B displays a digital elevation map of the area (AHN4), with a zone consisting of till that was elevated by glacial activity at the western side. The thinnest part of the bog initially covered the top and slope of the elevated till ridge, and the greatest peat thickness was reached in the topographical depression east of the ridge. The undulating landscape presented by the now-underlying deposits of Pleistocene age determined the availability of space to accommodate peat formation, which would follow local (ground)water levels that would have been higher (relative to ground-surface level) in the topographic lows than in ridges. This spatial distribution is also visible in the present subsurface, with remaining peat layers reaching thickness > 2 m in the eastern part of the study area (Figure 4B).

Figure 5C presents the 1929 cadastral map of the area. This shows that the area had already been fully turned into parcels and the lake Zwarte Meer, which is clearly visible as a gap in the survey plan, had vanished. The straight lines are ditches excavated to drain the former bog and control groundwater levels. This procedure probably led to shrinkage of the peat layer that remained after mining (i.e., it became thinner), a process that has also been observed in the western part of The Netherlands (Schothorst 1977, Carpentier *et al.* 2024).

The total peat volume on the mapped area in 1880 CE was ~ 0.26 km^3, whereas the peat volume remaining in the study area at the present day is ~ 0.10 km^3. This implies that ~ 37 % of the peat remains and the total volume of mined or vanished peat is ~ 0.16 km^3.

The vanished peat contained 8.32 Mton of soil carbon. This would have emitted 30.53 Mton of CO_2 into the atmosphere when completely oxidised. For comparison, approximately 3.1 Gton of CO_2 - two orders of magnitude more than estimated here - has been emitted from peat that disappeared from the coastal plains of The Netherlands during the last 1000 years (Erkens *et al.* 2016), underlining the magnitude of this country's past emissions from peat.

DISCUSSION

The above quantification provides very valuable underpinning for initiatives to restore peatland areas (see, e.g., Gaudig *et al*. 2024), such as the former Bargerveen peat mine, as growing mires. For instance, if lost peat volume and carbon stock are known, restoration goals can be set with a view to eventually regenerating surface elevation and carbon storage. Since the Drenthe Archive holds multiple peat survey maps, spatial upscaling of this study is feasible.

KEY FINDINGS

An unprecedented dataset of surveyed peat thickness in a pristine bog prior to peat extraction, conducted in 1880 CE in the Bargerveen area (The Netherlands) is analysed to quantify vanished peat volume. In total:

- The cut peat volume is 0.26 km^3; the remaining peat volume is 0.10 km^3, making the total volume of mined peat 0.16 km^3.
- The morphology of Pleistocene geology determined the thickness distribution of the pristine bog, with the thickest peat (12.0 m) in former valleys thinning out towards the flanks (1.50 m), with an average thickness of 5.28 m.
- The cut peat contained 8.32 Mton of soil carbon which, when fully combusted/oxidised, would produce a CO_2 emission of 30.53 Mton.

We conclude that the deployment of archived legacy borehole data from peat surveys is a very suitable approach for reconstructing volumetric peat loss, which could provide essential information to underpin peatland recovery initiatives.

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AUTHOR CONTRIBUTIONS

KK and SS initiated this manuscript; MvdB and AdK collected the data; KK and SS conducted the data analysis. All authors discussed the results and contributed to the final manuscript.

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