



Mapping depth-to-clay using fitted multiple depth response curves of a proximal EMI sensor

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ABSTRACT

As an alternative for the depth response approximations based on the theoretical Maxwell's equations, a procedure was proposed to fit depth response curves for different coil configurations. A 39 ha study area was selected in the Belgian loess belt, where loess material was situated on a Tertiary substrate. A survey with the DUALEM-21S electromagnetic induction instrument was carried out to map the depth-to-clay (z_{clay}). The depth response curves were fitted both for the vertical and perpendicular coil configurations using 85 depth observations of z_{clay} .

The resulting depth response curves $R(z_{\text{clay}})$ were:

$$R_{p,s}(z_{\text{clay}}) = 0.8135 \cdot e^{-1.4131 \cdot \left(\frac{z_{\text{clay}}}{s}\right)}$$

for the perpendicular coil configuration (with s as the intercoil spacing) and

$$R_{v,s}(z_{\text{clay}}) = 0.9802 \cdot e^{-0.8102 \cdot \left(\frac{z_{\text{clay}}}{s}\right)}$$

for the vertical coil configuration.

A set of 4 equations based on the developed depth response functions was used to model z_{clay} at each of the 209 400 measurement points. These z_{clay} predictions were validated using geo-electrical imaging. With two multi-electrode resistivity arrays, z_{clay} was 1D-inverted at 95 locations along two transects, assuming a two-layered soil system. A coefficient of determination of 0.95, with a root mean-squared estimation error of 0.22 m, was found between the predicted and 1D-inverted depths. This procedure allowed the accurate 3D-reconstruction of the paleolandscape before the deposition of the loess. Flow lines were modelled on this paleosurface, revealing past or subsurface stream patterns not visible on the present relief.

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1. Introduction

Electromagnetic induction (EMI) instruments measure a depth-weighted average of the soil electrical conductivity. Quantitative applications of EMI sensors to subsoil investigations depend on the ability to transform the measured apparent electrical conductivities (ECa) into horizontal and vertical variations of relevant soil properties such as soil type, soil horizons, soil water storage and soil organic matter (Domsch and Giebel, 2004; Saey et al., 2009b; Tromp-van Meerveld and McDonnell, 2009). Although useful for looking at lateral spatial variation, the ECa gives limited information on how conductivity varies with depth (Pellerin and Wannamaker, 2005). Generally,

the propagation of EMI radiation into the soil is described by Maxwell's equations (Reynolds, 1997). The relative response to the primary magnetic field created by the EMI instruments varies with depth and is therefore expressed as a depth response function. This response function is the weighting function for the ECa (= depth-weighted conductivity) (Morris, 2009).

McNeill (1980) defined the depth response functions of EMI instruments in homogeneous soils by asymptotic approximations of the Maxwell's equations. Hendrickx et al. (2002) proved these approximations to be valid in heterogeneous soils. They are based on the assumption that the induction number (β) is very small (Spies and Frischknecht, 1991). This is equivalent to stating that the current that flows in any loop of the magnetic field is completely independent of the current that flows in any other loop since they are not magnetically coupled (McNeill, 1980). The induction number is the ratio of the intercoil separation s to the skin depth δ . This skin depth is defined as the

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distance at which the propagating magnetic field strength has been attenuated to e^{-1} of the strength at the surface and varies inversely with the ECa at low frequencies. Within the restriction of a small β , the McNeill approximation (1980) holds which means that the instrument output is proportional to the ECa and the depth response functions are independent of ECa (Hendrickx et al., 2002). However, Callegary et al. (2007) proved with numerical models based on Maxwell's equations that the depth response can be altered by soil properties affecting the ECa. Especially under high electrically conductive conditions, the simulated depth response function deviates from the function predicted from the McNeill (1980) approximation.

Saey et al. (2009a) used the depth response curves of McNeill (1980) and Dualem Inc. (2007) based on Wait (1962) for the vertical and perpendicular coil configurations to predict the depth-to-clay (z_{clay}) in a two-layered soil. Monteiro Santos et al. (2010) used a one-dimensional, laterally constrained algorithm to invert field-measured ECa data collected with a DUALEM-421S instrument. A forward modelling subroutine, based on the cumulative response from McNeill (1980) was used to calculate the apparent conductivity response of the model. Low z_{clay} values were associated with high ECa values and corresponding high β what makes the asymptotic approximations for the theoretical depth response functions deviating from the real depth response. On the other hand, different numerical inversion simulations based on Maxwell's equations fail to handle the depth functions for the perpendicular coil configurations. Therefore, the objective of this study was to fit depth response curves for different EMI coil configurations in a two-layered soil and apply these to map z_{clay} in a study area within the Belgian loess belt.

2. Materials and methods

2.1. Study area

In Belgium, the Weichselian Pleistocene loess belt occupies a low plateau (altitude 50–200 m) across the central part of the country (Fig. 1). In the loess belt, plateaus alternate with rolling hills and

valleys. The mean annual temperature is about 10 °C, while annual precipitation ranges from 700 to 900 mm (Hufty, 2001).

The 39 ha research area was located in Heestert (Belgium) (Fig. 1). It is situated on a southeast facing hillside with an elevation ranging between 25 to 45 m above sea level (a.s.l.). The site consists of eleven neighbouring arable fields (central coordinates: 50°47'58"N, 3°24'41"E). On the national soil map (scale 1:20,000), the soil series of the study area are characterized by a shallow or deeper clay substrate, a silt loam topsoil texture, moderately wet conditions and a textural B-horizon. This soil type corresponds to a loess-derived Haplic Luvisol (World Reference Base, 1998), which is characterized by an argic horizon ranging from 0.3–0.35 m up to 1.3–1.4 m in depth. Initially, the deposited loess was calcareous, but it decalcified mostly to a depth of 2–2.5 m (Hubert, 1976). Generally, a two-layered soil system is acceptable with silty-loess material above a clayey substrate.

2.2. DUALEM-21S electromagnetic induction sensor

In its simplest configuration, a proximal EMI soil sensor consists of two coils separated by a given fixed distance which is put on top of a soil. 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; Saey et al., 2009b). From this response the ECa of the bulk soil can be obtained. We used the DUALEM-21S instrument (DUALEM Inc., Milton, Canada) which consists of one transmitter coil and four receiver coils located at spacings of 1, 1.1, 2 and 2.1 m. 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 (1.1P and 2.1P) (see Saey et al., 2009a for schematic overview). McNeill (1980) provided a simple form of vertical sensitivity analysis using his cumulative depth response. Cumulative depth response (R) can be used to determine the sensitivity of EMI instruments to all material above or below a given depth. Depths are normalized to facilitate comparisons of

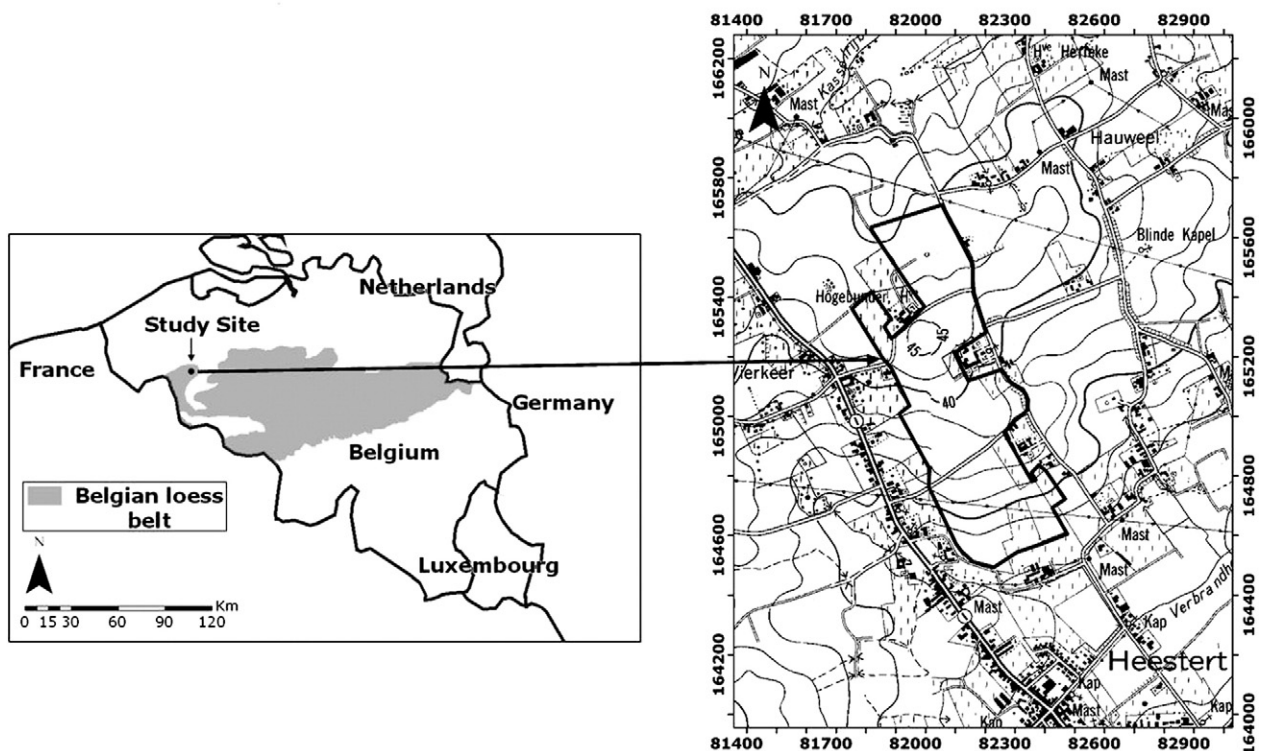


Fig. 1. Localisation of the study area in the Belgian loess belt and topographic map with indication of the boundaries (coordinates are according to the Belgian metric Lambert 72 projection).

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