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The relative contribution of peat compaction and oxidation to subsidence in built-up areas in the Rhine-Meuse delta, The Netherlands

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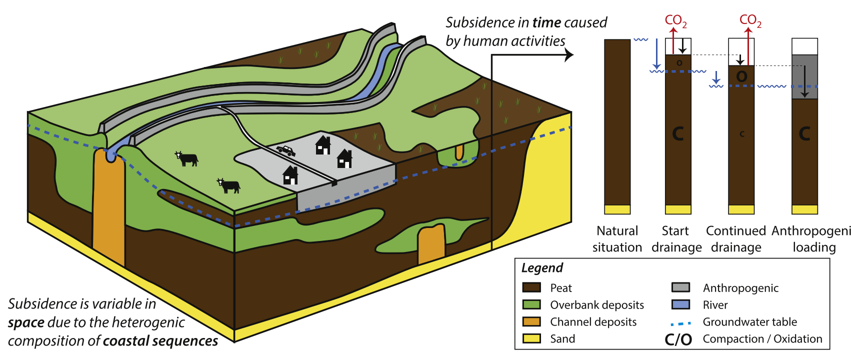
HIGHLIGHTS

- Subsidence by peat compaction and oxidation severely impacts built-up coastal areas.
- Field data shows that this type of subsidence is highly variable in time and space.
- This variability mostly relates to subsurface buildup and characteristics and groundwater depth.
- We expect a considerable subsidence potential in many peat-rich coastal areas.
- Therefore we call for subsurface-based spatial planning in peat-rich coastal zones.

GRAPHICAL ABSTRACT



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ABSTRACT

An increasing number of people lives in coastal zones with a subsurface consisting of heterogenic soft-soil sequences. Many of these sequences contain substantial amounts of peat. While population growth and urbanization continues in coastal zones, they are threatened by global sea-level rise and land subsidence. Peat compaction and oxidation, caused by loading and drainage, are important contributors to land subsidence, and hence relative sea-level rise, in peat-rich coastal zones. Especially built-up areas, having densely-spaced urban assets, are heavily impacted by land subsidence, in terms of livelihoods and damage-related costs. Yet, built-up areas have been largely avoided in peat compaction and oxidation field studies. Consequently, essential information on the relative contributions of both processes to total subsidence and underlying mechanisms, which is required for developing effective land use planning strategies, is lacking. Therefore, we quantified subsidence due to peat compaction and oxidation in built-up areas in the Rhine-Meuse delta, The Netherlands, using lithological borehole data and measurements of dry bulk density, organic matter, and CO_2 respiration. We reconstructed subsidence over the last 1000 years of up to ~4 m, and recent subsidence rates of up to ~140 mm$\cdot$yr^{-1} averaged over an 11-year time span. The amount and rate of subsidence due to peat compaction and oxidation is variable in time and space, depending on the Holocene sequence composition, overburden thickness, loading time, organic-matter content, and groundwater-table depth. In our study area, the potential for future subsidence due to peat compaction and oxidation is substantial, especially where the peat layer occurs at shallow depth

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and is relatively uncompacted. We expect this is the case for many peat-rich coastal zones worldwide. We propose to use subsurface-based spatial planning, using specific subsurface information mentioned above, to inform land use planners about the most optimal building sites in organo-clastic coastal zones.

1. Introduction

Over the last decades, the number of people living in coastal plains and deltas at elevations <10 m above mean sea level (MSL) has increased to over 625 million, often concentrated in megacities (Neumann et al., 2015). These areas are predicted to face continued population growth and urbanization in the future (Neumann et al., 2015). At the same time, many coastal zones are subject to land subsidence due to both natural and anthropogenic processes (Giosan et al., 2014; Syvitski et al., 2009). Natural processes causing land subsidence are tectonics, isostasy and sediment compaction. Human-induced subsidence is especially caused by withdrawal of hydrocarbons and groundwater, loading of soft soils, and shallow groundwater table lowering. Human-induced subsidence rates are usually higher than natural subsidence rates (Stouthamer and van Asselen, 2015).

The Holocene subsurface of coastal plains and deltas usually consists of soft soils and may contain large quantities of peat (e.g., Charman, 2002; Törnqvist et al., 2008; Gastaldo, 2010; Drexler, 2011; Van Asselen, 2011). Examples of peat-rich populated coastal zones are the Rhine-Meuse delta (NL), the Sacramento-San Joaquin delta (USA) and the Mississippi delta (USA). In these deltas, a significant part of total land subsidence has been caused by peat compaction, peat oxidation, shrinkage and/or peat mining (Schothorst, 1977; Deverel and Rojstaczer, 1996; Long et al., 2006; Törnqvist et al., 2008; Drexler et al., 2009; Van Asselen, 2011; Deverel et al., 2016; Erkens et al., 2016). In this paper, we define compaction as a mechanical process of volume reduction due to the expulsion of pore water induced by an increase in effective stress (= overlying weight − pore water pressure) (Paul and Barras, 1998). Oxidation is a biogeochemical process of soil organic matter decomposition by micro-organisms (Schothorst, 1977), also causing a volume reduction.

Thus, a combination of physical processes (compaction), biogeochemical processes (soil degradation) and human activities (e.g. loading and groundwater table lowering) causes land subsidence in low-lying coastal zones. The main objective of our research was to assess the relative contribution of peat compaction and oxidation to total land subsidence in built-up areas in the Rhine-Meuse delta (NL). In addition, we will discuss some implications of these processes for land-use and construction planning strategies in soft-soil coastal zones.

Land subsidence, in combination with global sea-level rise, causes an increase in flood frequency, flood inundation depth and flood duration in low-lying coastal zones, which results in flood damage (Giosan et al., 2014). Land subsidence may also lead to coastal erosion and land loss (Day et al., 2007). Furthermore, differential subsidence causes direct damage to buildings and infrastructure, both at and below the surface. Oxidation of peat does not only cause land subsidence, but in the process CO_2 is emitted, a greenhouse gas, linking land subsidence to climate change (Deverel and Rojstaczer, 1996; Zanello et al., 2011; IPCC, 2014).

Coping with the negative effects of land subsidence in populated low-lying coastal zones requires a thorough understanding of the processes causing subsidence, their spatial and temporal variability and their relative contributions to total subsidence. Such knowledge is essential for developing tailor-made effective land-use and construction planning strategies. For example, if peat compaction is the main contributor to total land subsidence, lighter construction materials could be used, a long pre-loading phase may apply, or it may be decided that the area should not be built on at all (e.g., Long and Boylan, 2013). If peat oxidation is the main contributor to land subsidence, solutions may be found in raising the water table, or changing the local drainage system (e.g., Querner et al. 2012). A better insight into the processes causing land subsidence also helps in identifying who is responsible for mitigating impacts.

It is important to use field data for studying peat compaction and oxidation, in addition to computer models. Field data enables to make detailed reconstructions of the subsurface composition in 2D or 3D, which is needed to assess spatial variation in geotechnical soil properties and related vulnerability for land subsidence. In models, the subsurface composition is usually schematized, at 1D, thereby ignoring any heterogeneity that is often seen in peat-rich delta sequences (Price et al., 2005; Van Asselen, 2011). Moreover, field data is useful for calibrating and improving numerical models (Van Asselen et al., 2011).

Most previous field-based studies have investigated subsidence due to peat compaction and oxidation independently, predominantly in rural or pristine areas (e.g., field-based compaction studies: Bloom, 1964; Cahoon and Reed, 1995; Cahoon et al., 2000; Bird et al., 2004; Törnqvist et al., 2008; Van Asselen, 2011; field-based oxidation studies: Van den Bos, 2003; Hendriks, 2009; Hooijer et al., 2012; Brouns et al., 2015). Built-up areas are typically avoided in field-based peat compaction and oxidation studies, because sealed surfaces and restricted property access hamper investigating the subsurface, and hence, subsidence processes in these areas. This is unfortunate, while especially these areas are subject to anthropogenic loading and drainage activities causing substantial land subsidence due to peat compaction and oxidation. Moreover, compared to rural and pristine areas, built-up areas comprise much densely-spaced assets such as sewage systems and buildings, resulting in higher risks and costs related to damages due to land subsidence and flooding (Van den Born et al., 2016).

Thus, those areas which are most heavily impacted by land subsidence have not yet received the full attention of land subsidence field research. To overcome this knowledge gap, we have studied land subsidence caused by peat compaction and oxidation in three villages built on Holocene deltaic sequences containing substantial amounts of peat, in the central part of the Rhine-Meuse (RM) delta, The Netherlands. First, we made cross sections based on borehole data to reveal the lithological composition of the Holocene sequence underlying the villages. At selected sites, the current degree of compaction of peat sequences was determined based on high-resolution organic-matter and dry bulk density measurements from continuously sampled peat cores. Based on the compaction calculations and rates of natural subsidence, we assessed the relative contribution of compaction and oxidation to total subsidence since 1000 years ago at 5 core locations, using a reconstructed surface elevation model of 1000 years ago as a reference (Erkens et al., 2016). The calculated (derivative) contributions of subsidence due to oxidation were verified based on CO_2 respiration measurements of peat samples extracted from the saturated zone. Finally, we assessed the potential for future land subsidence at our study sites.

2. Study site description

2.1. The Rhine-Meuse delta

The Holocene RM deltaic wedge is composed of intercalated tidal, estuarine, and fluvial deposits, including organic beds (Berendsen and Stouthamer, 2001; Bos, 2010; Gouw and Erkens, 2007; Hijma and Cohen, 2011), underlain by predominantly Weichselian fluvial sands and gravely sands. The wedge is ~25 m thick in the very west, nearby the present coastline, and thins to ~2 m eastwards to the delta apex