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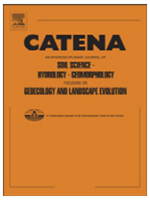

Using a multi-receiver survey of apparent electrical conductivity to reconstruct a Holocene tidal channel in a polder area

Timothy Saey [a,*], Mohammad Monirul Islam [a], Philippe De Smedt [a], Eef Meerschman [a], Ellen Van De Vijver [a], Alexander Lehouck [b,c], Marc Van Meirvenne [a]

[a] *Research Group Soil Spatial Inventory Techniques, Faculty of Bioscience Engineering, Ghent University, Coupure 653, 9000 Gent, Belgium*
[b] *Abdijmuseum Ten Duinen 1138, Koninklijke Prinslaan 6-8, 8670 Koksijde , Belgium*
[c] *Department of Medieval History, Faculty of Arts and Philosophy, Sint-Pietersnieuwstraat 35, 9000 Gent, Belgium*

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ABSTRACT

Most geological and soil maps are not detailed enough to represent the high lateral and vertical textural variability in the subsoil of coastal lowlands. Intensive sampling campaigns need to be carried out to quantify this variability. As an alternative, a proximal soil sensing procedure based on a single survey with an electromagnetic induction instrument was used to map a 6.5 ha Holocene tidal area in Belgium. We investigated the effectiveness of a multi-receiver apparent electrical conductivity (ECa) survey for mapping the trace of tidal paleochannels. From a limited number of augerings, a three-layered soil was observed composed of a clayey top layer, a clayey infilling of the tidal channel above a subsoil consisting of coarse sandy material. A fitting procedure allowed modelling the conductivities of both subsurface layers, after which the four simultaneous ECa measurements were combined to model the depth of the interfaces between the three layers. The predictions were validated by 16 depth observations along a 150 m transect. A correlation coefficient of 0.91, with an average error of 0.23 m, was found between the predicted and measured depths of the clay-sand interface. We concluded that the dense ECa measurements (2 by 2 m resolution) allowed reconstructing a precise three-dimensional representation of the tidal channels.

1. Introduction

After centuries of soil tillage, the topsoil has lost most traces of natural and anthropogenic events in most European countries. Although the subsoil might still contain useful information, it is less accessible. In the past soil augerings were the major modus to conduct such investigations. These are punctual observations, becoming very costly when a large number of data is required to characterize the small-scale spatial variability (Vitharana et al., 2008). Moreover, most soil maps aimed at supporting agricultural developments and thus focused on the topsoil (Kværnø et al., 2007). On the other hand, geological maps represent an overview of the geographical distribution of outcropping deposits, often at a rather coarse scale preventing detailed interferences (Smirnoff et al., 2008).

Soil and geological maps are often of little use in the Holocene coastal plains because the sedimentary sequences are characterized by a high lateral and vertical variability (Bertrand and Baeteman, 2005). Yet, they still contain information about the recent history of these landscapes, which, in Europe, were cultivated in medieval times. Questions about the landscape build-up at that time and human interferences for land reclamation are open to modern historians, geomorphologists and archaeologists.

The recent introduction of non-invasive proximal soil sensing systems offers new perspectives to study subsoil variability in detail providing several advantages over traditional invasive measurement methods (Cockx et al., 2007; Saey et al., 2008, 2009b). These advantages include lower cost, increased efficiency and above all, much denser results (Sudduth et al., 2005). Generally, these systems aim at mapping differences in electrical conductivity that could be linked to variations in water content and/or conductivity of the pore water and/or soil texture within the unsaturated zone, both laterally and vertically (Massuel et al., 2011). A promising technique is electromagnetic induction (EMI) (Brenning et al., 2008). With EMI, bulk measurements of the soil apparent electrical conductivity (ECa) can be obtained, which act as an indicator of important soil properties such as clay content, moisture content, and organic matter content (Domsch and Giebel, 2004; McBratney et al., 2005; Saey et al., 2009b; Sudduth et al., 2001). Additionally to the fact that geospatial ECa measurements are reliable, quick, and easy to obtain, they can be made mobile, allowing to cover larger areas fairly efficiently (Corwin et al., 2006).

The objective of this research was to develop a methodology to predict the interfaces between contrasting layers in a three-layered soil, or more specifically to map the upper and lower interface of a

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* Corresponding author. Tel.: +32 9 264 60 42; fax: +32 9 264 62 47.
E-mail address: Timothy.Saey@UGent.be (T. Saey).

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Holocene tidal channel in a coastal area. A fitting procedure must allow to simplify the three-layered soil conductivity model, to be able to integrate the multiple ECa measurements of the multi-receiver EMI sensor. This way, the potential to simultaneously model two 'sharp' interface depths across the field should be evaluated. Quantifying the dimensions of the tidal channel, as specific objective, should resolve questions about the medieval landscape in the coastal plain.

2. Study area

The study area is a 6.5 ha agricultural field located in the western part of the coastal plain of Belgium (central coordinates: 51°06′48″N and 2°42′04″E) (Fig. 1). The coastal plain is part of the lowlands of the southern North Sea which stretch from Cap Blanc Nez in northern France to Skagen in Denmark. The Belgian coastal plain is a polder area of about 15-20 km wide with an extension in the western part of the plain along the river IJzer. The plain was created by embankment following post-glacial sea-level rise and is situated behind a belt of aeolian sand dunes (Baeteman, 1999; 2008; Baeteman and Declercq, 2002). Its particular microrelief results from both natural and man-induced processes. Sea-level rise at the onset of the Holocene initiated peat formation and sediment accumulation behind the coastal barrier. A decrease in sea-level rise starting around 7500 year BP caused increasing sedimentation in the newly formed tidal basin. As sea-level rise continued to drop ca. 5500–5000 year BP, the thickest peat layers accumulated, lasting until about 1500 year BP (Baeteman, 1991; 2008). Throughout the evolution of the coastal plain, tidal channels were formed in the peat layers and the underlying sediments, which in their turn were filled up by sandy and, in more recent systems, clayey sediments. Radiocarbon dating showed that these tidal channels were active until the 7th century AD (Ervynck et al., 1999).

In the larger study area, which has been part of the IJzer Estuary and palaeovalley, late-Holocene sand and silt deposits are dominating. Sand-filled tidal channels were formed during the *La Tène* (from 560 year BC) and Roman period, incising through the older deposits and causing peat erosion. Finally, the channels were filled with clayey sediments under calm and smooth conditions, which started in the 7th century AD (Baeteman, 2008). Unprocessed data of the recent archaeological and pedological research will inform us about the exact end date of the infill. The soil characteristics are rather uniform throughout the entire study site. The topsoil (plough layer and the bioturbated zone beneath) consists of clayey sediments overlaying the sandy deposits. The present topography of our study area (Fig. 1) is flat, and the topsoil has been homogenised by tillage. The national soil map (1/20,000) is not very detailed, it shows two dominant soil series within our study site, both indicating heavy clay and clay of varying thickness overlying sandy material.

3. Multi-receiver electromagnetic induction (EMI) sensor

In its simplest configuration, a proximal EMI soil sensor consists of two coils separated by a given fixed distance. A primary magnetic field (H_p) is created by the transmitting coil. This field creates eddy currents in the soil below, which induce their own magnetic field (H_i). The induced secondary field is superimposed on the primary field and both H_p and H_i are measured by the receiving coil (McNeill, 1980). From this response the ECa of the bulk soil can be obtained. We used the DUALEM-21S instrument (DUALEM, Milton, Canada) which consists of one transmitter coil and four receiver coils located at spacings of 1, 1.1, 2 and 2.1 m (Saey et al., 2009a). The 1 and 2 m transmitter-receiver pairs form a vertical dipole mode (1 V and 2 V), while the 1.1 and 2.1 m pairs form a perpendicular dipole mode (1P and 2P). Both transmitter-receiver spacing and orientation determine the depth and weighting response pattern of the signal. The cumulative response (expressed as % of the measured signal, relative to 1) from the soil volume above a depth z (in m) was given by McNeill (1980) for the vertical ($R_v(z)$) dipole mode and by Wait (1962) for the perpendicular ($R_p(z)$) dipole mode:

$$R_v(z) = 1 - \left(4 \cdot \frac{z^2}{s^2} + 1\right)^{-0.5} \tag{1}$$

$$R_p(z) = 2\frac{z^2}{s^2}\left(4\frac{z^2}{s^2} + 1\right)^{-0.5} \tag{2}$$

with s being the transmitter-receiver spacing.

These cumulative response functions allow the determination of the depth of exploration (DOE), defined as the depth where 70% of the response is obtained from the soil volume above this depth down from the soil surface. This DOE differs for the different coil configurations: 0.5 m, 1.0 m, 1.5 m and 3.2 m for the 1P, 2P, 1 V and 2 V coil configurations respectively (Saey et al., 2009a). Measurements of soil temperature allowed the conversion of the measurements to a reference temperature (conventionally 25°C is used).

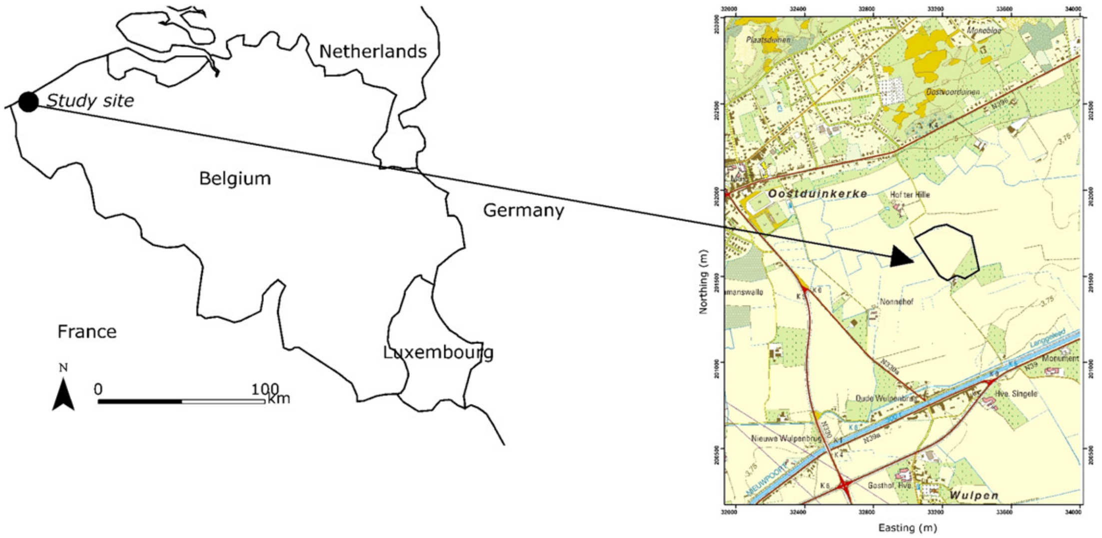

Fig. 1. Localisation of the study site in Belgium and topographic map with indication of the study site (black).