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Predicting saturated hydraulic conductivity in a sandy grassland using proximally sensed apparent electrical conductivity

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ABSTRACT

Finding a correspondence between soil hydraulic properties, such as saturated hydraulic conductivity (*Ks*) and apparent electrical conductivity (ECa) as an easily measurable parameter, may be a way forward to estimate the spatial distribution of hydraulic properties at the field scale. In this study, the spatial distributions of *Ks*, of soil ECa measured by a DUALEM-21S sensor and of soil physical properties were investigated in a sandy grassland. To predict field scale *Ks*, the statistical relationship between co-located soil *Ks*, and EMI-ECa was evaluated. Results demonstrated the large spatial variability of all studied properties with *Ks* being the most variable one (CV = 86.21%) followed by ECa (CV ≥ 53.77%). A significant negative correlation was found between ln-transformed *Ks* and ECa (r = 0.83; $P \leq 0.01$) at two depths of exploration (0–50 and 0–100 cm). This site-specific relation between ln *Ks* and ECa was used to predict saturated hydraulic conductivity over 0–50 cm depth for the whole field. The empirical relation was validated using an independent dataset of measured *Ks*. The statistical results demonstrate the robustness of this empirical relation with mean estimation error MEE = 0.46 (cm h^{-1}), root-mean-square estimation errors RMSEE = 0.74 (cm h^{-1}), coefficient of determination $r^2 = 0.67$ and coefficient of model efficiency Ce = 0.64. The relationship was then used to produce a detailed map of *Ks* for the whole field. The result will allow model predictions of spatially distributed water content in view of irrigation management.

1. Introduction

Agricultural management requires detailed data at relevant management scales such as the field or the landscape scale. Digital soil property mapping methods and characterizing hydraulic properties at the field scale using proxy data (Brosten et al., 2011; Chaplot et al., 2011; Doolittle and Brevik, 2014; Sudduth et al., 2013) are increasingly being used. Such data in combination with hydraulic properties measured at multiple locations in the field are vital to predict and understand flow, solute and energy fluxes in soil (Vereecken et al., 2007).

Generally, accurate information about the spatial variation of field-scale soil hydraulic properties is required in water management, flow and transport processes (Farzamian et al., 2015), hydrology and hydrogeology (Niwas and Celik, 2012) and irrigation management (Gumiere et al., 2014). Direct measurements of these properties (in the field or laboratory) are not only time-consuming, labor-intensive and expensive, but they also perturb the system. Moreover, a high sampling density (in size and space) is generally required (Jury and Horton, 2004) to obtain an acceptable spatial resolution.

Linking hydraulic properties to apparent electrical conductivity (ECa) measured with electromagnetic induction (EMI) may be a way forward to estimate the spatial distribution of these hydraulic parameters across a field. Such ECa measurements are extensive, less expensive, non-destructive, efficient, reliable and timely (Corwin and Lesch, 2005; Niu et al., 2015; Segal et al., 2008; Sudduth et al., 2005). In addition, in precision agriculture, EMI measured ECa (Hedley et al., 2013) allows to complement the limited density of direct soil samples (Saey et al., 2009b) and assess soil hydraulic properties at higher resolution. Soil ECa is a function of a variety of soil properties including soil-water content, porosity, texture and structure (bulk soil properties), salinity (soil solution properties), cation exchange capacity (CEC), organic matter content, particle shape, size and distribution (solid particle properties), and soil layer thickness and topology (Corwin and Lesch, 2005;

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Friedman, 2005; Saey et al., 2008; Sudduth et al., 2013). Parameters affecting ECa are similar to those that affect soil physical and hydraulic properties, especially hydraulic conductivity, *K* (Doussan and Ruy, 2009; Niu et al., 2015; Pulido Moncada et al., 2014; Sudduth et al., 2005). Therefore, ECa can be considered as an indirect indicator of hydraulic properties.

Over the past two decades, a large volume of research has focused on predicting hydraulic properties from basic soil properties to map *Ks* distribution (Slater, 2007). On the other hand, empirical and semi-empirical relationships were established between ECa and soil properties. Researchers have applied Archie's semi-empirical law (Archie, 1942) to link *K* and ECa (Huntley, 1986). Both positive and negative significant linear regressions between log ECa and log *K* were reported (Brosten et al., 2011; Chaplot et al., 2011; Doussan and Ruy, 2009; Morin et al., 2010; Mualem and Friedman, 1991; Purvance and Andricevic, 2000a).

It was shown before that field water content predictions using a hydrological model are very sensitive to saturated hydraulic conductivity, *Ks* (Gumiere et al., 2014; Rezaei et al., 2015; Verbist et al., 2012). In our study site, Rezaei et al. (2015) concluded that the use of detailed digital elevation models, geophysical measurement techniques such as electromagnetic induction or ground penetrating radar as proxies for hydraulic parameters will serve as valuable data sources for hydrological models to calculate variable irrigation requirements within agricultural fields. Therefore, a better characterization of the field scale heterogeneity of *Ks* by using ECa data is very beneficial for precision management purposes. The present paper investigates empirical relationships of field ECa data and *Ks* to predict *Ks* more effectively and precisely at the field scale. In a first step, we performed a statistical analysis of the soil properties (*Ks*, ECa, bulk density, texture and organic carbon). We established statistical relationships between co-located *Ks*, selected soil physical properties and EMI-ECa. These relationships were then evaluated using an independent dataset of *Ks*. Finally, we estimated the *Ks* at the locations where the ECa was measured and produced a detailed map of *Ks* which may be used for irrigation management at the field scale.

2. Materials and methods

2.1. Study site description

The study site was located in a sandy agricultural area at the border between Belgium and the Netherlands (central coordinates 51°19′05″ N, 05°10′40″ E) characterized by a temperate maritime climate with mild winters and cool summers. The site is almost flat (less than 1%) and runoff is not considered to be important. This sandy soil is classified as a typical Podzol (Zcg-Zbg type according to the Belgian soil classification or cambisol according to WRB, (FAO, 1998)). The depth of the ground water table was between 80 and 155 cm below ground surface at various locations across the field depending on the topography, sloping up from NW to SE and SW. The field site is around 10.5 ha and is partly artificially drained by parallel pipes connected to a ditch in the North-West border of the field (Fig. 1) placed in 10 to 20 m intervals at around 90 cm below soil surface (as measured in the ditch). The field was planted with grass during the study period 2011–2013.

2.2. ECa measurements

ECa was measured at 5 m intervals between the measurement lines with a DUALEM-21S sensor (DUALEM, Milton, ON, Canada) on 25 March 2011. In this work, the perpendicular coil configuration data were used, corresponding to depths of exploration near 50 cm ($ECa_{p,50}$) and 100 cm ($ECa_{p,100}$). Details about the applied methodology for measuring ECa with the DUALEM-21S sensor can be found in Saey et al. (2009a, 2011b, 2012). In brief, the DUALEM-21S EMI sensor consists of one transmitter and four receiver coils at 1, 1.1, 2 and 2.1 m spacing from the transmitter coil. The receiver coils at 1 and 2 m from the transmitter are in horizontal coplanar mode and those at 1.1 and 2.1 m are in the perpendicular mode. In this study, all ECa measurements were converted to a reference temperature of 25 °C (Slavich and Petterson, 1990).

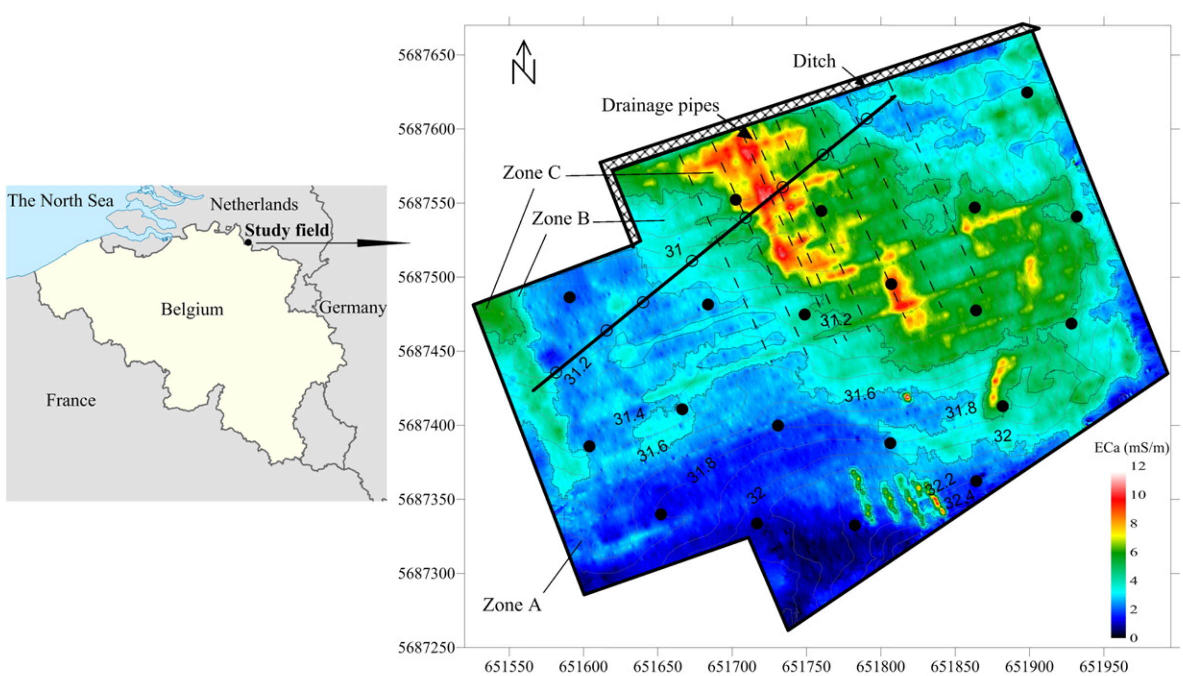

Fig. 1. Location of the study field and the classified map of 0–100 cm soil ECa with location of the 20 soil sampling locations (black bullets) from the ESAP software (calibration) and the eight additional points along the transect (validation). The 20 locations are well distributed over the FuzzyMe-derived ECa classes, with 7 locations belonging to class A (0.02 < ECa < 2.949 mS m^{-1}), 6 locations to class B (2.95 < ECa < 4.629 mS m^{-1}), and 7 locations to class C (4.63 < ECa < 11.96 mS m^{-1}) with indication of elevation contour intervals (labels in m a.s.l.).