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Identifying the plough pan position on cultivated soils by measurements of electrical resistivity and penetration resistance

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ABSTRACT

Long term tillage has led to soil profile degradation in many cultivated fields. The topsoil is disturbed by plowing. The movement of fine particles from the topsoil to the subsoil and direct pressure from agricultural machinery create an abrupt delineation in the form of a plough pan with very low permeability. The plough pan prevents water infiltrating deeper into the soil profile and reduces the water supply to the lower layers. The plough pan also has a negative effect on the root growth of the crop, leading to a reduced yield. In this paper we discuss the feasibility of using electrical resistivity tomography and penetrometry to identify the presence and the position of plough pans, and also their spatial uniformity, on two fields with different tillage depths. Electrical resistivity measurements were subjected to a comparison with soil physical characteristics, such as soil water content, porosity and bulk density. Standard statistical and geostatistical methods were used. Electrical resistivity tomography seems to be an attractive method that offers a faster and more efficient method than standard invasive soil sampling for obtaining continuous information about the plough pan. It has been shown that the position of a compacted layer within the soil profile can be identified reasonably well by combining electrical resistivity data and penetration resistance data. The semivariogram showed higher variation by orders of magnitude in the topsoil than in the subsoil. This suggests macroscopic homogeneity of the compacted layer formatted in the subsoil in two differently tilled fields. We conclude that a short span between the electrodes should be used (app 10 cm) in order to observe the shallow positioned plough pan clearly.

1. Introduction

Soil compaction, which may lead to the formation of a plough pan, is a well-recognized phenomenon in agricultural lands. Crop root degradation is one of the most dangerous effects of soil compaction. Roots are of reduced length (Lipiec et al., 2012) and there is reduced biomass (Colombi et al., 2016) in the compacted layer. Various effects can influence the degree of compaction in a field. Climatic or weather conditions, tillage system (Pagliai et al., 2004), the condition of the soil during harvesting (Boizard et al., 2002) and the machinery that is used (Pagliai et al., 2003) can lead to an increase or reduction in soil compaction. As a consequence, the hydraulic properties of the soil are affected. Ahuja et al. (1998), for example, showed how the water retention capacity of a field changes according to the tillage conditions. Dörner and Horn (2009) investigated of the isotropy/anisotropy of hydraulic conductivity in conventionally and conservationally tilled fields. Unlike conservationally tilled fields, conventionally tilled fields exhibited anisotropic conditions in the seedbed and in the plough pan.

A number of studies have investigated changes in the properties of porous media due to compaction. Bertolino et al. (2010) concluded that, in comparison with soils treated by minimum tillage, smaller and less connected pores occurred in the plough pan of conventionally tilled soil. Direct compaction due to the passage of traffic causes large differences in porosity (n) and differences in bulk density (ρ_{bd}) which leads to changes in the saturated hydraulic conductivity (Kim et al., 2010). However, the lower hydraulic conductivity of the plough pan is not necessarily the only reason. A significant decrease in hydraulic conductivity in combination with flow irregularity may also occur due the role of trapped air in the upper layer during infiltration (Císlerová et al., 1990; Sněhota et al., 2008). In contrast, Roulier et al. (2002) presented evidence of undisturbed bio-macropores in the plough pan, formed after soil cultivation or not yet disturbed e.g. by shrinkage, which allows water to flow through preferential pathways and to bypass the compacted plough pan. This consequently increased the overall hydraulic conductivity.

Changes of soil properties due to compaction lead to changes in the electrical properties of the soil. The changes in soil water content (θ), in the salinity of the water, in the clay fraction or in the bulk density lead

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to changes in the electrical resistivity (ρ) of the soil (e.g. Besson et al., 2004); Loke et al., 2013). The specific surface area of soil particles affects the resistivity because of an adsorbed water film on the soil particles (Revil et al., 2012), whereas the soil particles themselves (irrespective of size) and the soil air are often considered as an insulating material (e.g. Fukue et al., 1999). Macropores, cracks or voids and organic residues usually increase the electrical resistivity of the soil (Besson et al., 2013). Since the specific surface area of soil particles alters the electrical resistivity of the soil ρ, and it is affected by of soil compaction causing changes in the bulk density and in the structure of the soil, we assume that measurements of changes in ρ can provide information about the plough pan depth and homogeneity.

We used the electrical resistivity tomography (ERT) technique to obtain the position and the spatial uniformity of the plough pan. The study covered a series of 10 specific ERT transects. In general, this approach faces a few ambiguities. The electrical properties of soils, e.g. their electrical resistivity, are affected by several factors. It is problematic to recognize which factor is of major influence. Kowalczyk et al. (2014) conducted experiments with a sandy material in which it was shown that changes in electrical resistivity are caused by changes in bulk density, water content and total porosity. Similar results in field soils were observed by Besson et al. (2013), where the ERT data was influenced by the degree of water saturation. The bulk density was therefore tricky to determine. Organic carbon can also affect resistivity measurements, especially in the uppermost layer of the soil in agricultural land (Hadzick et al., 2011). When all quantities except the bulk densities are excluded, i.e. their effect is set as constant over a measured sample, the influence of bulk density is clearly present (Besson et al., 2004). In a study performed by Besson et al. (2004), 2D ERT measurements were compared with a visual inspection of the uncovered soil profile transect on an experimental plot. Although the resistivity was significantly lower in the plough pan, its exact position could not be determined. ERT did not detect the position of all clods in the topsoil. However, a clear negative relationship was found between electrical resistivity and bulk density for field soil samples. When the topsoil was less heterogeneous, it was less problematic to indicate the position of the plough pan.

Séger et al. (2009) presented a comparison of identifying topsoil features using 2D and 3D ERT. The 2D method was influenced by the hemisphere integration effect (Séger et al., 2009). The electrical current introduced to the ground by electrodes along a line introduces to the ground an electrical field that is hemispherical in shape. The records are therefore affected by lateral features to the side of the 2D line. Séger et al. (2009) showed that 3D measurements diminish the hemisphere integration effect, and enhance the sensitivity of the method to the structure of the topsoil. In qualitative terms, large clods, which occupied the whole depth of the topsoil (ca 30 cm), had the lowest resistivity; loose material had slightly higher resistivity, but smaller clods (∅ ca 5–10 cm) embedded in loose material had markedly higher resistivity. However, the position of the plough pan appeared only in the form of smoother changes in the horizontal 2D cross-sections of the 3D measurements. ERT and a penetration test were used by Basso et al. (2010). To assess the variations in soil resistivity in several differently tilled plots. They concluded that ERT can assist in identifying a compacted layer in the soil profile.

After a rain event, the infiltration capacity of the plough pan can be exceeded due to its low permeability. This causes the formation of lateral flow, (Coquet et al., 2005). Higher saturation above the plough pan affects data acquisition and makes the results more difficult to interpret. A detailed laboratory analysis of changes in the resistivity of different clays under variably saturated conditions was undertaken by Fukue et al. (1999). They measured abrupt changes in electrical resistivity at a certain saturation, at which the water film on the surface of a clay particle becomes connected, or ceases to be connected. The soil structure appeared to have a limited effect on the electrical resistivity (or conductivity) (Nadler, 1991). In many studies, the relationship between bulk density and electrical resistivity is assumed to be negative. However, some other studies have reached the opposite conclusion (e.g. Naderi-Boldaji et al., 2014). Electrical resistivity measurements of soil are also used in hydraulic conductivity assessments, (Mazáč et al., 1988), in soil classification based on resistivity distinctions between soil layers (Buvat et al., 2014) and in tracking distinct pedological volumes in a single soil layer (Séger et al., 2014).

The objective of our study is to assess the feasibility of using the ERT technique to determine the position of the plough pan, and its spatial uniformity and continuity. It is not our ambition to obtain the concrete physical properties of the soil layers. We utilize the sharp contrast in electrical properties between the topsoil and the subsoil caused by a combination of attributes such as organic matter content, clay particles, bulk density or current saturation to identify the divide. Data collection took place at two sites exposed to different tillage. From the agricultural, pedological, geological and climatological point of view, the two sites are representative of their region. The penetration resistance tests and the measurements of soil physical properties were collected in order to compile a data set for a comparative analysis. The results of the measurements are analyzed by means of standard statistical and geostatistical methods.

2. Material and methods

Our study consists of ERT measurements, penetration tests and measurements of the physical properties of soil core samples. We conducted four measurement campaigns. In each campaign, several ERT transects were measured. In selected ERT transects, three to five penetration tests were performed and soil core samples were collected at different depths. The penetration tests were performed to a depth of ca 65 cm. The soil core samples were taken at three to six depths, down to a depth of ca 50 cm. At least one set of core samples was taken from the top soil, and at least one was taken from the compacted layer if a plough pan was present. The penetration tests provided evidence of the presence and the position of a plough pan. The physical properties of the soil, namely soil bulk density, total porosity and water content, were evaluated to clarify the interpretation of the ERT data. The setup for typical ERT transect measurements, together with penetration tests and the collection of soil core samples is shown in Fig. 1. Each measurement campaign has its unique identifier (character A–D). The distribution of the measured transects (*T*) within the experimental catchment is depicted in Fig. 2. A summary of all measurements is shown in Table 1.

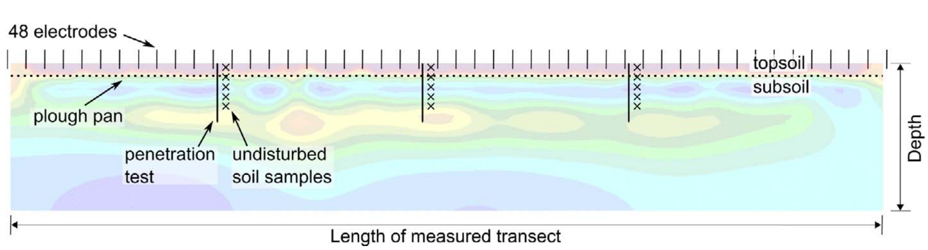

Fig. 1. Set up of ERT, penetration test and undisturbed soil sample sites at one ERT transect.