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Mapping potential acid sulfate soils in Denmark using legacy data and LiDAR-based derivatives

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A B S T R A C T

Leaching large amounts of acidity and metals into recipient watercourses and estuaries, acid sulfate (a.s.) soils constitute a substantial environmental issue worldwide. Mapping of these soils enables measures to be taken to prevent pollution in high risk areas. In Denmark, legislation prohibits drainage of areas classified as potential a.s. soils without prior permission from environmental authorities. The mapping of these soils was first conducted in the 1980's. Wetlands, in which Danish potential a.s. soils mostly occur, were targeted and the soils were surveyed through conventional mapping. In this study, a probability map for potential a.s. soil occurrence was constructed for the wetlands located in Jutland, Denmark (c. 6500 km^2), using the digital soil mapping (DSM) approach. Among the variety of available DSM techniques, artificial neural networks (ANNs) were selected. More than 8000 existing soil observations and 16 environmental variables, including geology, landscape type, land use and terrain parameters, were available as input data within the modeling. Prediction models based on various network topologies were assessed for different selections of soil observations and combinations of environmental variables. The overall prediction accuracy based on a 30% hold-back validation data reached 70%. Furthermore, the conventional map indicated 32% of the study area (c. 2100 km^2) as having a high frequency for potential a.s. soils while the digital map displayed about 46% (c. 3000 km^2) as high probability areas for potential a.s. soil occurrence. ANNs, thus, demonstrated promising predictive classification abilities for the mapping of potential a.s. soils on a large extent.

1. Introduction

Acid sulfate (a.s.) soils constitute a major environmental issue, presumably affecting more than 200,000 km² of coastal areas worldwide (Andriesse and van Meensvoort, 2006). In many cases, these soils occur in heavily populated areas with a consequent high demand on clean water. They also cause severe ecological damage (i.e. killing fish and other aquatic organisms), as well as the degradation of underground concrete and steel structures to the point of failure. In northern Europe, a.s. soils are mostly located along the coasts of the Baltic Sea and North Sea; they have been studied in Finland (Yli-Halla, 1997; Österholm and Åström, 2004; Roos and Åström, 2005; Toivonen et al., 2013), Sweden (Sohlenius and Öborn, 2004), Denmark (Madsen et al., 1985; Madsen and Jensen, 1988) and Poland (Urbańska et al., 2012). In the western part of Denmark (i.e. Jutland; Fig. 1), drainage of wetlands, mainly for farming, can lead to the formation of a.s. soils; iron sulfides (mostly pyrite; Madsen et al., 1985) oxidize and sulfuric acid is produced, causing the leaching of metals and the soil pH dropping below 3.0. Subsequently, a.s. soils release a toxic combination of acidity and metals (mainly iron, but also to a lesser degree, aluminium, arsenic, cadmium, cobalt, nickel, zinc and rare earth elements) to the recipients such as streams and estuaries (Nystrand and Österholm, 2013). In particular, the large amounts of leached iron can result in a heavy ochre pollution in water courses (Madsen et al., 1985), easily recognizable by its yellow/orange color.

Notably small hotspots of a.s. soils may impact large water bodies. Therefore, mapping of these soils constitutes a critical step to plan and carry out effective mitigation. In Denmark, legislation prohibits drainage of areas classified as potential a.s. soils without prior permission from

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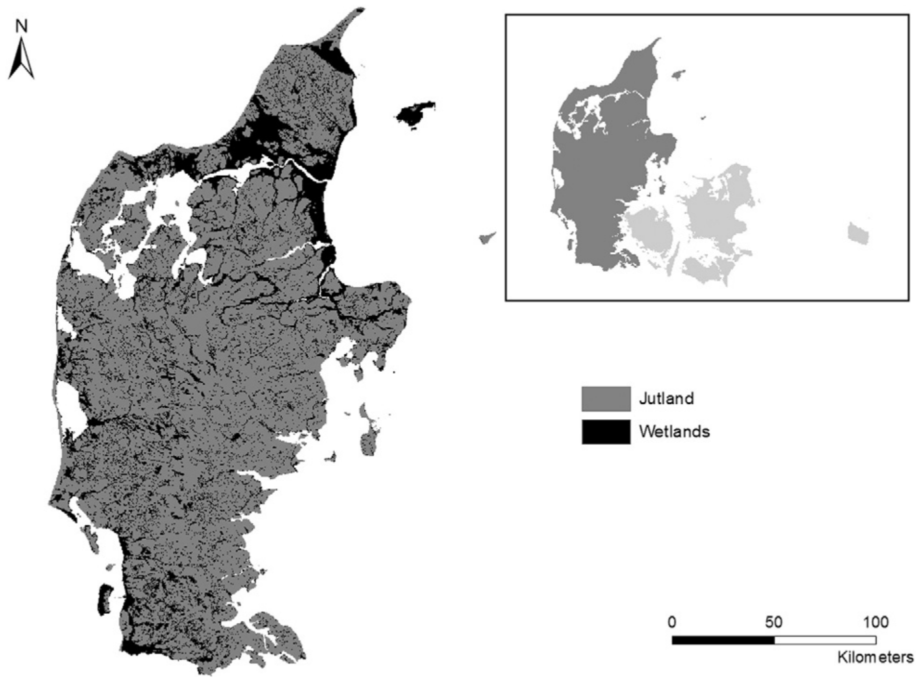

Fig. 1. Distribution of the wetlands in Jutland, Denmark.

environmental authorities. The mapping of these soils was carried out in the 1980's. Wetlands were targeted and soils were surveyed through conventional mapping, the procedure including soil sampling and the subsequent determination of pH at the time of sampling and after incubation, as well as the calculation of pyrite content and acid-neutralizing capacity (Madsen et al., 1985). Traditional soil mapping being time- and resource-consuming, alternative spatial modeling techniques may be useful to predict the occurrence of a.s. soils at various scales and extents. Within the Digital Soil Mapping (DSM) approach (McBratney et al., 2003), several techniques have recently been evaluated for mapping a.s. soils. A fuzzy *k*-means algorithm for clustering analysis was applied on a relatively small coastal a.s. soil area in Australia (Huang et al., 2014a, b). Fuzzy logic and Artificial Neural Network (ANN) techniques were assessed on a.s. soils in Finland at regional and catchment scale, respectively (Beucher et al., 2013, 2014, 2015). The empirical, data-driven ANN techniques constitute efficient pattern recognition and classification tools (Bonham-Carter, 1994), with the ability to generalize from imprecise input data (Porwal et al., 2003) and to handle large datasets (Gershenfeld, 1999). For this study, an ANN method was selected because of the availability of large input datasets (i.e. soil observations and environmental variables). Furthermore, ANNs are frequently applied in DSM for predicting soil attributes (Chang and Islam, 2000; Minasny and McBratney, 2002; Lentzsch et al., 2005; Viscarra Rossel and Behrens, 2010) or soil classes (Zhu, 2000; Behrens et al., 2005; Boruvka and Penizek, 2007; Cavazzi et al., 2013; Chagas et al., 2013; Silveira et al., 2013). The main objective of this study was to assess the predictive classification abilities of an ANN technique for potential a.s. soil mapping of the wetlands in Jutland, Denmark (Fig. 1).

2. Study area

The wetlands located in Jutland constitute the study area (Fig. 1). They cover about 6500 km^2 and represent approximately 20% of Jutland (Madsen et al., 1985). Wetlands correspond to saturated soils, such as histosols, fluvisols and gleysols (IUSS Working Group WRB, 2006). Plant communities such as *Juncus effusus* constitute their natural vegetation. Wetlands were mainly used for hay production until the second half of the 19th century when tile drainage was introduced (Greve et al., 2014). Thus, most of the wetlands (c. 5100 km^2) have been artificially drained and intensively farmed using fertilizer and lime, the main crop being cereals and grass (Bou Kheir et al., 2010). The study area comprises various landforms (Madsen et al., 1992); the western part of the study area consists of low-relief sandy glaciofluvial outwash plains from the Weichselian glaciation (i.e. Last Glacial Maximum; c. 1200 km^2 of the wetland areas), which surrounds slightly protruding islands of older and strongly eroded moraine landforms from the Saalian glaciation (c. 700 km^2 of the wetland areas; Madsen et al., Madsen and Jensen, 1988). The eastern part of the study area is composed of Weichselian moraine landforms (c. 900 km^2 of the wetland areas) while the northern part consists of late- and post-glacial marine sediments (c. 2400 km^2 of the wetland areas; Madsen and Jensen, 1988). Sub-surface geology varies from North to South in the study area. Cretaceous limestone dominates in northern Jutland and Djursland while Tertiary mica-rich sand and clay prevail in the rest of Jutland (Madsen and Jensen, 1988). The study area has a temperate climate with a winter mean temperature of 0 °C and a summer mean of 16 °C. The average annual precipitation is about 800 mm in central Jutland (Danmarks Meteorologiske Institut, 1998).

3. Material and methods

3.1. Soil observations

Soil observations used in this study were extracted from the Ochre Classification database resulting from the potential a.s. soil mapping which was conducted in the 1980's (Madsen et al., 1985). Soils in wetland areas were targeted and surveyed through conventional mapping. Field work was carried out from May to October over a three-year period (1981–83). The selection of 8007 sampling sites was based on historical topographic maps (at scale 1:20,000), geological maps, soil maps and maps from previous moorland studies, and representing an even distribution in wetlands and soil types (Madsen et al., 1985). Each profile was sampled using a portable auger down to 2.5 m and samples were taken from major horizons below or near the groundwater table