Anthropocene 22 (2018) 1–9

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Three-dimensional distribution of organic matter in coastal-deltaic peat: Implications for subsidence and carbon dioxide emissions by human-induced peat oxidation

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ARTICLE INFO

Article history:
Received 8 August 2017
Received in revised form 13 March 2018
Accepted 30 March 2018
Available online 3 April 2018

Keywords:
Human induced peat oxidation
Coastal-deltaic plain
Holocene peat
Land subsidence
CO_2 emissions

ABSTRACT

Human-induced groundwater level lowering in the Holocene coastal-deltaic plain of the Netherlands causes oxidation of peat organic matter, resulting in land subsidence and carbon dioxide (CO_2) emissions. Here, a three-dimensional (3D) analysis of the distribution of the remaining peat organic matter is presented, to quantify the potential of this area to further subsidence and CO_2 emissions by oxidation. Hereto, we established relations between dry mass ratios of organic matter and sediment in peat formed in different environmental settings. This was combined with a high-resolution 3D geological model of the subsurface of the Netherlands to map the proportions of organic matter, clastic sediment and void space in peat.

The 3D model indicates that c. 15 km^3 of Holocene peat is embedded in the coastal-deltaic plain subsurface, of which c. 1.5 km^3 consists of organic matter, 0.4 km^3 of sediment, and 13.1 km^3 of void space. During future human-induced oxidation, this peat has a volumetric loss potential of 14.6 km^3, responsible for locally 0.4–6.0 m of subsidence, and a CO_2 emission of 2.0 Gton.

The 3D modelling revealed that the amount of peat organic matter varies considerably between regions. Especially the subsurface of urban areas overlying back-barrier peat were identified as hot-spots accommodating the highest quantities of peat organic matter. The peat in agricultural areas contains less organic matter but is more prone to oxidation than peat underlying urban areas, because in the latter settings anthropogenic brought-up soil restricts oxidation. Future mitigation strategies should therefore focus on restricting peat oxidation in the agricultural areas of the coastal-deltaic plain.

1. Introduction

Human-induced lowering of groundwater levels in peat-rich coastal-deltaic plains has resulted in significant land subsidence and carbon dioxide (CO_2) emissions (e.g. Venice Lagoon: Gambolati et al., 2006; Mississippi delta: Dixon et al., 2006; Sacramento Delta: Drexler et al., 2009). Oxidation of the easily biodegradable organic matter in peat causes strong volumetric loss as it is converted into CO_2 (Wösten et al., 1997; Kool et al., 2006; Hooijer et al., 2012). The resulting land surface subsidence increases the vulnerability of these low-lying areas to flooding, damages infrastructures and buildings, and on the long run leads to the loss of reclaimed agricultural land (Syvitski et al., 2009; Higgins, 2016), while the emissions of CO_2 contribute to the global increases in greenhouse gas concentrations (Hiraishi et al., 2014). Groundwater level lowering exacerbates subsidence, since it reduces pore water pressure, which causes compression of peat below the unsaturated zone. As a consequence, previously aerated peat may subside below the groundwater table, terminating further biodegradation and oxidation (Hooijer et al., 2010).

The densely populated and peat-rich coastal-deltaic plain of the Netherlands is a primary example of an area with excessive surface lowering due to human-induced peat oxidation (Fig. 1a). This commenced at local scales in the first millennium AD and expanded at regional scales with systematic peat reclamation campaigns from 1000 CE onwards (Borger, 1992; Pierik et al., 2016). Erkens et al. (2016) estimated that these reclamations have resulted in the volumetric loss of c. 20 km^3 of Holocene peat, emitting 2.02–5.72 Gton CO_2 into the atmosphere during a period of 1000 years. Continued groundwater lowering and land use

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https://doi.org/10.1016/j.ancene.2018.03.001
2213-3054/

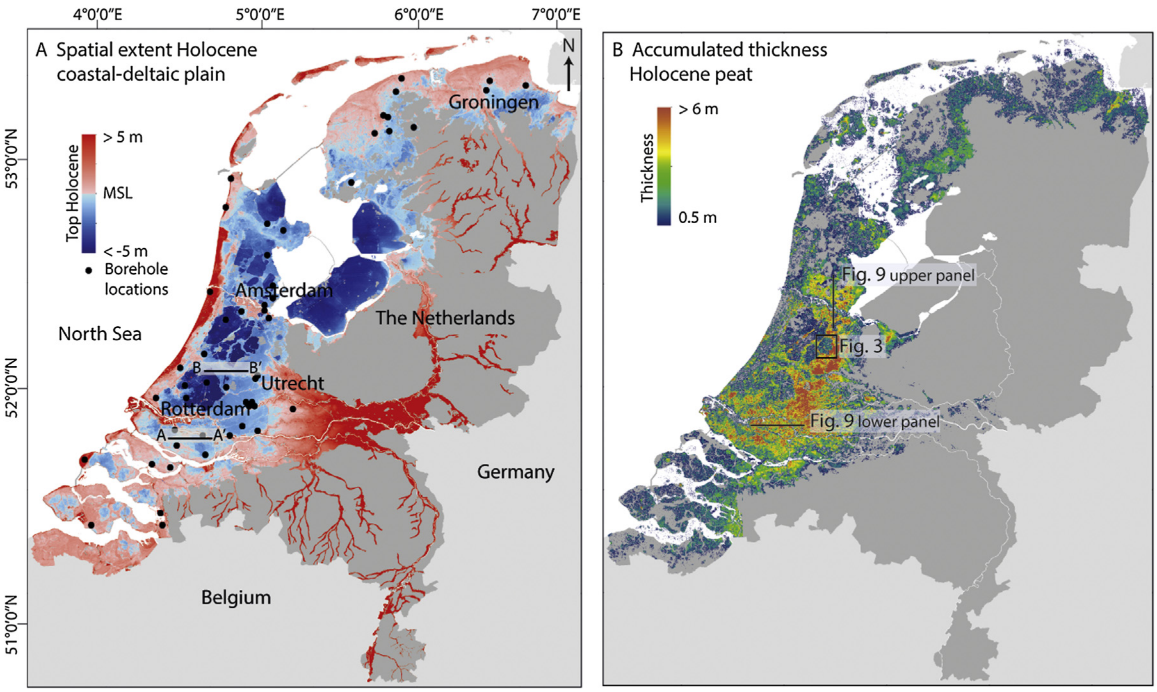

Fig. 1. a Digital elevation model of the surface of the Holocene coastal-deltaic plain of the Netherlands (TNO-GSN, 2016). Approximately 50% of the coastal-deltaic plain is presently situated below mean sea-level. The lines indicate the positions of the cross-sections in Fig. 2. The axes labels represent the Dutch national coordinate system in meters (Rijksdriekhoekstelsel). b Accumulated thickness of peat embedded in the coastal-deltaic plain of the Netherlands (TNO-GSN, 2016). The lines indicate the positions of the sections in Fig. 8.

practices make that present-day averaged land subsidence rates range between 1 and 12 mm/yr (Nieuwenhuis and Schokking, 1997; Van den Born et al., 2016) with local rates up to 20 mm/yr (Van den Akker et al., 2008), of which approximately 65% is attributed to oxidation (Schothorst, 1977).

At present, over 15 km^3 of Holocene peat remains as beds in the shallow subsurface of the coastal-deltaic plain of the Netherlands (TNO-GSN, 2016), emphasizing the potential of this area to further oxidation when groundwater levels are progressively being lowered (Fig. 1b). This peat however, is not entirely consisting of biodegradable organic matter, as it contains volumes of incorporated clastic material and void space.

In coastal-deltaic settings, peat forms in environments distal to main sediment dispersing rivers and coastal inlets, but still receives modest amounts of clastic sediment (Kosters et al., 1983; Bos et al., 2012; Ishii et al., 2016; Morris et al., 2016). The amount of clastic sediment varies between peat beds of different setting, relating to local and regional depositional circumstances, and typically varies between 20 and 100% of the dry mass of peat (Den Haan and Kruse, 2006; Morris et al., 2016). Under pristine conditions, peat is very porous, with 90–95% of its volume occupied by water and gas (Landva, 2006). This decreases with depth, as increasing vertical effective stress (vertical force exerted on peat particles) densifies a peat body by expulsion of water and gas from its voids. Owing to differences in sedimentation history and vertical effective stress, strong lateral and vertical variation exist in the volumes of organic matter contained in the coastal-deltaic peat layers.

Here, we demonstrate the effect of mapping organic matter, sediment and void space in peat beds embedded in the coastal-deltaic plain of the Netherlands for quantifying peat oxidation, and its implications for land subsidence and CO_2 emission. We use a three-dimensional (3D) mapping approach to determine from available field data the volumes of organic matter, sediment, and void space in peat beds, depending on their differences in stratigraphical settings and burial depth. The starting point in this analysis was a 3D geological voxel model that comprises Holocene peat: GeoTOP (Stafleu et al., 2011; Van der Meulen et al., 2013), the high-resolution geological voxel model of the Geological Survey of the Netherlands (TNO-GSN). A geological voxel model schematise the subsurface in regular grids of rectangular blocks ('voxels' or '3D cells') in a Cartesian coordinate system (x, y, z). GeoTOP is a voxel model with a voxel size of 100 × 100 × 0.5 m (x, y, z). In its current release, each voxel holds attributes informing on lithology (grainsize composition) and lithostratigraphy (nomenclature of sediment deposits based on its stratigraphic position and grainsize). The task of populating peat voxels with a parameter holding the volumes of organic matter, clastic admixture, and void space, and the subsequent analysis for oxidation calculations, was executed in TNO-GSN's software environment for 3D model development and data management.

The aim of this study was 1) to determine proportional relations for the quantities of organic matter and sediment in peat beds based on previously collected field-data, 2) to do this for peat from different environments and stratigraphic positions, including vertical variations *within* individual peat layers, 3) determine the void space of peat beds with various organic matter content subjected to differential vertical effective stress, 4) to deploy these relations to produce spatial distributions of organic matter, sediment, and void space for GeoTOP voxels that are modelled as peat, and 5) to evaluate the produced map predictions of to-expect subsidence and CO_2 emission by peat oxidation under future groundwater management.

2. Geological setting, holocene peat formation, and peatland reclamation in The Netherlands

With 17,500 km^2, approximately 50% of the surface area of the Netherlands comprises of Holocene coastal-deltaic deposits. The thickness of these coastal-deltaic deposits varies from several