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PAPER

Double trouble: subsidence and CO_2 respiration due to 1,000 years of Dutch coastal peatlands cultivation

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Abstract Coastal plains are amongst the most densely populated areas in the world. Many coastal peatlands are drained to create arable land. This is not without consequences; physical compaction of peat and its degradation by oxidation lead to subsidence, and oxidation also leads to emissions of carbon dioxide (CO_2). This study complements existing studies by quantifying total land subsidence and associated CO_2 respiration over the past millennium in the Dutch coastal peatlands, to gain insight into the consequences of cultivating coastal peatlands over longer timescales. Results show that the peat volume loss was 19.8 km^3, which lowered the Dutch coastal plain by 1.9 m on average, bringing most of it below sea level. At least 66 % of the volume reduction is the result of drainage, and 34 % was caused by the excavation and subsequent combustion of peat. The associated CO_2 respiration is equivalent to a global atmospheric CO_2 concentration increase of ~0.39 ppmv. Cultivation of coastal peatlands can turn a carbon sink into a carbon source. If the path taken by the Dutch would be followed worldwide, there will be double trouble: globally significant carbon emissions and increased flood risk in a globally important human habitat. The effects would be larger than the historic ones because most of the cumulative Dutch subsidence and peat loss was accomplished with much less efficient techniques than those available now.

Keywords Climate change · Compaction · Subsidence · Geohazard · The Netherlands

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Introduction

Most present-day coastal plains and deltas developed during the last 8,000 years under conditions of an accelerating and subsequently decelerating eustatic sea level rise (Stanley and Warne 1994; Hori and Saito 2007). Under natural circumstances, a coastal plain represents a dynamic balance between the creation of accommodation space (the space available for sedimentation) on the one hand and the filling of this space by sedimentation on the other. The sediment bodies that are formed in this particular environment are typically clastic (often sandy and/or muddy), but peat may be an important constituent as well, growing where clastic sedimentation is low or absent.

In most modern inhabited coastal plains, sedimentary and hydrological processes are managed, i.e., controlled, confined, or suspended, in many ways and for reasons ranging from flood safety to arability. Additionally, sediment inputs to the world's coastal plains have been reduced as a result of the construction of dams (e.g. Syvitski et al. 2005, 2009; Walling 2006; Blum and Roberts 2009; Giosan et al. 2014). Many deltas and coastal plains accumulate less sediment and are now sinking. Human impact on peat growth in coastal plains is even more dramatic. To cultivate coastal peatlands, they are drained, after which peat immediately stops forming. Moreover, aeration causes peat to first shrink and then oxidise (aerobic decomposition), resulting in volume reduction and emissions of CO_2 and other greenhouse gasses. In addition to that, peat consolidates when loaded, resulting in a further volume reduction and subsidence. Thus, putting an end to peat growth actually reverses the process, 'emptying' accommodation space that was initially filled with organic material. Altogether, cultivation of coastal peatlands has a double environmental impact: subsidence locally challenges water management and enhances flood risk, and the associated CO_2 respiration contributes to greenhouse gas concentrations in the atmosphere (Hiraishi et al. 2014 and references therein).

Reference studies are needed to explore the potential consequences of cultivation of coastal peatlands on both local and global scales. The processes causing subsidence and CO_2 respiration from drained peatlands are fairly well known, and various field studies at plot to regional scales have reported subsidence measurements (e.g. Stephens 1956; Schothorst 1977; Gambolati et al. 2006; Drexler et al. 2009; Deverel and Leighton 2010), sometimes in combination with CO_2 emissions (e.g. Deverel and Rojstaczer 1996; Wösten et al. 1997; Grønlund et al. 2008; Van den Akker et al. 2008; Hooijer et al. 2012).

While intensive land use in most coastal peatlands dates back several decades, measurements of both subsidence and CO_2 respiration are short, often limited to a couple of years. Even longer available records of peatland subsidence date back less than two centuries, for instance Holme Post, England (UK), where 4 m of subsidence has been recorded since 1848 (Hutchinson 1980). Moreover, most peatland subsidence records are point measurements. Measuring subsidence in peatlands across larger areas is notoriously difficult, due to the large error ranges associated with the measurement techniques, and the low, yet varying rates of subsidence. In fact, it is questionable whether available measurements can be scaled up to entire peat landscapes over longer timescales at all, as the underlying processes and their relative contributions, including cultivation and drainage techniques, are non-stationary. This limitation is unfortunate, because the limited spatial scales of the available subsidence measurements present a strong contrast with the continuously increasing scales of human impact, which is now rapidly extending across entire coastal plains on a global scale. Year after year, more peatlands, mostly tropical ones, are drained for agricultural use (e.g. Hooijer et al. 2006, 2010), the cumulative effects of which on the longer term are still largely unknown.

This paper presents estimates of the compaction, oxidation and exploitation of peat, the associated subsidence and CO_2 emissions for the Dutch Holocene coastal plains over the past 1,000 years. This area is particularly interesting for a reference study for two reasons of which the most important is that, in the coastal plain, peat is prevalent and the peatlands arguably have the longest history of intensive draining and exploitation in the world. The cumulative effects are therefore large and well identifiable. Secondly, it is a well-studied area, offering an abundance of data and prior studies, allowing for quantitative estimations.

Geographical setting and history of the Dutch coastal plain

The Dutch coastal plain is part of the North European Plain (Fig. 1) and has a surface area of about 16,800 km^2. A Holocene coastal sedimentary wedge of as much as 20 m in thickness developed during the last 8,000 years under conditions of relative sea level rise, fluvial and marine sedimentation and peat growth in a tranquil back-barrier environment (e.g. Beets and Van der Spek 2000; Berendsen and Stouthamer 2000; Vos 2015). When relative sea level rise decelerated during the late Holocene, primary marshes and mires started evolving into ombrotrophic peat domes (bogs dominated by *Sphagnum* spp) surrounded by minerotrophic fens composed of *Phragmites*, *Carex*, and occasional tree species such as *Alnus* (Verhoeven 1992; Pons 1992). Over the last 2,500 years, large storm surges breached the northern and southern parts of the coastal barrier. Here, back-barrier peatlands were extensively eroded and covered by marine clastic deposits (Vos and Van Heeringen 1997). The central part of the coastal barrier remained intact, effectively sheltering the peat area from storm energy.

During the High Middle Ages, the Netherlands saw a strong increase in population, as well as a transition towards an ever more urbanised society (Van de Ven 1993). In order to feed the growing population, between AD 1000 and 1300, the coastal peatlands were drained to create arable land in a co-operative effort, creating the water boards that still manage water in the Netherlands. As a result, the peatlands subsided and from the 14th century onwards, drainage using natural gradients became impossible. Progressively more windmills needed to be erected to drain the coastal plain and to maintain sufficient freeboard. Still, most peatlands remained too wet for crop farming and could only be used as livestock meadows, which are still the dominant land use to date.

A growing demand for fuel accompanied the increasingly urbanised and industrialised society. Because of an increasing scarcity of wood, the Dutch started mining the highly calorific ombrotrophic peat from around AD 1100 onwards (Gerding 1995). Until the late 19th century, peat deposits were completely excavated across large areas, down to the underlying clastic sediments, creating deep lakes (up to ~6 m). The peaty lakeshores turned out to be vulnerable to erosion, especially during storms, and from the 17th century onwards most of these lakes were reclaimed to counter erosion and create more farmland. At present, a quarter of the country is below

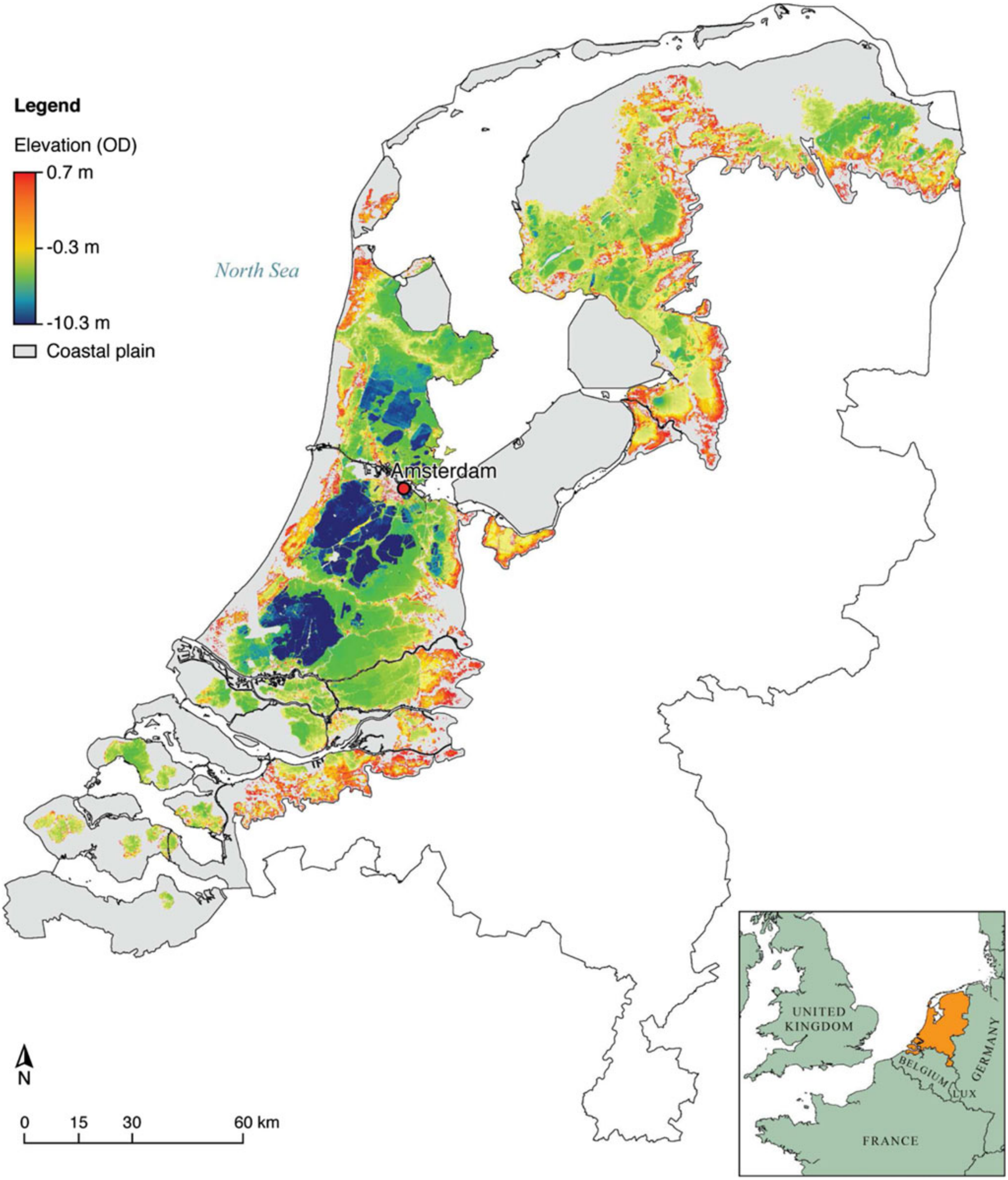

Fig. 1 The coastal plain (*grey area*) in The Netherlands, in northwestern Europe (*inset*). The landward boundary of the coastal plain was defined geologically or by elevation (see text for explanation). The *coloured areas* indicate the present-day elevation of the peatlands in the Dutch coastal plain using the 2005 version of AHN (Anonymous 2016). The lowest elevations are found in reclaimed lakes. Extreme values (of more than −10 m below OD) are probably recent excavation sites and are very limited in spatial extent. The lowest elevations as a result of historical human land use are just over 6 m below OD

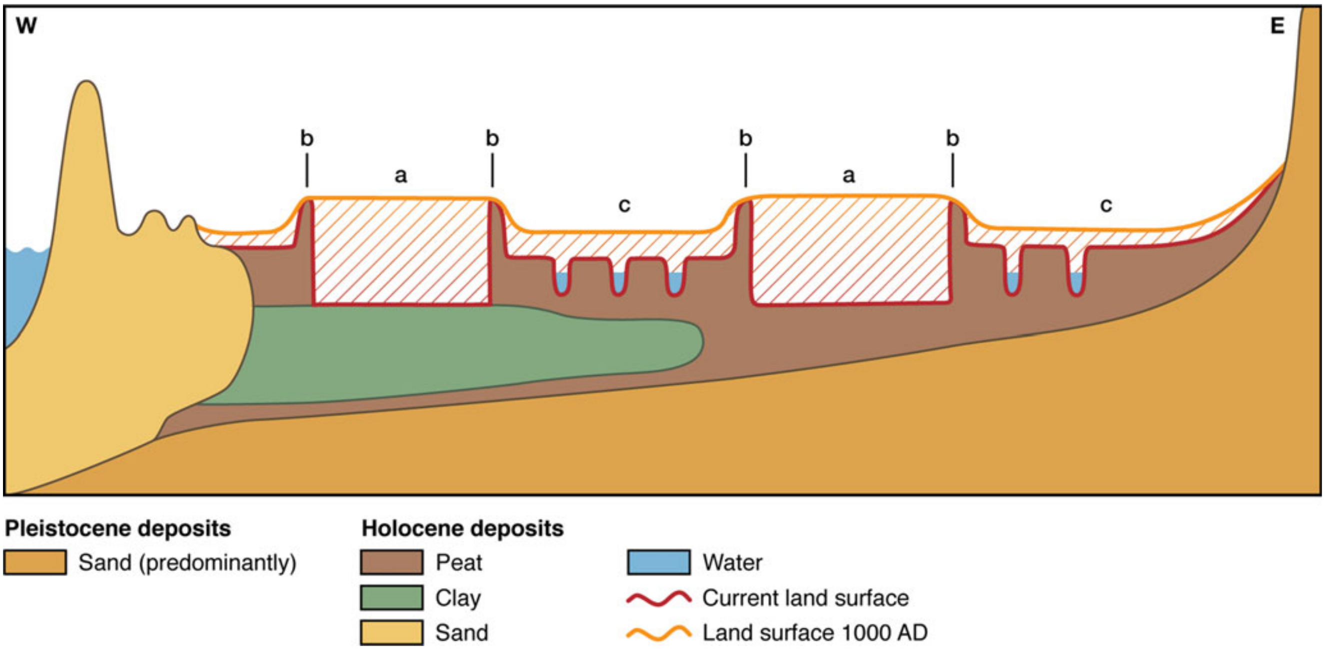

Fig. 2 Schematic cross-section across the Dutch coastal plain in its most peaty development. A sandy coastal barrier is present in the west. On the landward side, a wedge of fine-grained clastic back-barrier deposits is enveloped in organic deposits. The land surface of AD 1000 represents a more or less pristine bog and fen landscape; the current land surface reflects the effects of a thousand years of cultivation. The current lowest areas are mined peat bogs (*a*), the remnants of which function as dykes (*b*). Fen areas (*c*) are primarily lowered by subsidence attributed to water table drainage, as indicated schematically by ditches. *Hatching* between the historic and present land surface indicates the volume loss of peat, the reconstruction of which is the first objective of the study

mean sea level (MSL), and subsidence is ongoing as a result of the continuous drainage of the peatlands (Fig. 2).

Approach, materials and methods

General approach

The approach followed to calculate the peat loss over the last 1,000 years is based on the main steps that are depicted in Fig. 3 and further detailed in the following. First, a historical elevation model was created. To estimate subsidence (elevation change) over that period, a present-day elevation model was subtracted from the historical one (providing a 1,000-year height difference map). Subsequently, areas that experienced elevation changes that could not be attributed to peatland cultivation were excluded. Then, a distinction was made between elevation changes that were caused by peat excavation, and by subsidence proper (i.e. resulting from drainage). In order to assess CO_2 respiration, it is essential to distinguish between subsidence due to the oxidation of organic matter, which contributes to CO_2 respiration, and consolidation, which does not. For that purpose, geotechnical data from the literature and unpublished records were compiled.

The large-scale approach required making a number of assumptions and simplifications. The most important simplification in this paper is that all deposits with more than 20 % of organic matter by weight are referred to as peat, including deposits that are normally classified as clayey peat, muck, organic mud, organic matter detritus, or gyttja deposits. This corresponds to the whole range of organic deposits defined in international soil classification standards (e.g. Berendsen and Stouthamer 2000; USDA 2005). An important assumption is that bulk density and organic matter content values derived from current deposits are also valid for peat that has now disappeared. Finally, all emitted soil carbon (C) has been converted into CO_2, even though it may have partly been emitted in another form, for instance methane (CH_4).

For current elevation (further referred to as DEM2005), the 2005 version of AHN (Actueel Hoogtebestand Nederland) was used, which is a public domain, high-resolution digital elevation model published by the Ministry of Infrastructure and the Environment (Anonymous 2016). It is based on airborne laser-altimetry data, discretised on a grid of 1 × 1 m, the elevation values of which have a vertical precision of 5 cm.

Creating a historic elevation model

As a first step to create an elevation model for AD 1000 (further referred to as DEM1000), the extent of the coastal plain at that time needed to be determined, which was defined as all land in the present coastal plain (grey area in Fig. 1) that is currently

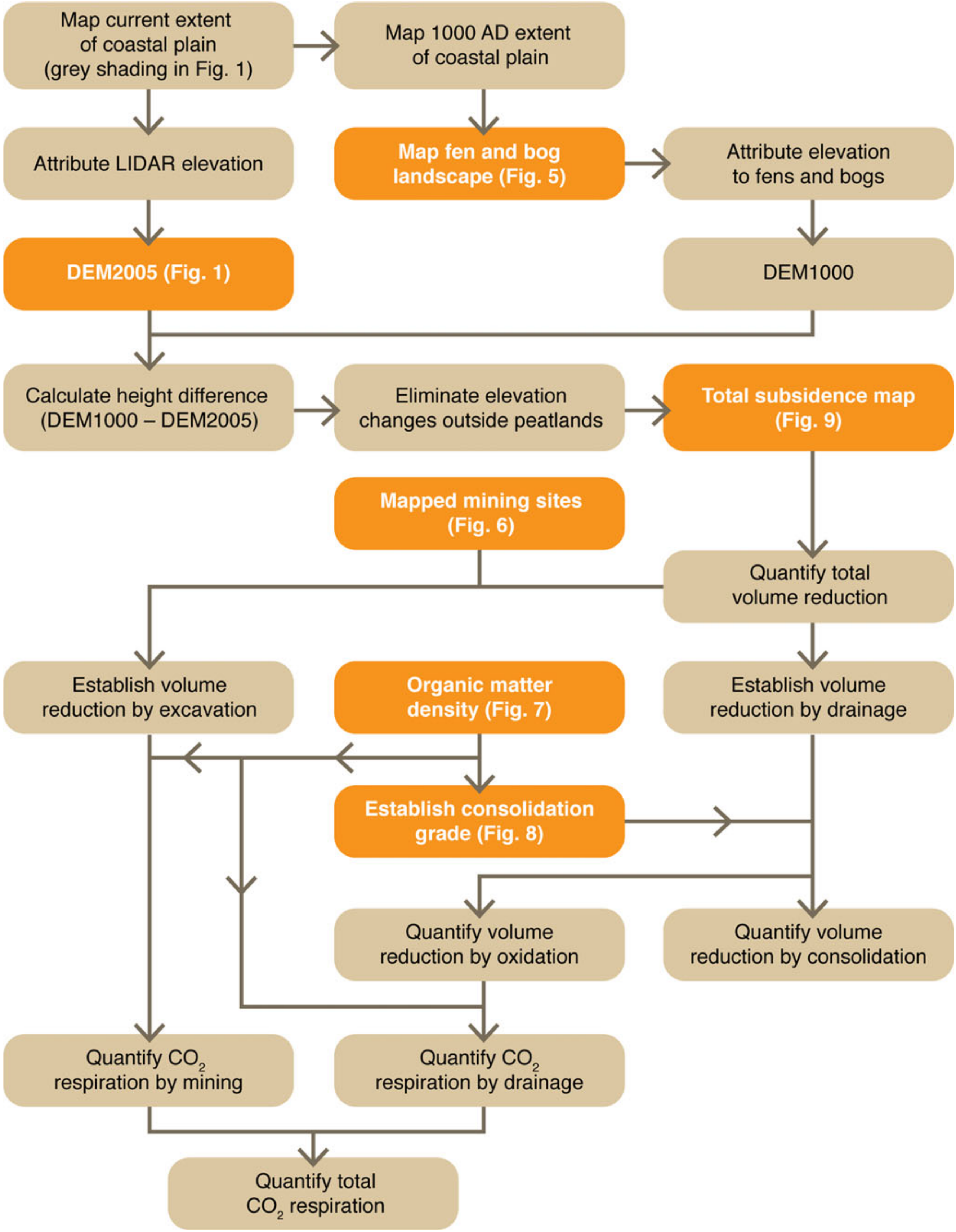

Fig. 3 Flowchart of the procedure of the study (see text for explanation)

below the mean high water of AD 1000 (further referred to as MHW1000). On the basis of detailed palaeogeographic reconstructions, Vos and Knol (2013) put that level at 1 m above mean sea level (amsl) of AD 1000, which, in turn, is 0.3 m below current mean sea level (Van de Plassche 1982). As eustatic sea level rise over the past 1,000 years has been close to zero (Peltier 2002), the 0.3-m rise is entirely attributed to background subsidence, i.e. natural consolidation (auto-compaction), isostacy and tectonic movement (Kooi et al. 1998). Hence, MHW1000 is put at 0.7 m above current msl (i.e., 0.7 m above Dutch ordnance datum). This value was used to clip DEM2005 and define the study area (the coloured area in Fig. 1).

Once the extent of the coastal plain of AD 1000 was established, the historical peat landscape was reconstructed as a next step in creating a palaeo-elevation model for the coastal peatlands. It was assumed that the coastal plain of AD 1000 was still largely in equilibrium, so sedimentation and peat growth had been able to keep up with relative sea level rise until that time, and the entire surface elevation was above msl (cf. Pons 1992). Peatlands are complicated patchworks of different peat types depending on, among other factors, local hydrology, sediment inputs, vegetation succession and subsurface characteristics. For the purpose of this particular study, the only distinction that needed to be made was between bogs and fens, because of the difference in peat volumes held in these two landscape types.

Bogs are domes formed by peat growing *above* the regional groundwater level, creating relief, unlike fens, where growth is limited by the regional groundwater level, forming the lower elevated landscape. Previous studies used the extent of dykes and parcelling patterns to reconstruct peat bog colonization, and delineate the former peat bog area (Pons 1992); an example of this is given in Fig. 4. Another source of information is presented by nationwide palaeogeographic reconstructions of Vos et al. (2011) and Vos (2015), which are based on detailed sampling and dating of cores taken from the Dutch coastal plain. Both palaeobotanical and palaeogeographic reconstructions were used to arrive at a simplified historical bog and fen landscape, with some open water in between (Fig. 5). Where no information on the palaeo-environment was available, a (low) fen landscape was conservatively assumed to have been present.

There is an abundance of data on the height of peat bogs in current peatlands (e.g., Borger 1992; De Bont 2008), and height estimates from palaeo-landscape reconstructions (Pons 1992; De Bont 2008), which was used to transform the historic peat landscape to the desired elevation model (DEM1000). It was conservatively assumed that all peat bogs had reached an elevation of 2 m amsl (i.e., 1.7 m above Dutch Ordnance Datum to correct for background subsidence), with a range of 1–4 m. The fact that bogs have slopes was not accounted for in this study. The slight overestimation of height at the fringes of bogs due to this simplification is insignificant on the scale and resolution of this study.

A best estimate of fen height of 80 cm amsl (i.e. 0.5 m above Dutch Ordnance Datum), with a range of 50–150 cm, is similarly conservative. Where a fen or bog directly overlay outcropping Pleistocene deposits at the fringes of the coastal plain, the peat was assumed to have sloped parallel to the gradient of that surface, in accordance with palaeobotanical reconstructions of De Bont (2008) and Van Loon et al. (2009). The effects of uncertainty in the bog and fen height estimates were assessed by using the lower and upper elevation values in minimum and maximum volume scenarios, respectively.

Excluding subsidence outside peatlands

Not all differences between DEM1000 and DEM2005 can be attributed to subsidence caused by peatland cultivation. Water bodies in the area may have silted up, or enlarged due to erosion. In addition, artificially raised grounds and mining pits have altered the elevation of the current landscape. Existing topographic maps and a query of DEM2005 for outliers (e.g., sand pits having depths of 50 m) were used to identify and eliminate such areas and processes from the calculations made in this study.

Areas formed by clastic deposition, mainly tidal sediments, may have experienced local elevation changes due to sedimentation and erosion, and regionally due to ripening and consolidation. Although this shows up as elevation difference when subtracting the DEMs, these processes are not the focus of this study and were eliminated from the calculations. In addition, areas where peat oxidation was impeded by a clayey topsoil of at least 1.5 m were discarded. The extent of these areas was inferred using results from GeoTOP and NL3D, high-resolution national 3D models issued by the Geological Survey of the Netherlands. GeoTOP is a systematically produced voxel model, attributed with lithostratigraphic unit, lithologic class and their uncertainties, having a 3D resolution of 100 × 100 × 0.5 m (Stafleu et al. 2011; Van der Meulen et al. 2013; Maljers et al. 2015). GeoTOP does not have national coverage yet; where unavailable, its predecessor NL3D, which has a resolution of 250 × 250 × 1 m, was used (Van der Meulen et al. 2013). The resolution difference with GeoTOP is largely insignificant at the scale and level of simplification of the present study, and extra detail was obtained from the digital soil map of the Netherlands (De Vries et al. 2003) and the palaeogeographic maps of Vos et al. (2011) and Vos (2015).

Virtually all peat considered is the main lithologic constituent of the Nieuwkoop Formation; peat (including other organic deposits) also occurs as a subordinate lithology in the marine clastic Naaldwijk Formation (lithostratigraphic nomenclature cf. De Mulder et al.

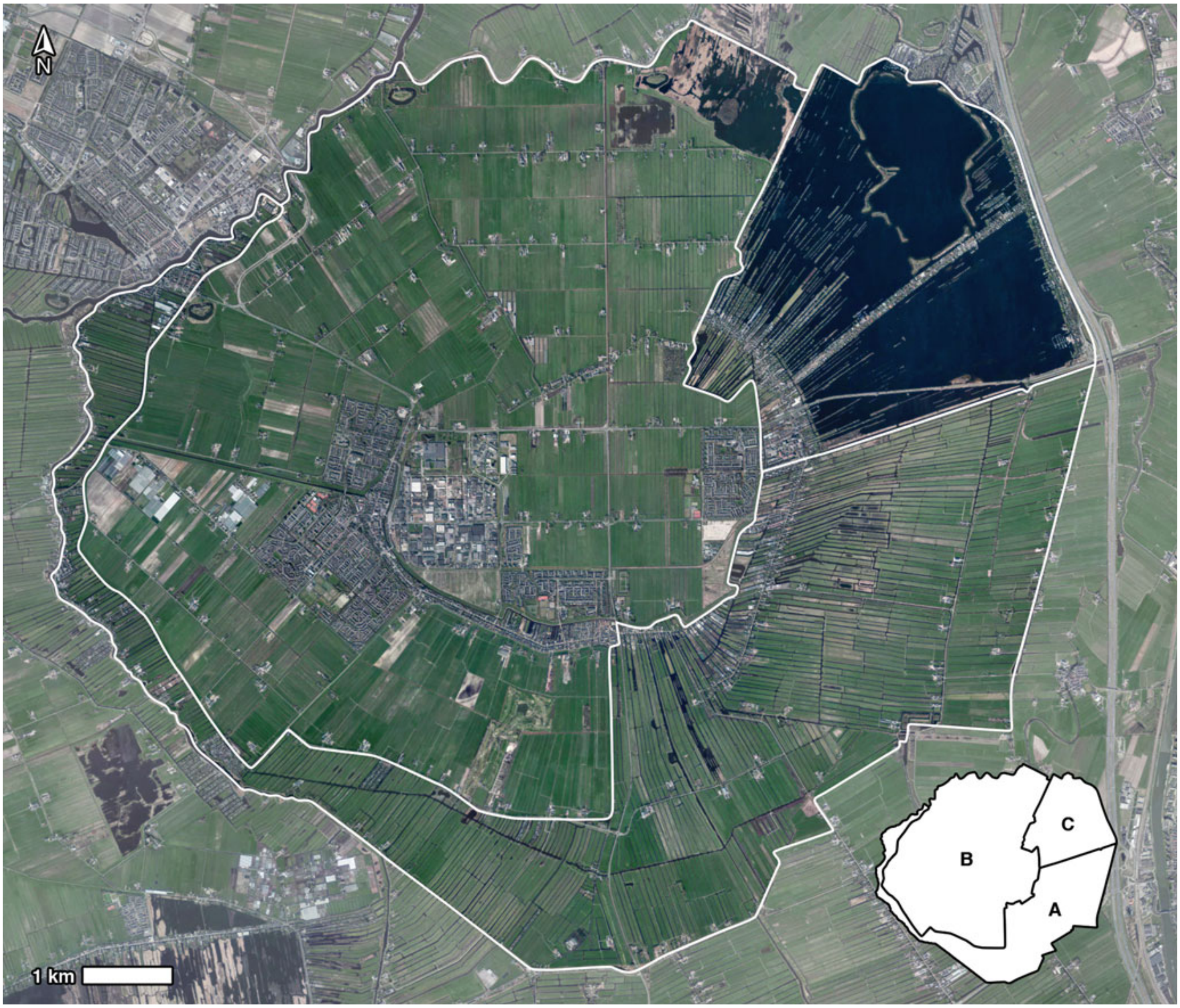

Fig. 4 Aerial photo of De Ronde Venen ('the round peats'), a former peat bog south of Amsterdam, identifiable by parcelling patterns and landscape elements (see Fig. 5 for location). The radial, tightly spaced ditch pattern in zone *A* reveals how the bog was colonised and drained from outside inwards, starting from the surrounding natural creeks. The blocky, less obtrusive parcelling observed in zone *B* indicates that peat mining led to the exposure to the underlying clastic deposits (which needs less drainage). The lakes in zone *C* were mined as well, but never reclaimed. Background image created with licensed ArcGIS® software, using imagery published by Aerodata/Cyclomedia on the ArcGIS online platform (powered by ESRI)

2003). GeoTOP and NL3D allowed to query stratigraphically and lithologically in 3D, zooming in on peat within the depth range of interest (cf. Van der Meulen et al. 2005, 2007a). Exclusion from the volumetric calculations took place by clipping the differential elevation map with the extents of all the aforementioned features. In the resulting reconstruction, the Dutch coastal peatlands have an area of 7,874 km^2 (including the extent of removed peat) and make up 47 % of the total extent of the coastal lowlands around AD 1000.

Mined peat

Two processes causing volumetric loss were distinguished (Fig. 2): peat drainage, which occurred in the entire coastal plain, and peat mining, which was undertaken in designated sites. This differentiation is relevant for CO_2 emission estimates: one can safely assume that excavated peat has all been burnt, generating CO_2, unlike volumetric loss caused by consolidation.

To estimate the contribution of mining to the total peat volume reduction, a database of nation-wide historical land

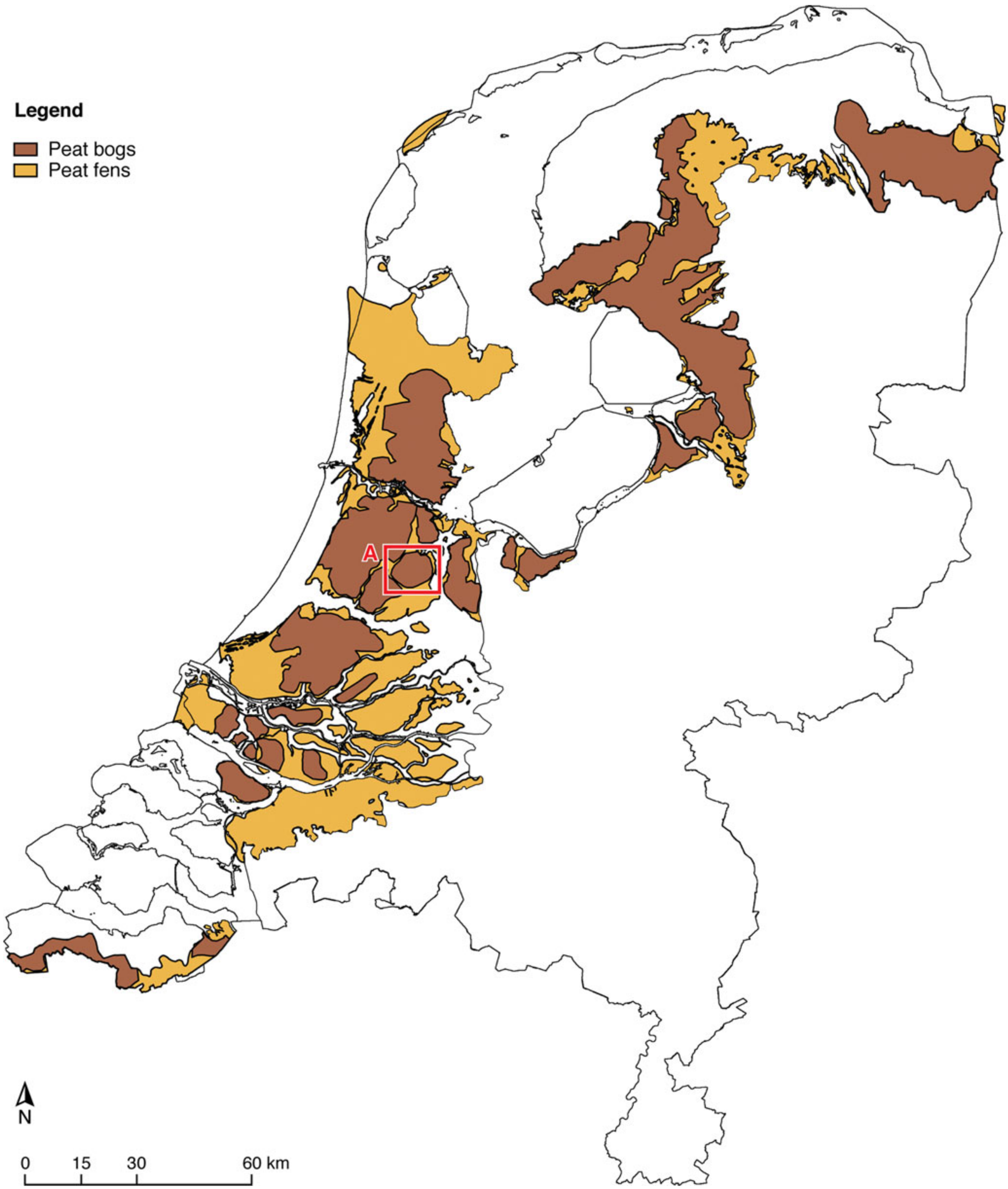

Fig. 5 Reconstruction of the peat bogs and fens landscape around AD 800, based on palaeobotanical and palaeogeographic reconstructions (Pons 1992; Vos et al. 2011; Vos 2015). The location of Fig. 4 is marked by the *red A*

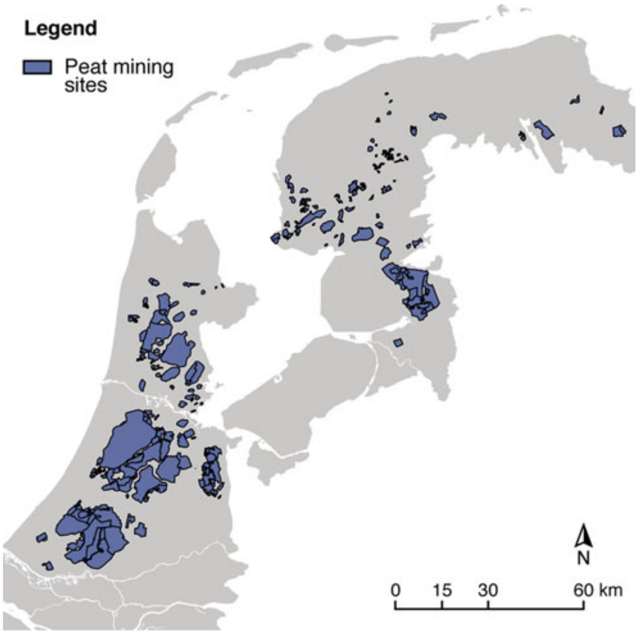

Fig. 6 Reconstruction of peat mining sites, based on a combination of landscape analysis and documentary sources

use (De Bont 2008) was used to delineate former mining areas (Fig. 6). The classification and mapping were supported and supplemented by historical records of windmill constructions over the last centuries (Dutch Wind and Water Mill database), local land reclamation information (e.g. Van de Ven 1993) and parcelling patterns (cf. Fig. 4). Depending on the source(s) of information, a confidence class was assigned to each mining site: *high* (supported by historical documents); *medium* (most characteristic landscape elements are present); and *low* (only based on elevation or parcelling). High confidence and medium confidence sites constitute 61 and 30 % of the total extent of peat mining, respectively. The medium confidence category refers to sites for which it is unclear how much of it was created by mining, and how much resulted from subsequent erosion; however, because this erosion could only have happened after mining, this component was added to the volume lost by excavation. Most of the eroded peat will have been washed ashore, forming a deposit that is prone to oxidisation. A smaller, yet unknown amount was redeposited as detritus on the lake bottom, and may not have oxidised. For low confidence sites (9 %), volume loss could result from either post-mining or natural erosion. These sites were nonetheless included in the budget calculations; the maximum volume overestimation associated with this uncertainty is 2.5 %.

Distinguishing between peat oxidation and consolidation

After isolating mined peat, the focus was put on the areas where peatlands subsided solely as a result of drainage. Volumetric loss of peat caused by drainage is the combined result of shrinkage, oxidation and consolidation (Schothorst 1977). Shrinkage refers to the volume loss caused by the contraction of plant fibres and pores when peat is exposed to air. Shrinkage is largely irreversible, rehydrated peat will not regain its initial volume. Shrinkage happens fairly quickly and occurs only in the zone above the phreatic groundwater level. In the same zone, the introduction of oxygen increases the decomposition of organic matter, i.e. the peat oxidises. Peat oxidation persists as long as there is organic matter available above the phreatic water table, and as subsidence in cultivated peatlands will provoke more drainage, it becomes a self-perpetuating process, continuing as long as peat is available for oxidation.

Consolidation is volume loss caused by compression. The density of peat is so close to that of water that buoyancy significantly reduces autocompaction in a saturated peat column. However, once drained, the weight (load) of the peat above the lowered water table will lead to consolidation of the peat below the groundwater table. The weight of farming equipment or any structure that is put on top of the peat will cause additional loading and consolidation. After applying a load, most of the consolidation occurs within a few years, but visco-plastic deformation (creep) persists for decades.

Shrinkage, oxidation and consolidation all contribute to land subsidence, but only oxidation causes CO_2 emission. In order to quantify the CO_2 respiration, the contribution of peat oxidation to the overall loss of peat volume in the study area had to be estimated. This is not straightforward, especially in the Dutch case, where a cultivation history of 1,000 years had to be considered. Experimental drainage studies in agricultural-used peatlands (Schothorst 1977) show that as much as 50 % of all surface subsidence occurring during 6 years of deep drainage can be attributed to oxidation, 15 % to shrinkage, and 35 % to consolidation (referred to as compaction in the original paper). In these studies, maximum drainage depths between 50 and 100 cm below the surface were applied. Historical drainage depths will have been considerably shallower, on the order of ~20 cm (Kuhlman et al. 2010). The associated loading effect will have been accordingly lower, so the measured contribution of consolidation by Schothorst (1977) must therefore be considered a maximum for this study. When considered on time scales beyond those of available experiments, all shrunken peat will ultimately oxidise, so the volumetric reduction by shrinkage may be added to that by oxidation, attributing the original density to the aggregate volume. Experimental geotechnical studies indeed suggest that at present at least 70 % of the human-induced subsidence in the Netherlands is due to oxidation (Den Haan and Kruse 2006).

In this study, the amount of peat consolidation was quantified by comparing the dry bulk density of consolidated with fresh, unconsolidated, peat (Bird et al. 2004; Van Asselen 2011). This was done for a database consisting of 985 organic matter and dry bulk density measurements of peat samples, collected over the entire coastal plain. These samples were analysed by the Geological Survey of the Netherlands and by Utrecht University (Erkens 2009; Van Asselen 2010). The organic matter content (percentage by weight) was determined using the loss-on-ignition method as described by Heiri et al. (2001). Bulk density was measured by weighing and drying peat samples with a known volume (Van Asselen 2010). By multiplying the dry bulk density (kg/m^3) of the sample with the relative organic matter content (%), the organic matter density is derived (kg/m^3; Fig. 7).

Based on measurements by Van Asselen (2011), it is estimated that fresh, unconsolidated Dutch peat has an organic matter density of ca. 70 kg/m^3. For a subset of peat samples which have a relative organic matter content > 20 % and range between fresh and consolidated, the method described by Van Asselen (2011) was used to calculate the amount of consolidation (expressed as percentage volume loss) that was needed to obtain the measured organic matter density. The method was not applied to samples that experienced extra consolidation as a result of burial and loading by thick (>150 cm) clastic deposits. Because of the burial depth, this peat is not likely to oxidise, and including these samples would increase the average organic matter density values beyond realistic extents. For the remaining 447 samples, the consolidation was plotted against the organic matter density (Fig. 8). The consolidation of individual samples ranges between 0 and 57 % depending on the organic matter density. The variation in consolidation

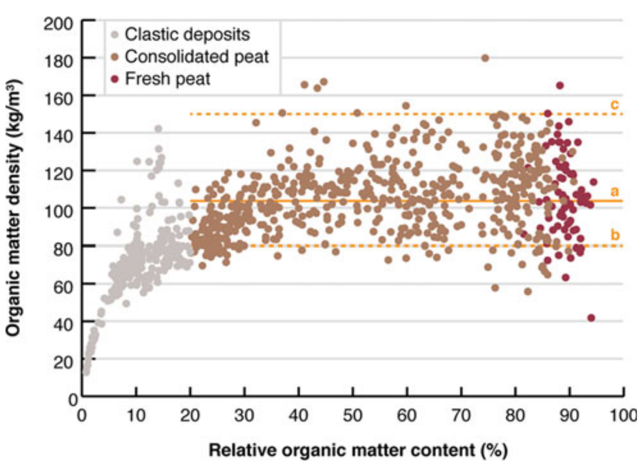

Fig. 7 The relation between relative organic matter content (%) and organic matter density (kg/m^3) for samples (n = 985) taken from the Dutch coastal peatlands. The organic matter density is largely independent of the organic matter content for values greater than 20 %. The average organic matter density of these samples is 103 kg/m^3 (a), with a lower and upper estimated average value of 80 and 150 kg/m^3, respectively (b and c). This range reflects porosity variations of peat, and depends on the degrees of consolidation and decomposition, and on peat composition. The range in organic matter density of fresh peat samples coincides with that of consolidated peat, which suggests that none of the samples are strongly consolidated

for single organic matter density values is the result of the clastic content of the samples, as represented in the x-variation in Fig. 7; samples with lower clastic content consolidate more than samples with higher clastic content.

Calculating CO_2 respiration

To calculate CO_2 respiration (as a result of oxidation or combustion), the amount of organic carbon per volumetric unit is needed. Organic matter density is independent of the relative organic matter density for samples with a relative organic matter content > 20 % (Fig. 6). This implies that clay and silt content, which is highly variable in the Dutch subsurface, has no impact on the amount of organic matter per unit volume, and it is justifiable to attribute a single value per scenario for organic matter content to all organic deposits in the Dutch coastal plain. The average organic matter density of peat in the Dutch subsurface is 103 kg/m^3; minimum and maximum scenarios have values of 80 and 150 kg/m^3, respectively. When the carbon content of organic matter is assumed to be 50 % (cf. Kuikman et al. 2003), the resulting average carbon density for peat becomes 52 kg/m^3, a value that compares well with literature data (e.g. Gorham 1991; Page et al. 2010). This value was used to convert the loss volume attributed to oxidation and combustion to calculate the total mass of soil carbon (soil-C) lost. Ratios of 1.00:3.67 for the conversion of soil-C to CO_2, and 1.00:0.47 for the conversion of CO_2 to atmospheric carbon in parts per million in volume (cf. Van den Bos 2003) were subsequently applied.

Consolidation values were assigned to the density scenarios using Fig. 8. In the minimum density scenario, consolidated organic matter density is 80 kg/m^3, which means that 7 % of the total volume loss in drained areas was the result of consolidation (and 93 % due to oxidation). In the maximum density scenario, organic matter density of the lost peat is

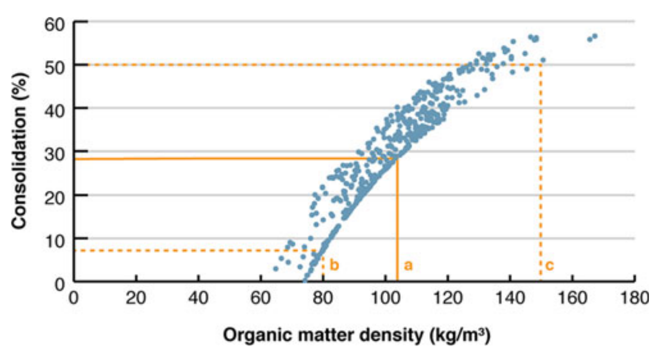

Fig. 8 The relation between the volumetric consolidation (%) as a result of loading of peat in the Dutch coastal plain, and the organic matter density (kg/m^3) (n = 447). Based on these values three density scenarios were defined: (a) *best estimate*, with an organic matter density of 103 kg/m^3 and a consolidation of 28 %, (b) *minimum*, with an organic matter density of 80 kg/m^3 and a consolidation of 7 %, and (c) *maximum*, with an organic matter density of 150 kg/m^3 and a consolidation of 50 %

150 kg/m^3, in which case consolidation caused 50 % of the total volume reduction. A best estimate scenario uses the average organic matter density (103 kg/m^3) and an associated consolidation value of 28 % (and a contribution of oxidation of 72 %). These density scenarios were added to the volumetric scenarios, arriving at a total of seven scenarios: best estimate (best estimates for volume and density), minimum and maximum density (with best estimate for volume), minimum and maximum volume (with best estimate for density), and absolute minimum and maximum (all parameters set at minimum or maximum, respectively).

Results

Subsidence

According to the best estimate scenario, the reduction in peat volume in the Dutch coastal plain over the last 1,000 years was 19.8 km^3. Figure 9 shows the spatial distribution of the associated subsidence. Over the total peatland area (Fig. 1), this equates to a spatially averaged land surface lowering of 2.5 m over 1,000 years, at an average rate of 2.5 mm/year. This excludes background subsidence due to natural consolidation, isostacy and tectonic movement, which would add an additional 0.3 mm/year. Table 1 shows the variation in the results obtained by applying the minimum and maximum heights for fens and bogs. The resulting volume-loss and subsidence estimates range from 14.5 to 30.0 km^3 and from 1.84 to 3.83 m, respectively.

The patterns in Fig. 9 clearly reflect the two processes that contribute to subsidence. Peat mining sites stand out as zones of maximum land level lowering in the central western part of the coastal plain. Figure 10 shows a bimodal frequency distribution of total subsidence calculated for the best estimate scenario: mining sites were typically excavated over a depth of 6–6.5 m, while the average subsidence of drained areas, reflected in a second peak, is 1.5–2.0 m. Peat has been mined over an area of 1.2 × 10^3 km^2, which amounts to 15 % of the surface area of the coastal peatlands (7.9 × 10^3 km^2). Peat loss due to mining, including subsequent lakeshore erosion, amounts to 6.8 km^3 or 34 % of the overall volume reduction. The share by volume is larger than the share by surface because the mining was mainly undertaken in the elevated peat bog areas (Fig. 4). In the remaining parts of the coastal peatlands, a total of 13.0 km^3 (66 % of the total volume loss) has been lost as a result of drainage. Here, the average total subsidence is 1.9 m, at an average rate of 1.9 mm/year over the past millennium, in addition to background subsidence.

CO_2 respiration

In the best estimate density scenario, the volume reduction due to consolidation was 3.7 km^3, 9.4 km^3 of peat oxidised, and 6.8 km^3 of peat was mined or eroded after mining, and assumed to have been oxidised as well. By combining the latter two volumes, a total of 16.2 km^3 of peat respired. This volume is estimated to have held 0.83 Gton of soil carbon, so Dutch management of coastal peatlands over the last 1,000 years resulted in the release of an estimated 3.1 Gton of CO_2 into the atmosphere.

Table 1 shows the range of CO_2 respiration amounts for different scenarios of volumetric loss and organic matter density combined with oxidation/consolidation ratios. CO_2 emission ranges from 2.02 to 5.72 Gton, which is largely determined by the uncertainty in the volumetric estimates and less so by the density scenarios. This is due to the correlation between consolidation and organic matter density: the contribution of consolidation decreases with decreasing organic matter density, counteracting the effect of the lower density in the C-loss calculations. The share of total estimated CO_2 release by drainage (1.79 Gton) is larger than that of peat burning (1.28 Gton). The average estimated CO_2 emission resulting from the drainage of the Dutch coastal peatlands is 2.3 t/ha/year over the last 1,000 years.

Discussion

Overall costs and consequences of water management

A thousand years of peatland cultivation and exploitation lowered the Dutch coastal lowlands 2.5 m, to an average 1.3 m below sea level. Water-table management in terms of peat drainage, the prime cause for this subsidence, results in a positive feedback loop between water-table lowering and subsidence: water-table lowering causes peatland subsidence, and land surface lowering provokes further water-table lowering. Direct water management costs in the Netherlands are now on the order of 2 billion euros per year (OECD 2014), an amount that is likely to increase with ongoing drainage and subsidence, and further population and economic growth. It has recently been suggested that necessary improvements of the water management and flood protection systems in the Netherlands may cost an additional 3.1 G€/year until 2050, which equates to about 0.5 % of the current gross national product (GNP) of the Netherlands (Kabat et al. 2009).

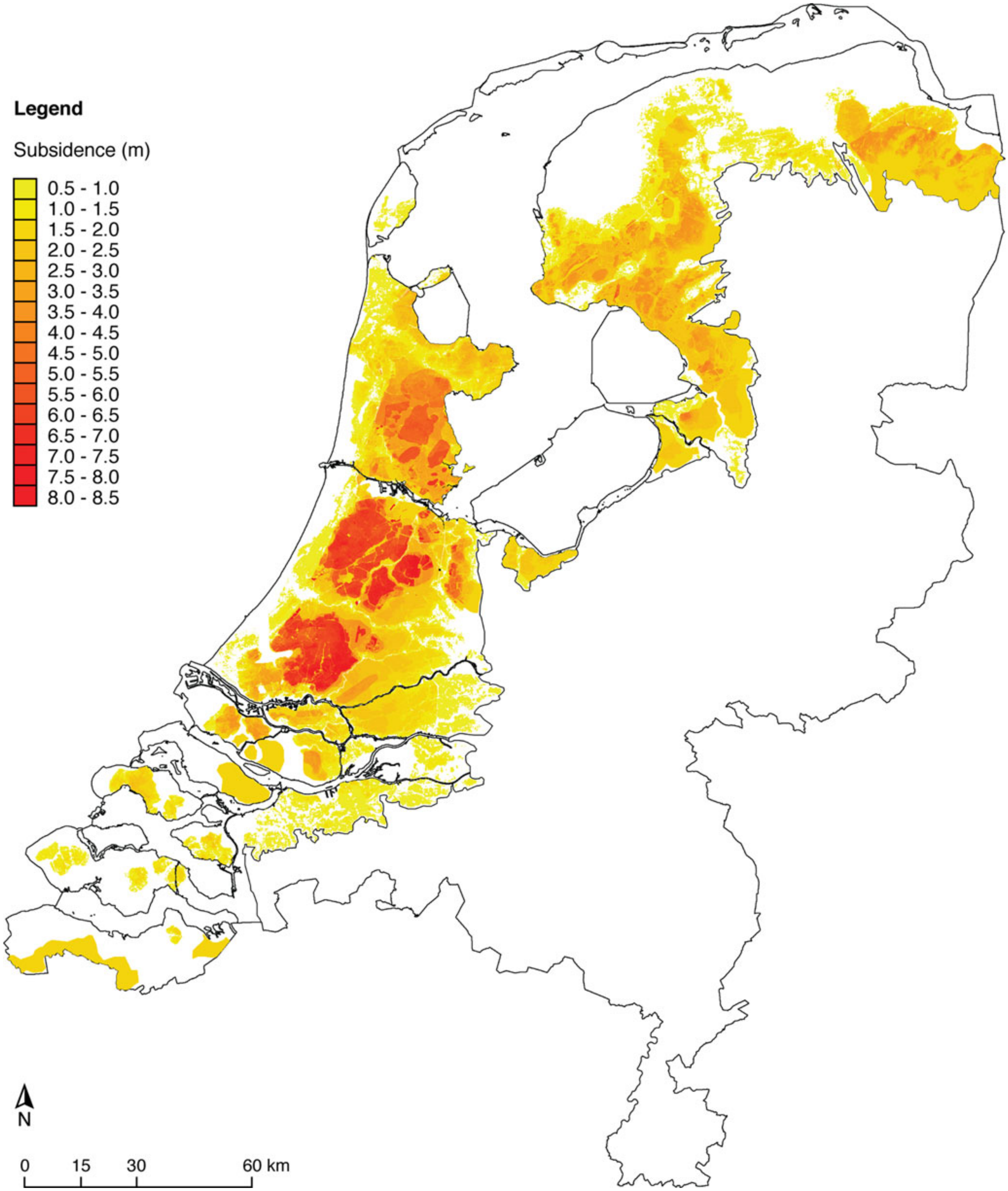

Fig. 9 Subsidence of the peat landscape since AD 1000, obtained by subtracting the current elevation (DEM2005) from the reconstructed palaeo-elevation (DEM1000). Depicted are the results for best estimates of bog and fen height. A comparison with Figure 6 reveals that the highest values are found in former peat mining areas. In the legend, a subsidence range of 'a – b' denotes the interval 'a – <b'

Table 1 Subsidence and CO_2 respiration for different volume and density scenarios. Best estimate values are in *italic*

Scenario[a]	Bog height (m)	Fen height (m)	Volume reduction (km^3)	Total subsidence[b] (m)	Organic matter density (kg/m^3)	Soil carbon equivalent (Gton)	CO_2 equivalent (Gton)	Atmospheric carbon equivalent (ppmv)[c]
Absolute minimum	1	0.5	14.5	1.84	80	0.55	2.02	0.26
Minimum volume	1	0.5	14.5	1.84	103	0.61	2.22	0.28
Minimum density	2	0.8	19.8	2.49	80	0.76	2.78	0.36
Best estimate	*2*	*0.8*	*19.8*	*2.49*	*103*	*0.83*	*3.07*	*0.39*
Maximum density	2	0.8	19.8	2.49	150	1.00	3.66	0.47
Maximum volume	4	1.5	30.0	3.84	103	1.30	4.78	0.61
Absolute maximum	4	1.5	30.0	3.84	150	1.56	5.72	0.73

[a] See text for explanation

[b] Spatially averaged

[c] Parts per million by volume

Historic vs current emissions of CO_2 from Dutch peatlands

During the past 1,000 years, peat has been mined for an estimated 800 years. During that period, the estimated average annual CO_2 emission as a result of peat combustion was 1.60 Mton/year, which is only slightly less than the estimated average respiration of 1.79 Mton/year due to drainage. Peat mining has not been constant over time, however, due to variations in economic and population growth, and the varying availability of other energy sources, i.e., the phasing out of wood and the phasing in of coal.

The historical peat-combustion-related CO_2-emissions peak presumably coincided with the peak of coastal peat excavation in the 17th century during a period of economic prosperity. A reconstruction of Dutch energy consumption in AD 1650 from historical sources based on average energy demand (Gerding 1995), assuming that peat was the main energy source, was used to estimate that 3.0 Mton of CO_2 was emitted per year by peat combustion. This maximum value exceeds the estimated average CO_2 respiration due to drainage, and because drainage of peatlands peaked much later (subsequent section), it is implied that peat mining was the largest source of CO_2 emissions in the Netherlands at that time.

Today, the Dutch residual demand for peat, primarily for horticultural purposes, is met by imports, mainly from Germany (Van der Meulen et al. 2007b), and CO_2 emissions from Dutch coastal peatlands result solely from drainage. Both estimated average CO_2 emission due to drainage and the estimated 17th century emission peak resulting from large-scale peat combustion are considerably lower than the annual drainage-related release of 4.0 to 8.0 Mton CO_2 in the Netherlands measured during the last decades (e.g. Van den Akker et al. 2008; Joosten 2009). This shows that drained peatlands have become a larger source of CO_2 than peat mining ever was. The estimated current contribution of CO_2 respiration from peatlands to the total Dutch national CO_2 emissions is about 3 % (Van Den Bos 2003; Van den Akker et al. 2008).

Similarly, the reconstructed average subsidence rate of 1.9 mm/year over the last 1,000 years is much lower than present-day subsidence rates, which are estimated to range from 2 to 25 mm/year (e.g. Van der Meulen et al. 2007a; Hoogland et al. 2011). Over the last centuries, windmills were replaced by pumping-engines and pumping techniques were continuously improved, which allowed for deeper drainage. Over the last 50 years, the average depth of drainage was further increased to support heavy agricultural machinery, accelerating subsidence even more. The historical values derived in this study should thus be seen as minimum values, both for subsidence and CO_2 emissions in reclaimed coastal peatlands; contemporary and future land-use related subsidence in coastal peatlands elsewhere in the world are likely to be considerably higher. This especially applies to drained

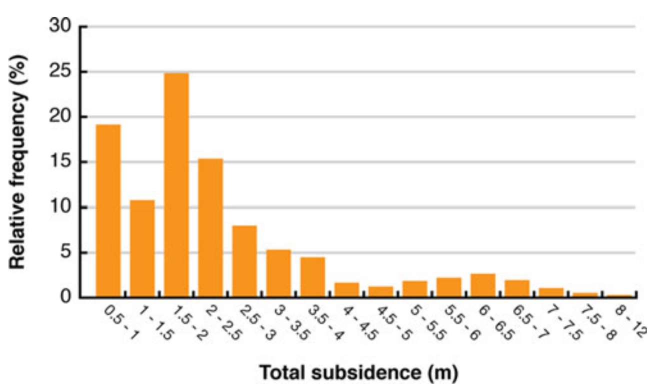

Fig. 10 Histogram of estimated total subsidence in the Dutch coastal plain since AD 1000, as derived from the subsidence grid in Fig. 9. The two peaks in the bimodal distribution correspond to the two processes that caused volumetric loss: drainage of peatlands (peaking at 1.5–2.0 m) and peat mining (peaking at 6.0–6.5 m). Range 'a – b' denotes 'a – <b'

low latitude peatlands, which degrade faster due to higher soil temperatures (Stephens 1984). Current land subsidence rates of as much as 5 cm/year are reported from the tropics (Hooijer et al. 2012).

Coastal peatlands: from Holocene carbon sinks to Anthropocene sources

After 1,000 years of drainage and mining, an estimated volume of about 20 km^3 of peat still remains in the Dutch coastal plain (Van der Meulen et al. 2007a). This volume holds about 1.03 Gton of soil-C, which corresponds to 3.8 Gton of CO_2 in the atmosphere. This carbon was largely sequestered from 5,000 years ago onwards, i.e. after the onset of large-scale peat growth. Figure 11, drawn under the assumption that storage rates partly depend on the rate of relative sea level rise, shows that the estimated maximum storage of soil-C in the coastal peatlands, achieved 1,000 years ago, amounted to about 6.9 Gton of CO_2. This implies that the Dutch coastal lowlands sequestered an average amount 1.73 Mton CO_2 per year over a period of 4,000 years until 1,000 years ago, or 60 g/m^2/year when expressed in soil-C per unit surface area. This is twice the estimated global average C-storage rate in peatlands (29 g/m^2/year) during the Holocene (Gorham 1991).

The fact that the rates reported in this paper are above the global average is attributed to the coastal setting, at the margins of a subsiding basin, where rates of sediment accommodation space creation are higher than in continental settings. If peat accumulation would have increased with the same rate over the last 1,000 years, an estimated 8.6 Gton could have been stored, although this may be overestimated because existing limits to bog growth and decelerating relative sea level rise were not considered; instead, peatland cultivation turned the coastal peatlands from a carbon sink into a carbon source. During the last millennium, the estimated average rate of CO_2 *release* from the coastal peatlands as a result of drainage (1.79 Mton/year) is more or less similar to the estimated average Holocene *storage* rate, even though the area over which these values are calculated differs somewhat. Including mining, the estimated release rate of carbon (3.1 Mton CO_2 per year) was twice the estimated rate of sequestration.

However, not all carbon that is still present in the coastal peatlands will respire, because some of it is buried under thick clastic units, sheltering it from oxidation, and because the subsidence caused by the disappearance of all peat would be unacceptable and unsustainable from a water management point of view. Instead, the Netherlands is taking action to decrease the drainage depth in some of its peatlands, in an effort to reduce both subsidence and greenhouse gas emissions (Van den Bos 2003). Considering the high current estimated CO_2 respiration rates, it is however likely that the

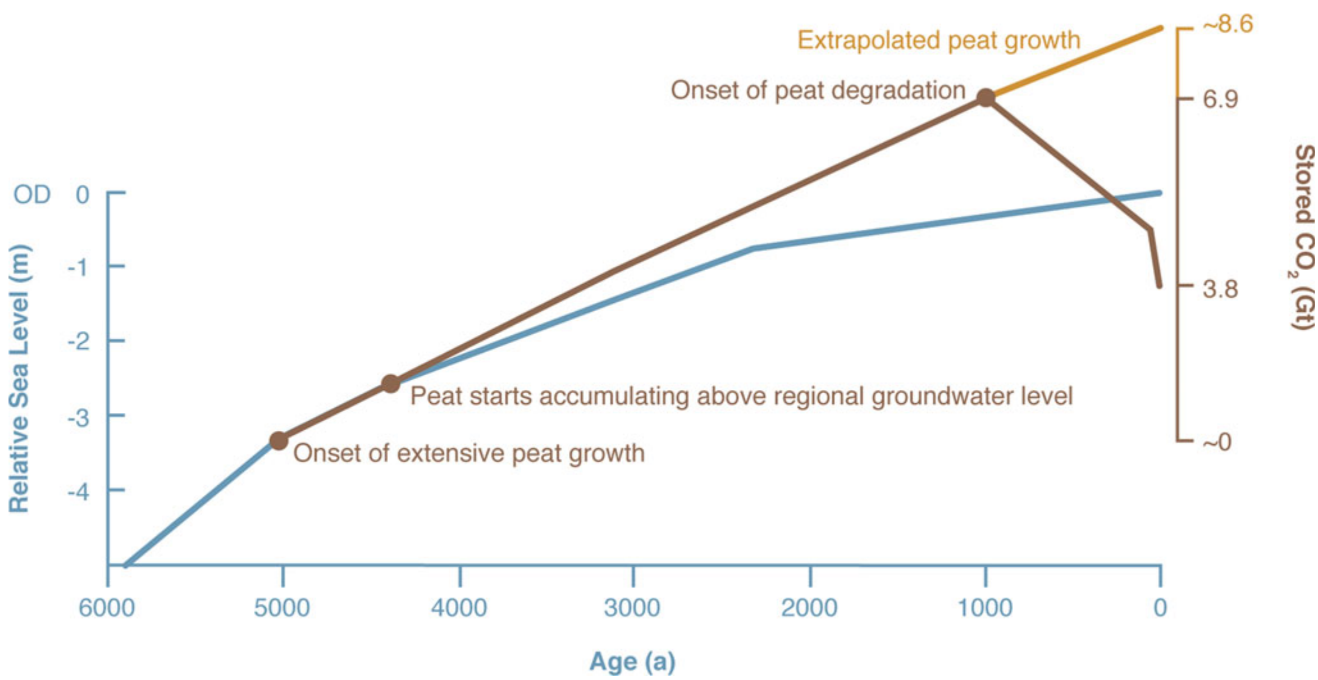

Fig. 11 Approximate CO_2 sequestration in and subsequent emission from the Dutch coastal peatlands over the last 5,000 years (see text for explanation). The relative sea level curve is derived from Van de Plassche (1982). After ~5,000 years ago, relative sea level rise decelerated, and peat growth has eventually outpaced the relative sea level rise. Note that the onset of peat growth above the regional groundwater level is an approximation, and is probably diachronic over the coastal plain. The estimated maximum storage of carbon in the coastal peatlands occurred 1,000 years ago, when the elevation of the bogs and fen landscape was on average 1.2 m above Ordnance Datum (*OD*)

peatlands, if drainage continues, will remain a CO_2 source for decades to come.

The Dutch contribution to pre-industrial anthropogenic CO_2 emissions

In the best estimate scenario, 0.83 Gton of soil-C has emitted over the last 1,000 years, 0.28 Gton of which originates from peat mining. This is equivalent to an atmospheric CO_2 concentration of 0.39 ppmv (Table 1), although the net contribution will have been lower as a result of the uptake of CO_2 by the oceans and the biosphere. Global deforestation is considered to be the largest source of anthropogenic CO_2 in pre-industrial times, with estimates ranging from 60 to 120 Gton according to Ruddiman et al. (2011), or as much as 340 Gton when using land cover models (Kaplan et al. 2010). Ruddiman (2003) used rough estimates of population and fuel-use, and included ~10 Gton of soil-C that has supposedly been released during 2,000 years of using peat for combustion globally.

Considering the small size of the area, the contribution of the Dutch emissions (~8 %) to the estimated total pre-industrial CO_2 emissions from peat is remarkably high. More importantly, this study suggests that Ruddiman's global estimated range is low, because it omits CO_2 emissions as a result of drainage of peatlands. When considering the total human-induced pre-industrial release of soil-C by Ruddiman et al. (2011) and Kaplan et al. (2010), the Dutch coastal peatlands contributed as much as from 0.2 to 1.4 % to the global emission. This share is substantial considering that the Dutch coastal peatlands constitute only 0.2 % of the total peatland area worldwide (Joosten 2009). The total Dutch contribution to estimated global CO_2 emissions will have been even higher, as upland peat bogs have been mined as well, something which has not been considered in this study.

Current global CO_2 emissions from coastal plains

The estimated share of the world's soil organic carbon is stored in peatlands is considerable (329–525 Gton C with a mean value of 462 Gton; Immirzi et al. 1992). However, the extent to which this carbon is expected to respire is among the largest uncertainties in climate scenarios (Dorrepaal et al. 2009). This is partly owing to the lack of information on peat thickness. According to Gorham (1991), the estimated average thickness of boreal and subarctic upland peatlands is 2.3 m, which is much thinner than those observed in coastal peatlands (about 5 m in the Dutch case, not corrected for consolidation). In upland peatlands, peat accumulation is limited by local and internal peat growth dynamics, whereas in a sedimentary basin environment, accommodation space keeps being created. Thus, when converted to arable land, these thick coastal peatlands will become long-lasting sources of carbon.

Over the last decennia, the use of coastal peatlands for agriculture has strongly increased, especially in the tropics, and so have the associated subsidence and CO_2 emissions (e.g. Hooijer et al. 2006, 2010, 2012). If recently cultivated coastal peatlands worldwide would be drained as persistently as the Dutch coastal peatlands, this could lead to enormous releases of carbon into the atmosphere, impacting on global climate. In addition to that, large stretches of coastal peatlands would subside, leading to increased flood probability.

Conclusions

During the past 1,000 years cultivation of the Dutch coastal lowlands resulted in an estimated loss of 19.8 km^3 of peat, 34 % of which was due to excavation and combustion, 18 % due to drainage consolidation, and 48 % due to the associated peat oxidation. To date, this loss led to an estimated average land level lowering of 1.9 m, at an accelerating rate averaging 1.9 mm/year, and subsidence will continue as long as the Dutch persist in lowering water tables in their coastal peatlands. Currently, 26 % of the Netherlands lies below mean sea level, largely as a result of this particular subsidence mechanism, and habitation of its lowlands has come to rely on careful water management.

Since medieval times, an estimated 3.07 Gton of CO_2 was released as a result of the oxidation and combustion of peat in the Netherlands, which is equivalent to an atmospheric concentration of about 0.39 ppmv. The example of the Netherlands show that historically drained peatlands may have been a considerable source of pre-industrial anthropogenic CO_2 emissions, something which is not accounted for in existing estimates. In fact, coastal peatlands are globally mostly overlooked in this particular context, despite the fact that, because of their combined geological and geographical setting, they probably hold the thickest peat accumulations of all peat environments, and are preferred human settlement areas that are rapidly being cultivated all over the world.

The Dutch coastal peatlands were drained very persistently for a thousand years, and have been thoroughly exploited for fuel. The results of this study hold a strong warning message: the cultivation of coastal peatlands, even without peat mining, inevitably brings double trouble. It turns huge carbon sinks into carbon sources, and the burden presented by the mitigation of an ever-increasing flood risk, caused by subsidence, will eventually become unsustainable.

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